Chapter 3. A comparison of the first stages of biofouling in two offshore wind farms in the Belgian part of the North Sea


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In remembrance of our colleague Jean-Sébastien Houziaux, who left us far too early.
Abstract

In this contribution, the species composition and ecological succession of the biofouling on the subtidal zone (circalitoral) of selected foundations of two offshore wind farms in the Belgian part of the North Sea, the C-Power farm on the Thorntonbank and the Belwind farm on the Bligh Bank, are studied through time. As observed in many other studies, the colonization of the bare substratum has been very fast in the two studied wind farms.

No less than 50% of the total species pool (41 taxa out of 78 taxa) was shared between both wind farms and both wind farms were dominated by the amphipod *Jassa herdmani* with up to 90000 ind./m² (i.e. about 70% of the enumerable fauna). Other dominant species in both wind farms comprised the starfish *Asterias rubens* and the amphipod *Stenothoe valida*. The first year of the succession also showed a highly similar trajectory, with particularly mobile species, e.g. *J. herdmani* and *Corophium acherusicum* displaying a typical summer – winter oscillation pattern in both wind farms. This similarity was however less obvious for the sessile species such as *Pomatoceros triqueter* and *Clytia hemisphaerica*, and seemed to strongly diverge after the first year. The concrete gravity based foundations (GBFs) at the Thorntonbank hosted more species than the steel monopiles at the Bligh Bank (70 taxa versus 49 species). The presence of some coastal, soft sediment species such as the bivalves *Abra alba* and *Mysella (Kurtiella) bidentata*, only in the C-Power farm, further contributed to the dissimilarity between both wind farms. The biofouling on both wind farms exhibits direct influence by the same pool of species originating from the surrounding artificial and natural hard substrata.

As for shipwrecks, specific features of the studied structures such as verticality, substratum composition or lower depths may explain specific patterns of taxonomic composition such as an impoverished sessile epifauna compared to the surrounding natural hard substrata. Predatory activities are an important factor controlling the succession of sessile species on the substratum. The high degree of patchiness suggests that the colonization process is still ongoing and the mature state, the *Metridium senile* biotope, characteristic for this type of substrata in the North Sea is not fully reached yet.

Apart from the slipper limpet *Crepidula fornicata*, no introduced species have been observed thus far in the permanently submerged part of the wind turbine foundations. This observation contrasts with the intertidal and splash zone, where many introduced species were present in the biofouling community.

Samenvatting

Deze bijdrage is gewijd aan het onderzoek van de soortensamenstelling en de ecologische successie van de aangroeigemeenschap op het subtidale (circalitorale) deel van de funderingen van 2 windmolenparken in het Belgische Deel van de Noordzee, Namelijk het C-Power windmolenpark op de Thorntonbank en het Belwind windmolenpark op de Bligh Bank.

Zoals reeds in talrijke andere studies werd waargenomen, vond er een snelle kolonisatie plaats van het beschikbare substraat. Nee minder dan de helft van het totale aantal aanwezige soorten (41 van de 78 taxa) werd in beide windmolenparken aangetroffen. Op allebei de windmolenparken was de amphipode *Jassa herdmani* dominant aanwezig met dichtheden tot 90.000 ind./m² (dit is 70% van de telbare soorten). Andere dominante soorten in de beide windmolenparken waren de zeester *Asterias rubens* en het vlokreeftje *Stenothoe valida*. Tijdens het eerste jaar verliep de successie in beide windmolenparken zeer gelijkaardig met enkele mobiele soorten zoals *J. herdmani* en *Corophium acherusicum* die een typische zomer – winter oscillatie vertoonden. De sessiele soorten zoals *Pomatoceros triqueter* en *Clytia hemisphaerica* vertoonden een sterk verschillend kolonisatiepatroon waardoor de overeenkomsten na het eerste jaar minder duidelijk waren. Op de betonnen graviitaire funderingen van het C-Power windmolenpark op de Thorntonbank werden beduidend meer soorten aangetroffen dan op de stalen monopiles van Belwind op de Bligh Bank (respectievelijk 70 en 49 soorten). Het verschil tussen beide parken werd bovendien nog benadrukt door het voorkomen op de C-Power funderingen van enkele soorten die typisch zijn voor kustgebonden mobiele sedimenten zoals de tweekeleppigen *Abra alba* en *Mysella (Kurtiella) bidentata*. De biologische aangroei op beide
parken vertoont sterke gelijkenissen met de aangroeigemeenschappen op de artificiële en natuurlijke harde substraten in de omgeving en de rekrutering gebeurt blijkbaar uit een gemeenschappelijke soortenpool.

In vergelijking met de omliggende natuurlijke harde substraten is de taxonomische samenstelling van de sessiele epifauna verarmd. Dit kan, net zoals bij scheepswrakken, verklaard worden door specifieke kenmerken van de bestudeerde structuren zoals verticaliteit, samenstelling van het substraat of een lagere waterdiepte. Daarnaast speelt de activiteit van predatoren een belangrijke bepalende rol bij de opeenvolging van sessiele soorten. Deze fenomenen zorgen voor de specifieke patronen. De hoge mate van ruimtelijke heterogeniteit (patchiness) suggereert dat het kolonisatieproces nog niet voltooid is. De climaxgemeenschap, de *Metridium senile*-gemeenschap, die kenmerkend is voor dit type van substraten in de Noordzee wordt bijgevolg nog niet maximaal bereikt.

