Dune dynamics safeguard ecosystem services

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Abstract

Intensively used coastal zones often know a history of hard defense structures to prevent erosion and protect infrastructure against floods. The interruption of sand transport between sea, beach and dunes however causes a domination of late successional stages such as dune shrub. With the decline of young, dynamic vegetation types, a change occurs in the provision of ecosystem services. In spite of the growing awareness on the role of dune dynamics to support human well-being and biodiversity, redynamisation of dunes is rarely implemented in coastal zone management. It has been argued in research documents that this may be caused by a failure to make those benefits tangible and specific. This study aims to underpin the added value of dynamic versus fixed dunes. Five different ecosystem services in a case-study in Belgium were quantified based on (compound) indicators and expressed in monetary units. The value of a natural, dynamic dune system covering the entire gradient of dune succession and dominated by young successional stages was compared with the value of a fixed dune system dominated by late successional stages. The results indicate that a dynamic dune complex may create up to ~50% higher economic benefits, and that the main benefits are on account of recreation and coastal safety maintenance. The results underpin the statement that we can only continue benefitting from the services dunes provide if we accept their mobile nature, but that redynamisation requires a site-specific feasibility analysis.

Key-words

Coastal safety; dune succession; hard erosion defence; nature-based adaptation; redynamisation

1. Introduction

In recent years, several studies demonstrated the contribution of coastal dunes to the delivery of ecosystem services such as protection against floods, recreation, salinization prevention and drinking water production (Doody et al. 2005; Everard et al. 2010; Arens et al. 2013; Lithgow et al. 2013). Coastal dunes in Europe are also known to hold large biodiversity values (Martínez et al. 2004). In north Belgium for example, they harbour 40 to 60% of the total number of species in an area covering less than 1 % of the region's total surface area.

In spite of the important benefits they provide for human well-being and the high biodiversity values, coastal dunes are among the most damaged ecosystems. The main causes of degradation are urban development, agriculture, waste disposal, mining and military activities (Lithgow et al. 2013). Around the world, the rate of change associated with construction in coastal zones has been occurring several times faster than changes occurring inland (Martínez et al. 2004). In Belgium, urbanization has led to devastation of nearly 50 % of the coastal dunes. Besides direct destruction of dunes, dunes also suffer from degradation resulting from the placement of shore protection structures to protect these developments against erosion and flooding (Nordstrom 2000; Pilkey & Cooper 2014). Hard engineering structures such as dykes and groynes block sand transport and may in some cases even aggravate erosion (Pilarczyk 1998; Boers et al. 2009; Vaidya and Kudale 2015). Fragmentation by roads, houses, railways, land use changes, … obstructs the flow of sand and prevents dunes from rejuvenating. Consequently, dynamic dune systems covering the entire range of dune habitats and with an important portion of bare sand and young vegetation types evolve towards a fixed ecosystem dominated by late successional stages. The loss of pioneer stages does not only affect the ecosystem services typically associated with these habitats (Boerema et al. 2016), but also decreases biodiversity. Research demonstrates that habitats with the highest biodiversity values in coastal dunes are associated with early successional stages that depend on the supply of fresh sand (Howe et al. 2010; Provoost et al. 2011).

As stated by Favennec (2002): “To continue to benefit from the ecosystem services dunes provide, we must accept the mobile nature of dunes and their fluctuations in sand budget.”. Not only does conventional flood defence hamper sand dynamics, its maintenance may also become unsustainable in light of sea level rise. Nature-based solutions are a long-term sustainable alternative with multiple additional benefits (Temmerman et al. 2013). To date, the economic benefits of a dynamic dune system remain undocumented, which may explain why decision-makers in most European countries are reluctant to allow natural forces to shape coastal defence (Nordstrom et al. 2015).

This study provides evidence for the socio-economic benefits of dynamic dunes for the case of Flanders, Belgium. To this purpose it builds further on the methodology and accounting framework to quantify and monetise the ecosystem services from natural areas in Flanders (Staes et al. 2017), in order to estimate more in detail the ecosystem services of coastal dunes along the Westcoast in Flanders. In a second step, we describe, quantify and monetise the differences between dynamic and fixed dunes, which thus far have mainly been expressed in descriptive analyses (Everard et al. 2010; Hanley et al. 2014; Feagin et al. 2015). The question addressed in this paper is if a dynamic dune system with constant sand movement provides more and/or more valuable ecosystem services than a dune system fixed by vegetation. In other words: can remobilization of dunes, by removing hard structures that hamper sand transport, result in significant socio-economic profits?

This paper does not address issues related to the concept or available methods and data for mapping, quantifying and monetising ecosystem services in general (as e.g. discussed in Liekens et al. 2013; Landuyt et al. 2016). This paper discusses the limitations and uncertainties in methods and data for the selected ecosystem services and the case study, and indicates the range of uncertainties in quantification and monetisation. This is only one part of the overall uncertainties related to assessing ecosystem services and the socio-economic importance of natural areas like coastal dunes.

2. Methodology

2.1 Study area

The study area (Figure 1) is located in the northwest of Belgium and covers the nature reserve 'Westhoek' (~340 ha). The area used to be a highly mobile dune field dominated by dynamic vegetation such as marram grass (Ammophilia arenaria), both in the frontal zone (up to 50-200m from the shoreline) and more inland (>1000m from the shoreline). The frontal dunes became largely fixed and dominated by shrub after the construction of a dune revetment blocking the transport of sand from beach to dune at the end of the 1970s. The large mobile dune in the central part of the reserve also got increasingly fixed, most probably due to increased climatic variability and – as a result – increased precipitation in certain years (Provoost et al. 2014). In more recent years, the government spent great efforts to maintain the diversity of habitats and prevent the area to develop into an entirely fixed dune complex dominated by shrub and eventually woodland. This included the creation of 2 artificial breaches (Figure 1).

Figure 1.

2.2 Ecosystem services analysis: quantification and economic valuation

This study builds on the methodological framework of the ECOPLAN project to assess, quantify and monetise the ecosystem goods and services in Flanders (www.ecosysteemdiensten.be). This accounting framework has been used for assessment at the national level of all NATURA 2000 sites (Staes et al. 2017), in the context of the Flanders Regional Ecosystem Assessment (Jacobs et al. 2016) and to evaluate impacts of policies at the regional scale or at the project level (Broekx et al. 2013). Based on a qualitative assessment of the importance of ecosystem services provided by coastal sand dunes (Everard et al. 2010), interviews with stakeholders and visitors (De Nocker et al. 2015) and local site specificities, five ecosystem services were selected: water provision, coastal safety maintenance, water quality regulation, climate regulation and recreation. Ecosystem services related to the capture of air pollutants by vegetation or impacts from nearby natural areas on real estate values or public health are relevant for this area but were not included because of the limited scope for better assessment within this study. Other ecosystem services which are considered in similar studies on dune ecosystem services (e.g. Everard et al. 2010) have not been included, such as wood production, military use and educational use. These were either absent in the study area or had low economic value.

