Shellfish aggregations in the Dutch waters: an exploration towards a definition of a shellfish bed

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Contents

Summary

For the extraction of sand a permit is required, as described in the ‘Ontgrondingenwet’, since January 2024 followed up by the ‘Omgevingswet’. Since 2008, the permit conditions under the *Mineral Extraction Law* (‘Ontgrondingenwet’) set a distance of 100 meter to living banks of shellfish to be maintained during extraction. However, there is no general accepted definition of a shellfish bed.

In this study, we explored some approaches to define shellfish beds, focusing on minimum density and minimum bed size. While we considered multiple species that could potentially form shellfish beds in the sand extraction area, we ultimately concentrated on *Spisula subtruncata* as our model species. This species experiences periodic population booms (Troost et al. 2024) and serves as a key food source for flatfish and diving sea ducks, making it ecologically significant. Our investigation considered both the intrinsic value of shellfish beds (the characteristics of a bed with respect to densities and bed size of different age classes) and their functional aspects (as food for diving common scoters).

Based on our analyses, we propose a minimum density of 1000 individuals per m^2 for juveniles and 100 individuals per m^2 for older animals. Defining the minimum bed size, however, proved more variable. But, it is clear that protecting a few percentage of the coastal waters, in areas where the highest densities occur, could result in protecting 50% of the total stock. At least in years where there is a substantial stock, after a good recruitment.

Although we focused on *S. subtruncata* for practical reasons, our proposed definition is a preliminary approach, intended as a working model. Other species may require different parameters, though few, aside from the Atlantic razor clam (*Ensis leei*), occur at comparably high densities.

1 Introduction

Dutch coastal policy mandates that the coastal foundation must be maintained in terms of volume up to the −20 m depth contour relative to the modified Amsterdam Ordnance Datum (AOD) and must grow in line with sea level rise (see annex 5 on Dutch coastal management). Adhering to this policy requires supplying large quantities of sand to the coast, which incurs considerable costs (Rijkswaterstaat North Sea 2013).

The sand along the Dutch coast provides natural protection against the sea. However, due to the constant action of wind, waves and currents, sand is continuously lost to deeper waters. To maintain the protection afforded by the beaches and dunes, Rijkswaterstaat conducts large-scale nourishment operations, replenishing the coast with millions of cubic meters of sand sourced from the North Sea seabed.

In the future, larger nourishment projects may be required to maintain the coastal sand balance, especially with rising sea levels and the increased frequency of violent storms. These operations not only contribute to preserving the coastline but also support local and regional goals for an economically strong and appealing coast (National Delta Programme 2024[1], Sand Decision[2]). In addition to maintaining the coastline, sand is also extracted for other purposes, such as fill sand for construction and infrastructure. The commercial bodies that extract fill sand are united in the LaMER foundation.

Since January 2024, sand extraction requires a permit under the 'Ontgrondingenwet' (Excavation Act), which has been succeeded by the 'Omgevingswet' (Environmental Law). In order to obtain a permit, an environmental impact assessment (EIA) is required. The Netherlands Commission for Environmental Assessment ('commissie MER') prepares advisory reports to the government on the scope and quality of these environmental assessments. Specifically, the MER has to describe the possible damage to shellfish beds and its impact on scoters (zie o.a. RWS 2014).

In 2008, the 'commissie MER' recommended identifying shellfish banks more effectively to improve control over extraction and nourishment activities. Since then, the permit conditions under the *Mineral Extraction Law* ('Ontgrondingenwet') require maintaining a 100-meter distance from living shellfish banks during extraction (conform BOR) (van Duin et al. 2017). However, applying this law is challenging due to the lack of an accepted definition of a shellfish bed, including criteria such as species, density, minimum surface area, extent, etc.

Why protect shellfish habitats ?

The presence of bivalves provides increased structural heterogeneity within the sediments, with potential for a larger number of different favourable microhabitats in the interstitial spaces and thus increased diversity (Gutiérrez et al. 2003, Norkko & Shumway 2011). On the other hand, a mass recruitment might result in a decrease in diversity and the community will need some time to recover (Van Hoey et al. 2007). However, bivalves provide more services than biodiversity. Locally, areas with high densities of *Spisula subtruncata,* for instance, can attract large numbers of shellfish-eating ducks in coastal waters (Leopold 1996, Degraer et al. 2007, Fijn et al. 2017). Shellfish provide a range of ecosystem services such as food provision, habitat for fish and invertebrates, water filtration, fish production and shoreline protection (Gillies et al. 2018 and references therein). Bivalves are major players in the modification of sediments, and the effects we observe are a combination of both bioturbation and bioirrigation. The term "bioturbation" refers to the reworking of aquatic sediments by the organisms in the sediments and, in its broadest sense, includes the structuring activities of both burrowing animals and rooting plants, as well as microbes. "Bioirrigation" on the other hand, refers to the enhanced transport of solutes between the sediment and the overlying water. This is the flushing of burrows that stems from the suspension feeding of the animals and their ventilation activities to facilitate transport of oxygen and excretory products. Therefore, bioturbation and bioirrigation are integral to

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[1] https://english.deltaprogramma.nl/documents/publications/2023/09/19/delta-programme-2024-english

[2] https://english.deltaprogramma.nl/three-topics/flood-risk-management/sand-decision

a healthy soft-sediment ecosystem and, in general, infaunal bivalves such as clams have a positive, desirable influence on the sand or mud in which they live, just as the earthworms in a vegetable patch or garden compost (Norkko & Shumway 2011). Hence, traits of shellfish might physically change the sediment conditions. Moreover, if shells are extending from the sediment, this will modify the near bottom currents and, thus, bottom roughness (as e.g. for *Ensis leei*, Witbaard et al. 2017). These changes depend on the size and density of the shells themselves, as well as local current conditions.

The habitats created by molluscs can be classified into three main types: 1) reefs, consisting of a veneer of living and dead animals; (2) aggregations, composed of both living and dead organisms; and (3) shell accumulations, made up of dead shells, often referred to as "shell hash." Some habitats may fall under either category 2 or 3, depending on the relative abundance of dead shells versus live organisms (Coen & Grizzle 2007). A more detailed description of these mollusc-created habitats is provided in the following paragraphs.

Reefs

A reef is defined by its three-dimensional structure of biologically generated substrate near the surface (Lowery et al. 2007). The structure of the reef may be composed mostly of the reef-building organism and its tubes and shells, or it may to some degree also be composed of sediments, stones and shells bound together by the organism (Holt et al. 1998). Blue mussels (*Mytilus* sp.) and Pacific oysters (*Crassostrea* sp.) are examples of reef-forming shellfish. Above a certain density they form a distinct, three-dimensional structure. These bivalve-created ecosystems can be seen as hotspots for biodiversity, although not invariably (Craeymeersch & Jansen 2019), and provide a range of ecosystem services such as food provision, habitat for fish and invertebrates, water filtration, fish production and shoreline protection (Gillies et al. 2018 and references therein). This also holds for the European native oyster (*Ostrea edulis*) (zu Ermgassen et al. 2021).

Aggregations

Other shellfish species do not form reefs, but often occur in aggregations. Aggregations refer to shellfish species that are not attached to one another, but still occur at densities sufficient to provide structural habitat for other organisms. The term bed is often used to refer to the same type of structure (Lowery et al. 2007). The sea scallop (*Placopecten magellanicus*), for instance, often occurs in adequate densities to provide habitat for other species (Langton & Robinson 1990). The clumps of dead shells and oysters can support large numbers of ascidians, polychaetes and seaweeds (OSPAR Commission 2009). Other bivalves such as the cut through shell (*Spisula subtruncata*) and razor shells (*Ensis* sp.) can be found in high densities just below the surface of the sediment.

Accumulations

A third type of shellfish habitat is formed by species such as the ocean quahog (*Arctica islandica*), surf clam (*Spisula solidissima*) and sand gapers (*Mya arenaria*) whose shells can persist long after the inhabiting organism has perished. Sometimes abandoned shells accumulate on the seabed to provide significant structure and habitat for a variety of organisms. Concentrations of *Spisula solidissima* shell accumulations (more than 20cm in depth), for instance, provide habitat for juvenile lobster, crabs and benthic fishes (Coen & Grizzle 2007)[3].

In our case, we can focus on the first two categories—reefs and aggregations—since the permits for sand extraction are specifically limited to living banks. This means our study on defining a shellfish bed, including criteria such as species composition, density, minimum surface area, and extent, will be restricted to habitats where living shellfish form dense structures, either as reef-building organisms or in aggregations. Non-living shell accumulations fall outside the scope of the current permits and will not be considered in this study.

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[3] Maximum length of *S. solidissima* is 19cm

2 Material and methods

2.1 Species potentially forming shellfish beds

We reviewed literature (Eisma 1966, Holtmann et al. 1996, de Bruyne et al. 2013) and data from the fish and shellfish stocks assessments (WOT program) (Smaal et al. 2001, Tulp et al. 2008, Tulp et al. 2010, Verver 2015, Troost et al. 2017, Troost et al. 2024)[4] to make an overview of species potentially forming shellfish beds in the sand extraction zones.

2.2 Definition of a shellfish bed

Aspects to be considered are the minimum coverage (%) or density (number of individuals per square meter) of the species, the minimum spatial extent of the area with that coverage or density (bed size), or a combination. Population structure of bivalves often exhibits – at least – a bimodal size frequency distribution, with a clear distinct juvenile cohort and one or more larger adult cohorts. Successful recruitment is often followed by a heavy post-settlement mortality (Degraer et al. 1999, Cole et al. 2000). Thus, the minimum density to be set is likely to be different for juveniles and adults.

We reviewed the literature for existing definitions using the aspects mentioned above and assessed their applicability to the selected species list.

Since the existing definitions proved inadequate for defining beds of infaunal aggregations (see Results), we thought about alternative approaches taking into account either the density or the spatial extent of an area with a certain density. Both approaches were calculated for different r age classes. The definition would then be based on the intrinsic value of the species, although it would be preferable to base it—at least in part—on functional aspects. In shallow waters this might be related to its value as food stock for diving birds (Fijn et al. 2017, van de Wolfshaar et al. 2023) or to shoreline protection (Boulenger et al. 2024). In deeper waters it might be related to its function as habitat and/or food for fish, but little is known. It might also be related to its positive effect on sediment mixing, if there is a minimum density and bed size which results in a positive effect on the sediment mixing (bioturbation and bio-irrigation) and/or changing sediment roughness. At present, however, knowledge on the ecological role in non-coastal waters is very limited.

Shellfish beds may consist of multiple species, such as mussels and Pacific oysters in the Wadden Sea (Nehring et al. 2009). Endobenthic species may also coexist. Sea. However, as there are at present no definitions of beds of endobenthic bivalves, we did not touch upon this. also verified whether the selected species occur together in high densities.

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[4] See "schelpdiermonitor": https://shiny.wur.nl/Schelpdiermonitor_Kust/

3 Results

3.1 Species potentially forming shellfish beds

Over 100 bivalve species occur in Dutch marine waters (de Bruyne et al. 2013). About 40 of these species can be found in the area of interest, where sand extraction is allowed. However, most of them are, and likely will be, found only in very low densities (see Schelpdiermonitor, https://shiny.wur.nl/Schelpdiermonitor_Kust/). About 10 species (*Table 1*) can occur in large numbers, mostly in aggregations at nearby locations, thus, potentially forming beds. Most of these species are infaunal, with the exception of the edible oyster (*Ostrea edulis*). The distribution and density of selected species are given in Annex 1.

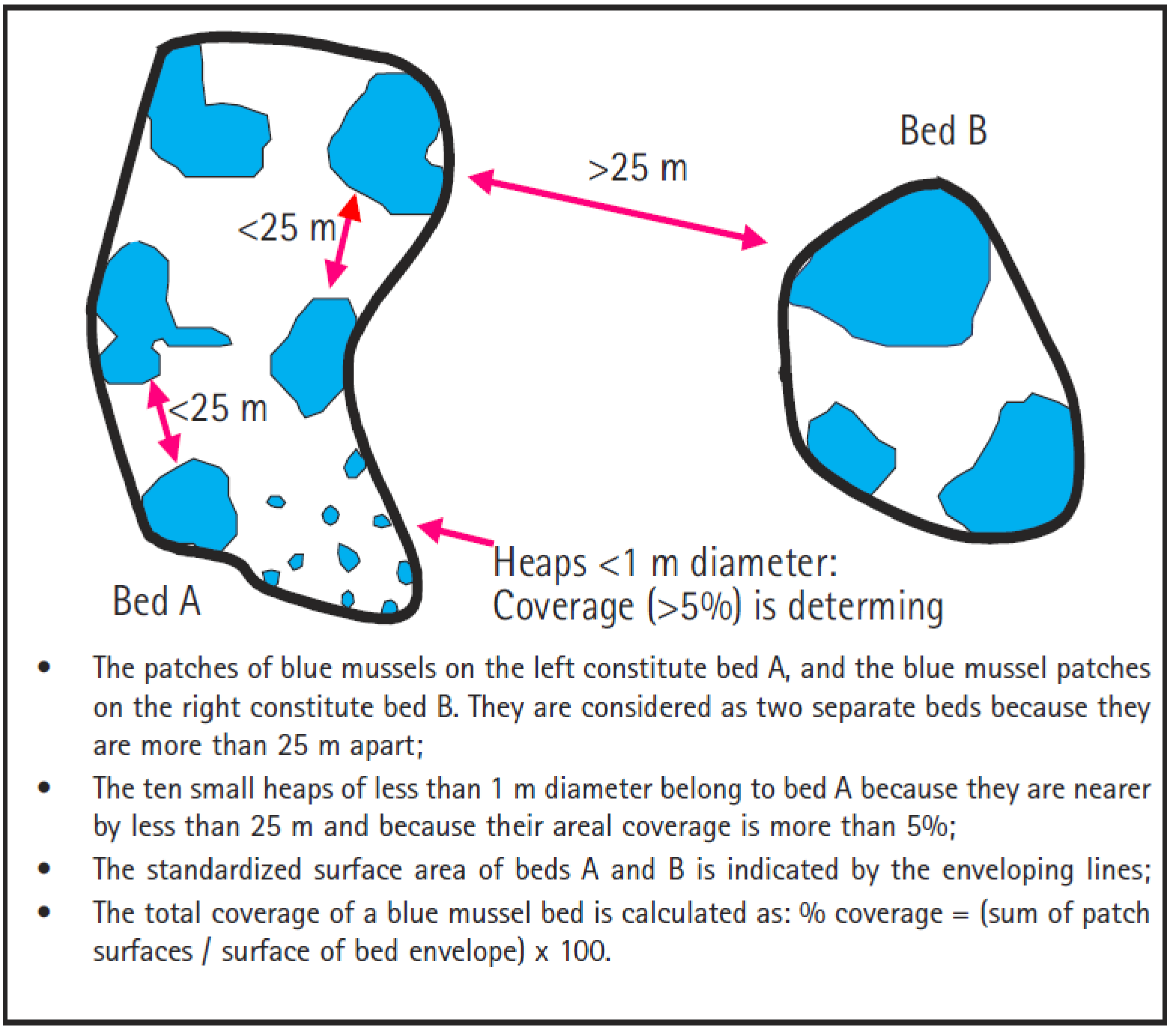
3.2 Definition of a shellfish bed

3.2.1 Literature review

Literature only gives definitions for some epibenthic species, though often only partially. In San Francisco Bay, hard substrate shellfish beds (*Ostrea lurida*, *Mytilus californianus*, *Mytilus trossulus*/*galloprovincialis*, *Geukensia demissa*, *Musculista senhousia*) are defined as locations where a shellfish species occupies more than 50% of an area lager than a few square meters (Schaeffer et al. 2007 in Anonymous 2010). The OSPAR Commission (2009) defines *Ostrea edulis* beds as having densities of 5 or more individuals per m², though no minimum bed size is specified. This density is higher than that recorded in the Wadden Sea at the end of the 19th century, when all oyster beds (1200-2000 ha) were in a 'good' condition, with a density of 0.5 ind/m^2 (Berghahn & Ruth 2005). For the North Sea, Berghahn en Ruth (2005) report a minimum of 0.125 ind/m^2. For mussels (*Mytilus edulis*) in the Wadden Sea (Netherlands, Germany, Denmark), a common trilateral definition of a mussel bed was established in 2002 (Essink et al. 2005) (de Vlas et al. 2005). A group of mussel patches is considered a bed if the patches are less than 25 meters apart and cover at least 5% of the sea floor. The coverage exceeds 5% if the average distance between patches is less than four times the patch diameter (Figure 1). Thus, the minimum bed size is 1 m^2 with a minimum coverage of 5%.

