Using remote sensing to predict macrobenthos abundance in the Banc d'Arguin, Mauritania

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Abstract

The tidal zone of the Banc d'Arguin, Mauritania is famous for its large number of birds, in particular wintering waders. The ecosystem is characterized by diverse tidal flats ranging from bare, dry and sandy flats to very silt and moist seagrass covered mudflats. These physical and biological differences have great influence on the local macrobenthic communities, which in their turn affect the density of foraging birds. The goal of this research is to investigate the relations between remotely sensed variables and parameters such as seagrass cover and moist content and to link those with macrobenthos occurrence and abundance.

We took 111 samples on 56 different stations over the extent of the whole ecosystem. On each station we quantified seagrass cover, moist content, penetrability and detritus content. From each sample we determined the species composition and estimated the Ash-Free Dry Mass (AFDM). 4289 benthic specimens were found on a total surface area of 2.014 m^2. The average AFDM of the total macrobenthos found was 28.6 g per m^2. 70 Different species were identified, with bivalves being most abundant in numbers (1535 per m^2), and Mass (25.2 g AFDM per m^2). The large bloody cockle *Anadara senilis* accounted for 20.3 g AFDM per m^2. Polychaetes and gastropods were most diverse in terms of species numbers: in both taxa 19 species groups were identified.

Different layers of Landsat7 satellite images were used to calculate NDVI and proxies for inundation time and temperature. Groundtruthing was performed by comparing this remotely sensed data to the groundparameters collected in the field. Most significant positive correlations were found between NDVI and seagrass and between temperature and moist content. The total AFDM of bivalves was positively correlated with seagrass and temperature derived from satellite images. Detritus content of the sediment was positively correlated with gastropod abundance.

Regression analyses show that for some species, in particular *L. lacteus* large amount of the variation in the abundance can be accounted for by the remotely sensed data (McFadden R^2 = 0.74). Based on these statistical models and the bands from the satellite image covering the whole area it was possible to accurately predict the abundance of *L. lacteus* in each location. *L. lacteus* makes up 69 percent of the total amount of harvestable food in the Banc d'Arguin for the red knot. Hence, a red knot (*C. canutus*) resource map could confidently be constructed.

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1. Introduction

The Banc d'Arguin, Mauritania consists of about 12000 km^2 of shallow waters, tidal flats, adjacent coastline and desert (figure 1).

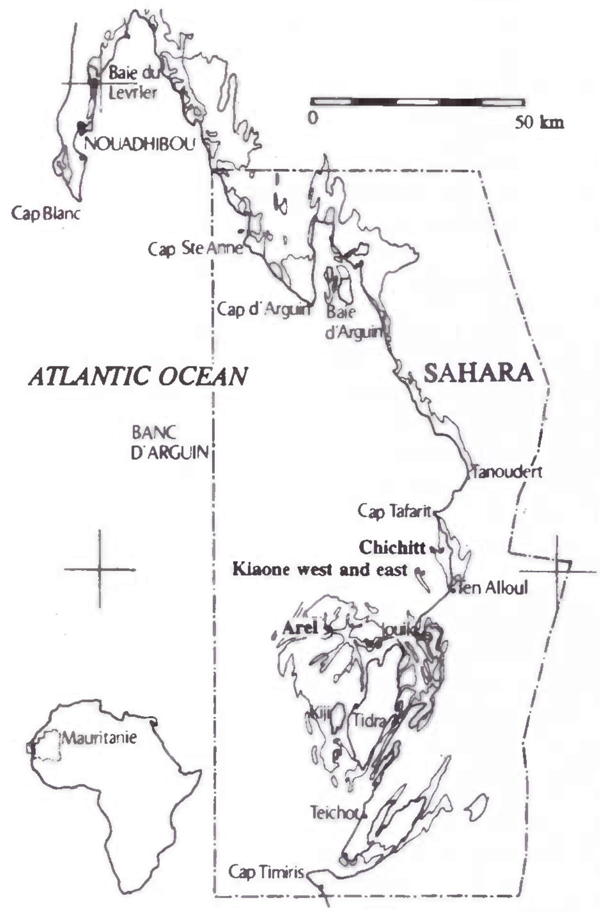

Figure 1: The national park of the Banc d'Arguin (from Altenburg et al., 1982)

About 80 % of the approximately 500 km^2 area of tidal flats is covered with the seagrass *Zostera noltii* (Wolff & Smit, 1990), sometimes mixed with *Halodule wrightii*. The shallower parts of the adjacent channels, gullies and intertidal pools are mostly covered with *Cymodocea nodosa*.