For all ecosystem services except coastal safety maintenance, quantification and monetisation are performed using today's configuration of habitats (see appendix for habitat description) and socio-economic use of the nature reserve. Because of the presence of an artificial sea defence, which partly replaces the natural protection against floods, it was not possible to assess coastal safety maintenance based on today's configuration of habitats. Instead, the situation from before construction of the dune foot revetment was used (year 1953).

For each of the selected ecosystem services a compound indicator was developed that expresses how much of an ecosystem service is being delivered per year (**Fout! Verwijzingsbron niet gevonden.**). The total value of the ecosystem services in € y^{-1} is the product of these indicators with its monetary value. Using the ArcGIS-tool 'Zonal Statistics' (ESRI 2016) a mean value per habitat type was calculated for each ecosystem service (€ ha^{-1} y^{-1}). To take into account uncertainty on the values, a low and high estimate of the value was provided when data was available.

2.2.1 Water provisioning

Coastal dunes are typically associated with a freshwater lens. The coarse texture of the dune sand allows quick replenishment of the reservoir while the infiltrating rain water is naturally purified in its course through the sand. The shallow location of the reservoir makes dunes attractive for abstraction of drinking water, as pumping and treatment costs are limited. In the case of the study site, water abstraction infrastructure is located at 200m distance from the border of the study area. Part of the extracted water comes from the dunes within the study area. Recently, the extraction was reduced so the reserve is no longer affected by desiccation. The applied methodology for calculating water provisioning is described in Staes et al. (2017) and Van der Biest et al. (2015). This GIS-tool first estimates the amount of naturally infiltrated water based on precipitation, soil texture, groundwater depth and vegetation type. Secondly, cones of depression were modelled which take into account the yearly volume of water abstracted.

Groundwater as a source for producing drinking water is very valuable in the coastal region, because there is a limited capacity to produce drinking water in that region and demand is high, especially in the summer season due to tourism. There are no real market prices for the capture of groundwater as a source for producing groundwater, although licenses to capture groundwater are limited, and a specific natural resource tax is applied to groundwater abstraction (0.075 € m^{-3}). This Flemish groundwater tax can be seen as an indicator to compensate for the environmental and resource costs, as defined in the Water Framework Directive, and is used as the lower bound for the monetisation in the overall ECOPLAN framework. However, the marginal value of groundwater is higher in that region, which is illustrated by the high prices local drinking water companies pay to import water from other regions or the high costs of specific technologies used to produce water locally. These additional costs are estimated at 0.2 € m^{-3}, which reflects the high estimate of the monetary value (Broekx et al. 2013). The drinking water companies and its clients are the beneficiaries of this ecosystem service.

2.2.2 Water quality regulation

One of the important criteria for good groundwater quality, both for the purpose of clean drinking water provision as for biodiversity support, is a sufficiently low concentration of nitrogen (N). In the study area, N is mainly available through atmospheric deposition caused by industry, traffic and agriculture (yearly average of 11 kg N ha^{-1}, VLM 2011). Nitrogen in dune ecosystems can either be retained in the ecosystem by plants and organic matter, or lost by leaching, nitrification and subsequent denitrification, and grazing (Olff et al. 1993). N retention is strongly influenced by the presence of calcium in dune sand and uptake by vegetation. Calcareous soils (young sand deposits), are characterised by higher nitrification rates in comparison with soils with a decalcified top layer (ten Harkel et al. 1998). With low degrees of denitrification, this causes nitrate leaching to groundwater (ten Harkel et al. 1998; Pinay et al. 2007). Nitrification rates are smaller in more developed soils with a decalcified top layer and lower pH. Incorporation in plants is also higher in well-developed soils, which directly take up ammonium from atmospheric deposition and where nitrate is partly lost through mineralisation and nitrification of dead organic material. Ten Harkel et al. (1998) showed that in foredunes in the Netherlands about 70% of the atmospheric deposition (ammonium) leaves the soil as nitrate, while at non-grazed, dry innerdunes (grasslands which are decalcified down to 40-50 cm depth) only 13% leaches to groundwater. In dune slacks of older successional stages (as found in the study area), where groundwater flow reaches the surface, N removal by denitrification is estimated to account for 5 % of the atmospheric deposition (Adema and Grootjans 2003). Dune shrub with Hippophae rhamnoides lives in symbiosis with N-fixing bacteria and nearly triples the amount of leaching to groundwater compared to atmospheric deposition (Stuyfzand 1984). In the absence of literature values for dune shrub with S. repens, we used the denitrification value for old dune slacks (5%), as this vegetation type often evolves from dune slacks. Average N-leaching from forests within the study area is estimated 29% (Staes et al. 2017).

The monetary value of N retention is based on the benefits to society from health problems (intestinal cancer) associated with N intake through drinking water (Van Grinsven et al. 2010). The benefits of the ecosystem service are for the health care insurance (avoided expenses) and the patients and their families (avoided private health care costs and suffering). For Belgium, this value is estimated at a range of 0.6 to 2.4 € kg N^{-1}, accounting for uncertainties in the exposure assessment (% of population using drink water from the controlled tap water network).

2.2.3 Coastal safety maintenance

Protection against floods comprises two aspects: (1) the mass of sand deposited in the past that now forms a physical barrier against waves and water; and (2) the maintenance or improvement of this mass of sand by the supply of fresh sand, and the capacity of the system to keep up with sea level rise. The first is usually estimated by quantifying the damage costs and number of casualties caused by flooding (TEEB 2010; Koks et al. 2014). The second can be valued using the replacement cost for artificial dune foot nourishment. As this study focusses on the dynamic processes of erosion and sedimentation in dunes and their contribution to human well-being, it was decided to use the replacement cost for dune foot nourishments to value the benefit of coastal safety maintenance.