Table 1 *Species that might occur in large densities in sand extraction zones, and characteristics that might influence detectability (Ritsema et al. 2020). Degree of attachment refers to whether the organism is attached to the substrate or to another organism e.g. reef forming shellfish such as oysters Ostrea edulis attach to a substrate and to each other, while burrowing organisms like the Venus clam Chamelea striatula burrow in the sediment. Trophic types are the feedings types: Su = suspension feeder; SuDe = suspension and/or deposit feeder.*

species	**body length**	**motility**	**Degree of attachment**	**lifespan**	**Trophic type**	**Living habitat**	**Burrowing depth**	**Sediment characteristics**
Chamelea striatula	3-10 cm	sessile	null	3-10 yrs	Su	Burrow-dwelling	0-5 cm	Generally muddy, fine sand bottoms but also found in clean sand
Donax vittatus	1-3 cm	sessile	null	1-3 yrs	Su	Burrow-dwelling	5-15 cm	Clean fine sand (50-250 um)
Ensis leei	10-20 cm	sessile	null	3-10 yrs	Su	Burrow-dwelling	>15 cm	Gently sloping subtidal region on low grading shifting sands, but can also be found in mud and gravel
Ensis siliqua	10-20 cm	sessile	null	3-10 yrs	Su	Burrow-dwelling	>15 cm	Burrows in fine, sometimes muddy sand
Ensis magna	10-20 cm	sessile	null	3-10 yrs	Su	Burrow-dwelling	>15 cm	Lives in coarser sand than E. siliqua
Lutraria lutraria	10-20 cm	sessile	null	3-10 yrs	Su	Burrow-dwelling	>15 cm	Muddy sand
Mactra stultorum	3-10 cm	sessile	null	3-10 yrs	Su	Burrow-dwelling	5-15 cm	Clean sand
Spisula elliptica	3-10 cm	sessile	null	3-10 yrs	Su	Burrow-dwelling	0-5 cm	Sand, gravel, mud
Spisula solida	3-10 cm	sessile	null	3-10 yrs	Su	Burrow-dwelling	0-5 cm	Coarse-grained sediments
Spisula subtruncata	3-10 cm	sessile	null	3-10 yrs	Su	Burrow-dwelling	0-5 cm	Sand and muddy fine sand
Tellina fabula	1-3 cm	sessile	null	3-10 yrs	SuDe	Burrow-dwelling	5-15 cm	Fine (muddy) sand
Ostrea edulis	3-10 cm	sessile	attached	>20 yrs	Su	Attached to substratum	0 cm	Muddy fine sand, sandy mud mixed sediments. There may be considerable quantities of dead oyster shell making up a substantial proportion of the substratum



- The patches of blue mussels on the left constitute bed A, and the blue mussel patches on the right constitute bed B. They are considered as two separate beds because they are more than 25 m apart;
- The ten small heaps of less than 1 m diameter belong to bed A because they are nearer by less than 25 m and because their areal coverage is more than 5%;
- The standardized surface area of beds A and B is indicated by the enveloping lines;
- The total coverage of a blue mussel bed is calculated as: % coverage = (sum of patch surfaces / surface of bed envelope) x 100.

Figure 1. *Blue mussel bed measuring protocol, with mussel patches (blue) and envelope (black) (Essink et al. 2005)*

3.2.2 Alternative approaches

These definitions are insufficient for defining ‘beds’ of infaunal aggregations of the species that might occur in large densities in the sand extraction zones. Since these species also occur in shallower zones, it is presumed that any definition based on the shallow zone will apply to the entire coastal area, up to the 12 nautical mile boundary. As a first step, we will focus on a single species, namely *Spisula subtruncata*, because this species had high stocks in the late 1990s and early 2000s, up until 2001, and again during the period from 2016 to 2023 (Figure 2).

The approaches are based on literature and/or on analyses of survey data of the shellfish stock assessments in the Dutch coastal waters. The Dutch coastal area has been monitored for bivalve distribution and stock assessment since 1995 (WOT survey). Following a stratified approach, 800-1000 samples are taken in the coastal area each year in spring. The survey area is divided into strata, based on the expected density of the target species. In areas where high densities are expected, more samples are taken. The standing stock is calculated according to the each location: data from sampling stations are multiplied with the surface corresponding to the stratum of that station, i.e. the total surface of that stratum divided by number of sampling points in that stratum. The standing stock is then calculated as the sum of these data points (Troost et al. 2024). See Annex 2 for a schematic presentation of the sampling design and the stock assessment calculations.

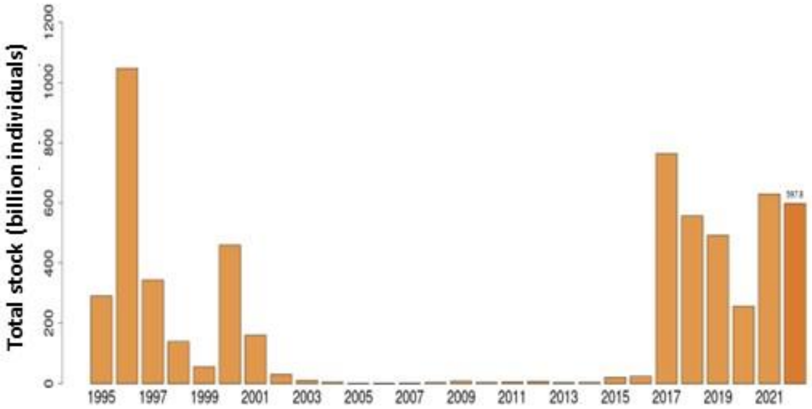


Figure 2. *Total stock of Spisula subtrucata in Dutch coastal waters (Troost et al. 2024)*

As mentioned before, we aim to define both minimum density and minimum bed size.
Minimum density was estimated in three ways: two methods based on intrinsic values (1: minimum density at individual locations needed to get a certain percentage of the total stock, 2: chance to find a certain density), and one based on functional aspects (minimum density in areas where common scoters were feeding).
Minimum bed size was determined using two methods: one based on intrinsic values (minimum bed size at certain percentages of the total stock), one based on functional aspects (the smallest areas where common scoters were found in shallower waters).

3.2.2.1 Minimum density

Minimum density, method 1

In this section, we analyzed the minimum density at various sampling locations to get a specific percentage of the total *Spisula subtrucata* stock. We calculated the contribution of each sampling point to the total standing stock, starting from the highest densities and determined at which densities 30%, 40%, 50%, 60%, 70% and 80% of the total stock were reached per year. We expected to observe an inflection point in a plot of density vs. percentage of total stocks (Figure 3). Locations with lower densities do not add much to the total stocks. Analyses were done for 1-year old and older individuals, for the years 1995 – 2022.

We expect that the most interesting years for defining minimum density will be those with high standing stocks. Therefore, we only show figures of those years in the main text. All years can be found in annexes. In the discussion, we will compare periods with different stocks.

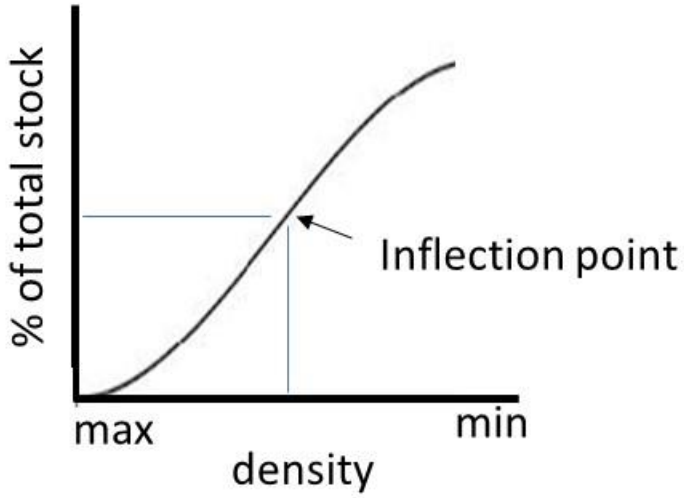


Figure 3. *Expected plot of density versus percentage of total stock*

In contrast to our expectations, we do not observe such inflection points for either 1-year-old or older animals, except for a few years: 2021 and 2022 for older individuals (Figure 4 and Figure 5), and 1999 for 1-year-old individuals (annex 3)

Therefore, we checked the minimum densities for all years at different percentages of the stocks (Table 2). Logically, there are large yearly differences. In years with low total stock, the minimum densities are very low (e.g. 2005) while in years with a large stock, the minimum densities are much higher (e.g. 2021).

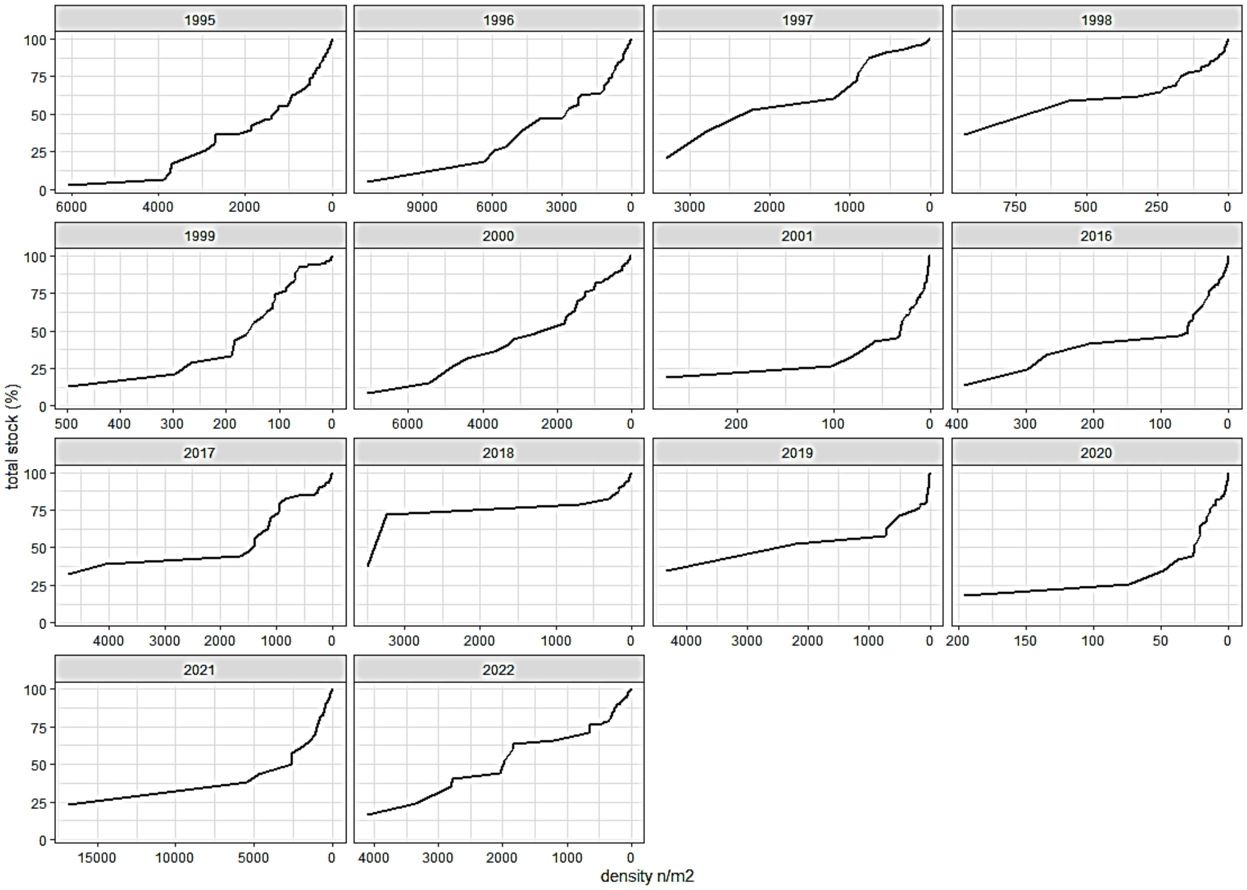


Figure 4 *Density of young (one-year) Spisula subtruncata (n/m^2) vs. percentage of the total stock. This is a selection of years where densities where particularly high. See Annex 2 for an overview of all years*

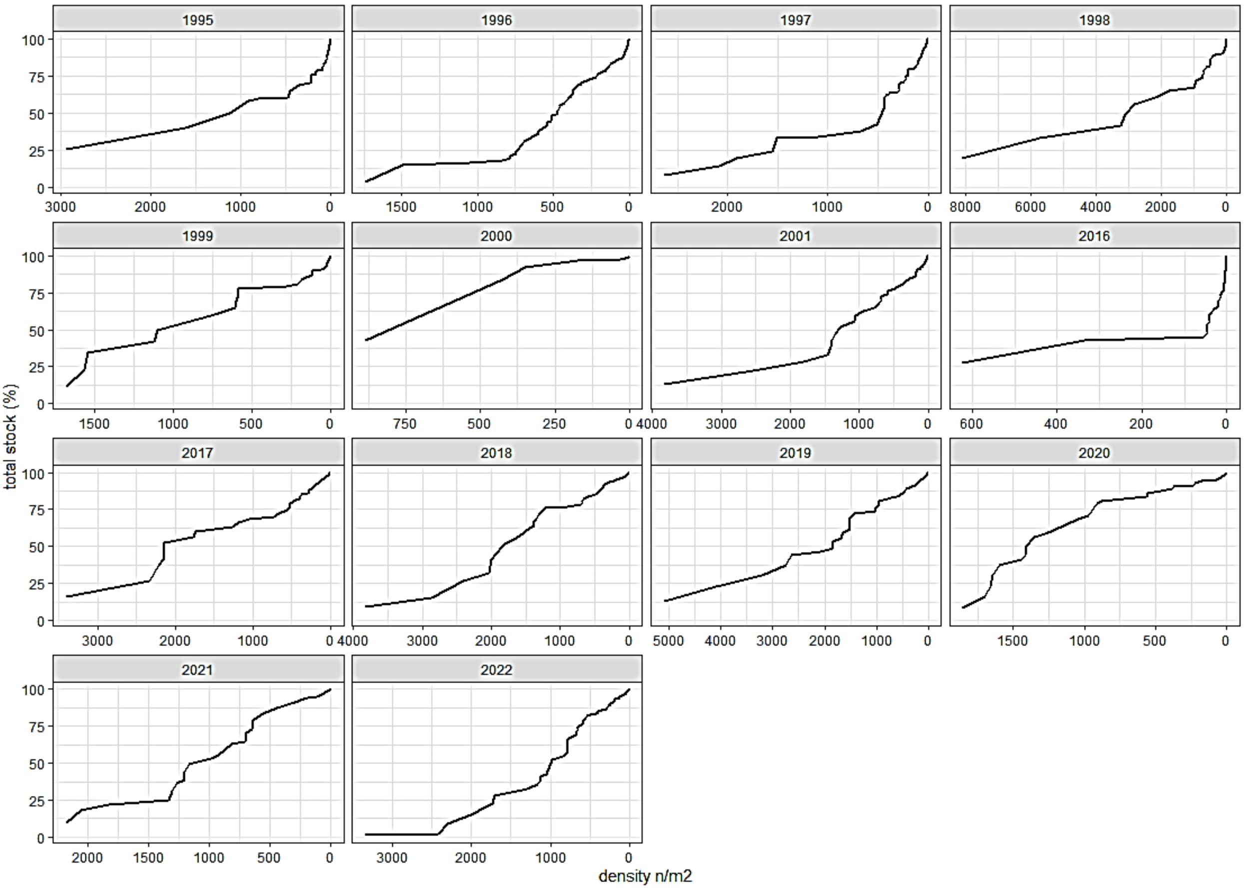


Figure 5 *Density of older (>1 year) Spisula subtruncata (n/m²) vs. percentage of the total stock. This is a selection of years where densities where particularly high. See Annex 2 for an overview of all years.*

Table 2. *Minimum density of 1-year old and older individuals to reach different percentages of the total stock, per year. Years with low stocks are shadowed.*

	≤1 year old				**> 1 year old**			
Year	**50%**	**60%**	**70%**	**80%**	**50%**	**60%**	**70%**	**80%**
1995	1389.02	996.13	513.43	365.63	1119.97	792.07	228.78	86.44
1996	2947.45	2259.31	1124.80	693.70	473.40	405.31	315.56	144.07
1997	2228.75	1206.29	921.33	896.74	482.60	429.74	273.23	135.85
1998	747.47	564.96	185.10	95.54	3104.94	2185.40	961.34	647.46
1999	153.51	131.61	111.69	85.62	1101.08	734.57	598.05	274.59
2000	2354.77	1741.44	1443.77	959.29	772.00	656.27	540.55	424.83
2001	31.37	25.52	13.66	5.75	1264.82	1056.76	682.93	428.66
2002	2.79	2.24	1.89	0.89	297.56	124.55	60.57	35.65
2003	21.36	10.61	7.04	3.36	25.26	15.63	9.76	4.54
2004	2.65	1.56	0.94	0.59	10.09	5.99	3.33	1.59
2005	1.58	1.00	0.82	0.55	1.89	1.63	1.01	0.56
2006	2.04	1.42	0.89	0.50	1.99	1.43	0.92	0.67
2007	2.11	1.53	0.81	0.53	1.46	1.01	0.75	0.48
2008	2.42	1.98	1.47	1.01	1.85	1.12	0.75	0.49
2009	8.46	6.06	4.40	2.48	12.14	6.36	2.81	1.53
2010					3.84	2.18	1.47	0.80
2011					1.92	1.20	0.84	0.51
2012					163.27	22.06	10.17	4.73
2013					3.63	2.93	2.01	1.10
2014					1.39	0.99	0.64	0.42
2015					88.44	58.61	33.64	11.81
2016	60.86	51.50	35.73	19.97	46.42	40.65	19.51	6.18
2017	1386.02	1252.58	1108.38	942.62	2142.32	1740.02	714.93	518.30
2018	3412.20	3324.17	3236.14	675.57	1850.02	1500.83	1356.46	680.13
2019	2219.07	730.29	516.12	59.20	1840.82	1648.52	1500.72	939.10
2020	25.57	21.48	16.21	9.46	1404.07	1270.70	972.59	880.41
2021	2586.38	1820.03	1166.63	749.25	1169.06	873.52	696.98	604.21
2022	1966.32	1842.08	665.15	345.59	976.10	786.09	673.47	551.67

Minimum density, method 2

In the second method, we examined the probability of finding a certain age group with a certain density. We assumed that certain density values are more likely to be found within the beds than outside the beds. Thus, we identified the most likely density within a bed. The analyzes were carried out using data collected during the WOT shellfish survey in the spring (April-June). This means that the youngest animals are 1-year-old.