Behalve het muiltje, *Crepidula fornicata*, werden geen andere geïntroduceerde soorten aangetroffen op de permanent ondergedompelde (subtidale) delen van de windmolenfunderingen. Deze waarneming contrasteert sterk met de intertidale en spatzone waar in de biologische aangroeigemeenschap overwegend geïntroduceerde soorten aangetroffen werden.

### 3.1. Introduction

With the construction of offshore wind turbines in the Belgian part of the North Sea (BPNS), a new habitat of artificial hard substratum is introduced in a region mostly characterized by sandy sediments. This largely enhances the habitat heterogeneity of the region and the effect of the introduction of these hard substrata is regarded as one of the most important changes of the marine environment caused by the construction of wind farms (Petersen & Malm, 2006).

It is well known that submerged artificial hard substrata are rapidly and intensively colonized by biofouling (e.g. Horn, 1974; Connell & Slatyer, 1977). This had been found to be the case with wind turbines in the North Sea (e.g. Schröder *et al.*, 2005; Kerckhof *et al.*, 2009; Kerckhof *et al.*, 2010). Fouling assemblages will develop successively, which may resemble epibioses on natural substrata (e.g. Connell, 2001). The wind turbines will also enable the establishment of species previously not present in an environment dominated by soft sediment habitats, as well as the further spread of non-indigenous species (stepping stone effect) (e.g. Kerckhof *et al.*, 2011). Certain warm water species may also take advantage of the increased presence of hard substrata to spread further into the North Sea due to climate change. Alternatively, the foundations and associated scour protection may allow for the re-establishment of biological communities previously present on nearby gravel beds.

Fish populations including commercial fish are also attracted (Reubens *et al.*, 2010). Furthermore, Belgian wind farms are closed to fisheries and may thereby act as protected areas. One of the major reasons causing fish to aggregate around such artificial structures and reefs emerging from the seafloor is the provision of food through the development of a species-rich hard substratum epifauna community (Reubens *et al.*, 2010). The systematic monitoring of this new biofouling community in the area is therefore an important factor to take into account when researching the biodiversity within wind farms.

The establishment of a biofouling community usually follows a clear successional development: the new structures will be gradually colonized by a number of species. These organisms will each influence the environment in a species-specific way, as such preventing other organisms to get established (i.e. inhibition) or creating the right circumstances for other species to join in (i.e. facilitation) (Connell & Slatyer, 1977). Consequently, the number of individuals of each species in the community will change and gradually new species will arrive that may progressively replace the first inhabitants. This long term process is known as ecological succession.

It is expected that differences in the nature of the substratum will create different (initial) conditions for the development of a biofouling layer, likely influencing the next colonization steps. On the other hand, the two wind farms are located at different distances from the shore (~25 km for C-Power, ~35 km for Belwind). Van den Eynde *et al.* (2010) showed that higher levels of turbidity are reached in winter at the Goote Bank, nearby the Thorntonbank (C-Power farm), compared to the Bligh Bank (Belwind farm). No data has yet been processed on the Thorntonbank itself (Michael Fettweis, pers. comm.). The C-Power site is thus expected to experience a more pronounced influence
of coastal waters than the more offshore located Belwind farm though this may be weak. However, parameters such as the verticality of the substratum, its nature, or slight differences in environmental drivers are likely to drive site-specific differences, as was observed on some shipwrecks of the area (Zintzen, 2007). Furthermore, the installation of wind turbines was not carried out simultaneously at the two wind farms: the C-Power gravity-based foundations were installed by mid-spring 2008, while the steel foundations of Belwind were installed by early winter 2009-2010. Yearly variations in the benthic composition of the zooplankton (larvae and dispersing adults) are expected to strongly influence the initial species composition independently from other site-specific features.

In this contribution, the species composition of the subtidal zone (circa littoral) of selected foundations is studied through time in the two aforementioned wind farms. The analysis aims at tentatively detecting site-specific differences and disentangling the influence of the various environmental parameters driving the fouling process. We hypothesize that, even though the nature of the substratum, geographic position and installation time will drive site-specific differences, the faunistic patterns will be dominated by a common pool of species that also dominates on the surrounding natural and artificial hard substrata of the area. We further discuss the species composition and discuss the occurrence of introduced species.

3.2. Material and methods

3.2.1. Study area

In late spring 2008, the first six concrete foundations of the C-Power wind farm were installed on the Thornton bank, some 30 km off the Belgian coast. Between September 2009 and February 2010, 56 steel monopile foundations were installed at the Belwind wind farm on the Bligh Bank. Both banks belong to the Zeeland Banks system (Cattrijsse & Vincx, 2001). Local water depth within the wind farms ranges from 7 - 30 m and the surrounding soft sediment seabed is composed of medium sand (mean median grain size: between 350 and 500 µm (Coates et al., 2010). The average residual water transport is oriented to the northeast (Ruddick & Lacroix, 2006).

The two offshore wind farms are situated along the eastern border of the BPNS, relatively close to each other (about 25 km) and almost equidistant from the gravel grounds of the Hinder banks (about 15 km; see Houziaux et al., 2008). Various shipwrecks are found in the area (see Zintzen, 2007).

3.2.2. Sample collection and processing

A monitoring programme was set up to sample the hard substrata associated with the wind turbines (Kerckhof et al., 2008). The first sampling took place in late summer 2008 at C-Power and in winter 2010 at Belwind (Figure 1). Samples were collected from a selected set of wind turbines: wind turbines D5 and D6 (GBF) (Figure 2) at the C-Power farm and wind turbines C2, B8 and C8 (steel monopile) at the Belwind farm (see Brabant et al., 2011 for the geographic positions of the considered wind turbines).
Figure 1. Temporal distribution of sampling occasions and weekly-averaged temperature at the C-Power (blue bullets) and Belwind (red bullets) wind farms, grouped on a monthly basis. Upper arrows indicate the installation time of the considered wind turbines.