The volume of sand accumulated per year in shifting dunes along the shoreline is used as indicator for the maintenance of coastal safety. Several studies have shown that Ammophila species require a certain amount of sand burial each year in order to remain vigorous (De Rooij-Van Der Goes et al. 1995; Keijsers et al. 2015). Without supply of fresh sand, soil starts to develop and marram grass degenerates because of the occurrence of nematodes. The presence of marram grass can thus be used as indicator of active sand transport. According to Aggenbach and Jalink (1999), marram grass thrives under deposition rates of more than 10 cm per year. Vegetation remains dynamic at lower rates of deposition (4 cm y^{-1}), but turns into moss at 2 cm y^{-1}. This is in line with the findings of Martin (1959), who states that annual sand burial rates of more than 7 cm are needed to keep Ammophila vegetation vigorous. In the situation from before construction of the dune foot revetment (1953), a continuous strip of Ammophila is found from the beach up to ~200m inland (frontal dunes). It can be expected that, given the large distance from the beach, a certain amount of the deposited sand originates from wind erosion within the frontal dunes. The estimate of sand deposition (4 to 10 cm y^{-1}) should be corrected for this. Based on a comparison with average sedimentation rates in coastal dunes in neighboring countries (5 to 10 m^3 m^{-1} y^{-1} in The Netherlands, Arens et al. 2013; 2 m^3 m^{-1} y^{-1} in France, Carter 1980), it is assumed that half of the sediment in the shoreline is transported from the beach and half originates from erosion within the dunes. The minimum and maximum estimates of coastal safety maintenance are thus a sedimentation rate of 2 and 5 cm y^{-1}, resulting in an additional sand volume of 4 to 10 m^3 m^{-1} y^{-1}, or 200 to 500 m^3 ha^{-1} y^{-1}, for a frontal dune zone of 200 m wide. Within the study area, marram grass is also found at a distance of up to 1 km from the shoreline. These inland shifting dunes however do not form a continuous complex with those from the shoreline but are separated by a strip of fixed dunes parallel to the coast. The occurrence of marram grass here can be attributed solely to eolian and management related (trampling, grazing) forces continuously reworking the present sand, rather than deposition of fresh sand from the beach. Accumulation of fresh sand, and thus coastal safety maintenance, is only taken into account for the embryonic and shifting dunes in the frontal dune zone. To estimate the benefit, the surface area covered with embryonic and shifting dunes along the shoreline should be multiplied with the yearly sedimentation rate.

The cost to replace natural supply of sand by artificial nourishments is used as indicator for the economic value of sand accumulation. According to Deltafact (2012) 1 m^3 of dune foot nourishment costs 16 €. The economic value for coastal safety maintenance by dunes (**Fout! Verwijzingsbron niet gevonden.**) corresponds relatively well with the costs to maintain an existing dyke (60 to 150 € m^{-1} y^{-1}) and increase its height as adaptation to sea level rise by 2100 (5000 € m^{-1}) (MDK 2016). When spreading these expenses over the period 2017-2100, this would lead to a cost of 0.15 to 0.26 million € y^{-1} for the entire stretch of the reserve (1260 m).

2.2.4 Climate regulation

Climate regulation through soil organic carbon sequestration is quantified using the results of an empirical study on local field measurements in northern Belgium (Ottoy et al. 2015). In this study, total amount of carbon stored in the upper first meter of the soil is estimated based on statistical characterization of soil profile characteristics (texture and groundwater depth) and land use type. Yearly additional sequestration is then calculated by dividing the amount of stored carbon – which represents equilibrium soil concentrations – by 100, assuming that soils reach their equilibrium SOC concentration without further accumulation after a period of 100 years (Broekx et al. 2013). The obtained values (**Fout! Verwijzingsbron niet gevonden.**) compare relatively well with measurements of soil organic carbon in coastal dunes in the United Kingdom (Beaumont et al. 2014), where mean sequestration rates in the upper 15 cm over a period of 160 years were estimated at 582 ± 262 kg C ha^{-1} y^{-1} in dry dune grasslands and 730 ± 262 kg C ha^{-1} y^{-1} in wet dune slacks.

The benefits from carbon storage are valued based on the literature on the social costs of carbon and the guidelines by mainly European economic administrations on how to account for carbon emissions or capture in economic analysis. The benefits relate to the avoided damages from climate change, which are however hard to estimate and with great uncertainty. Therefore, the marginal costs of meeting the greenhouse gas emissions reduction targets - as part of policy plans to limit global warming to 2°C temperature increase relative to the pre-industrial level of 1780 - is used as a proxy of the value policy makers and society give to carbon storage. Using data from literature and recommendations from economic agencies, this can be estimated at 220 € ton C^{-1} (Aertsens et al. 2013).

2.2.5 Recreation

Although it is well accepted that the study area is important for recreation and tourism, there are no area specific data to assess the total number of visits per year to the site. Therefore, the number of visits has been estimated using a detailed model analysis that accounts for attractiveness of landscapes, infrastructure for recreation, the proximity of population, data and preferences of visits to natural areas in Flanders and data on tourism and their activities (De Nocker et al. 2017). It is estimated that the study area attracts around 300000 to 500000 visits a year.

To assess the total economic value of the area as a whole, and accounting for the limited studies on economic valuation of recreation in Flanders, we used the data from scientific literature on the estimation of the welfare benefit a visitor attaches to its visits (Staes et al. 2017). To this purpose, we build on the meta-analysis of relevant literature on site-specific per-visit values, taking into account spatial variation and differences per habitat type made in the context of the National ecosystem assessment for the UK (Sen et al. 2014). This amounts to 4.5 € per visit on average, with a range of 3-9 € per visit, accounting for the large uncertainties in assessing this value and the benefit transfer to the study area. This amounts to 0.9 – 4.5 € y^{-1}).

This meta-analysis confirms that the values for coastal nature are in line with the average values, but does not allow to distinguish between the detailed habitat types we use in our study. Therefore we used additional information on preferences from visitors to attribute this value to different habitat types. First, we used the number of pictures taken from each habitat type and uploaded to the websites Flickr and Panoramio (Figueroa-Alfaro and Tang 2016) as an indicator of the relative importance of different habitat types for these visitors. The contribution of each habitat in attracting visitors to the reserve is assumed to be reflected in the relative number of pictures taken in the different habitat types compared to the total number of pictures (239). Each of the 239 uploaded pictures was assigned a habitat type based on visual interpretation of the image and, when available, description of the photo. An additional correction factor was applied for the non-linear relationship between surface area of attractive landscapes and number of visits (an increase in surface area of highly attractive habitats is expected to result in a relatively smaller increase in number of visits). In the absence of quantitative data, studies were used that assess the relationships between natural surface area (independent of its attractiveness) and number of visits (Colson 2009; Siikamäki 2011). An increase in natural area of 10% resulted in an increase in numbers of visits of 4%. This correction factor was applied to the difference in monetary value between the habitat in the fixed and in the dynamic scenario.

2.3 Scenarios

The benefits of dynamic dunes are estimated by comparing the economic value of a dune system consisting of both dynamic and stabilized dune types (dynamic scenario) with the value of a largely stabilized dune landscape (fixed scenario).

A dynamic dune system is characterized by an important amount of bare sand which is subject to eolian sand transport. All the different stages in dune development are present, creating opportunities for high species diversity. Embryonic and shifting dunes dominate the frontal dunes. Vegetation here is adapted to constant burial and acts as sediment trap, thus building up new dunes (Feagin et al. 2015).