Low densities, in particular, have a high risk of occurrence for both 1-year-old and older animals (left figures in

Figure 6**). When analyzing higher densities, both age classes show that a density of 200-225 ind /m^2 seems to have a higher chance of occurrence than higher or lower densities (figures on the right in**

Figure 6).

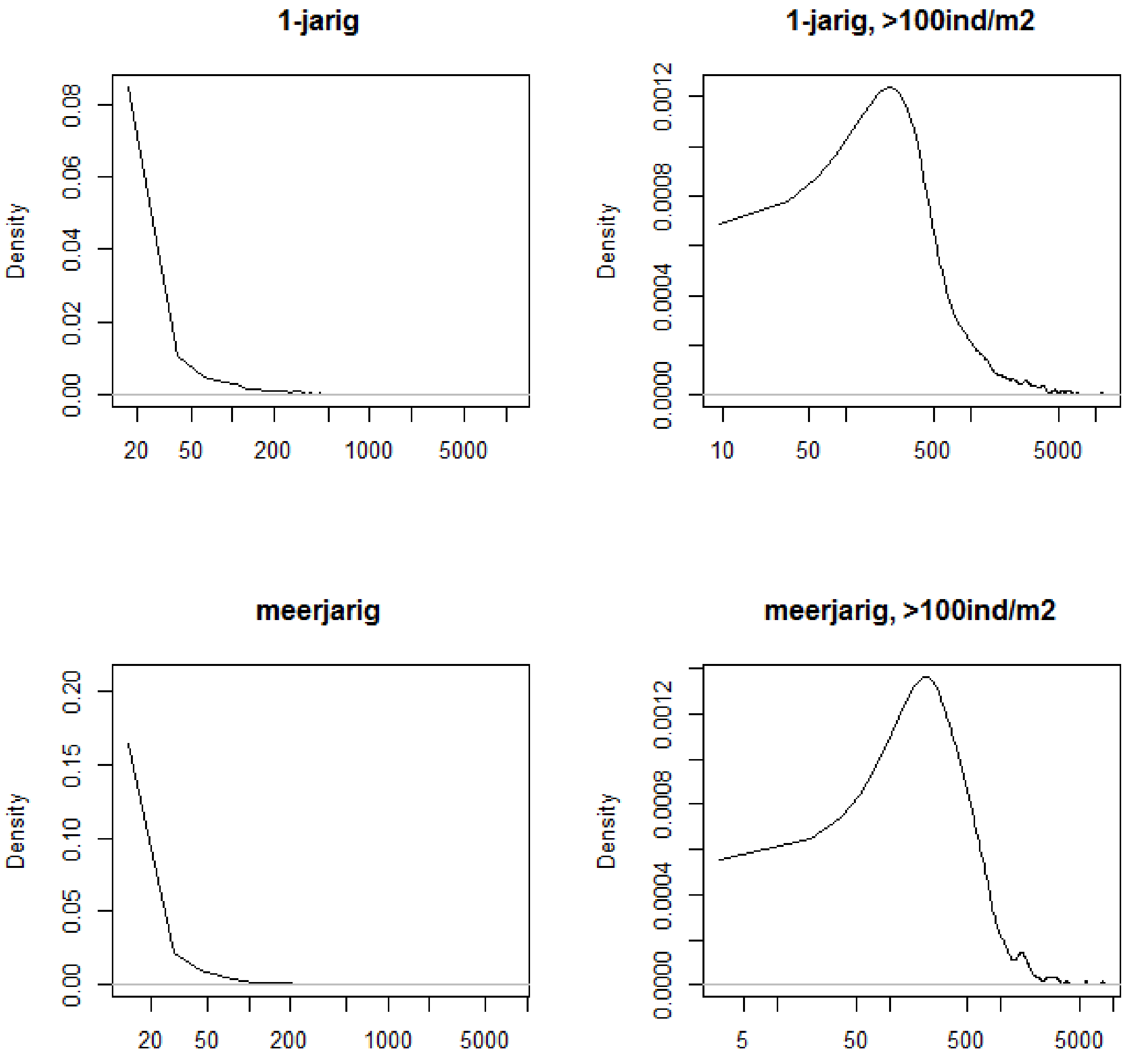


Figure 6 *Relative likelihood (density) for 1-year old (upper panels) and older Spisula (lower panels) to occur at a certain density (x-axis). Left panels: based on all data, right panels: based on data where density is above 100 ind/m^2 (data: WOT shellfish survey 1995-2014)*

Minimum density, method 3

This approach, to define minimum bed density, relates to its potential as food for diving ducks. We assume that the resulting definition of a bed will be similar for other functions, including those in deeper waters. Moreover, based on the energy budget of common scoters, deeper situated *Spisula* beds seems to be as important as more shallow situated beds (Wolfshaar & Daalen 2024). In this method our proposed definitions are based on a literature review. We realize that there are areas with high food availability but without scoters due to other factors (e.g. disturbance). Furthermore, there may be small areas where scoters forage on a shellfish bed that go unrecorded.

Degraer et al. (2007) monitored the development of the Belgian coastal zone for three years in an area on the Belgian west coast that is currently designated as Natura 2000 area due to the (then) high numbers of common scoters. In mid-1995, there was a good spatfall (newly settled 0-year old) with densities between 10,000 and 1,000,000 ind/m^2 (Figure 7) (Table 3). After the first winter (classified as 1-year-old), these densities decreased to about 100-10,000 ind/m^2 in January 1996. This is in line with findings by Leopold et al. (1998), who found north of the Wadden Islands densities of juvenile *Spisula* above 10,000 ind/m^2 in December 1995.

The key question regarding food for scoters is how many 0-year *Spisula* (or 1-year-old animals in the beginning of the year after the first winter) and/or older *Spisula* are necessary to serve as a suitable food source for common scoters. Should the minimum density be set at 10,000 ind/m^2 for 0-year-olds and 100 ind/m^2 for older individuals, or is the food requirement much lower?

In the late 1980s (1986-1988), the Voordelta was an important area for common scoters, with a maximum of about 27,000 wintering common scoters (Leopold 1996). After this period, maxima of fewer than 10,000 birds were observed, in contrast to other areas in the Dutch coastal zone. During the winter of 1990/91, benthos samples were taken in the Voordelta at a location abandoned by the ducks. It was shown that, densities of likely 0-year-old shells (lengths between 10 and 20 mm) decreased from 1,500 ind/m^2 in November 1990 to 1,200 ind/m^2 in February 1991 (Table 3). However, according to Offringa (1991, in Leopold 1996) it is unlikely that the ducks' departure from the Voordelta was due to a lack of *Spisula*.

In the winter of 1990/91 the stock at Schiermonnikoog almost completely consisted of spat from 1990. In that year the most common scoters were found in that area, with a maximum of 100,000 birds. The median length class of *Spisula* in 1990/91 was about 1 cm. Apparently the combination of size (median value about 1 cm) and number (6000 ind/m^2 in November 1990, to 2500 ind/m^2 in March 1991; Table 3) was sufficient (Leopold 1996). Not in all years or at all locations a length of 1 cm is reached by winter (see e.g. Figure 7, location P20). For juveniles, densities lower than 10,000 ind/m^2 appear to be adequate as a food source for common scoters. Thus, we propose setting the minimum density for juveniles at a conservative lower limit of 1,000 ind/m^2 for *Spisula* until further evidence suggests otherwise.

When choosing between young and older shellfish, common scoters prefer the older ones. Young animals must be consumed in large quantities for the ducks to maintain their condition (Leopold et al. 1998), which suggests that scoters can sustain themselves on lower densities of shellfish. In the spring of 1993 about 125,000 common scoters were observed near Terschelling. The *Spisula* densities were at a maximum of 655 ind/m^2 (Table 3). These were multiyear animals (median size 28 mm) (Leopold 1996). Thus, with regard to adult animals, the average density was below the 1000 found in de Voordelta, and 100 ind/m^2 may be a safe lower limit.

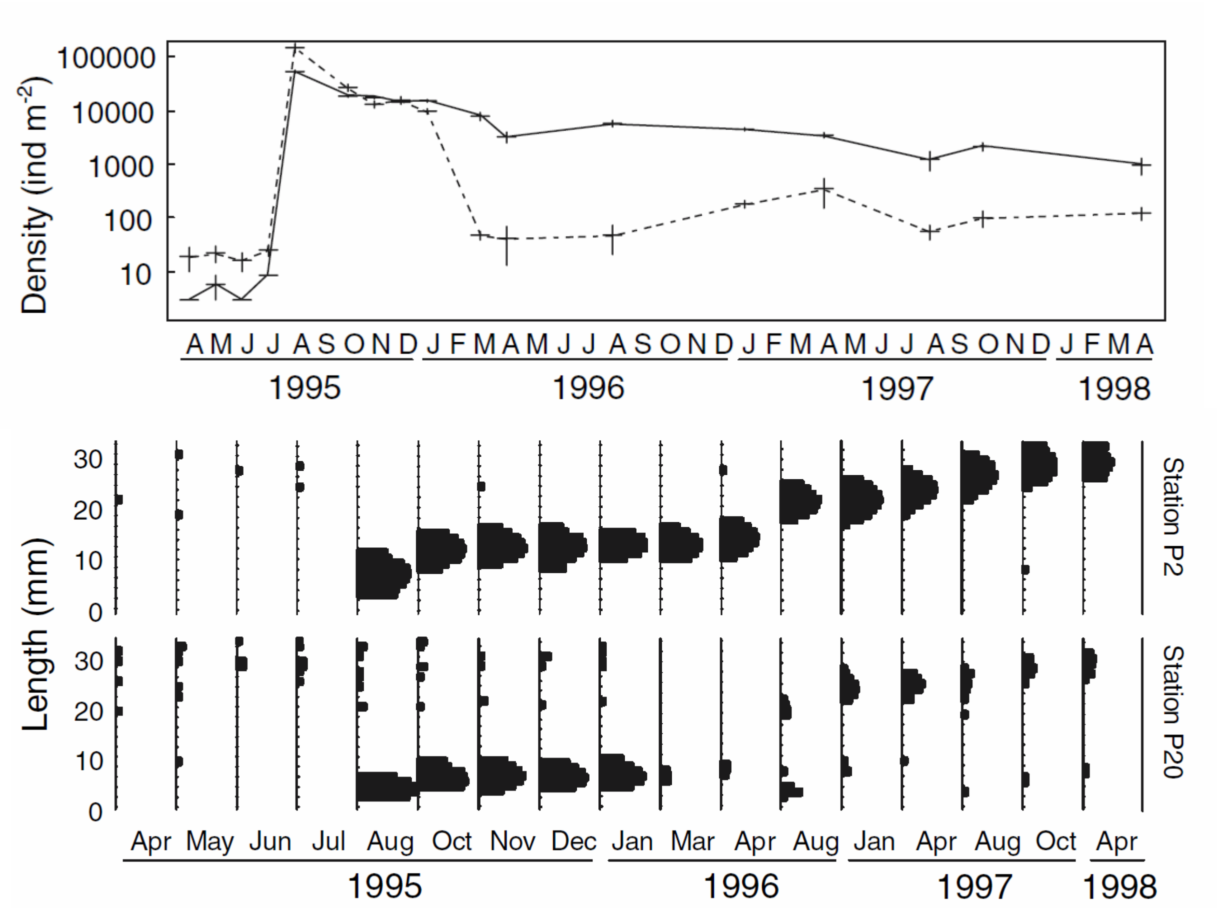


***Figure 7**. Upper figure: temporal variation of the density (ind/m2) of S. subtruncata at stations P2 (solid line) and P20 (dashed line). Lower figure: Length-frequency distribution at stations P2 and P20 (Degraer et al. 2007)*

***Table 3.** Literature review of densities of juvenile and older Spisula subtruncata and foraged by common scoters.*

reference	region	winter	year class	aug	nov	dec	jan	feb	mar
Degraer et al (2007)	Belgian west coast	1995-1996	yc 1995	$10000\text{-}10^6$			100-10000		
Leopold (1996)	Schiermonnikoog	1990-1991	yc 1990		6000				2500
	Voordelta	1990-1991	yc 1990		1500			1200	
Leopold et al (1998)	north of Wadden Islands	1995-1996	yc 1995			10000			
Leopold (1996)	Terschelling	1992-1993	older					655	

3.2.2.2 **Minimum bed size**

Minimum bed size, method 1

In this method, we applied the same approach as in Method 1 for determining minimum density of a shellfish bed. We calculated the spatial coverage at different percentages of the total stock. We anticipate observing an inflection point, beyond which only a few locations exhibit high densities (Figure 8). We also examined the geographical distribution of the locations involved to assess their proximity and determine whether we can confidently refer to them as a single bed. he analyses were conducted for both 1-year-old and older individuals.

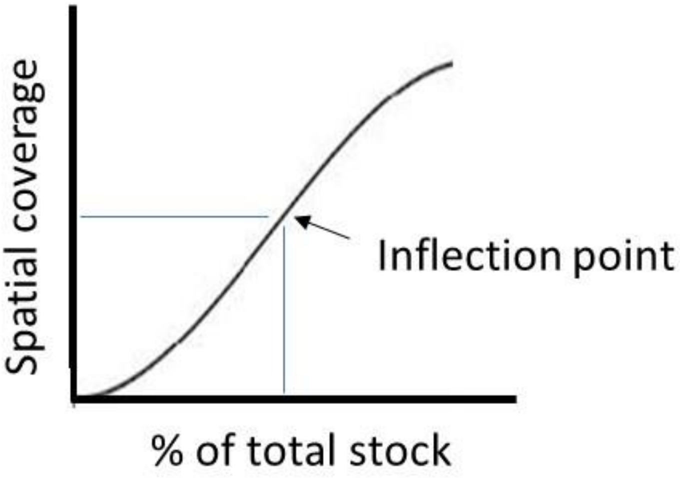


Figure 8. *Expected plot of percentage of total stock versus spatial area.*

Once again, we did not observe any inflection points for either 1-year-old or older animals. Therefore, we approached the analysis from a different perspective: comparing the percentage of the area where *Spisula subtruncata* was found against the percentage of the total stock (Figure 9 and *Figure 10*). As for density versus percentage of total stock, there are yearly differences. In years with a large stock, the area where you could find a stock of 50% was much smaller than in years with a low stock.