Figure 2. Concrete C-Power gravity based foundation (D5) with epifouling of blue mussels *Mytilus edulis* attached to a piece of rope, two colour forms of the sea-anemone *Metridium senile*, the white calcareous tubes of *Pomatoceros triqueter*, sea urchins *Psammechinus miliaris*, sea stars *Asterias rubens* and empty and living specimens of the barnacle *Balanus perforatus*. 
Subtidal samples were collected by scraping the fouling organisms with a putty knife from a sampling surface area of 0.25 m x 0.25 m. All scraped material was collected in plastic bags that were sealed under water and transported to the laboratory for processing (entailed fixation in 5% formaldehyde – seawater solution, sieving (1 mm mesh sieve), sorting and preservation in 75% ethanol), identification and quantification. Only the fraction >1 mm was considered in this study. Two to six replicates were collected during each sampling event.

Organisms were identified to the lowest possible taxonomic level and, where possible, counted. Densities were expressed as the number of individuals per m². Identifications were based on the most recent systematic literature and we followed the World Register of Marine Species (WoRMS) for the nomenclature and taxonomy at species level. Video footage collected by the divers was used to determine to what extent the scrape samples represent the actual fauna and to identify a number of rare, large and/or mobile invertebrate species that are otherwise not (adequately) represented in the scrape samples. A total of 111 replicate scrape samples collected at 36 stations were considered for this analysis.

### 3.2.3. Data processing

Prior to analysis and depending on the taxonomic level of identifications as well as their accuracy, some taxa were lumped to reach consistency in taxonomic resolution throughout the data. Records of skeletal parts, tubes, eggs, spat and larvae were removed from the data set to focus only on juveniles and adults of macrobenthic species that were alive at the time of sampling, the counts of which were summed. For colonial sessile species, which cannot be enumerated otherwise than with semi-quantitative estimates (e.g. SACFOR scale; Connor & Hiscock, 1996), records were converted to presence/absence data because not all data could yet be appropriately processed. The species were flagged according to their enumeration mode (two values: density or presence) and their living habits (two values: sessile or mobile) for further data selection and aggregation.

The seasons were arbitrarily defined depending on the yearly temperature pattern (Figure 1), with winter considered to comprise January, February and March. Sea surface temperature (SST) data were acquired from Bundesamt für Seeschifffahrt und Hydrographie, (Germany; see Loewe, 2003). Weekly-averaged values computed from a variety of field measurements (data source: http://www.bsh.de/aktdat/mk/nordsee/Digdat/) were interpolated in the 5 x 5 km grid of the MIRO&CO-3D model (Lacroix et al., 2007) to obtain average values representative for the Belwind and C-Power wind farms (Figure 1).

As the installation of the wind turbines did not take place simultaneously in the two farms, two time lines were created to chronologically analyze species composition: one time line of elapsed days since installation for each site and one calendar-based time line starting on April 1, 2008 (early spring; Figure 1).

### 3.2.4. Analysis strategy

Univariate as well as multivariate (statistical) analyses were carried out on replicate samples for various subunits of the data set: sessile species (presence/absence), mobile species (densities) and all enumerable species (densities). One sample was removed from the data-set due to out-of-range density (~10⁶ ind/m²) of the amphipod *Jassa herdmani*, apparently linked to the lower sampling depth of this sample (6 m instead of 15 m). The frequency of occurrence of the species in the samples was also considered. For comparison purposes, the C-Power data were further reduced to 800 days (calendar-based time line) and 510 days (time elapsed after installation).

Presence/absence transformation of the whole species range was not done since only few colonial species are frequent. Several univariate diversity indices were computed on a replicate sample basis (species richness, S; total abundance, N; Shannon-Wiener evenness based on log10; taxonomic breadth based on presence-absence data; taxonomic diversity based on density-weighed data) and were averaged per season and year. Multivariate analysis was carried out with the PRIMER-E software (version 6; Clarke and Warwick, 2001; Clarke and Gorley, 2006). The Bray-Curtis similarity matrix was computed on fourth-root transformed densities or on presence-absence data and
similarities were plotted through multidimensional scaling (MDS). The same analyses were repeated after removal of the super-abundant *J. herdmani*. Cluster tree analysis with SIMPROF permutation test, as well as the SIMPER procedure were applied to identify species most contributing to within-group similarities. An ANOSIM permutation test was further carried out to detect significant differences between samples on the basis of wind farm, season and season + year.

A principal component analysis (PCA) was used to determine the main structuring variables in the datasets (ter Braak and Prentice, 1988) and was performed on a selection of species (only species occurring in more than 25% of all samples from both farms) to tentatively track the chronological path of species compositions within samples through seasons and years on the basis of sampling event-averaged centroids for PCs 1 and 2.

3.3. Results

3.3.1. General faunistic composition: taxonomic abundance and richness

We considered a total of 78 taxa for analysis of the scrape samples. None of these were new to the BPNS. Eight taxa were exclusively present at Belwind and 29 taxa exclusively at C-Power, while 41 taxa were shared. The taxon richness was lower at Belwind, with a total of 49 taxa compared to 70 observed at C-Power (64 after 800 days). However, it is equally distributed at the Ordo level in both farms (Figure 3). About 50% of all species were either polychaetes or decapods.