Further inland, dune slacks are found that testify of recent blowout activity (Arens et al. 2013). A precondition for a dynamic dune system is the continuous transport of sand by wind and/or hydrodynamic forces, on the interface between beach and dune as well as more inland. No artificial structures should impede sand transport from sea to coast (e.g. by groynes) and between beach and dunes (dykes, revetments etc.), or act as traps for sand migrating further inland (roads and houses). For the study area, this scenario corresponds best with the situation before construction of the dune revetment. The habitat composition for this scenario (Figure 2 left, Table 1) is based on aerial photographs of 1953 (INBO, unpublished data).

In the fixed scenario (Figure 2 right, Table 1), which is best represented by the present situation, sand transport to, from and within the dunes is hampered by concrete structures. Without supply of fresh sand or regular disturbance (wind, herbivores, trampling, …), sand becomes colonized by vegetation and succession leads to fixation of the dunes by shrub and eventually woodland. Dune slacks become less profound and their water table lowers due to increased evapotranspiration, eventually leading to domination by shrub. Encroachment by dense vegetation impedes windblown formation of new dune slacks. Shifting dunes are found only in a narrow strip along the shoreline where strong eolian forces are able to blow some of the beach sand over the dyke into the dunes. The habitat composition for this scenario (Figure 2 right, Table 1) is based on satellite images of 2016 (INBO, unpublished data).

Based on the aerial photographs of 1953 it was not always possible to distinguish dune shrub with H. rhamnoides from dune shrub with Salix repens. For the ecosystem service calculations, the surface ratio between S. repens and H. rhamnoides in the present situation was extrapolated to allocate both types of shrubs where uncertainty exists in the photographs of 1953.

A comparison is made between the ecosystem services in both scenarios for the entire study area, for the dunes in the frontal zone (shoreline) and for the inner dunes. The frontal dune zone is defined as the dune area closest to the sea, which in a natural situation with active sand supply is dominated by embryonic and shifting dunes and may extend up to 200 m from the beach. It is delineated based on the extent of embryonic and shifting dunes in the dynamic situation of 1953 (Figure 2). In the fixed scenario, large parts of the embryonic and shifting dunes within the frontal zone have become fixed with moss, grass or shrub.

Figure 2.

Table 1.

3. Results

3.1 Ecosystem services of different dune habitats

In general, there are large differences in ecosystem service supply and associated values among the various habitats (Figure 3, **Fout! Verwijzingsbron niet gevonden.**), ranging from 1342 – 5514 € ha^{-1} y^{-1} (dunes with moss or grass) to 10649 – 52097 € ha^{-1} y^{-1} (shifting dunes with marram grass). This is the result of the high value for recreation and to a minor extent coastal safety maintenance, the latter being a service restricted to the frontal dunes. The habitats with the highest value for recreation are habitats associated with wet soils (dune slacks and dunes with S. repens) and habitats with shifting sand (shifting dunes with marram grass and embryonic and shifting dunes).

In comparison with coastal safety maintenance and recreation, average values for the three other ecosystem services are relatively small. The sum of the lowest estimates for recreation and coastal safety maintenance (1011 – 3033 € ha^{-1} y^{-1} for dunes with moss or grass) is still higher than the sum of the maximum estimate of the three other ecosystem services in the same habitat (307 – 454 € ha^{-1} y^{-1}).

Figure 3.

Table 2.

3.2 Ecosystem services of dynamic versus fixed dunes

The sum of the selected ecosystem services of the dynamic scenario (1.58 – 7.27 million € y^{-1} for the entire study area) is 54% higher than the sum of the fixed scenario (1.03 – 4.70 million € y^{-1} for the entire study area), (Figure 4). However, uncertainties on recreation and coastal safety maintenance, the two main ecosystem services, are large. The larger benefits for the dynamic scenario can be attributed to the greater extent of embryonic and shifting dunes in the front zone which are important for both coastal safety and recreation, and the presence of wet dune habitats and dunes with marram grass more inland where recreation is relatively high.

Figure 4.

The differences amongst the ecosystem services are even more pronounced when considering only the frontal dunes (Figure 5 left). Economic benefits in the dynamic scenario (0.18 – 0.71 million € y^{-1}) are double those in the fixed scenario (0.09 – 0.36 million € y^{-1}). While the habitats of the frontal dunes are important for coastal safety maintenance, they are negligible in terms of water provisioning, water quality regulation and climate regulation. Recreation and climate regulation become more important in the inner dunes (= the entire study area without the frontal zone) compared to the frontal dunes. Although climate regulation is rather small in most dune habitats (Figure 3) and seems negligible in comparison with recreation, benefits reach a total value of 0.10 million € y^{-1} in the dynamic and 0.09 million € y^{-1} in the fixed scenario. This is explained by the large extent of dune slacks (dynamic scenario) and the development of humus rich soils in woodland (fixed scenario).

Figure 5.

4. Discussion

4.1 Large benefits, few services

The data illustrates that recreation and coastal safety are two very important ecosystem services generated by dynamic dunes, providing important benefits for both inhabitants of the coastal zones and the entire region. Even if we account for the uncertainties and shortcomings for quantification and valuation of the different services studied, these services are more important compared to the other ecosystem services taken into account in this study.

The great difference between the value for coastal safety maintenance of marram grass dunes versus vegetation of stabilized dunes, is explained by the capacity of dynamic vegetation to withstand sand burial up to a meter per year. When sand is deposited, shoots rapidly grow through it and the new sediment is held with the roots. Vegetation of fixed dunes is not adapted to large amounts of sand burial and will die off. Woody vegetation is also more prone to erosion as stems are less flexible and not able to lie flat during high winds as grasses can (Feagin et al. 2015).

Water quality regulation and climate regulation are typically associated with well-developed soils (accumulation of organic matter), thus low in young deposits along the shoreline and increasingly important as dunes grow older. Even in fully developed soils of wooded dunes they however remain relatively small in comparison with inland habitats. This is related to the coarse texture of dune sand which – in comparison with soils containing a fraction of clay – generally has lower capacity to retain organic matter and nutrients, and higher decomposition rates because of the low resistance for air penetration (Wardle 1992). The average carbon sequestration rate for northern Belgium is 1409 kg C $ha^{-1} y^{-1}$ in the upper 1 m of the soil (Ottoy et al. 2015), while dune grasslands and shrubs vary between 1000 and 1250 kg C $ha^{-1} y^{-1}$. The wetter habitats of dune slacks form an exception to this (2113 kg C $ha^{-1} y^{-1}$) as they have a much higher biomass production and prevent breakdown of organic matter due to permanent wet soils.

The low value for water provisioning is explained by the gradual decrease of the water extraction rate over the last decennium and the low market price of water. The decrease in water extraction was needed to prevent salt water intrusion, but is also part of a policy to reduce the ecological impact of drinking water production (Vandenbohede et al. 2009).