Many studies have focussed on the diversity of the macrobenthic life on the tidal mudflats in the area, (Altenburg et al. 1982, Wolff et al. 1993, Wijnsma et al. 1999, Michaelis & Wolff 2001) all revealing a remarkable high biodiversity and low standing stock.

Even though the standing stock is low compared to other areas (e.g. Dutch Wadden Sea), numbers of up to 2 250 000 waders (Altenburg et al., 1982), overwinter in this relatively small area and rely on macrobenthos as their primary food source.

At the same time, the little islands in the area provide suitable nesting sites for a variety of waterbirds.

Not only does the area fulfil an excellent job in facilitating food for wintering or breeding birds, also rays, sharks, dolphins and turtles find a suitable habitat here. The shallow waters are furthermore used as breeding grounds for nektonic fauna of which the diversity is quite large (Jager 1993).

The Banc d'Arguin obtained the status of national park in 1976.

The presence of patches of mangrove swamps (*Avicennia africana*) in the tidal area reveals a history of fresh water inlet. The ecological and physical conditions of the area nowadays proceed from a moister geological period in which the Banc d'Arguin was a large estuary of river inflow from the Sahara Desert.

The Banc d'Arguin did not suffer much from philanthropical influences: the local population, the Imraguen are the only people allowed to fish in the area and only on a traditional and sustainable way. There are no clues for significant pollution or evidence of other severe pressure in the ecosystem.

This history together with the knowledge that the area never suffered much from human impact makes the current state of the Banc d'Arguin a unique ecosystem which could be very vulnerable to changes.

Yet, the area is under threat: decreasing fish stocks in the surrounding sea, have led mostly Senegalese fishermen to poach within the borders of the park.

Another possible threat is the rise of the seawater level due to global warming. If sediment is not suppleted, the area of mudflats that gets exposed during low tide will decrease, resulting in a reduced foraging area for the wintering waders.

But the most direct threat may be the possible exploitation of the bivalve *Venus*

sp. outside the park. Dredging for shells in the close proximity of the Banc d'Arguin could increase the turbidity of the surface waters reaching the seagrass beds. This increase in turbidity causes a reduction in light attenuation which in its turn probably would lead to a reduction in seagrass abundance. In situ experiments in the Banc d'Arguin show a higher vulnerability of seagrass leafs and lower growth rate under decreased light intensities (Vermaat et al. 1993). Giessen et al. (1990) conclude that the extinction of Eelgrass (*Zostera marina L.)* in the Dutch Wadden Sea was probably due to increased turbidity of the water.
The sediment of the mudflats that are covered with seagrass is generally very soft with a high organic content and silt fraction (Honkoop 2007, unpublished data).
Seagrass beds could induce sedimentation of silt. Soft silt grounds might also be a better substrate for seagrass to grow on.

Reduction in seagrass abundance will have an effect on these sedimentation processes: The ecosystem could change from a system dominated by benthic primary production into a system dominated by algal growth. Such a profound change in ecosystem functioning could induce a domino reaction. The change in sedimentation and turbidity of the water reduces seagrass growth and filter feeding macrobenthos, which in their turn influences nektonic and avian fauna.

These possible future changes in the environment are reason for concern. Monitoring the Banc d'Arguin tidal area is necessary to quantify and qualify ecological change and in particular the dynamics of spatial seagrass distribution with co-occurring benthic communities. Remote sensing can be an efficient instrument for this matter.
The first step in this process is to investigate the relations between remotely sensed data and the biotic "truth", i.e. groundtruthing.
Then, monitoring over a large time span allows us to translate changes in satellite images to ecological consequences.