The samples from both wind farms displayed a wide taxonomic breadth but were strongly numerically dominated by one superabundant species, the amphipod *J. herdmani*, which caused the group Crustacea - Malacostraca to represent on average 67 and 76% of the enumerable sample content at Belwind and C-Power, respectively (Figure 4). When this species was removed, the species assemblage displayed a much larger proportion of barnacles (Arthropoda - Maxillopoda) at Belwind, representing about 50% of enumerable species, even when the data set was reduced to the first 800 days at C-Power. In the latter site, mobile crustaceans still numerically dominated the assemblages, while barnacles rapidly declined. Noticeably, the relative abundance of starfish (mostly represented by *Asterias rubens*) strongly increased in spring 2011. Octocorallians were represented by small colonies of dead man’s fingers *Alcyonium digitatum*, that appeared at both farms at the same moment.
3.3.2. Temporal evolution of the biofouling community at both wind farms

3.3.2.1. Univariate diversity indices

Species richness displayed similar trends at both farms during the first year after installation: in the first summer, a high number of taxa colonized the newly available substratum (Figure 5). This happened at C-Power in summer 2008 and at Belwind in spring and summer 2010. However, the first winter sampling at Belwind, eleven weeks after installation, yielded no macro fauna. In both cases, a very fast colonization of the substratum as well as a large variability in taxon richness is observed. The richness dropped in the first fall and winter, reflecting winter mortalities, and increased again in the next spring and summer as new recruits colonize the substratum.

During the second fall, the average taxon richness abruptly decreased at Belwind (from 12 to 5 taxa/sample), while at C-Power it remained relatively constant after fall 2009 (~18 taxa/sample). When split into their mobile and sessile components, the situations differed more markedly: at C-Power the number of sessile species quickly stabilized and did not follow the initial oscillation displayed by the more numerous mobile species. The richness of sessile taxa varied more at Belwind, where it showed a dramatic drop in the second fall (2011). The average richness of sessile taxa is low at the two locations and ranged from 2 (Belwind – fall 2011) to 12 taxa (C-Power - summer 2008).
In summer 2010, the two wind farms had very similar levels of taxon richness (Figure 6), even though the communities were at different stages. Belwind generally had lower levels compared to C-Power, whatever the time elapsed since wind turbine installation, although the variability among the individual samples was important. The taxonomic breadth (sDelta+; not shown) displayed exactly the same trends as the species richness.

When abundances are taken into account (total density; Shannon-Wiener evenness, H'), the amphipod *J. herdmani* exerted a strong influence (Figure 6) by its numerical dominance. The species was virtually absent from the first samples at C-Power, although juveniles were observed in the fine fraction (< 1 mm). Afterwards, *J. herdmani* densities always numerically dominated the rest of the species. At Belwind, the species had the opportunity to colonize the substratum in the first spring and densities comparable to that observed at C-Power were already measured in summer 2010.

When *J. herdmani* was removed, the total density of benthic species showed a similar increasing trend at C-Power except in fall 2009 and winter 2010. Within these periods, the population size of *J. herdmani* kept increasing while the total density of other species decreased, causing the Shannon-Wiener evenness to reach a minimum value. However, after removal of *J. herdmani* from the index the evenness remained fairly stable after the first winter at both farms, even in winter, indicative of a more even distribution of the relative abundances of the other species. The total densities of other species were lower at Belwind except during the first summer, but the Shannon-Wiener evenness was similar.

![Figure 5](image-url)

Figure 5. Temporal evolution of species richness since wind turbine installation in the two farms. Above: total species richness; below: sessile and mobile species richness. Open symbols: Belwind; Plain symbols: C-Power. Squares: sessile species; triangles: mobile species. Error bars are standard deviations.
Overall, when not overly influenced by *J. herdmani* abundance, the diversity indices point to a systematically lower biological diversity at the Belwind farm. This difference is further illustrated by a systematically lower frequency of occurrence of individual taxa at the Belwind farm, even when the C-Power data set was reduced to the first 800 days since installation. However, when the dataset was reduced to 510 days at C-Power (Figure 7), the taxon richness was more similar (54 taxa at Belwind versus 49 taxa at C-Power).

Figure 6. Temporal evolution of diversity indices averaged per wind farm, season and year since spring 2008; (a) taxon richness, (b) density of the amphipod *Jassa herdmani*, (c) total abundance, (d) total abundance, *J. herdmani* excluded, (e) Shannon-Wiener evenness (log10), (f) Shannon-Wiener evenness, *J. herdmani* excluded. Error bars are standard deviations.
3.3.2.2. Temporal trends in species composition

Over time, a progressive increase of the total density takes place as well as an increase of the *J. herdmani* population. However, as shown in Figures 5 and 6, the species richness remained relatively constant after the second summer at C-Power. Contrary to Belwind, some coastal soft bottom species were present in the C-Power assemblage. Of the 29 species found exclusively at C-Power, three species, *Abra alba* and *Mysella (Kurtiella) bidentata* (two bivalves) and *Pectinaria koreni* (a polychaete worm) are normally exclusively found in coastal muddy sands. They are among the numerically dominant species of the “*Abra alba* community” (Van Hoey et al., 2004, 2005).