The high value for recreation reflects the proximity to a densely populated and rich region, with a short coastline with highly developed touristic infrastructure and limited area of dunes. It confirms that the study area is an important area for recreation and tourism in Flanders, and the estimated number of visits is in line with these of other important areas for recreation with a similar size (Staes et al. 2017). The higher recreational value that was obtained for habitats associated with dynamic dunes (shifting dunes with marram grass and dune slacks) corresponds well with the study of De Nocker et al. (2015) in which 400 visitors of the nature reserve where asked to score the attractiveness of dune habitats based on different sets of photographs. Dune slacks and dunes with marram grass and bare sand were found to be most attractive because of the variety of species and colors and the presence of water (dune slacks) and because they are characteristic for the region (shifting dunes). Lowest scores were attributed to shrub, which visitors found rather monotonous. The relative value of forest is less than the value found by De Nocker et al. (2015). The woodland in the study area is mostly species-poor plantation of mainly populous species, while the woodland in the study of De Nocker et al. (2015) is species-rich oak forest. This may result in an underestimation of the value of a dune forest which evolves from natural succession. Uncertainty also exists on the relationship between surface area of attractive habitat and number of visits and the correction factor that was applied. In spite of this uncertainty, the results clearly demonstrate the importance of safeguarding habitats of young successional stages and preventing excessive shrub encroachment to maintain its high recreational value.

As explained above, the five ecosystem services capture the most important ones (based on total monetary value) but not all of them. Some of these provide a minor economic value in the protected nature reserve like wood production (coppice derived from nature management) and meat production (extensive grazing as nature management). Important regulatory services that are not included are the capture of air pollutants by vegetation and related impacts on public health, and impacts from nearby natural areas on real estate values or public health. These services are important for the area as a whole but not enough information was available to be able to make a clear distinction on the contribution of specific vegetation or habitat types.

The protected status also excludes ecosystem services such as hunting or military use, which are common practices in many coastal dunes in Europe (Everard et al. 2010) and may increase the economic value of certain dune habitats. The value for water production is also relatively low compared to other dune regions. An increase in the rate of water extraction would however reduce the value of other ecosystem services and especially of the conservation value. Dune slacks, for example, would desiccate and turn into drier vegetation types which are found less attractive by visitors (De Nocker et al. 2015). Recreation is an important service from the dunes, but it is also a potential threat, both in terms of loss of dune areas to build tourist infrastructure as in terms of managing visits within the protected area.

An additional underestimation of the value of dunes results from not taking into account the negative effects of climate change on the other ecosystem services besides coastal protection. As sea level rises, the frontal dunes will gradually erode, thus reducing the total surface area of dunes, leading to a reduction of the space available for ecosystem services (e.g. reduction of the volume of the groundwater reserve, less space for recreation and carbon sequestration, …). This effect will be less pronounced in dynamic dunes which are able to grow with sea level rise and compensate for the erosion by migrating inland, given that dune migration is not inhibited by the presence of infrastructure, agriculture, etc.

4.2 Dynamic dunes generate more socio-economic benefits

The results indicate that a dynamic dune complex with a large proportion of young successional stages is better to deliver the two single most important ecosystem services for the study area than a fixed dune system. The high value attributed to the characteristic habitats of dynamic dunes is in line with our overall understanding of the relative importance of uniqueness in attracting tourists (Lyon et al. 2011; De Valck et al. 2016). As dynamic dunes improve diversity of less familiar habitats, they are likely to attract more visitors.

The difference between dynamic and fixed dunes is most distinctive for the shoreline dunes, where coastal safety maintenance plays an important role. When focusing only on the frontal zone, redynamisation may increase the economic benefits up to nearly two times the value compared to the fixed scenario. To underpin this conclusion, a comparison is made with the investment costs for restoration of dynamic dunes. The Life Dunes project (Zevenberg and Zijlstra 2012), which aimed to restore 4700 ha of dunes along the Dutch coast, invested a total of 4.7 million € for measures to rejuvenate dunes, restore dune dynamics, combat grass encroachment and restore biodiversity. In case similar measures would be taken to restore natural dynamics in the study area (340 ha), it can be expected that this would require an investment of 0.38 million € (8% of 4.7 million €). Our assessment of the potential benefits of a dynamic dune system (Figure 4) suggests a very good benefit/cost ratio for this type of investment, even if we account for all uncertainties in the assessment. However, it is important to note that the benefits are not strictly for those who bear the investment costs. The total benefits calculated with the ecosystem services assessment are to be seen as benefits to society in general (direct or indirect financial benefits by e.g. creating health benefits or avoiding damage costs). Depending on the service, benefits can be assigned to specific stakeholders (e.g. recreation). Depending on the aim of the ecosystem services assessment, disaggregation of the costs and benefits for different stakeholders can be required to avoid hidden social inequality (Krutilla 2005). However, public investments such as Life projects have a broader aim to create societal benefits. In this case, calculating an aggregated overall benefit is informative to communicate about the overall importance of such projects.

Dynamic dunes along erosive coasts gradually lose the frontal dunes as a result of progressive erosion. Parts of the mobilized sand will be blown into the inner dunes, turning them into dynamic systems and allowing the dunes to migrate transgressively inland (Arens et al. 2010). If no space is available at the inner margin of the dunes (e.g. due to the presence of houses), additional measures such as beach nourishments are needed to guarantee coastal safety and allow for redynamisation. In order to complete the balance of benefits versus costs, these expenses should also be taken into account. Nourishments, however, in certain cases are also needed to reduce the impact of waves on dykes and prevent dyke instability during extreme storms (Verwaest et al. 2009).

4.3 Dynamic dunes generate benefits for biodiversity

Despite the higher economic benefits of dynamic dunes versus fixed dunes, this study does not advocate to convert all dunes to highly dynamic systems dominated by marram grass and dune slacks. One of the characteristics of dune landscapes is the extremely high diversity of habitats and species occurring in a small area (Brunbjerg et al. 2015). Sand deposition and erosion regularly disturb the equilibrium between abiotic and biotic conditions which is being reached as succession progresses. This increases the sharpness of multiple ecological gradients, such as topography, groundwater depth, lime content, pH, salinity and slope aspect (Pye et al. 2007b; Everard et al. 2010). Decreasing disturbance by sand dynamics leads to less pronounced gradients, reduction of habitat heterogeneity and consequent loss of (dune-specific) species (Bonte and Hoffmann 2005; Everard et al. 2010; Brunbjerg et al. 2014). This research does not specifically take into account these effects of (gamma-)diversity on ecosystem service delivery. Although literature exists that links structural complexity to landscape aesthetics and to number of visits (Harrison et al. 2014; De Nocker et al. 2015), it is a challenge to express in monetary terms its exact contribution in attracting people. A drawback of applying an economic valuation on ecosystems is that it does not fully account for the intrinsic value of biodiversity and the impact of species diversity on ecosystem services (TEEB 2010). The results of this study nevertheless are useful to underpin the societal importance of remobilizing dunes along the shoreline as described in earlier analyses (Pye et al. 2007b; Everard et al. 2010; Arens et al. 2013), and advocate to re-expose front dunes to natural hydrodynamic and eolian forces wherever possible (Pye et al. 2007a). In this case, this drawback is even irrelevant, since both a biodiversity and an ecosystem service approach benefit from an increase in dynamics (Howe et al. 2010; Provoost et al. 2014).