In Table 4 one can find the percentage of the area needed to find 50 – 80% of the total stock of the two age classes discriminated in this study (1-year-old and older individuals). In years with low stocks about 10% of the area where *S. subtruncata* was found, is needed for 50% of the stocks and up to almost 40% of the coastal area for 80% of the stock, while in years with high stocks 5-10% is needed for 80% of the stocks. Thus, in years with a high stock, small areas are important for the total stock, in years with low stock not. This is also clear from Figure 11, showing all locations that were needed to get 80% of the stock of animals older than 1 year. Again in years with low stocks, areas all over the coastal waters are needed, in years with high stocks, areas situated in rather limited areas are needed (e.g. in 1995 in Voordelta an and area along the coast of North Holland).

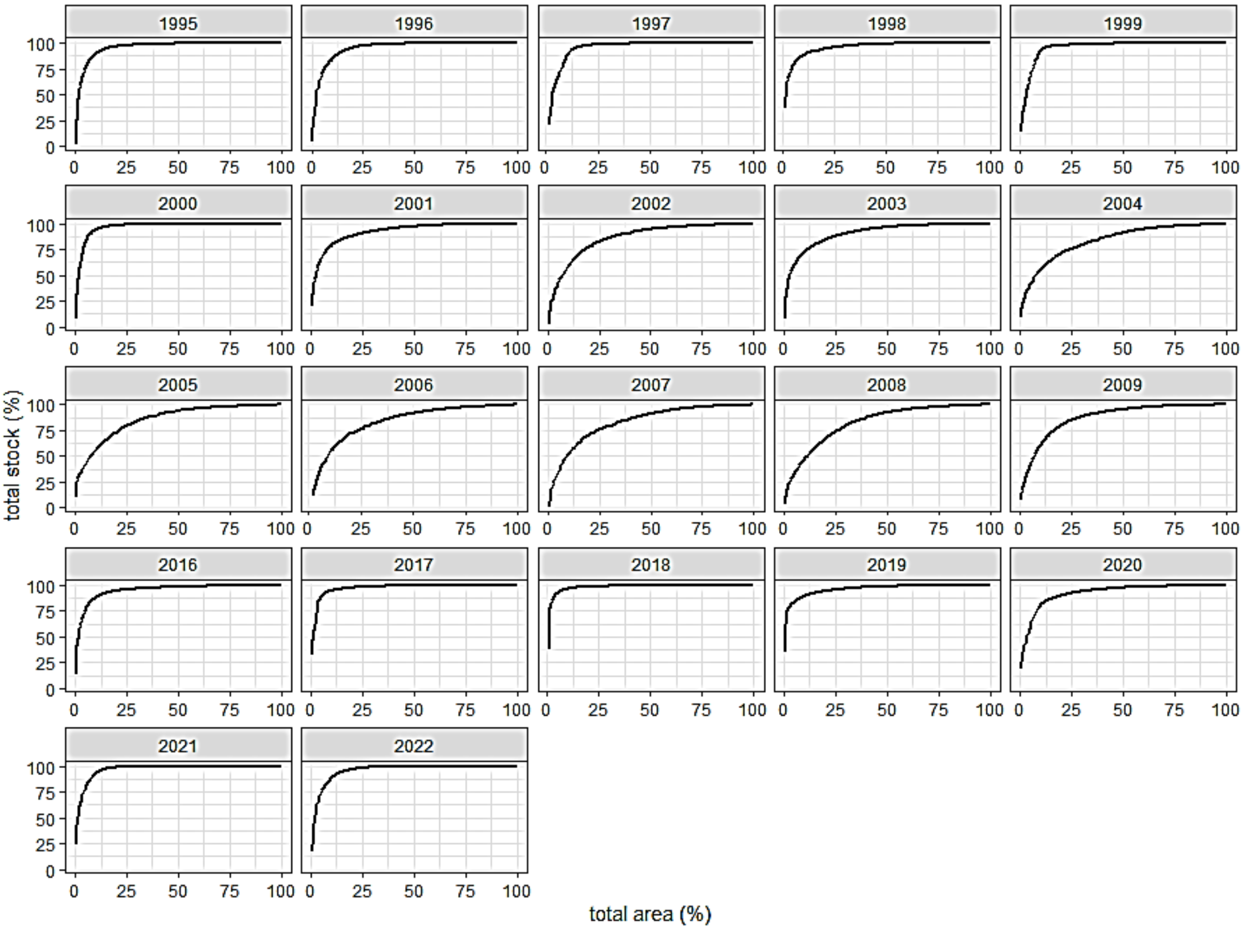


Figure 9 *Plots of percentage of total area (where Spisula subtruncata was occurring) versus percentage of total stock of 1 year old animals. Selection of years with high densities (>300 n/m^2)*

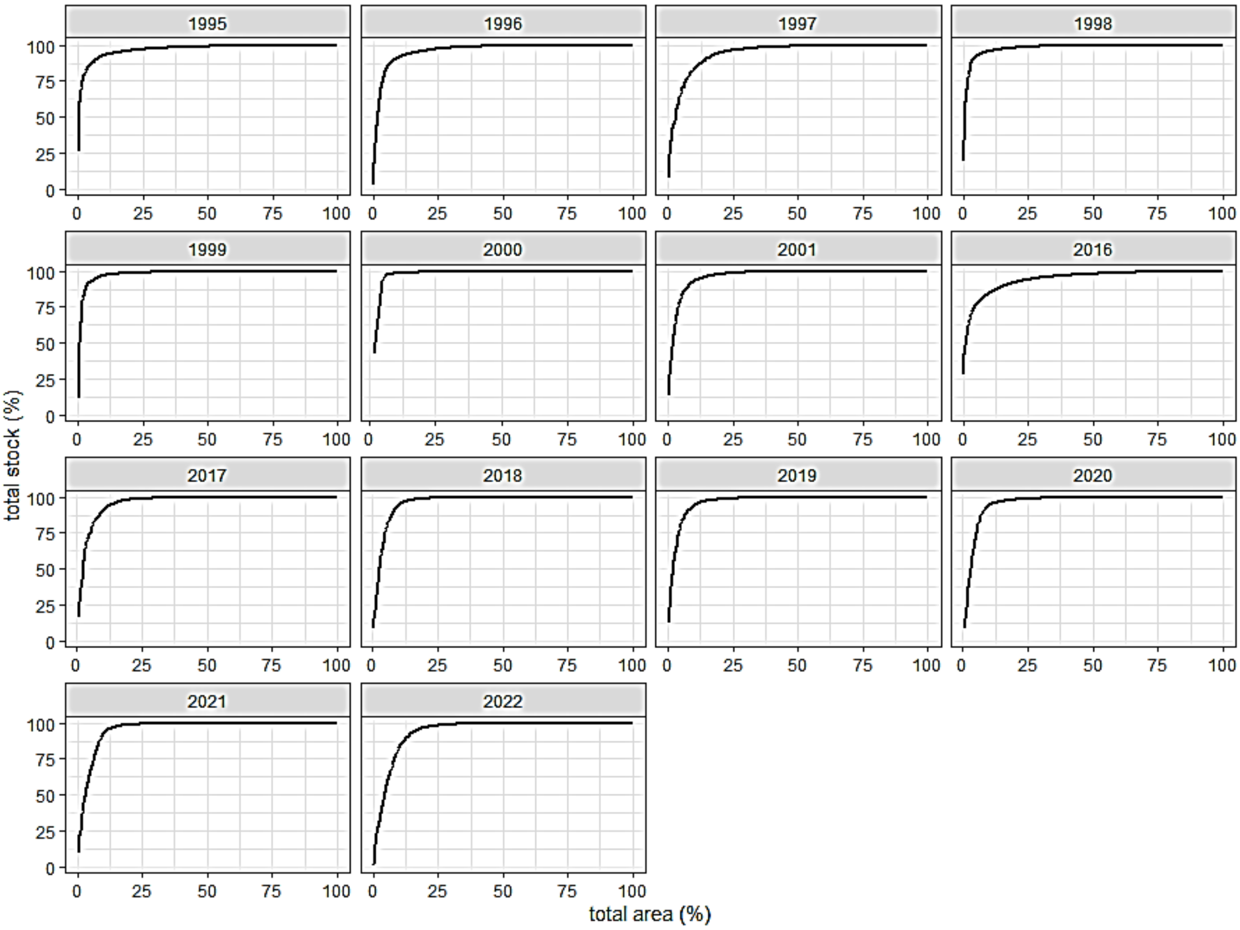


Figure 10 *Plots of percentage of total area (where Spisula subtruncata was occurring) versus percentage of total stock of animals older than one year. Selection of years with high densities (>300 n/m*^{2}*).*

Table 4 *Percentage of the area (where Spisula subtruncata occurred) where one could find the indicated percentages of the total stock (50% - 80%) for different years and different age classes of S. subtruncata. . Years with low stocks are shadowed.*

	≤1 year old				**> 1 year old**			
Year	**50%**	**60%**	**70%**	**80%**	**50%**	**60%**	**70%**	**80%**
1995	1.95	3.01	4.61	7.33	0.53	0.98	1.55	4.03
1996	2.61	3.72	6.23	9.77	1.95	2.49	3.41	5.36
1997	3.29	4.38	6.57	7.67	2.96	4.40	6.57	10.38
1998	2.07	2.97	4.54	7.62	0.56	0.85	1.55	2.25
1999	3.27	4.50	6.13	7.77	0.74	1.18	1.47	2.21
2000	1.83	2.67	3.67	5.34	2.04	2.71	3.39	4.07
2001	2.68	4.32	7.10	14.31	1.94	2.66	3.87	5.81
2002	8.12	11.84	16.67	27.08	1.34	2.28	4.39	7.97
2003	3.43	6.17	10.86	20.13	3.45	5.02	7.66	13.33
2004	8.99	13.95	23.45	37.39	4.39	7.46	13.26	23.75
2005	8.47	12.93	19.91	30.76	9.73	13.57	20.21	31.45
2006	9.21	14.05	21.60	35.20	10.76	16.40	24.37	36.07
2007	10.07	115.42	23.35	36.99	11.14	17.17	25.15	37.99
2008	13.03	18.46	25.42	35.82	9.74	15.19	24.16	37.88
2009	8.04	11.14	16.25	24.97	1.69	3.77	8.93	19.01
2010					8.87	12.61	19.46	30.24
2011					10.58	15.36	22.18	34.13
2012					0.56	2.25	5.19	12.29
2013					8.09	12.78	17.90	28.74
2014					10.28	16.68	25.88	39.49
2015					1.29	2.42	3.95	9.03
2016	1.78	2.76	4.50	7.66	1.05	2.18	4.21	10.18
2017	1.29	1.93	2.70	3.84	2.37	3.16	4.75	6.99
2018	0.59	0.74	0.89	2.21	2.69	3.68	4.66	6.50
2019	0.41	0.78	1.61	5.10	2.26	2.91	4.04	5.66
2020	3.80	5.49	7.53	12.20	3.03	4.11	4.76	6.27
2021	1.23	2.18	3.95	6.35	3.45	4.67	5.88	7.51
2022	2.17	2.91	4.63	8.13	4.77	5.71	7.98	10.48

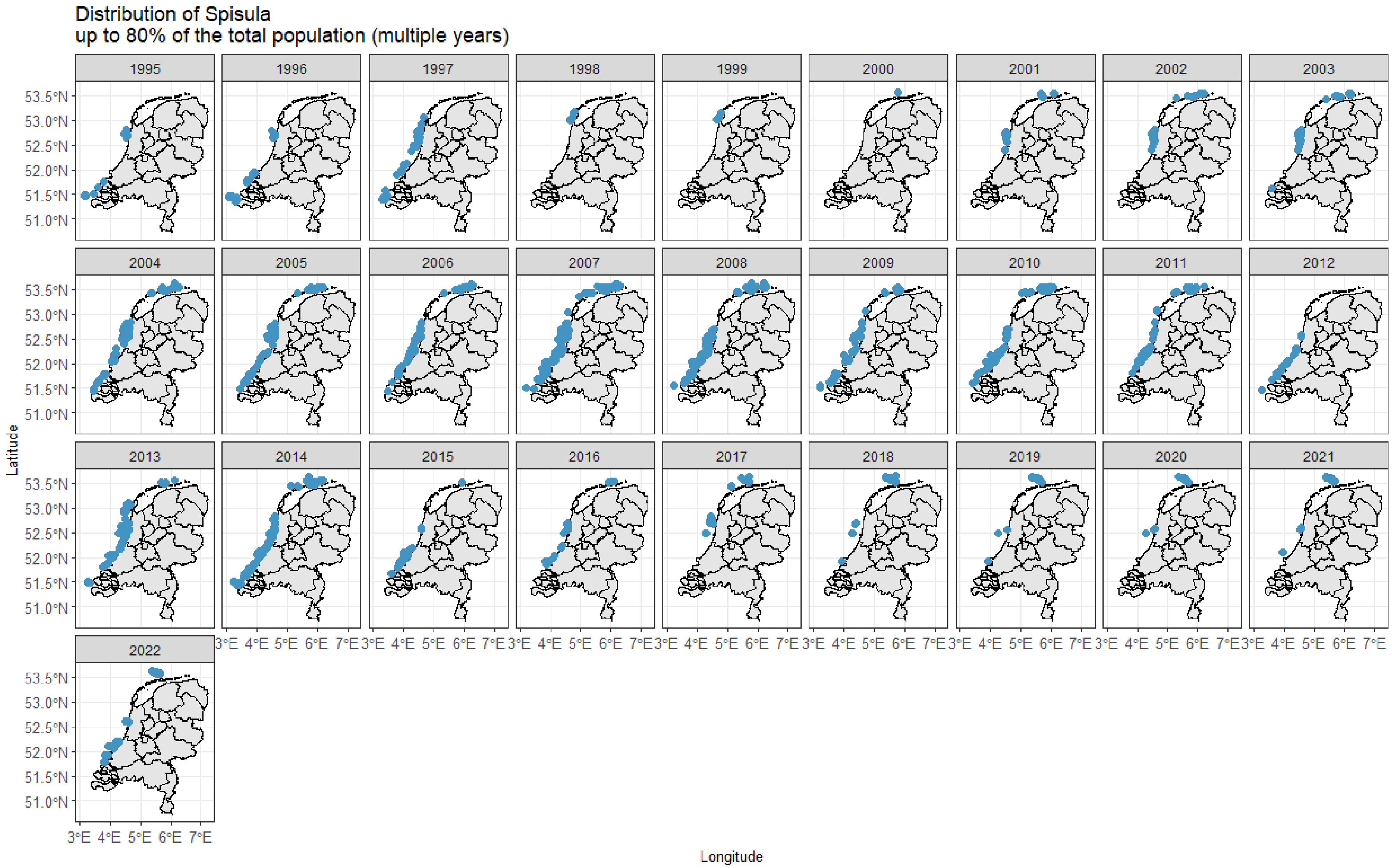


__Figure 11__ The locations of the total sampling locations needed to get 80% of the total stock of animals older than 1 year, in different years. Highest stocks were found in the years 1995-2001 and 2017-2022.

Minimum bed size, method 2

In the second method, we reviewed the literature regarding instances where common scoters were observed feeding in relatively small areas with high densities of *Spisula subtruncata*:

- Degraer et al. (2007) conducted a study on the Belgian Western Coastal Banks (), which we mentioned earlier. This area measures approximately 3.25 km².
- In January 2017, almost 1500 common scoters were recorded in northern part of the Voordelta, south-west Netherlands (green point in Figure 1) (data nature compensation monitoring Voordelta, Prins et al. 2020). In spring 2017 high densities of *S. subtruncata* were found in that area (red points) (WOT shellfish survey). Each sampling point in that area is representative for 4.22 km^2. Thus, we estimate the bed size at that time at about 16 km^2.
- In April 2018, more than 12000 common scoters were recorded in the Voordelta (Figure 14) (nature compensation monitoring Voordelta, Prins et al. 2020). In the preceeding Autumn, only at a few points there were higher densities of *S. subtruncata (*unpublished data Craeymeersch, data nature compensation monitoring Voordelta). In fact, several other potential food items had higher densities in that area at that time (*Figure 15*). Apparently, birds were not feeding on a single species aggregation, but on a mix. However, given the spatial scale of the scoter flock, we estimate the (mixed) bed size as 3-5 km^2.