At the C-Power wind farm, some of the species that colonized the substratum in spring/summer 2008 remained present in all samples after summer 2009, indicating that they have established permanent populations (Figure 8). The amphipod *Corophium acherusicum* became particularly abundant in 2010 and 2011, even in winter, while it remained rare at Belwind. Summer 2010 coincided with the early colonization phase at Belwind, characterized by a peak of total density and species richness and a larger abundance of a typical pioneer species, the barnacle *Balanus crenatus*. 
Figure 8a. Trends in densities of species that occur in more than 25% of the stations, excluding the superabundant *J. herdmani*, at C-Power and Belwind

In spring 2011, at C-Power, next to *J. herdmani* two species numerically dominated the samples, namely the starfish *Asterias rubens* and the amphipod *Stenothoe valida*. Exactly the same observation can be made at Belwind in this period, although their average density was lower.

The total number of colonial species was low at both wind farms (Figure 5). Most species were relatively rare, except for the hydroids *Tubularia* spp. and *Clytia hemisphaerica* and the bryozoan *Electra pilosa* (Figure 7). These species were early colonizers in both farms. Next to these colonial species, sea anemones (Actiniaria), represented by *Metridium senile*, *Sagartia troglodytes* and *Urticina felina*, were most frequent as well.

Fourteen sessile (colonial and solitary) species were found at both farms, nine species were found only at the C-Power farm, six only at Belwind. Most non-shared species are found only occasionally,
except for Balanus perforatus and Obelia spp. that were frequently observed at C-Power. Of the shared species pool, ten species displayed consistent temporal distribution patterns at both farms, being found throughout the sampling period, at its beginning or at its end.

At both farms, the number of sessile taxa which could establish permanent populations is low, explaining the pattern of Figure 5. Most of the variability in sessile taxon richness could be explained by occasional species. In fall 2011, when diversity indices dropped at Belwind, only four of the most frequent species were yet observed in these samples (Actiniaria, Pomatoceros triqueter, Lanice conchilega, C. hemisphaerica) along with Mytilus edulis. Sea slugs (Nudibranchia) that mostly feed on sessile species were noticeably frequent (Figure 7) and found throughout the sampling period. The barnacle B. perforatus was observed throughout the sampling period, in contrast to its close relative B. crenatus, found only in the earliest stages of the colonization process at both farms.

The overall taxon composition is analyzed focusing on all enumerable species (sessile and mobile). The non-metric MDS ordination of the Bray-Curtis similarity matrix shows a separation between the samples of both farms (Figure 9). The superabundant J. herdmani, which masks patterns explained by other taxon’s densities, is a characteristic species of almost all samples. Obviously, when J. herdmani is excluded from the data set, a larger dispersion is observed, but the relative positions of samples in the MDS plot are fairly conserved. This species hence does not drive the multivariate pattern but is clearly installing permanent and superabundant populations. It can be removed from the data set to investigate the evolution of the rest of the species assemblage.

Table 1: List of the sessile species thus far determined in the samples of Belwind and C-Power farms and their patterns of occurrence in the samples: “T”: Throughout the sampled period; “E”: Early colonist; “L”: Late colonist; “O”: occasional species; “-”: absent.

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The grouping of the C-Power samples after summer 2009 confirmed the trend towards a more similar species composition than the early samples. At Belwind, the spatial variability induced by sampling different foundations seems to play a role in the dispersion of the data. The species compositions are different between years 1 (2010) and 2 (2011). A similar distinction was found for C-Power between 2008 and 2009. The centre of the MDS plot coincides largely with years 2010 and 2011 at C-Power. An ANOSIM procedure resulted in very highly significant discrimination (p<0.001) between samples on the basis of farm, season as well as season + year. A cluster analysis of species compositions at C-Power (not shown) yielded clusters which indeed largely correspond to samples grouped by year, season and farm.

The distribution of the samples of C-Power in the multivariate space seemed to be driven by a seasonal oscillation and a yearly evolution, but these trends were yet unclear. A principal component analysis (PCA) on a selection of species (species occurring in more than 25% of the stations) yielded a seemingly clearer trajectory of samples through time and seasons, but less than 50% of the variance was explained by the two or even three first principle components. In such case, caution is advised by Clarke and Warwick (2001) in data interpretation, especially if the pattern is not conserved in the non-metric Bray-Curtis similarity matrix. This poor result indicates that at C-Power species are still subject to an important turnover after four years, even though the overall species richness stabilized after the second summer (Figures 5 and 6). In addition, the replicate samples display some variability (Figure 9), pointing to a high patchiness of the species composition.

Figure 9. MDS plots of the Bray-Curtis similarity matrix calculated between samples based on densities of enumerable species (after fourth root transformation). Left: including Jassa herdmani; Right: excluding J. herdmani. In both cases, scaled bubbles were superimposed for (i) abundance of J. herdmani in the samples, (ii) total abundance of enumerable species N (excluding J. herdmani) and (iii) total taxon richness S.
3.4. Discussion

3.4.1. General colonization patterns

As could be expected (e.g. Horn, 1974; Connell & Slatyer, 1977), both farms showed a high diversity of fouling organisms during the early settlement phase, despite the fact that the investigated wind turbines were installed at different moments of the year (i.e. winter and late spring). The two wind farms display differences in the frequency of occurrence of some species, even when the C-Power data were reduced to the first 510 and 800 days since installation to account for a comparable time period or number of summers. The numerically dominant species are the same and the overall taxonomic composition is similar, reflecting the background species composition.

The concrete foundations of C-Power, installed by late spring, were colonized by species that settle in late summer and early autumn such as the barnacle *B. perforatus*. Nevertheless, the highest species richness was measured during the first summer in both cases. Many of these species did not survive the winter. In the next spring and summer, the remnant species pool was further altered by new settlers. The data of summer 2010 show that many new spring settlers are the same in both farms, indicating that the species pool of potential species is shared at least to a large extent.