4.4 Benefits are site-specific

The values of the ecosystem services in this study are a function of the supply and the societal demand in the present day situation. The benefits for drinking water provision for example are low in all habitats because of the reduced water extraction. A similar exercise in another study area may generate other results and differences between habitats may appear stronger.

Although the results show that redynamisation of dunes may generate important economic benefits, this conclusion cannot be generalized and transferred to other study sites. This research was conducted in an environment where the dunes are wide and high enough to prevent flooding during an extreme storm and given a sea level rise of + 60 cm (Van der Biest et al. 2009). The method for calculating coastal safety maintenance is also based on the assumption that a net transport of sand from beach to dunes takes place. Where the shoreline is naturally subject to long-term erosion and relatively narrow, additional measures (e.g. nourishments) would be needed to compensate the negative sand budget (Arens et al. 2010) and prevent flooding. It is recommended to perform a detailed and site-specific evaluation of the effects of removing structures to remobilize dunes on flood risks and other ecosystem services (Arens et al. 2013; Lithgow et al. 2013; Nordstrom 2014; Ruckelshaus et al. 2016), and to compare with true benefits. Alternatives should be sought which allow remobilization of dunes so that, on the long term and with rising sea level, they continue to form a natural protection against floods. One of the main challenges in highly urbanized coastal zones is the lack of space to let dunes migrate inland, or to allow for managed retreat (Nordstrom et al. 2015). Recent advances in nature-based engineering seem promising (Stive et al. 2013; Arens et al. 2013;

Temmerman et al. 2015), but are not always viable (Narayan et al. 2016). Redynamisation of dunes requires space for dune to migrate. The most urgent needs to protect against floods are generally along settlements where buildings are constructed near the shoreline and no space is available between sea and buildings. Nature-based adaptation not only requires engineering solutions but also increasing flexibility and adaptation by decision-makers and coastal users. Adaptation measures might include the abandoning of existing activities or structures that are low-profitable or that lie in areas with important natural relics, or seaward expansion of the coastline.

5. Conclusions

Dunes create substantially more ecosystem services when sand transport between sea, beach and dunes is not hampered by artificial hard structures such as dikes and groins. Especially coastal safety maintenance and recreation depend on the constant supply and movement of sand and decline when dune vegetation evolves into shrub. The higher value of young dune vegetation compared to older successional stages is related to the capacity of plants of early stages to withstand sand burial and accumulate sand, and, for recreation, to the visitor appraisal of habitat types characteristic of dynamic dunes (shifting dunes and wet dune habitats). Climate regulation by carbon sequestration becomes more important as dunes get stabilized when sand transport diminishes, resulting from soil development under dense vegetation cover. The ecosystem service nevertheless remains relatively low in comparison with inland habitats due to the coarse texture of dune sand. This research underpins earlier descriptive studies on the ecosystem services and their societal benefits of dynamic dunes with quantitative information. Such information may help to convince decision-makers to restore natural dune dynamics wherever possible.

6. Contributions and aknowledgements

KVDB conceived the study, performed the analyses and wrote the manuscript. SP developed the scenarios. LD developed and wrote the methods for economic valuation. SP, AB, JS, LD and PM contributed critically.

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Tables

Table 1 – Surface area (ha) per habitat type in the dynamic and in the fixed scenario

Habitat	Dynamic		Fixed	
	ha	%	ha	%
Embryonic and shifting dunes along the shoreline	24,3	7	7,3	2
Shifting dunes with marram grass	126,1	38	39,4	12
Dunes with moss or grass	19,1	6	70,8	21
Dunes with Hippophae rhamnoides	76,9	23	162,7	48
Dunes with Salix repens	8,6	3	10,5	3
Dune slacks	75,8	23	24,6	7
Wooded dunes	5,2	2	21,0	6
TOTAL	*336,0*	*100*	*336,3*	*100*

Table 2 – Estimated ecosystem service delivery per habitat type. Negative values for water quality regulation reflect an enrichment of groundwater with nitrate. Values for recreation do not include the correction factor on the increase in surface area of a particular habitat.

		Embryonic and shifting dunes along the shoreline	**Shifting dunes with marram grass**	**Dunes with moss grass**
Water provisioning	$m^3\ ha^{-1} y^{-1}$	1281	1171	1008
	€ m^{-3}	0,075 (min) - 0,2 (max)	0,075 (min) - 0,2 (max)	0,075 (min) - 0,2 (
	€ $ha^{-1} y^{-1}$ [min]	96	88	78
	€ $ha^{-1} y^{-1}$ [max]	256	234	208
	€ $ha^{-1} y^{-1}$ [average]	176	161	143
Water quality regulation	kg N $ha^{-1} y^{-1}$	3,0	3,0	8,6
	€ $(kgN)^{-1}$	0,6 (min) - 2,4 (max)	0,6 (min) - 2,4 (max)	0,6 (min) - 2,4 (m
	€ $ha^{-1} y^{-1}$ [min]	2,0	2,0	5,7
	€ $ha^{-1} y^{-1}$ [max]	7,9	7,9	23,0
	€ $ha^{-1} y^{-1}$ [average]	5,0	5,0	14,4
Climate regulation	ton C $ha^{-1} y^{-1}$	0,7	1,1	1,2
	€ $(tonC)^{-1}$	220	220	220
	€ $ha^{-1} y^{-1}$	154	233	223
Coastal safety maintenance	$m^3\ ha^{-1} y^{-1}$	200 (min) - 500 (max)	0	0
	€ m^{-3}	16	16	16
	€ $ha^{-1} y^{-1}$ [min]	3200	0	0
	€ $ha^{-1} y^{-1}$ [max]	8000	0	0
	€ $ha^{-1} y^{-1}$ [average]	5600	0	0

Recreation (without correction factor area)	# visits $ha^{-1} y^{-1}$	1492 (min) - 2487 (max)	1828 (min) - 3046 (max)	522 (min) - 870 (m
	€ (# visits)$^{-1}$	3 (min) - 9 (max)	3 (min) - 9 (max)	3 (min) - 9 (ma
	€ $ha^{-1} y^{-1}$ [min]	5664	10325	1011
	€ $ha^{-1} y^{-1}$ [max]	28320	51627	5055
	€ $ha^{-1} y^{-1}$ [average]	16992	30976	3033
SUM	€ $ha^{-1} y^{-1}$ [min]	9117	10649	1342
	€ $ha^{-1} y^{-1}$ [max]	36734	52097	5514
	€ $ha^{-1} y^{-1}$ [average]	22925	31373	3428