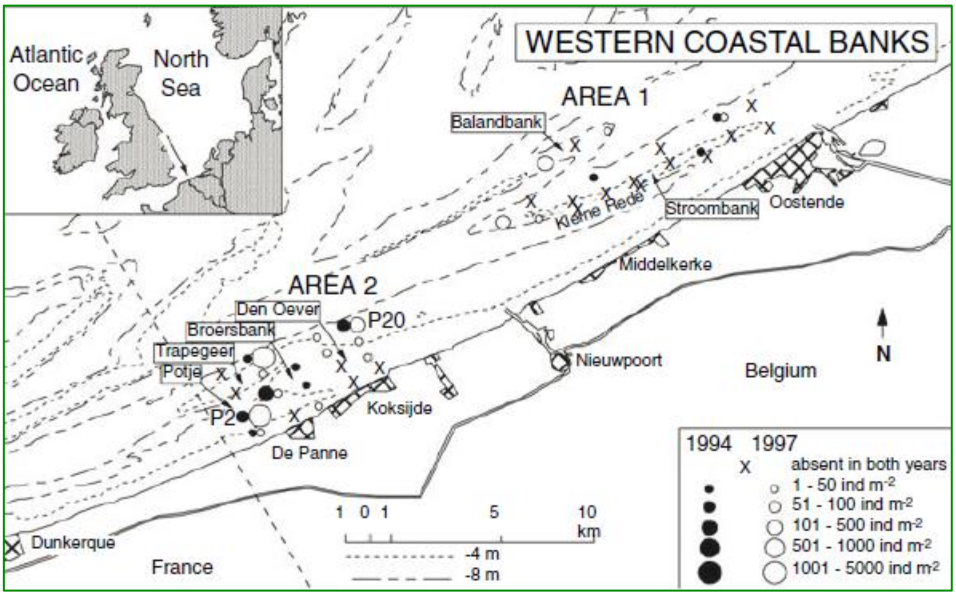


*Figure 12 Spatial distribution of S. subtruncata at the Belgian Western Coastal Banks in 1994 and 1997 (Degraer et al. 2007)***.**

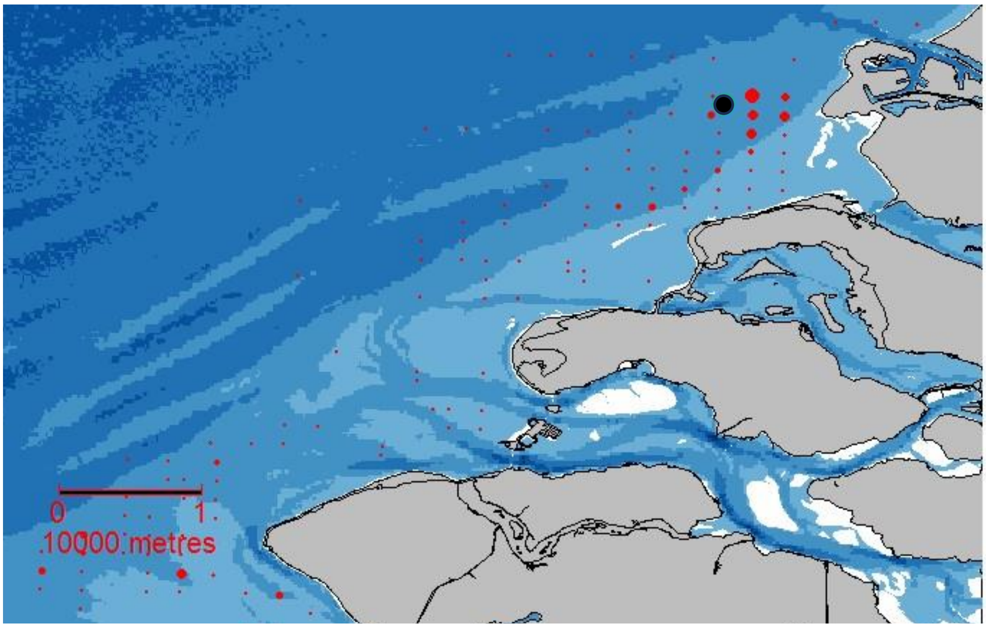


***Figure 13** Density of S. subtruncata in Spring 2017 (red points; diameter relative to density) and record of almost 1500 common scoters in January 2017 (black point).*

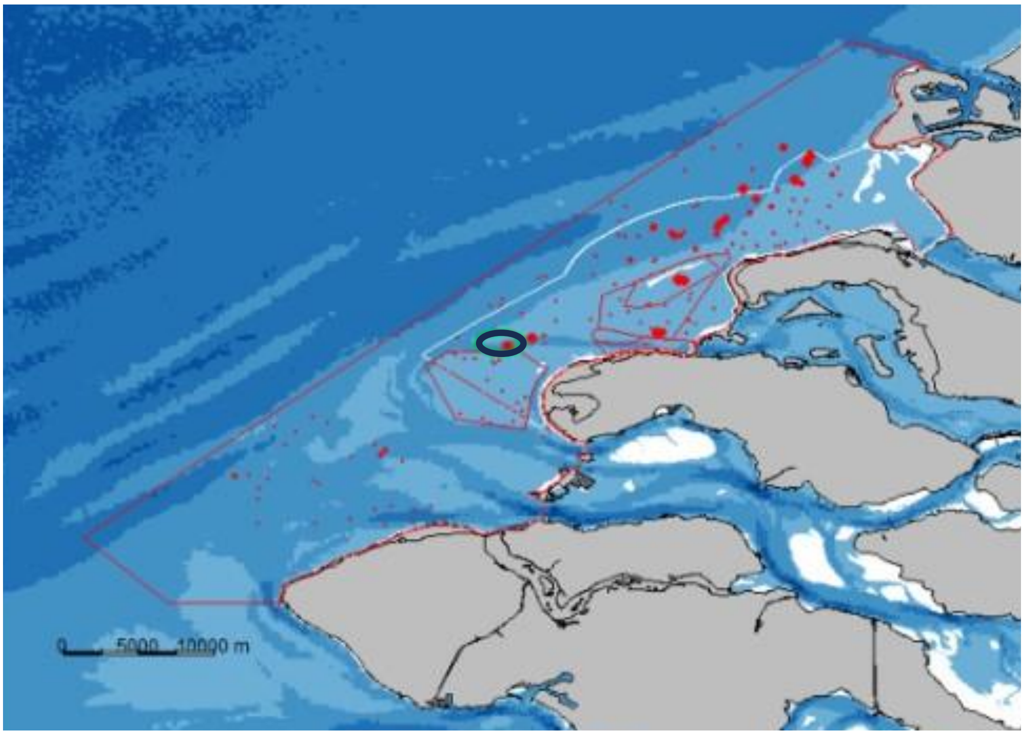


***Figure 14** Density of S. subtruncata in Autumn 2017 (red points; diameter relative to density) and record of more than 10000 common scoters in April 2018 (black ellipse).*

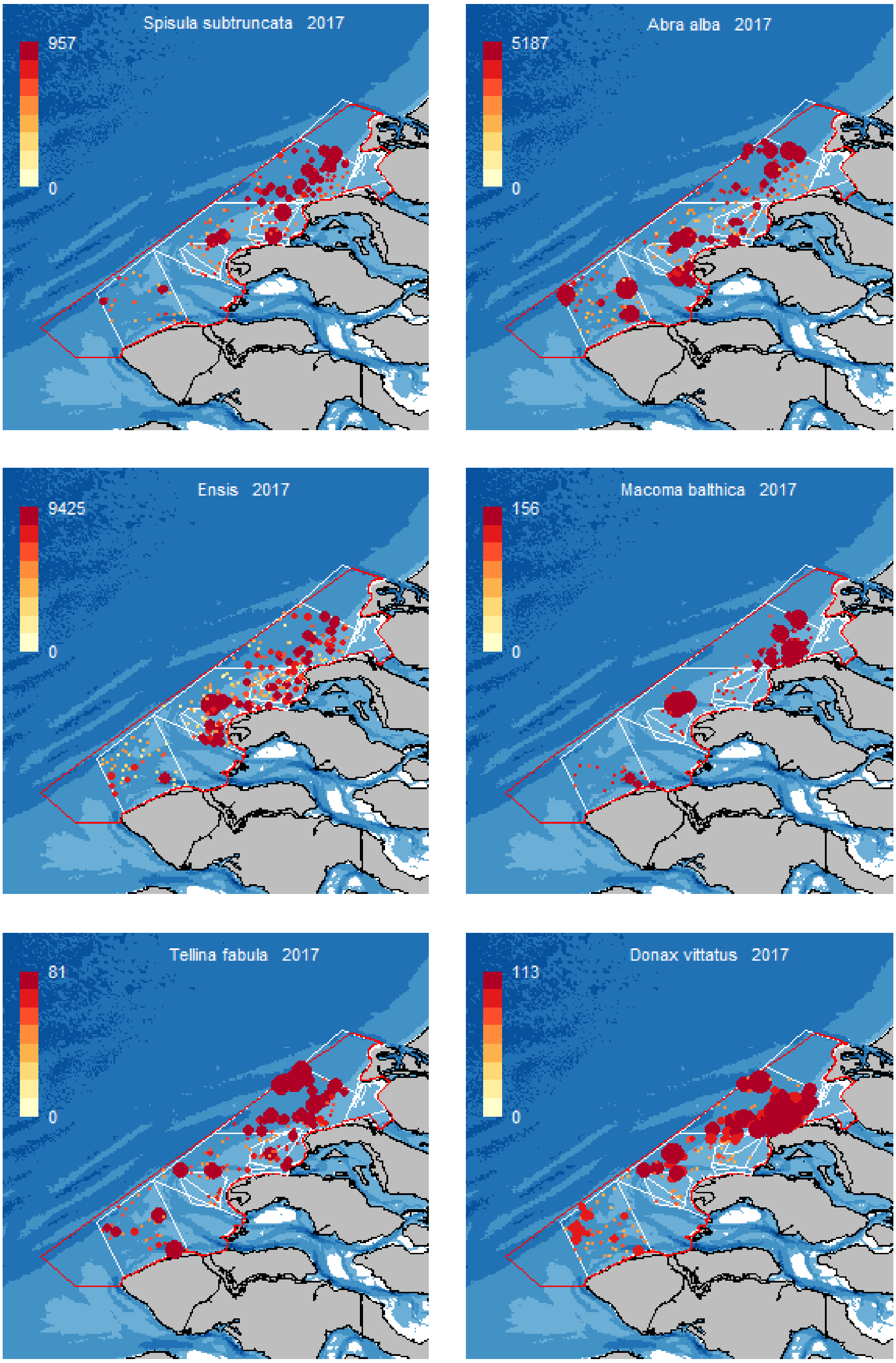


Figure 15 *Density (ind/m²) of some bivalves in the Voordelta, Autumn 2017 (diameter relative to density). The bar indicates minimum and maximum values.*

Co-occurrence of bivalves

In the previous chapter, we focused on a single species, *Spisula subtruncata*. While we noted the presence of certain other food items for common scoters in the same region, these did not correlate with higher densities at the sampling locations. To explore whether it would be beneficial or necessary to define a metric based on the combined density of multiple species, we investigated whether other bivalve species listed in Table 1 co-occurred with either *S. subtruncata* (*Figure 16*) or *E. leei* (*Figure 17*). We found that while other bivalve species do coexist, they do not do so in significant densities. The correlation between these species is generally weak, with correlation coefficients below 0.29 or nearly nonexistent values. However, we observed moderate correlations in two cases: between *Spisula subtruncata* and *Spisula solida*, and between *Spisula subtruncata* and *Fabulina fabula*, with correlation coefficients ranging from 0.30 to 0.49.

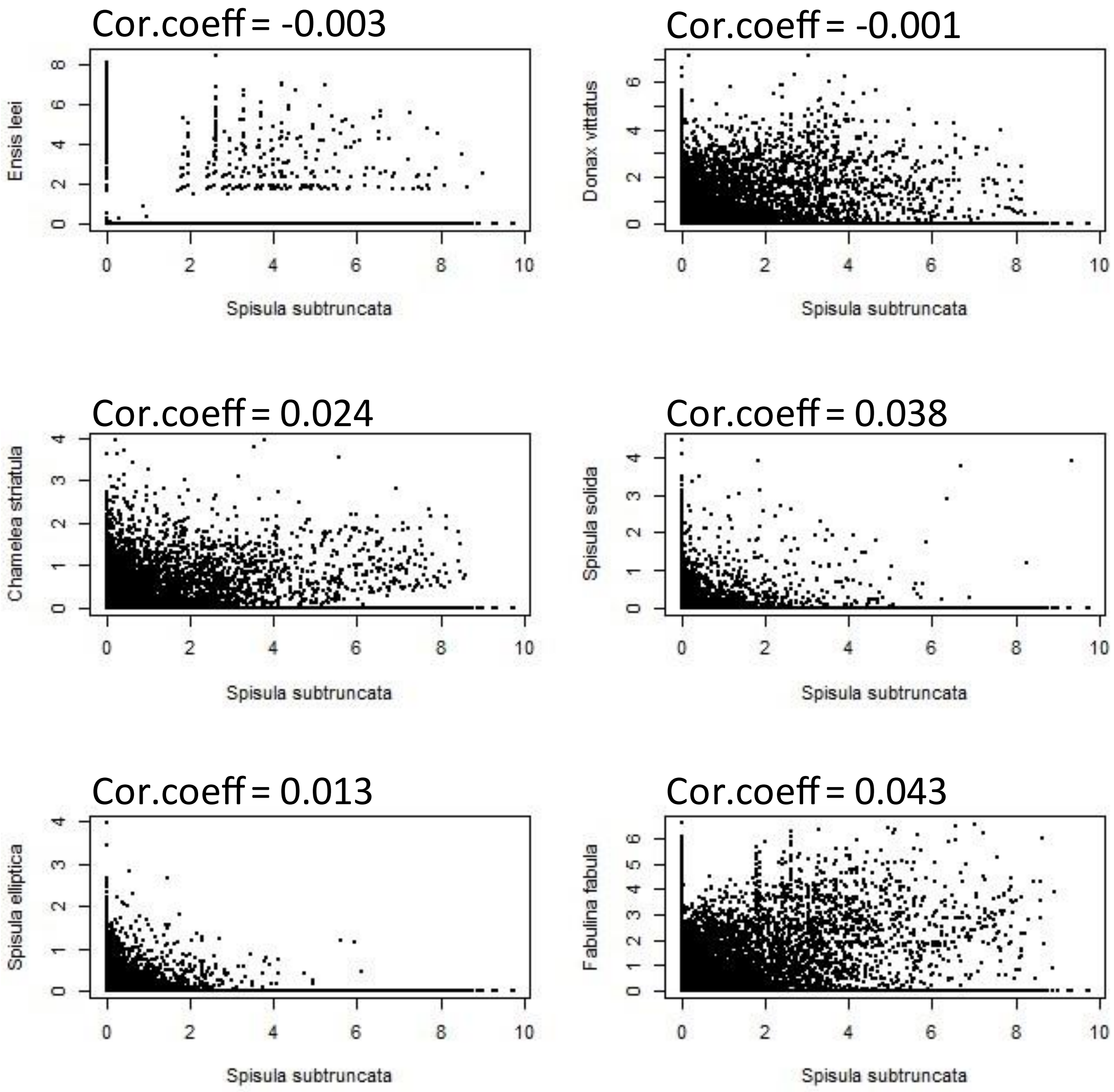


Figure 16 *Density (log(N+1) of S. subtruncata versus density of other bivalve species mentioned in table 1. Cor. Coeff = Pearson correlation coefficient.*