Estimates of seagrass cover and distinction between muddy or sandy tidal flats based on landsat satellite images in the tidal range in the Banc d'Arguin area have been made before (Altenburg 1982, Wolff and Smit 1990)
These 'groundparameters' (seagrass and sediment characteristics) are influential factors on macrobenthic spread (Van der Wal 2004, Honkoop 2007, unpublished data). Inundation time is also known to affect macrobenthic abundance and diversity (Beukema 2002).

According to the variety of possibilities of satellite image interpretation and the relation between physical/biological parameters, and macrobenthos spread, it is possible to relate satellite imagery directly to macrobenthos abundance. The main objective of this study is therefore:

How do seagrass cover, sediment characteristics and inundation time relate to macrobenthos abundance and diversity in the banc d'Arguin and to what extend is it possible to indirectly measure these factors through remote sensing.

Given a strong relationship between remote sensed data and benthic density it is possible to estimate the availability of food for benthivorous birds in locations not sampled. Excessive monitoring of macrobenthic life and its relation to foraging birds is carried out in many places (e.g. Dutch Wadden sea monitoring program). A lot of research in terms of food intake, carrying capacity and energy expenditure has been done in the wading species *Calidris canutus* (e.g. Zwarts and Blomert, 1992 A + B). In this study, an attempt is made to give an estimation of the available food for this modelbird using remotely sensed data.

2. Methods

2.1 Habitat characterization based on remotely sensed images

Analyses of images from the landsat 7 satellite of the banc d'Arguin area during low tide (January 2003[1]) were used for mapping and navigation in the area. With GIS software, the NDVI-index (Normalized Difference Vegetation Index) was computed enabling us to distinguish between Sahara sand, water and mudflats.

$$NDVI = \frac{band4 - band3}{band4 + band3}$$

The habitat that qualified as mudflat was furthermore separated into bare- and three levels of seagrass covered substrate (figure 2)

For estimation of ground temperature of the mudflats, band 6 of the landsat 7 satellite image was used (figure 3):

$$T = \frac{K_2}{\ln\left(\frac{K_1}{CV_R} + 1\right)}$$ *2

Where:

T = Effective at-satellite temperature in Kelvin

K1= Calibration constant 1

K2= Calibration constant 2

CVr = Spectral radiance (cell value)

(From the digital Landsat7 handbook[2])

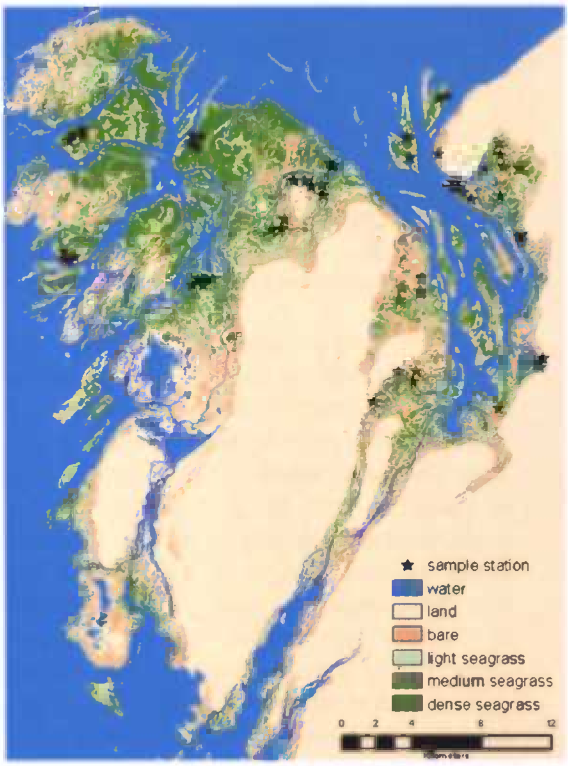

Figure 2: Interpretation of NDVI-values ranging from bare (dark pink) mudflats to dense seagrass covered mudflats (dark green). Stars represent sample stations.