Figures

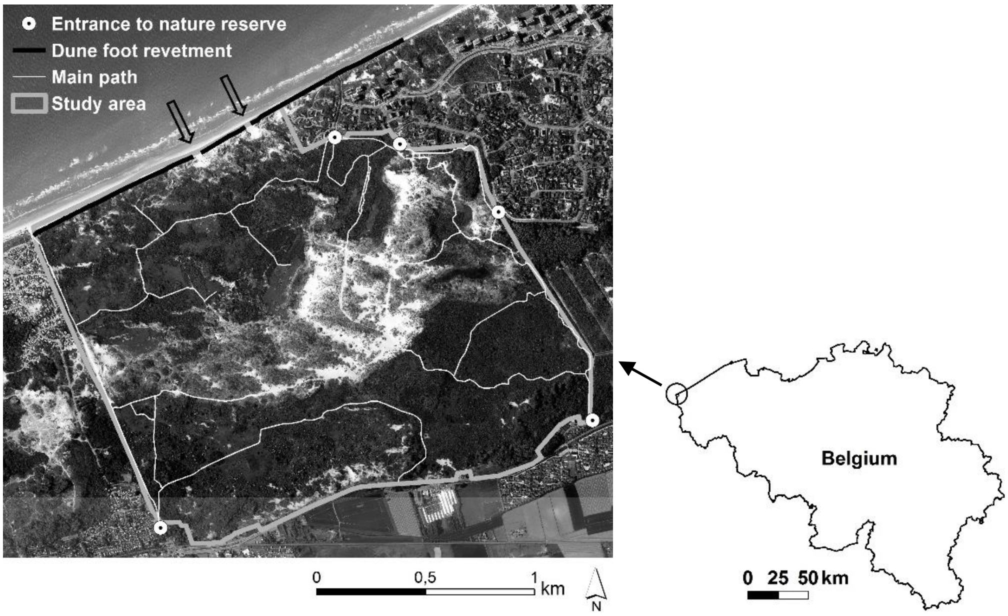

Figure 1 – Location and aerial photograph of the study area with indication of the breaches (arrows) (AGIV 2012)

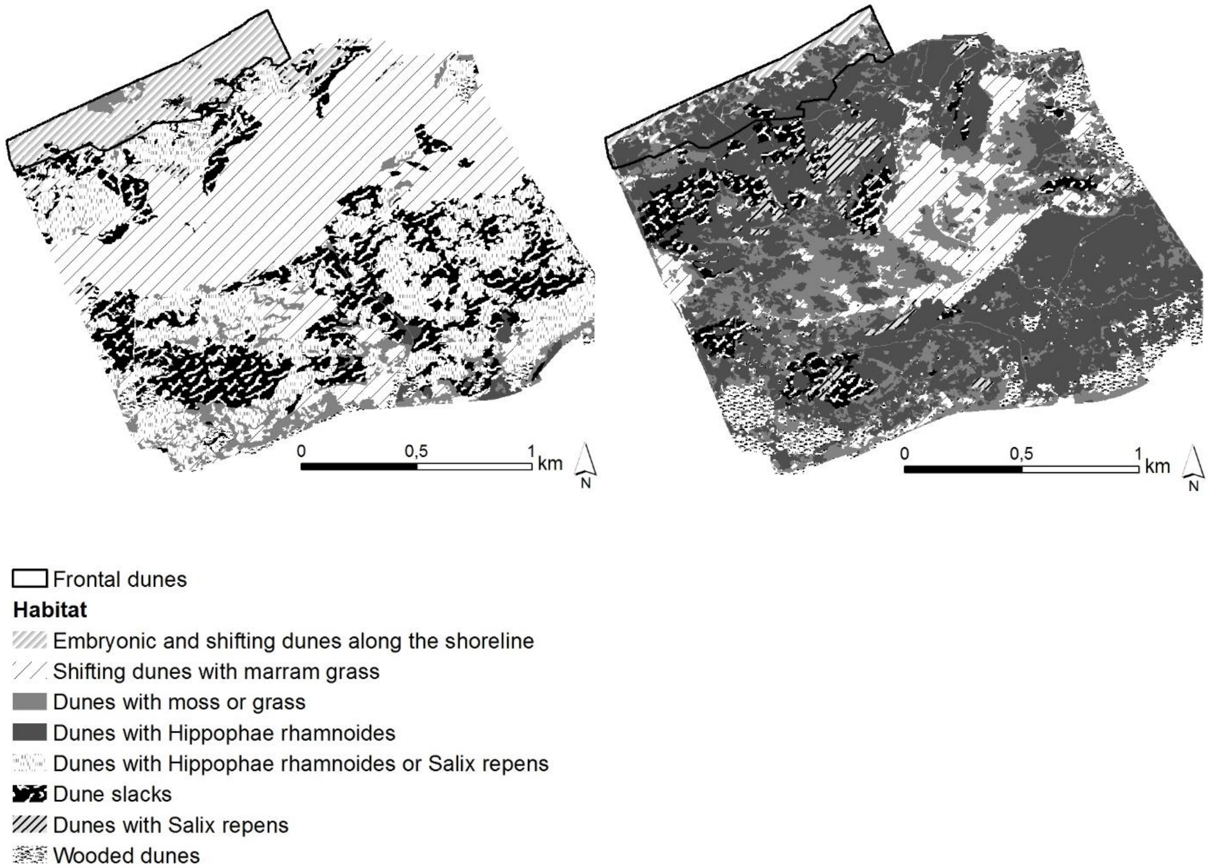

Figure 2 – Left: dynamic scenario (situation ~1953). Right: fixed scenario (situation ~2016).