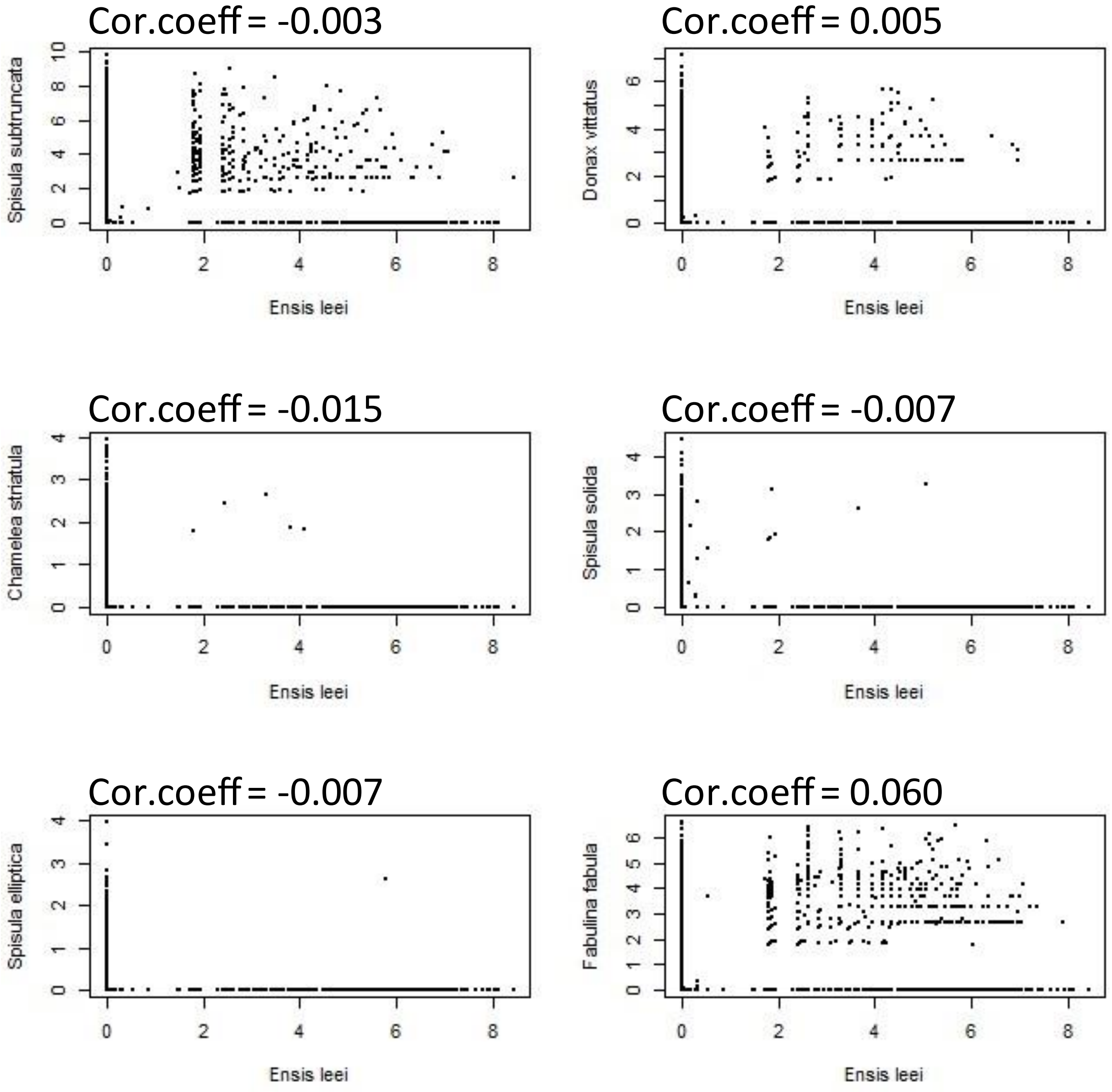


***Figure 17** Density (log(N+1) of E. leei versus density of other bivalve species mentioned in table 1. Cor. Coeff = Pearson correlation coefficient.*

4 Discussion and conclusions

Organisations with a permit for sand extraction should keep a 100 meter distance from living beds of shellfish. However, a universally accepted definition of what constitutes a shellfish bed is lacking.

In the Dutch marine waters, most of the shellfish species are infaunal. For the epibenthic bivalve *Ostrea edulis,* the definition of a shellfish bed should most likely be close to the ones used for other epibenthic species. The definition used in San Francisco Bay is – to our opinion – the most useful: the species occupies more than 50% of an area of more than a few square meter. The oyster bed – consisting of both Pacific and flat oysters - found in the Voordelta is about 1.3 km^2, with densities up to 5 living individuals of flat oysters per square meter (Sas et al. 2016). This oyster bed is established on hard substratum (the 'Blokkendam'). In other areas, the bed may also consist of numerous dead shells. Therefore, we propose a preliminary definition of an oyster bed as an area of at least 1 km^2 with an average density of five living individuals per square meter—an achievable but detectable threshold(Ritsema et al. 2020).

Definitions for epibenthic species are not very useful for infaunal species. in this study, we did explore potential definitions, based on density and bed size. We focussed on a single species, the cut through shell *Spisula subtruncata*, because this species has periodically high stocks (Troost et al. 2024) and because it is an important food source for flatfishes (Hagmeier 1930, Braber & de Groot 1973) and diving sea ducks (Leopold 1996, Fijn et al. 2017, van de Wolfshaar et al. 2023). Our investigation considered both intrinsic value (characteristics of a bed concerning densities and bed sizes of various age classes) and functional aspects (particularly as food for diving common scoters).

Minimum density

When plotting density versus percentage of total stock, we expected to find an inflection point , suggesting that locations with lower densities would contribute minimally to the total stock. no such inflection point was observed for either 1-year-old individuals or older individuals. Consequently, current definitions may require a degree of subjectivity.

Another important question that arises when defining shellfish beds is if we should consider data from all years or restrict our analysis to years with higher total stocks. It is probably not realistic to consider all years for a species like *S. subtruncata*, as there are several years with very low stocks and, consequently, low minimum densities, often lower than 1 ind/m^2. In years with low stocks, areas with low density add significantly to the total stock. However, the data show that after many years with low stocks, there might be a good recruitment resulting in high stocks. Thus, for the protection of the species on the longer term it seems not necessary to protect low density areas. With respect to sand mining, disturbance of a small area will not result in a large decrease of the total stock.

The definition might be based on the minimum percentage of a stock that we want to protect (intrinsic value). For instance, is 50% of the total stock of a specific age class adequate, with minimum densities of 1,000–3,000 ind/m^2? Or should we aim for a higher percentage, thereby necessitating a lower minimum density (100–1,000 ind/m^2)? This aligns with the results of our second analysis (200-225 ind/m^2), when only taking into account densities higher than 100 ind/m^2. Densities found in areas where common scoters were feeding ranged from 100 to 2,500 ind/m^2, suggesting that a threshold of 100 ind/m^2 might serve as a safe lower limit for individuals at least 1-year-old.

In the first two methods we analysed data for 1 year and older individuals. In the third method, relating to food for diving ducks, we could also look at new recruits, juveniles (year class 0). In the period between recruitment and start of the winter density values between 1500 and 10000 ind/m^2 were found. We therefore propose to set, until further notice, the minimum density of juveniles to a safe lower limit of 1000 ind/m^2.

Minimum bed size

Regarding minimum bed size, we did not identify an inflection point when plotting the percentage of total stock against spatial area. Once again, in years with low stocks, areas over the whole coastal waters are needed to protect a certain percentage of the total stock. In years with high stocks, the stock is concentrated in rather small areas Also here this depends on the percentage of the stock that has to be protected. At maximum (for percentages of stock > 50%) 10 % of the total area where 1 year old *S. subtruncata* was found should be protected. This is about 1.5 % of the total coastal area. The same holds for older animals. For 80% of the stock, these figures are respectively 3 and 3.6%. In summary, these figures mean areas between 100 and 250 km^2. Thus, protection rather small areas will result in the protection of a high percentage of the total stock. These figures are larger than the ones estimated from areas where common scoters were found to feed: 3 – 16 km^2. However, common scoters might use even smaller areas. Bauer & Glutz von Blotzheim (1969) (in describe how a group of about 1000 common scoters settled near Helgoland, shortly after a ship carrying a cargo of horse beans sank there. Plastering common scoters are rare off Helgoland, but this group remained in place for a month (pers. comm. M. Leopold).

4.1 Conclusions

Based on our analyses we recommend a minimum density of 1000 ind/m2 for juveniles and 100 ind/m2 for older animals. The results regarding minimum bed size reveal significant variability. However, it is evident that protecting a small percentage of coastal waters—specifically areas with the highest densities—can effectively conserve 50% of the total stock, particularly in years following successful recruitment when stock levels are substantial.

To mitigate the risk of substantial stocks overlapping with sand mining areas, we require a practical definition of shellfish beds. Ritsema et al. (2020) nitiated an inventory and assessment of geophysical methods for shellfish bed detection. At present further research is done by TU Delft using a multibeam echo sounders (see e.g. Bai et al. 2024). However, also the results of this detection method will likely vary depending on the species involved.

For practical reasons, we focussed on one species, *Spisula subtruncata*. Thus, the proposed definition should be seen as preliminary steps toward establishing a working definition. Other species may present different thresholds, though most do not exist in high densities except for the Atlantic razor clam (*Ensis leei*). Furthermore, abiotic conditions for other species differ from those experienced by *Spisula subtruncata* (see e.g. De Mesel et al. 2011). The approaches adopted in this study for *S. subtruncata* could be adapted for other species, but they will inevitably yield different density and bed size metrics.

Unfortunately, we were unable to establish an objective definition. Future research could evaluate the various approaches on intertidal *Mytilus* beds and compare them with the accepted definitions used in the Wadden Sea.

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5 Quality Assurance

Wageningen Marine Research utilises an ISO 9001:2015 certified quality management system. The organisation has been certified since 27 February 2001. The certification was issued by DNV.

Justification

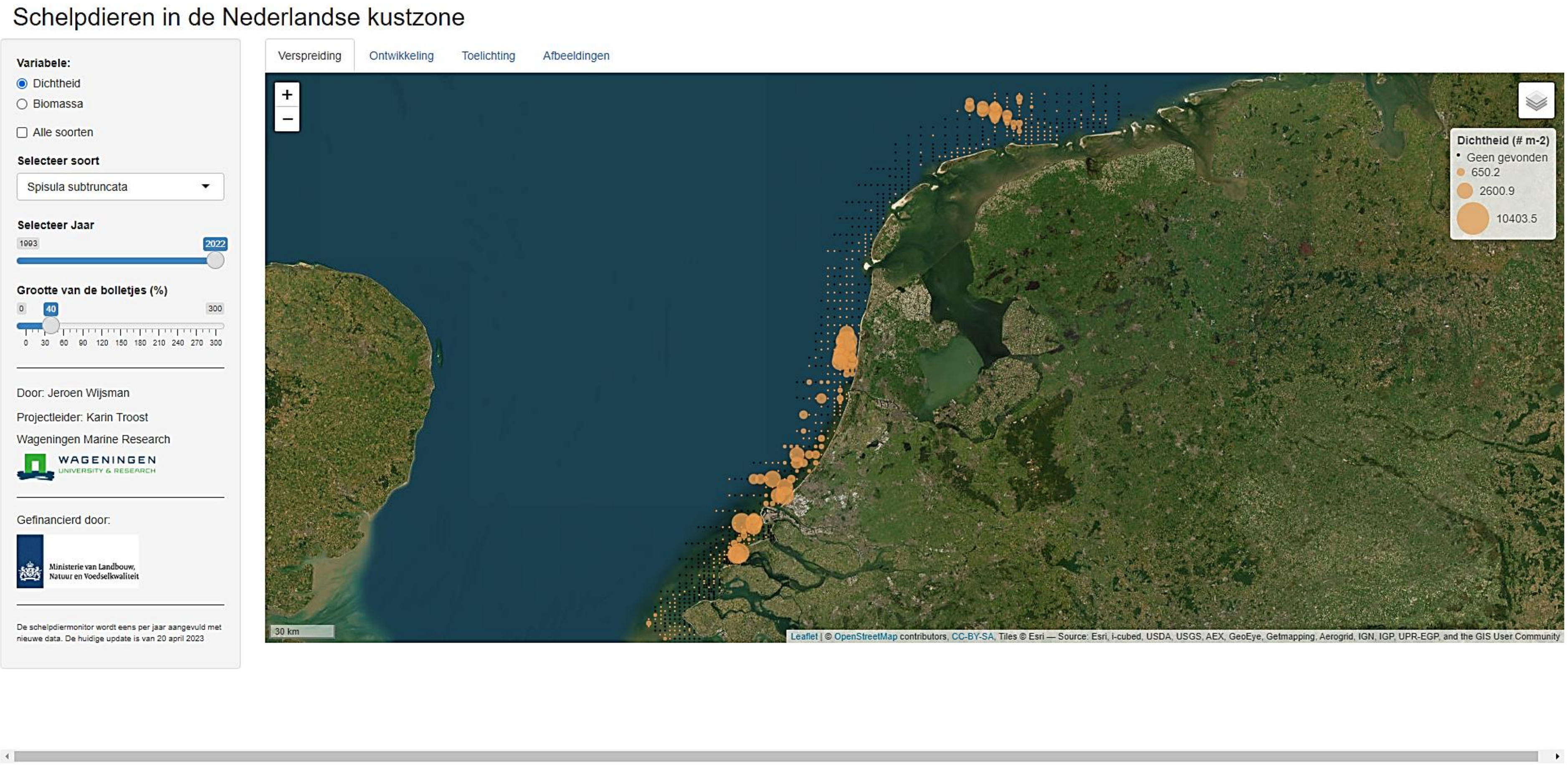
Report: C057/24
Project Number: 4313100106

The scientific quality of this report has been peer reviewed by a colleague scientist and a member of the Management Team of Wageningen Marine Research

Approved:	J. Schotanus Researcher
Signature:	
Date:	8 October 2024

Approved:	Dr.ir. T.P. Bult Director
Signature:	
Date:	8 October 2024

Annex 1 Distribution and density (ind/m2) ‘schelpdiermonitor’ (year 2022) : https://shiny.wur.nl/Schelpdiermonitor_Kust/



Schelpdieren in de Nederlandse kustzone

Variabele:

● Dichtheid

○ Biomassa

☐ Alle soorten

Selecteer soort

Spisula subtruncata

Selecteer Jaar

1993 – 2022

Grootte van de bolletjes (%)

0 – 40 – 300

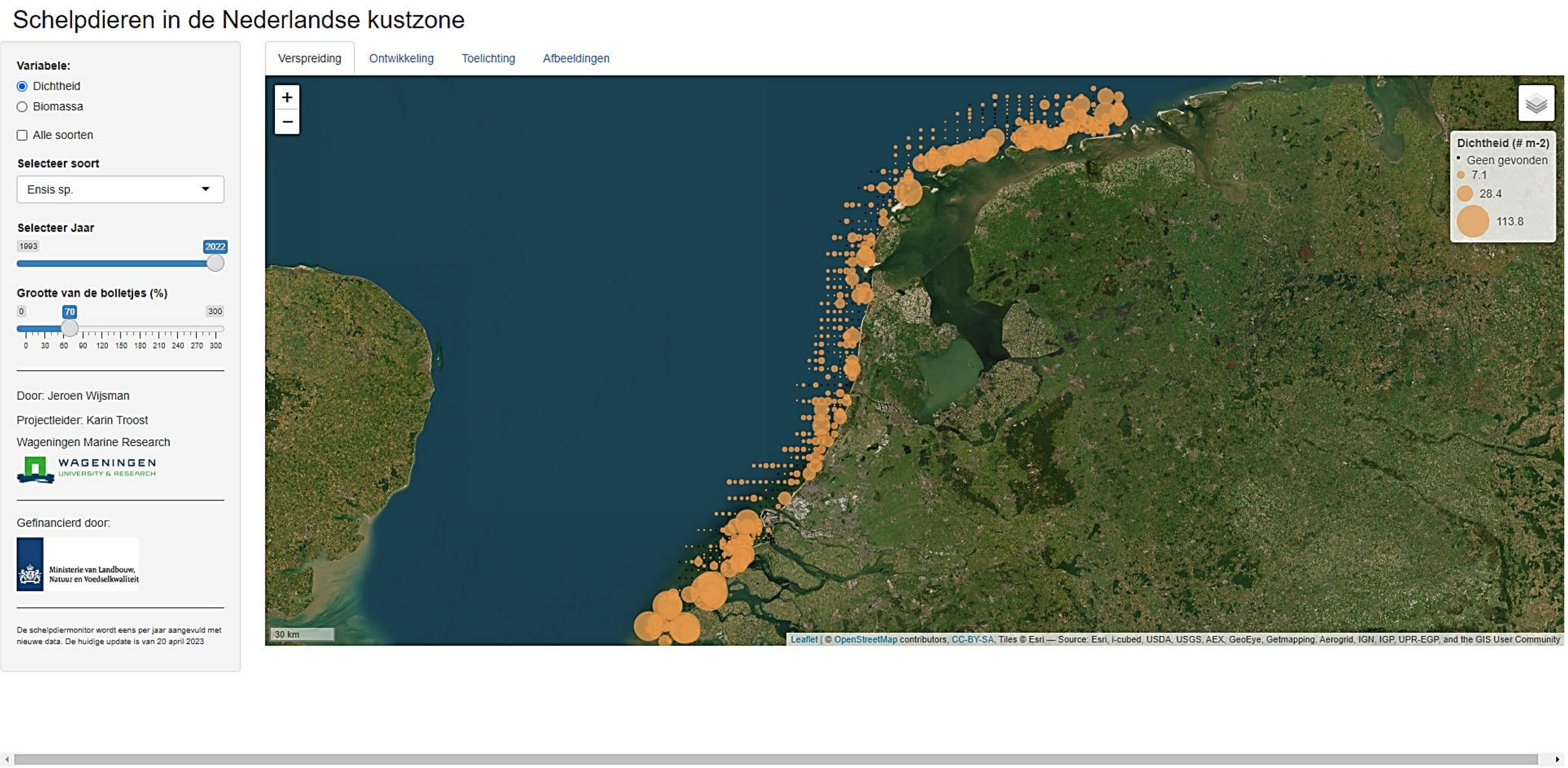
Door: Jeroen Wijsman

Projectleider: Karin Troost

Wageningen Marine Research

Gefinancierd door:

De schelpdiermonitor wordt eens per jaar aangevuld met nieuwe data. De huidige update is van 20 april 2023



Schelpdieren in de Nederlandse kustzone

Variabele:

● Dichtheid
○ Biomassa

☐ Alle soorten

Selecteer soort

Ensis sp.