All of the recorded species are typical colonisers of hard substrates and are regularly found on man made surfaces in Belgian waters (Zintzen, 2007) and elsewhere (Bouma & Lengkeek, 2009; Leonhard & Pedersen, 2006; van Moorsel *et al.* 1991; van Moorsel & Waardenburg, 2001). Below the infralitoral mussel zone, the foundations became dominated by echinoderms, anemones (predominately *Metridium senile*) barnacles, hydroids and the tube forming worm, *P. triqueter*. This community occupied the entire surface of the monopiles from the zone below the mussels to the sea floor, indicating that fouling organisms display a wide bathymetric tolerance. A similar habitat and zonation pattern in the subtidal has been reported on artificial hard substrata in the intertidal zone and on other wind farms in the North Sea (e.g. EMU, 2008; Whomersley & Picken, 2003; Joschko *et al*., 2008; Bouma & Lengkeek, 2009; Leonhard & Pedersen, 2006).
The numerically dominant taxa are those found abundantly on other hard substrata of the BPNS thus far studied (shipwrecks: Zintzen, 2007; gravels: Houziaux et al., 2008). Compared to the potential species pool of the area, the sessile component on the foundations, i.e. the vertical component of both wind farms appears to be impoverished. Sponges, branching bryozoans, tunicates, some tubicolous polychaetes as well as many branching hydroid species have not been found or only in low numbers. The data indicate that only few species were able to install permanent populations, while most other species are yet occasional in the samples. Noticeably, the dead man’s fingers A. digitatum, abundant on the nearby gravels but mostly as tiny colonies, appeared in 2010 at both wind farms, while it was absent at C-Power in the previous years. Some of these “missing” taxa can thus expected to show up in the next years as the communities evolve to a more mature stage, provided that they encounter suitable environmental conditions, room for settlement, as well as a predation pressure that is reasonably low.

However, our data indicates that there is still a large turnover of species and the whole fouling assemblage is still immature. We would expect the initial fauna of opportunistic species (r-strategists) to gradually be replaced by less opportunistic and more long-lived, slowly reproducing species (K-strategists). It is however possible that this will never happen and that these communities will remain in an impoverished state as has been observed on other artificial hard substrates, such as wrecks (Hiscocks et al., 2010; Zintzen, 2007). This would lead to a community that is distinctly different to natural stony reefs. In such case, the artificial hard substrates provided by the wind farms cannot be considered a replacement for damaged or destroyed natural stony habitats.

The exact combination of species and their relative abundance varies between farms and even replicates and is dependent on environmental characteristics and upon species interactions. Not surprisingly, the multivariate analyses revealed a major influence of seasons and years on the temporal evolution of the species composition at C-Power over a longer period. At Belwind, it seems yet to be too early to analyze the species succession. However, C-Power results, obtained on various wind turbines, highlight the patchiness of the colonization process.

We attempted to attribute the fouling community to one of the biotopes of the JNCC Marine Habitat Classification (Connor et al., 2004). Although for circalittoral rock some fouling communities are mentioned specially for new artificial hard substrata we were not able to find a full match. The Metridium senile biotope (CR.FCR.FouFa), typical for artificial hard substrates in the North Sea (Whomersley & Picken, 2003) and identified elsewhere on wind turbines in the North Sea, e.g. EMU, 2008; van Moorsel et al., 1991 is the closest match. Especially the abundance of echinoderms both Psammechinus miliaris and A. rubens differentiated our communities from the ones mentioned in the classification. The abundant presence of echinoderms seems to be a feature of the early phase of the colonization and is apparently also found on other wind farms in the southern North Sea (e.g. Bouma & Lengkeek, 2009). This situation may be a transitional one to the Metridium dominated biotope. Bare patches left after the passage of Psammechimus and Asterias will easily be colonized by anemones (mainly M. senile) and (tubes of) the small crustacean J. herdmani. There are indications that the dominance by echinoderms, especially sea urchins, takes place in the early colonization phase. Psammechinus miliaris, for instance, was very abundant on the wreck of the HMS Scilla in the first years, while it disappeared in a later successional stage (Hiscocks et al., 2010). Characteristic is a high degree of patchiness, with bare areas and areas where one particular species dominated e.g. Hydractina echinata (Figure 10), Tubularia spp., P. miliaris or M. senile, a phenomenon also noted by van Moorsel et al. 1991 on wrecks off the Dutch coast and called by them “associations”, with the M. senile association then being the final stage. Offshore shipwrecks might thus be indicative of a mature state of the subtidal epibiotic assemblages on such artificial substrates, namely a specific sub-assemblage of the local pool of hard substratum species. Noticeable, the calcareous tube building P. triqueter, despite being always present, did not manage to form reef like structures as is sometimes the case on other natural and artificial substrates.

A number of species typical for the soft sediment “Abra alba community” (Van Hoey et al., 2004, 2005) such as Abra alba and Mysella (Kurtiella) bidentata (two bivalves) and Pectinaria koreni (a polychaete worm) were found exclusively at C-Power. These species are normally found living in coastal muddy sands. Two of these species have also been recorded on ship wrecks: M. bidentata (found on two wrecks in the BPNS) and P. koreni on wrecks in the BPNS and Dutch waters (Zintzen, 2007; van Moorsel et al., 1991). All three species have further been found in the fouling community
on buoys (Kerckhof, unpublished data). They obviously take advantage of the presence of the muddy turf, largely as the result of the tube-building activities of the amphipods *Jassa* and *Corophium*, to settle.