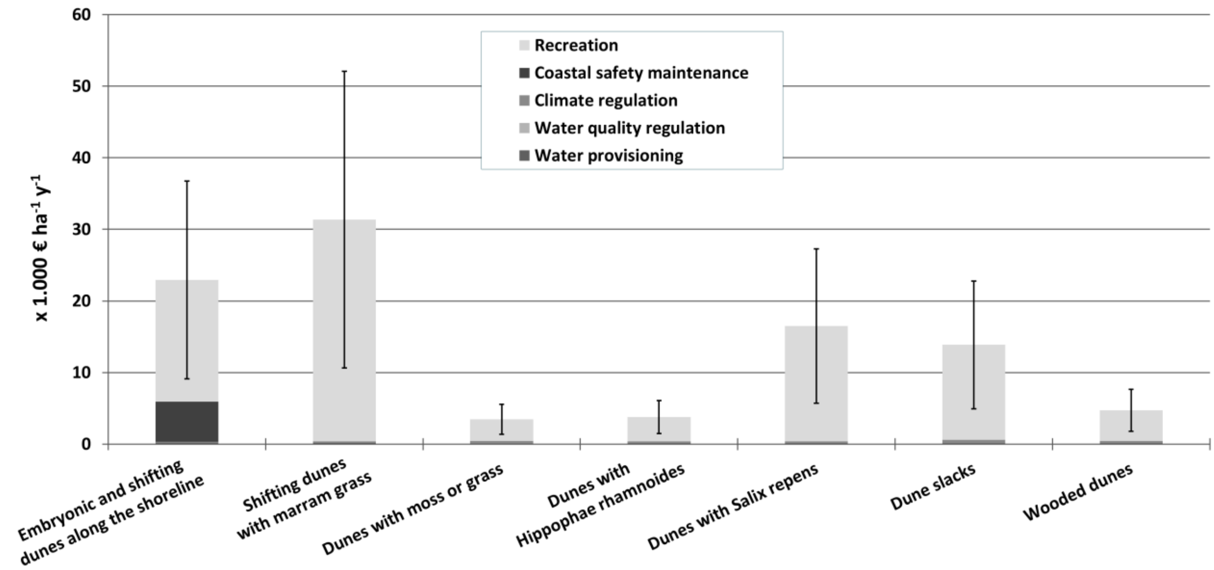

Figure 3 – Sum of the average economic value (x 1000 € ha^{-1} y^{-1}) of each dune habitat for 5 different ES. Error bars represent the sum of the minimum and the sum of the maximum estimates of the different ecosystem services per habitat type. Values for recreation do not include the correction factor on the increase in surface area of a particular habitat.

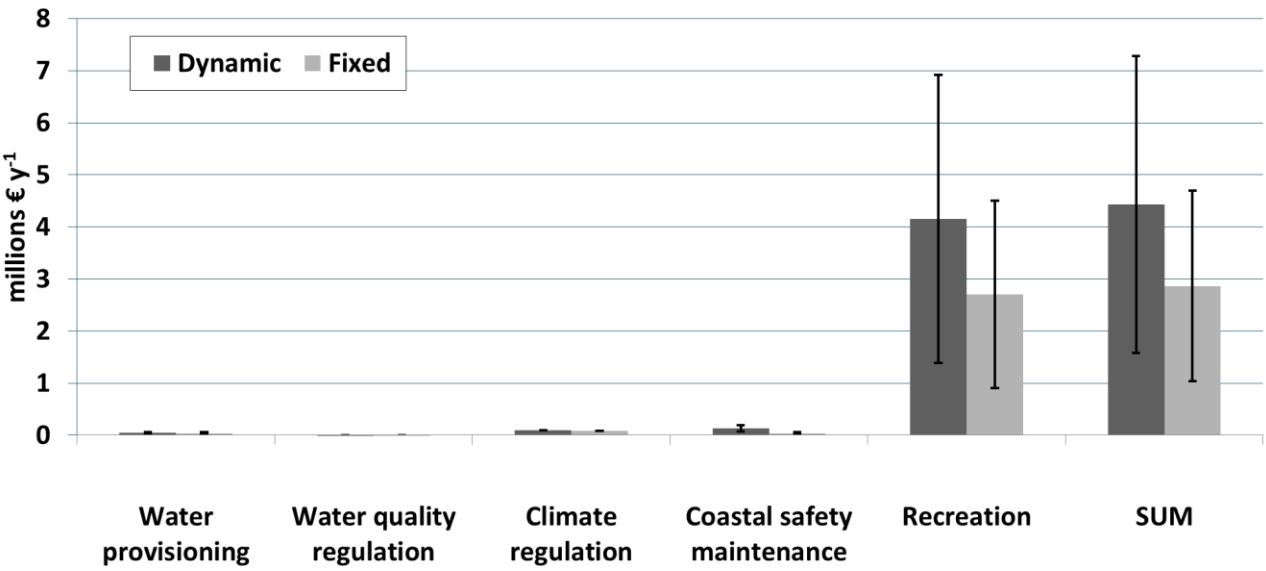

Figure 4 – Sum of the average economic value (x 1 million € y^{-1}) of the entire study area for 5 ES. Error bars represent the sum of the minimum and the sum of the maximum estimates. Values for recreation include the correction factor on the increase in surface area of a particular habitat.

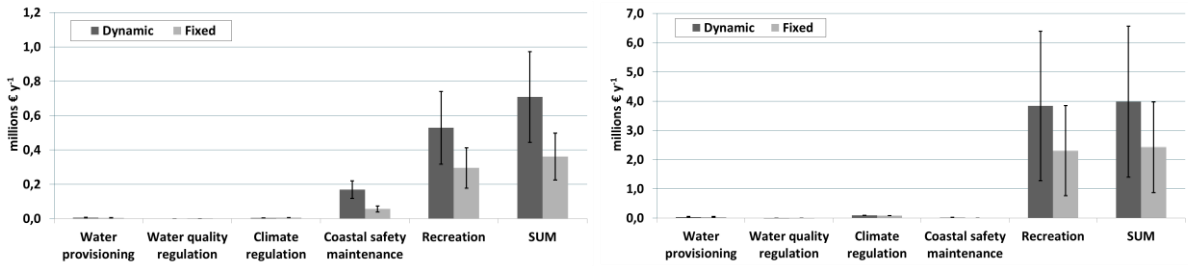

Figure 5 – Sum of the average economic value (x 1 million € y^{-1}) for 5 ecosystem services of the frontal dunes (left) and of the inner dunes (right). Error bars represent the sum of the minimum and the sum of the maximum estimates. Values for recreation include the correction factor on the increase in surface area of a particular habitat.

Appendix

Table I – Description of habitat types

Name	Description
Embryonic and shifting dunes along the shoreline	First row of dunes covered by pioneer and dynamic vegetation (often dominated by marram grass), alternated with patches of bare sand, and where active sand movement takes place (“white dunes”)
Shifting dunes with marram grass	Inner dunes dominated by marram grass and where active sand movement takes place (“white dunes”), certain portion of bare sand
Dunes with moss or grass	First stage in ecological succession after marram grass, start of dune fixation (“grey dunes”)
Dunes with Hippophae rhamnoides	Fixed dunes dominated by Hippophae Rhamnoides (sea buckthorn)
Dune slacks	Depressions in the dune system where the water table comes to the surface. Permanently wet soils, usually rich in species
Dunes with Salix repens	Dunes dominated by shrub of creeping willow. Associated with dune slacks
Wooded dunes	Final stage of ecological succession in dunes, often dominated by oaks