Selecteer Jaar

1993 – 2022

Grootte van de bolletjes (%)

0 – 70 – 300

Door: Jeroen Wijsman

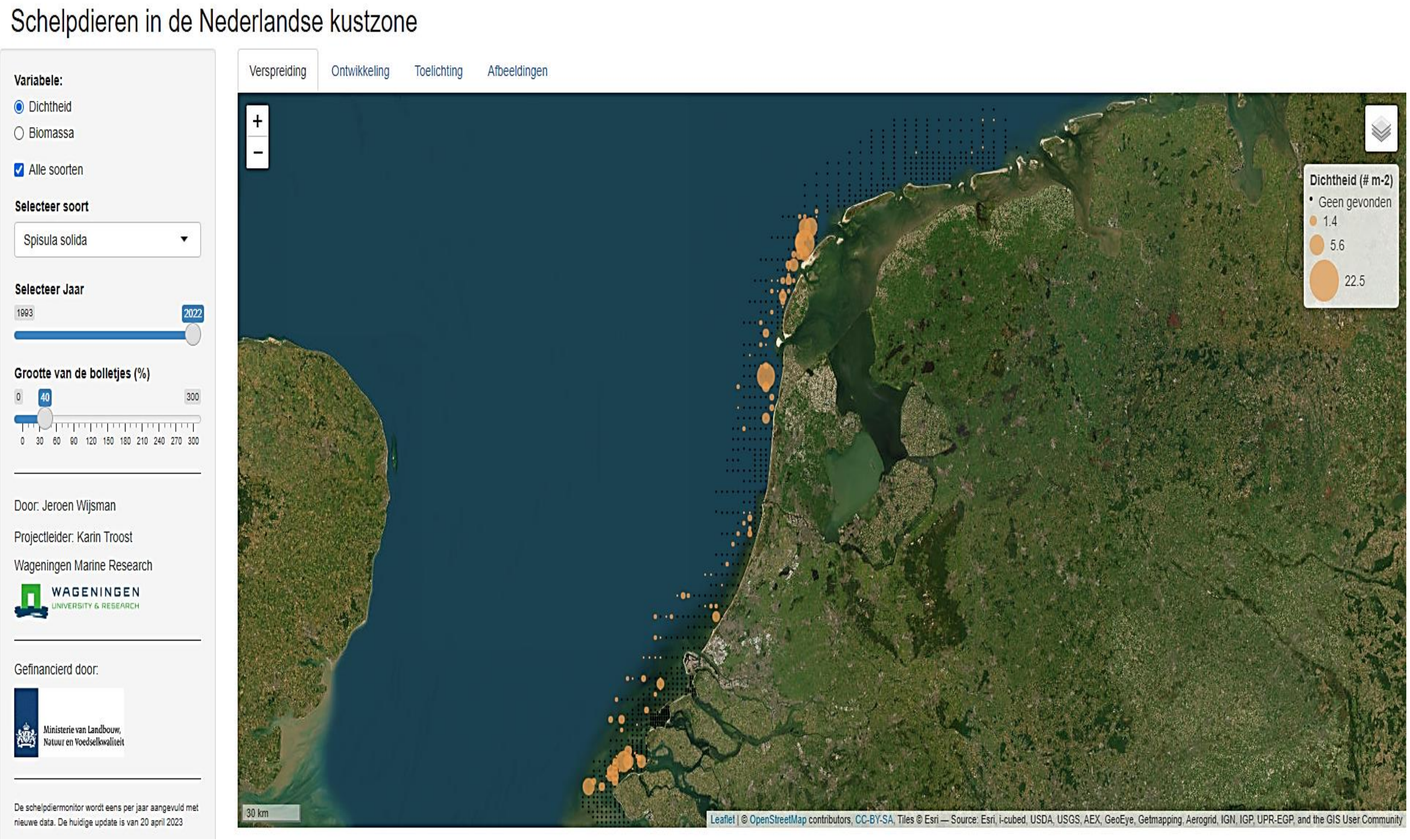
Projectleider: Karin Troost

Wageningen Marine Research

Gefinancierd door:

Ministerie van Landbouw, Natuur en Voedselkwaliteit

De schelpdiermonitor wordt eens per jaar aangevuld met nieuwe data. De huidige update is van 20 april 2023



Schelpdieren in de Nederlandse kustzone

Variabele:
● Dichtheid
○ Biomassa

☑ Alle soorten

Selecteer soort
Spisula solida

Selecteer Jaar
1993 – 2022

Grootte van de bolletjes (%)
40

Door: Jeroen Wijsman

Projectleider: Karin Troost

Wageningen Marine Research

Gefinancierd door:

Ministerie van Landbouw, Natuur en Voedselkwaliteit

De schelpdiermonitor wordt eens per jaar aangevuld met nieuwe data. De huidige update is van 20 april 2023

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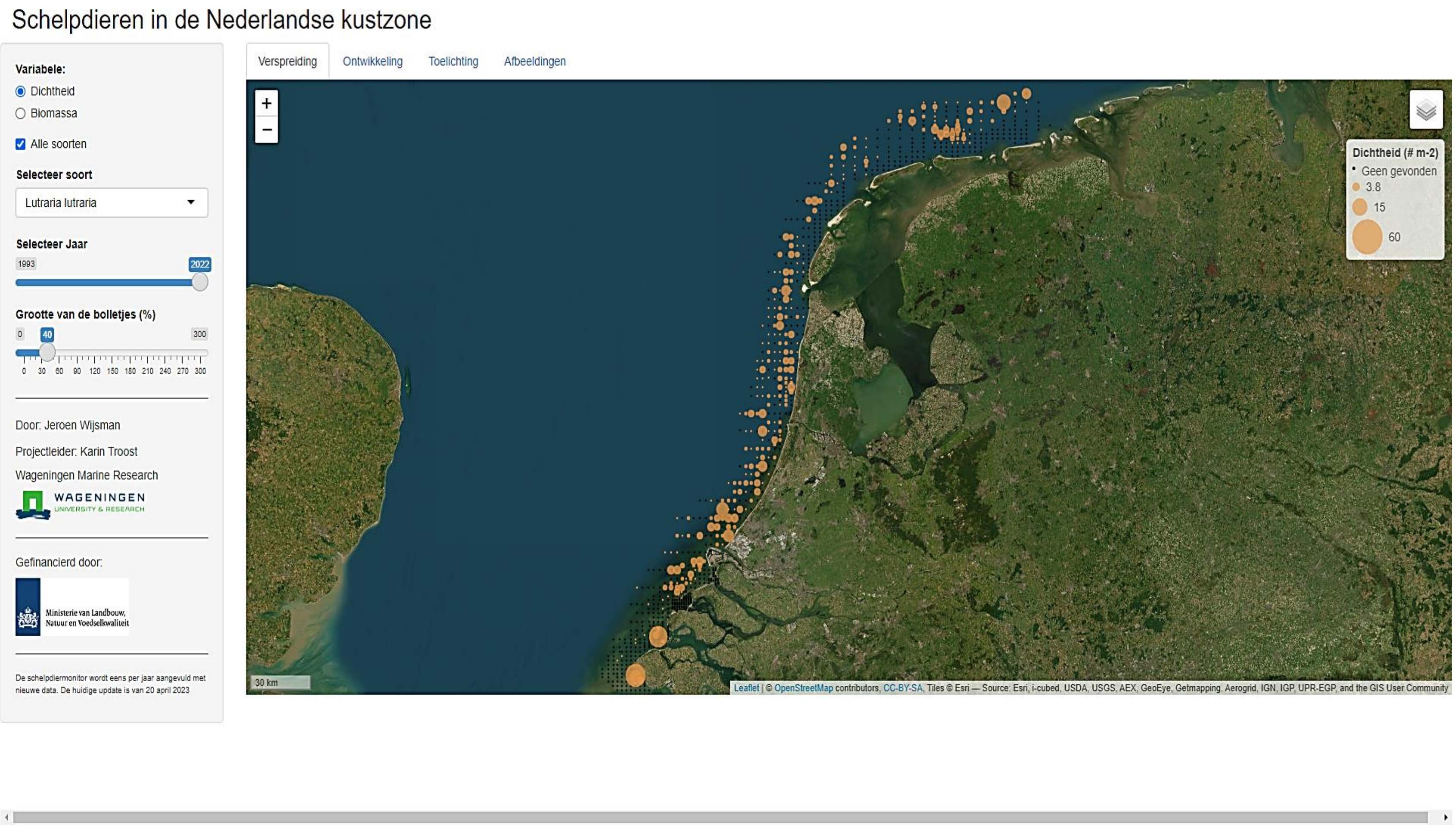

Schelpdieren in de Nederlandse kustzone

Variabele:
● Dichtheid
○ Biomassa

☑ Alle soorten

Selecteer soort
Lutraria lutraria

Selecteer Jaar
2022

Grootte van de bolletjes (%)
40

Door: Jeroen Wijsman

Projectleider: Karin Troost

Wageningen Marine Research

Gefinancierd door:

De schelpdiermonitor wordt eens per jaar aangevuld met nieuwe data. De huidige update is van 20 april 2023

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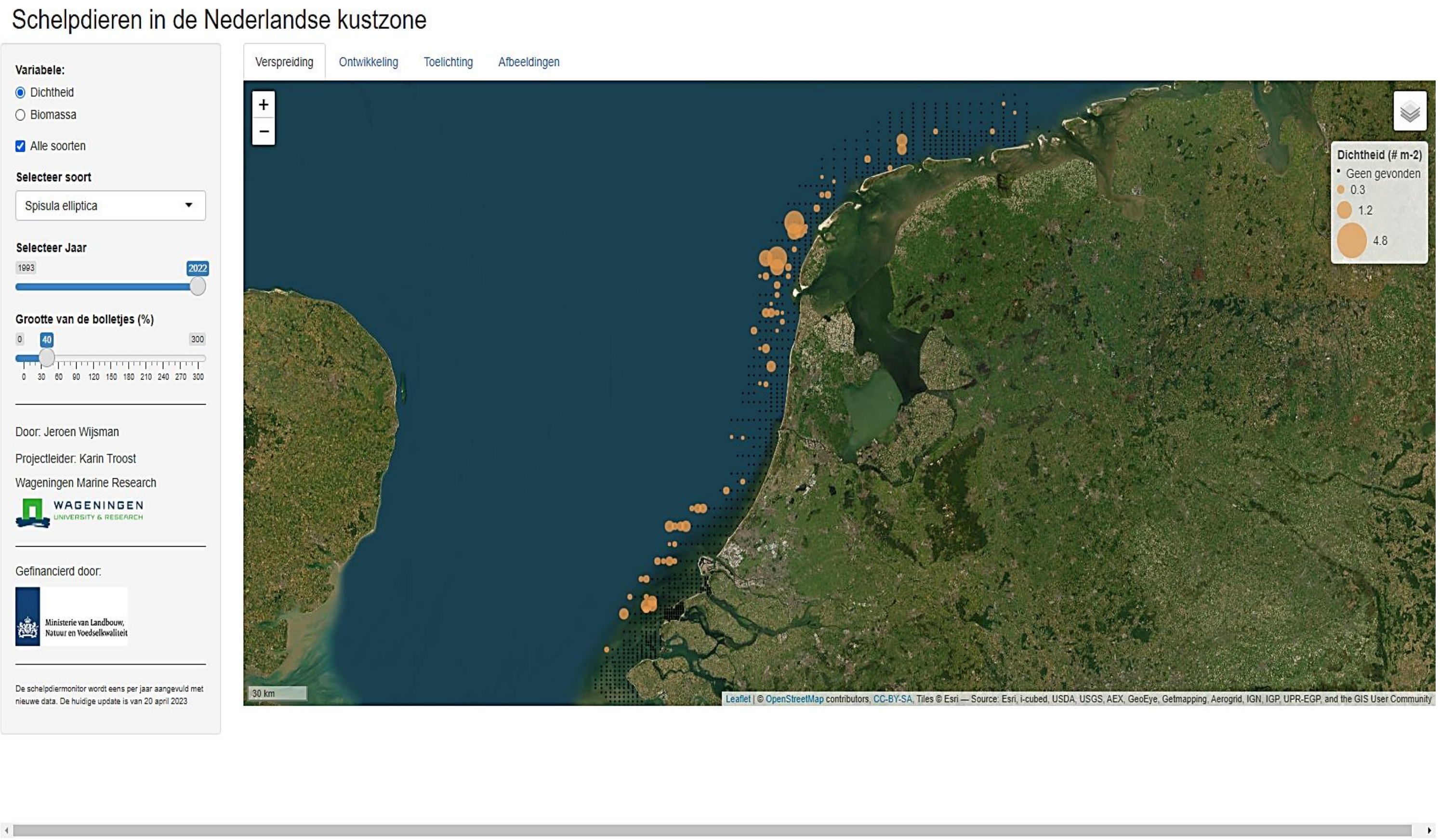

Schelpdieren in de Nederlandse kustzone

Variabele:
● Dichtheid
○ Biomassa

☑ Alle soorten

Selecteer soort
Spisula elliptica

Selecteer Jaar
1993 – 2022

Grootte van de bolletjes (%)
0 – 40 – 300

Door: Jeroen Wijsman

Projectleider: Karin Troost

Wageningen Marine Research

Gefinancierd door:

Ministerie van Landbouw, Natuur en Voedselkwaliteit

De schelpdiermonitor wordt eens per jaar aangevuld met nieuwe data. De huidige update is van 20 april 2023

Annex 2. WOT shellfish surveys: an example of stock assessment calculations

Suppose we have 19 sampling locations ($n = 19$) divided over 4 strata ($s = 4$), with grid cell sizes S of 60ha (red), 120ha (green), 240ha (blue) and 480ha (grey). At 2 locations (6 and 14) the sample was very large, and a subsample was taken (subsample factor resp. 2 and 4).

The standing stock is calculated as follows. First the density of each species at each location is calculated, based on the sampling area, the subsample factor and the number of individuals found in the (sub)sample. Then, densities at each location are multiplied with the surface area corresponding to the grid cell size of the stratum where the location belongs to.