![Figure 10. Detail of the fouling assemblage on the C-Power D5 with a prominent colony of *Hydractinia echinata* (centre) overgrowing some empty barnacles *Balanus perforatus*. In the right part of the picture a slipper limpet *Crepidula fornicata*, partly covered by *Jassa* - turf is visible, two sea urchins *Psammechinus miliaris* and a young starfish *Asterias rubens*, in the left corner a young plumose sea anemone *Metridium senile* can be seen.](image)

**3.4.2. Species interactions and community dynamics**

Predation is an important factor that controls the occurrence and succession of sessile species. Within the circalittoral zone information on biological interactions is not easily available, but sea urchins and starfish both have the potential to function in keystone roles. Some abundant grazers / predators on the sessile fauna, such as the sea urchin *P. miliaris* and the starfish *A. rubens*, may have prevented the dominance of barnacles – common in the very early phase – and mussels (never present in large numbers). *Psammechinus miliaris* is an omnivorous and voracious species feeding on a broad range of sessile organisms (Kelly & Cook, 2001) and it has been demonstrated that sea urchins can reduce the diversity of the biota by intense grazing (e.g. Mitchell *et al.*, 1983) or prevent the development of the normal invertebrate community (e.g. Sebens (1985 a, b). *Asterias rubens* also an omnivorous and voracious predator (Vevers, 1949) is also considered important in clearing space on rock by grazing barnacles, mussels and ascidians (Menge, 1982). *Asterias* reduced the cover of sessile species on settlement panels in Sweden to 20%, compared to 100% when they were excluded (Lundälv & Christie, 1986). Additionally, sea slugs (nudibranch molluscs) that were frequently and abundantly observed tend to be more specialized. Of the species thus far identified, *Facelina bostoniensis* and *Cuthona gymnota* are known to feed on *Tubularia* spp., *Eubranchus* spp. on *Obelia* spp., *Onchidoris bilamellata* on barnacles and *Onchidoris muricata* on *Electra pilosa* (Picton & Morrow, 1994). Also these species may hence play an important role in the evolution of the fouling community. In spring 2010 at the Belwind farm, for example we could witness the total disappearance of a dense *Tubularia indivisa* cover under the predatory activities of high densities of nudibranchs within no more than five weeks.

The yearly pool of species able to settle onto the artificial hard substrates is dependent upon the species’ population dynamics on the surrounding hard substrata, substratum composition, available space for settlement, predation pressure and the prevailing hydrodynamics conditioning their dispersal.
paths. It seems that sessile species better resist winter conditions at C-Power compared to Belwind, where their richness tends to drop and frequencies of occurrence in the samples remain lower. It seems that the steel foundations are more prone to vibrations induced by wind and/or waves and current (as indicated by the increased underwater noise levels observed in Norro, 2011), a parameter which could exert influence on the settlement and survival of certain species on the vertical surface next to differences in substratum roughness (painted steel versus concrete). Wetzel et al., (2011) also concluded that roughness was a key driver to species composition on artificial hard substrates. As the fouling process will continue over the next few years, this pattern will probably become more pronounced.

At the C-Power wind farm, the data collected over a period of four year showed that the mobile component is still subject to an important turnover, with an apparent alternation of numerically dominant species through time. The increased presence of *A. rubens* and *S. valida* in both wind farms during summer 2010 also points to a large influence of the fluctuation in the population dynamics of the species at a larger scale. The sessile component stays dominated by few species, while many other species appear to be occasional or rare. This pattern is also typical for the surrounding natural hard substrata, where most species are found in low densities (Francis Kerckhof, pers. obs.).

The tube dwelling amphipod *J. herdmani* is the most abundant species on both wind farms. Maximum densities of 200,000 ind/m² (only specimens larger than 1 mm), and even 1 million ind/m² in one shallow sample were observed at C-Power in July 2009. This high abundance was also observed in other studies dealing with artificial hard substrata in the southern North Sea such as shipwrecks (e.g. Zintzen, 2007) and other wind farms (e.g. Leonhard and Pedersen, 2006; Orejas et al., 2005). In a German study, even higher densities were recorded (max. 1.317.045 ind/m²; Orejas et al., 2005). This species was one of the earliest colonists and appears to be most successful in taking advantage of the new hard substrate habitats. Although it is a short-lived species, it has almost year-round reproduction and high fecundity (Nair and Anger, 1980). Consequently, juveniles were found in nearly all seasons. *Jassa herdmani* builds tubes and constructs mats that smother underlying species such as barnacles, in addition to making the surface less suitable for the settlement of other species. It seems that the abundance of this species may negatively impact the sessile component, but it was recorded abundantly at both locations. Another tube dwelling amphipod, *C. acherusicum*, was also common but appeared later in the succession. It is remarkable to find both tube dwelling amphipods living side by side on the same substratum. Despite the offshore location of the farms, under the influence of clear English Channel water (Kerckhof et al., 2009), there seems to be enough fine sediment in the water for these species to build their tubes. On the other hand, *S. valida*, a free-living amphipod typically associated with *Tubularia* mats, was also abundantly observed in spring and summer 2011. These species, together with the also abundant porcelain crab *P. longicornis*, constitute an important food source for fish species which aggregate in these wind farms (Reubens et al., 2010).

### 3.4.3. Taxonomic composition

A large diversity of phyla was able to settle down on these hard substrata explaining the large taxonomic breadth and huge species richness. We used 78 taxa in our analysis, but a total number of 85 invertebrate species was identified in our study. Zintzen (2006) found 99 macrofaunal invertebrate species in the scrape samples of the epifaunal assemblages of two shipwrecks of the BPNS. van Moorsel & Waardenburg (2001) recorded 44 macrofaunal invertebrates on an artificial reef off Noordwijk, The Netherlands, nine years after installation. On the FINO 1 research platform in the German Bight, a total of 44 species was found in the scrape samples during the first 2 years (Orejas et al., 2005). The number of species found on the recently installed wind turbines of the BPNS is thus remarkably high. However diversity remains much lower than that of natural gravels in the region such as the Hinder banks (Houziaux et al., 2008) and the Dover Strait (Foveau et al., 2008).

In addition to the conspicuous large species the biofouling community includes a diverse cryptofauna of small organisms such as nemerteans, polychaete worms and small (or juvenile) molluscs and crustaceans that live more or less hidden amongst the larger sessile fauna which also provides shelter and food for them. It is important to remind the reader that analyses were focused on the fraction larger than 1 mm. Some species reaching sizes slightly larger than 1 mm when mature
such as *Pusilina inconspicua* or *Odostomia turrita*, as well as juveniles of larger species were regularly observed in the fraction <1 mm of the samples (Francis Kerckhof, unpubl. data). For these species, the real frequency of occurrence will thus be larger than measured within the larger size fraction. Secondly, in this study we did not address the fauna of the stones of the scour protection. The barnacle *Verruca stroemia*, for instance, seems more abundant on this substratum (Francis Kerckhof, unpubl. data). It can as well be expected that larger crustaceans which need shelters such as those provided by cobble patches (e.g. the lobster *Homarus gammarus* or the edible crab *Cancer pagurus*), may be found more abundantly there. A different assemblage is thus expected to be found on this part of the wind turbine infrastructure, due to the larger size of the three-dimensional structure.

Zintzen et al. (2008) showed that the communities associated to shipwrecks display differences in their community composition in function of prevailing environmental drivers. Thus, differences were found between wrecks located in coastal and offshore waters. The two wind farms are located very close to each other, and clearly under the predominant influence of English Channel water (Otto et al., 2006; Zintzen, 2007; Kerckhof et al., 2009). The C-Power wind farm, closer to the coast, can be expected to be more under influence of coastal waters, depending on the prevailing hydro-meteorological conditions (see Van den Eynde et al., 2010). On the other hand, the weekly averaged temperatures (grouped per month in Figure 1) do systematically point to a larger temperature amplitude of about 0.5-1 °C in winter and summer at C-Power compared to Belwind. Environmental differences between the two farms do reflect an onshore-offshore gradient, which is nevertheless weak. The differences in species richness and frequency of occurrence are thus unlikely to originate from natural environmental differences.

### 3.4.4. Introduced species

Only one introduced species was found thus far in the subtidal zone namely the slipper limpet *Crepidula fornicata*. This is in contrast to the intertidal zone where the newly introduced hard substrata of the offshore wind farms proved to play an important role in the establishment and the expansion of the population size of non-indigenous species including introduced ones (Kerckhof et al., 2011). *Crepidula fornicata* is present in the BPNS since 1911 (Adam & Leloup, 1934) and constitutes now an important member of the local fauna due to its ability to colonize both soft en hard substrata (Kerckhof et al., 2007). Although *C. fornicata* does occur in the intertidal zone on groins along the Belgian coast (Francis Kerckhof, pers. obs.) it was not present in the intertidal samples of the wind farms studied (Kerckhof et al., 2011). In the subtidal, it was amongst the first colonists at the C-Power wind farm (juveniles were already present in the first sampling in autumn 2008) and the species was subsequently present in most of the samples, often as large specimens and even chains of two individuals. However, *C. fornicata* was only found in one Belwind sample (one juvenile specimen in august 2010). The virtual absence of *C. fornicata* in the Belwind farm cannot be ascribed to the different substratum composition, i.e. concrete versus steel or the position further offshore of the Belwind wind farm because *Crepidula* has been observed abundantly on – even remote – offshore buoys and on ships’ hulls (Kerckhof et al., 2007; Francis Kerckhof pers. obs.).

### 3.5. Conclusions

As observed in many other studies, the biofouling of the bare substratum has been very fast in the two studied wind farms. The results on sessile species do suggest that concrete foundations may offer a better settlement surface for hard substratum species, but the variability of overall species composition (turnover) induced by seasonal oscillation and yearly varying environmental conditions and predation is high and prevents robust conclusions at this point in the succession.

On the other hand, the biofouling on the two wind farms exhibits direct influence by the same pool of species originating from the surrounding artificial and natural hard substrata. As for shipwrecks, specific features of the studied structures such as verticality, substratum composition or lower depths may explain specific patterns of taxonomic composition such as an impoverished sessile
epifauna compared to the surrounding natural hard substrata. The predatory activities are an important factor controlling the succession of sessile species on the substratum.

The tube dwelling amphipod *J. herdmani*, and to a lesser extent its relatives *C. acherusicum* and *S. valida*, strongly take advantage of the newly available habitats. Together with the porcelain crab *P. longicornis*, these species have been shown by Reubens (2010) to be important prey items for the ichthyofauna that aggregates around the structures.

Apart from the slipper limpet *C. fornicata*, no introduced species have been observed thus far in the permanently submerged part of the wind turbine foundations. This observation contrasts with the intertidal and splash zone, where many introduced species were present in the biofouling community.

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3.7. References


Chapter 3. Hard substratum epifauna