The standing stock (*Ntot*) is then calculated as the sum of these data points. In the example (figure 1, table 1) this results in a total stock of 48.35 million individuals in the surveyed area.

$$Ntot = \sum_{i=1}^{n} \left\{ \left(\frac{f_i * N_i}{A_i} \right) * S_{i,s} * 10.000 \right\}$$

with:

$Ntot$ = stock in number of individuals (*ind*)
i = sampling location i
n = total number of sampling locations
f_i = subsample factor at sampling location i
N_i = number of individuals found in subsample at location i (*ind)*
A_i = sampling area at sampling location i (m^2)
S_s = surface area of grid cell size of the stratum s (ha) where sampling location i belongs to

Example of the stock calculations for stations in figure 1. Density (ind/m^2) given for species of interest

location	sampling area	stratum	stratum area (ha)	subsample factor	number in subsample (ind)	ind/m^2	stock (10^3 ind)	% of stock
1	12	4	480	1	4	0.33	1600.00	3.31
2	10	2	120	1	4	0.40	480.00	0.99
3	15	1	60	1	56	3.73	2240.00	4.63
4	17	1	60	1	13	0.76	458.82	0.95
5	18	2	120	1	6	0.33	400.00	0.83
6	15.6	3	240	2	2	0.26	615.38	1.27
7	12.4	4	480	1	4	0.32	1548.39	3.20
8	18.4	1	60	1	8	0.43	260.87	0.54
9	17.6	1	60	1	56	3.18	1909.09	3.95
10	14.5	2	120	1	34	2.34	2813.79	5.82
11	13	2	120	1	78	6.00	7200.00	14.89
12	15.2	1	60	1	35	2.30	1381.58	2.86
13	16.1	1	60	1	56	3.48	2086.96	4.32
14	17.6	2	120	4	32	7.27	8727.27	18.05
15	14.8	3	240	1	22	1.49	3567.57	7.38
16	14.3	4	480	1	13	0.91	4363.64	9.03
17	13.3	1	60	1	89	6.69	4015.04	8.30
18	13.9	1	60	1	45	3.24	1942.45	4.02
19	15.8	2	120	1	36	2.28	2734.18	5.66
			3120				48345.02	

Annex 3 Overview of density versus percentage of the total stock of 1 year old individuals

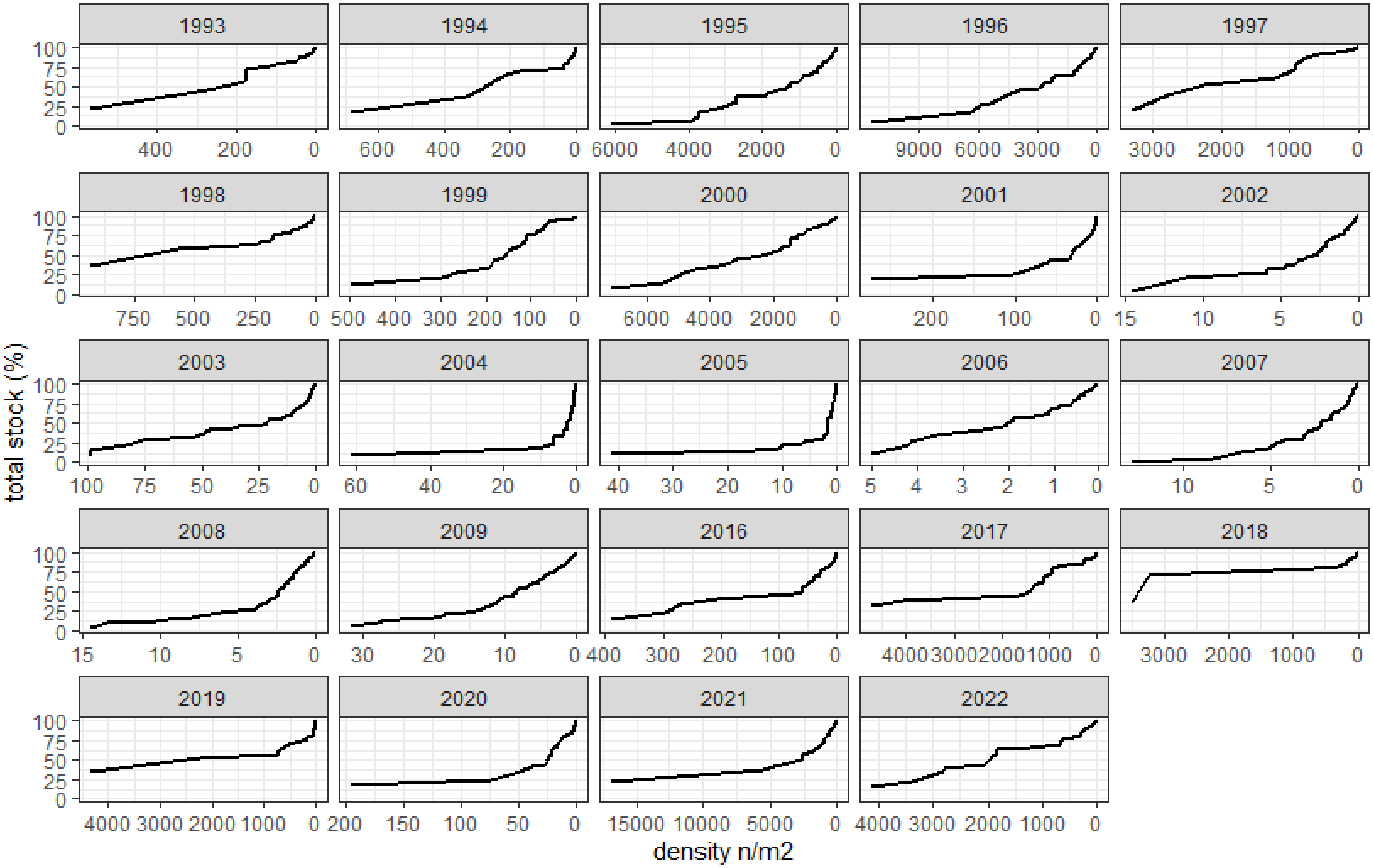

Figure 19 *Cumulative plot of density versus percentage of the total stock of 1 year old individuals (no 1 year old individuals in the period 2010-2015).*

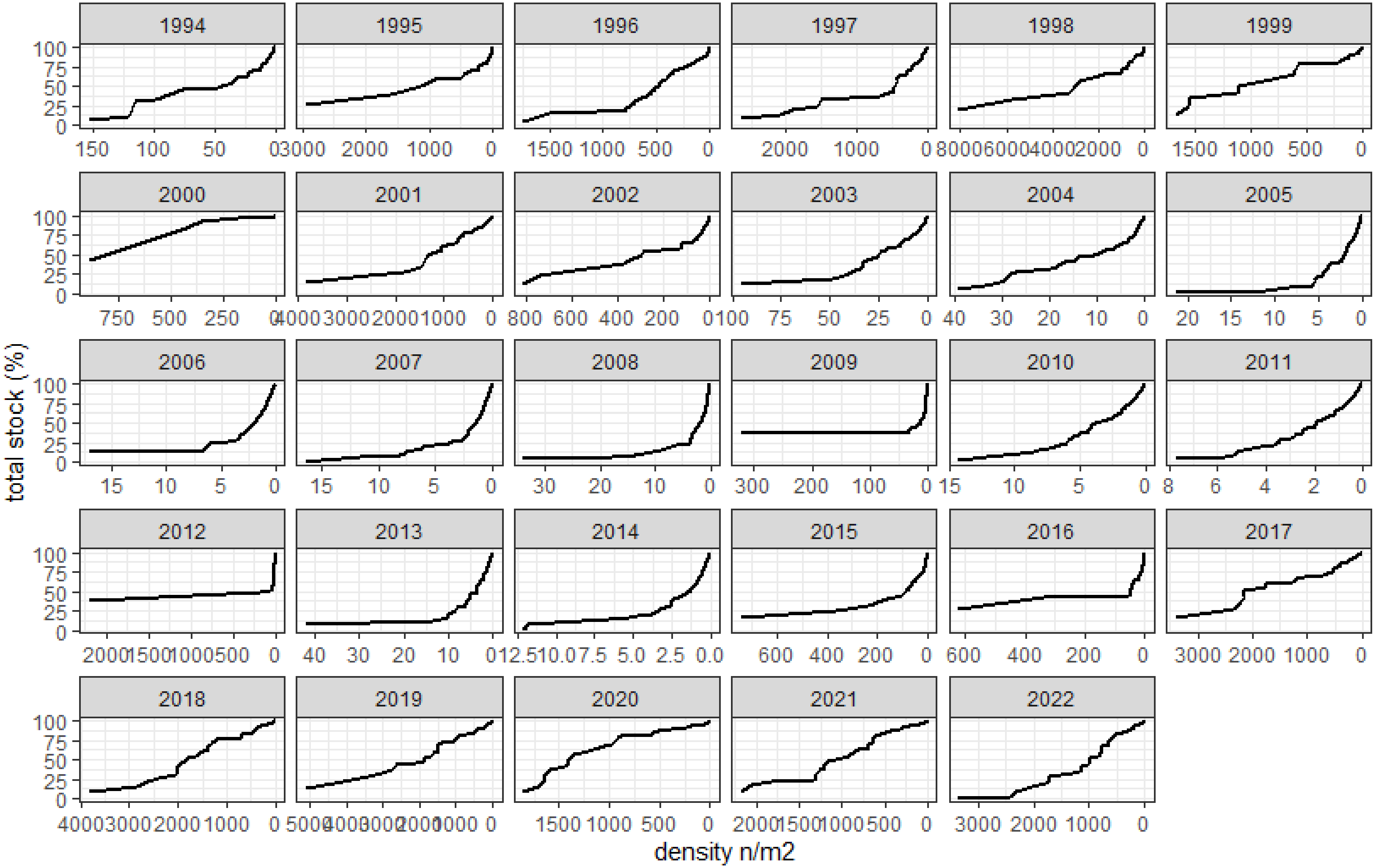

Figure 20 *Cumulative plot of density versus percentage of the total stock of individuals older than 1 year.*

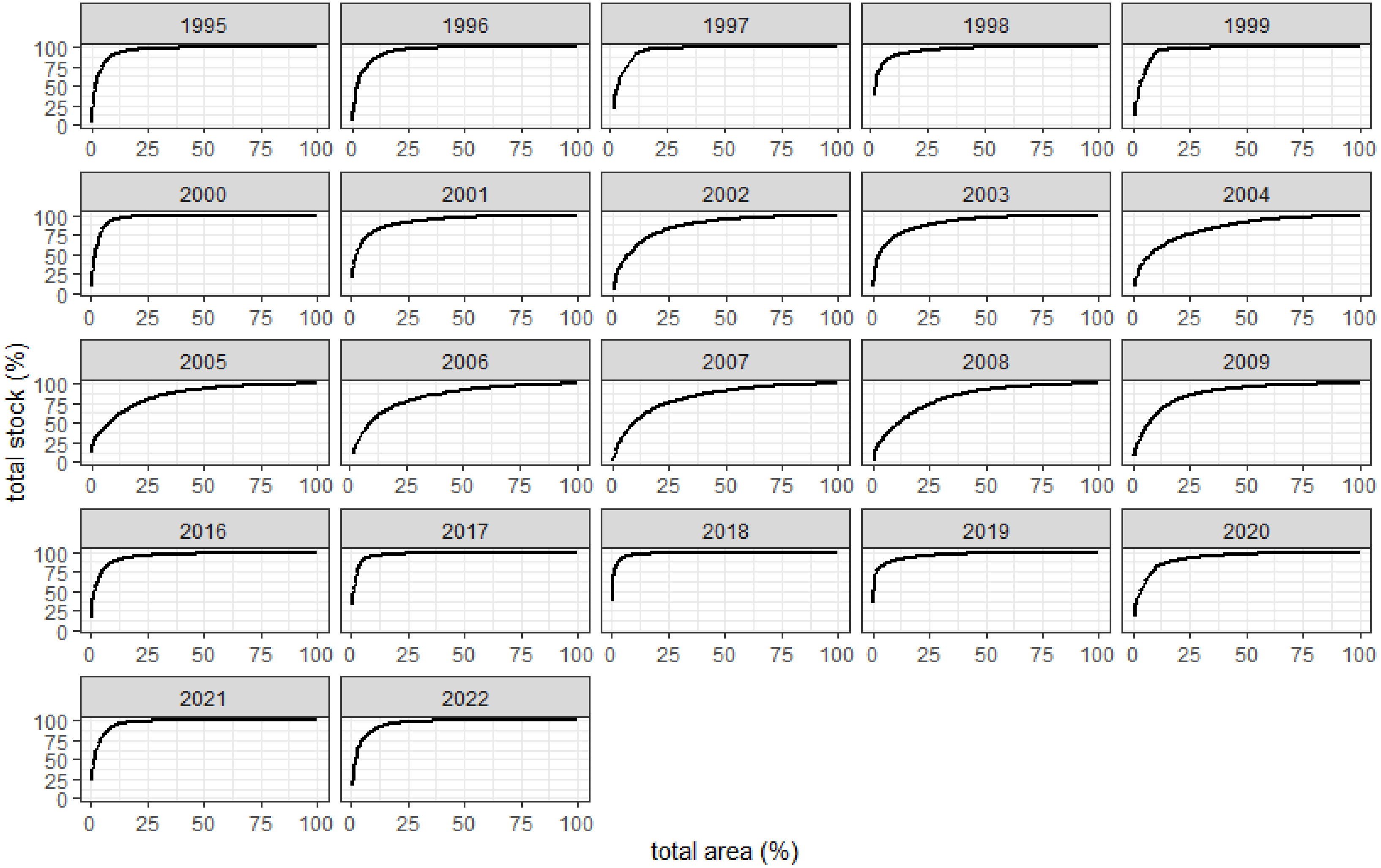

Figure 21 *Plot of percentage of total area (where Spisula subtruncata was occurring) versus percentage of total stock of 1 year old animals*

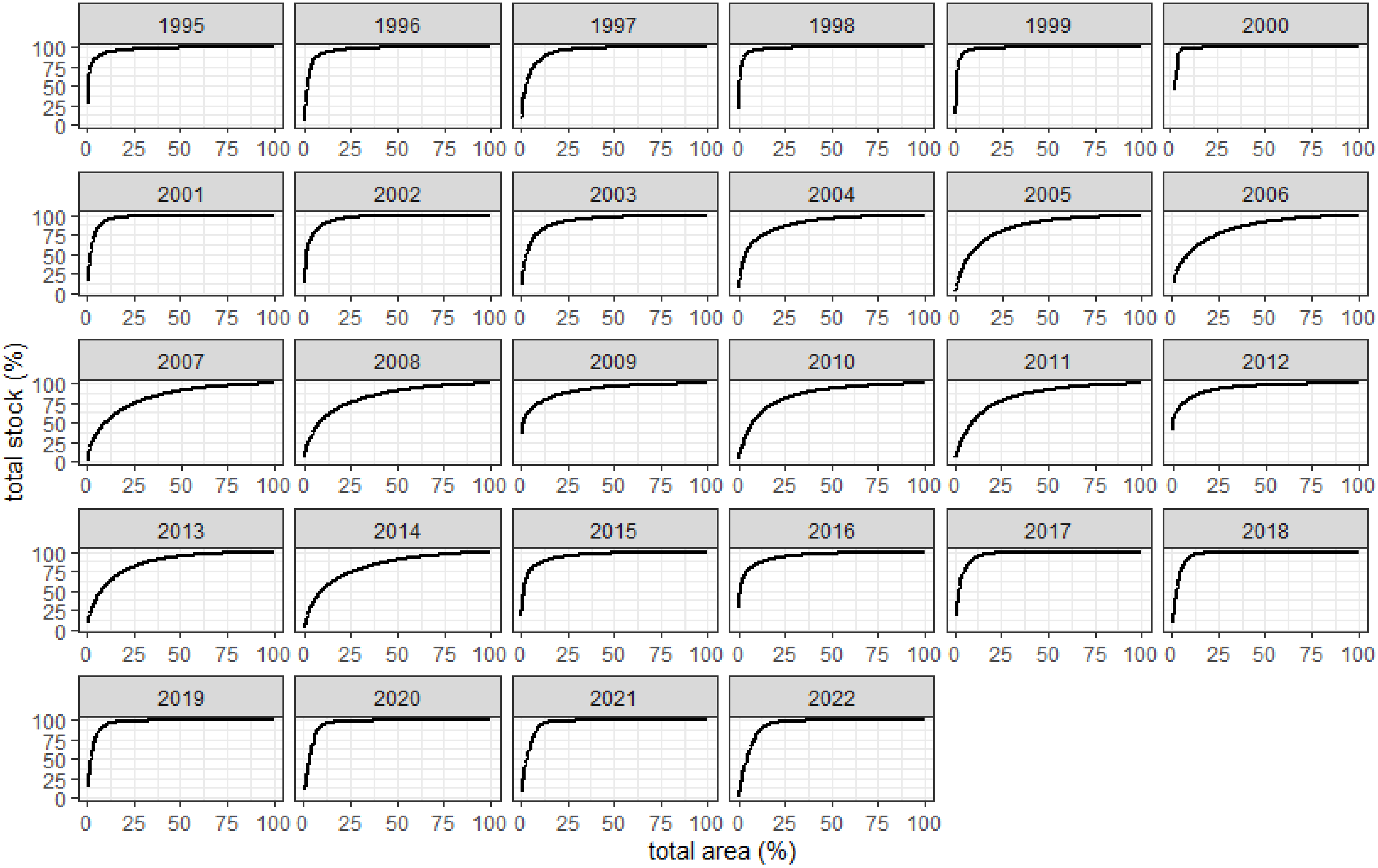

Figure 22 *Plot of percentage of total area (where Spisula subtruncata was occurring) versus percentage of total stock of animals older than one year*

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With knowledge, independent scientific research and advice, **Wageningen Marine Research** substantially contributes to more sustainable and more careful management, use and protection of natural riches in marine, coastal and freshwater areas.

The mission of Wageningen University & Research is “To explore the potential of nature to improve the quality of life”. Under the banner Wageningen University & Research, Wageningen University and the specialised research institutes of the Wageningen Research Foundation have joined forces in contributing to finding solutions to important questions in the domain of healthy food and living environment. With its roughly 30 branches, 7,700 employees (7,000 fte), 2,500 PhD and EngD candidates, 13,100 students and over 150,000 participants to WUR’s Life Long Learning, Wageningen University & Research is one of the leading organisations in its domain. The unique Wageningen approach lies in its integrated approach to issues and the collaboration between different disciplines.