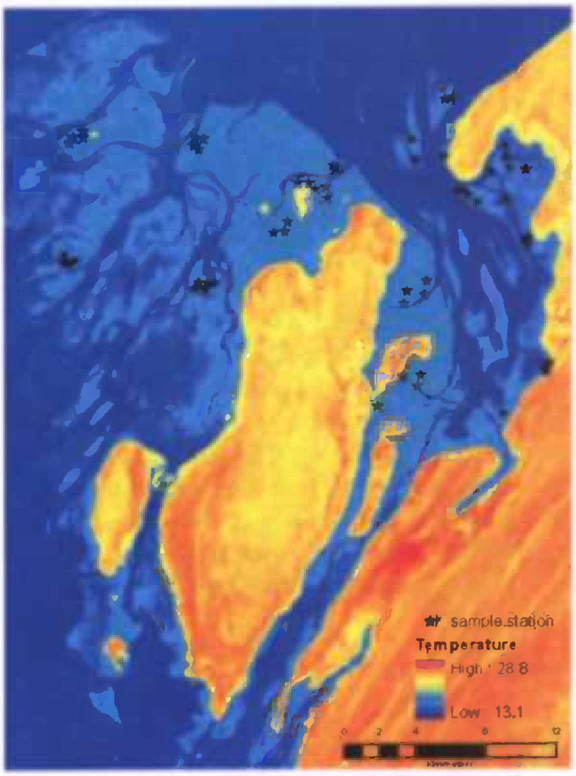

Figure 3: Band 6 from the landsat 7 satellite was used to calculate the at-ground temperature of the mudflats.

[1] More recent landsat 7 satellite images of the area are available, but at high costs

[2] http://landsathandbook.gsfc.nasa.gov/handbook/handbook_htmls/chapter11/chapter11.html

Due to the lack of bathometric maps on the intertidal area, the distance to the nearest gully at low tide for every point on the map was calculated and used as a proxy for inundation time (figure 4).

Figure 4: Distance to gully as a measure of inundation time. Lighter areas mean shorter inundation time.

500 sampling stations were generated randomly, but stratified so that the number of points in each NDVI class was in ratio with the abundance of that class. (Hawth tools, GIS) 58 of these stations were sampled (figure 2, 3, 4). The necessity to choose a subset of the generated stations was mainly due to logistic reasons (time constraint and slow transportation in-between areas). Within the subset of stations the different aspects of the area, was taken into account as much as possible. Sample stations in different NDVI classes were selected to ratio of occurrence.

2.2 Groundtruthing and sampling

The field work was carried out in March and April 2007. We attempted to sample from a large spatial extent in order to have our dataset as representative as possible. Due to limiting time we had to trade of the number of samples against spatial stratification. Five of the planned stations fell in deep water so that they could not be sampled. For some stations that were covered with water an alternative point was chosen and randomly generated in the field.
Two stations were situated on respectively sebhka and beach. In these habitats, no benthic life or seagrass coverage was encountered and therefore discarded from calculations.
Navigation was done with GPS (Garmin 12). The sample stations were approached as close as possible over water by a small kayak, sailing boat[3] or a small motorboat. The exact location was reached on foot with snowshoes to prevent sinking, in the very muddy substrate. At each station a square ¼ m^2 quadrant was casted to obtain the definite sample station (figure 5). Following a strict protocol in sample order and exact location in the quadrant the following actions were taken at each field station.
-Pictures were made of the quadrant and its surrounding environment.
-Two sediment cores were taken with a surface area of approximately 1.77 cm^2 to a depth of successively 1 and 10 cm and stored in plastic bags.
-Two cores of 20 cm deep were taken with a corer covering approximately 1/56 m^2 of surface area for benthos analyses. From these cores the top 4 cm was separated from the rest of the sediment and both parts were sieved over a sieve with a 1 mm mesh size. The amount of dead organic material (detritus) was visually estimated (three classes). The sieved material was stored in plastic bags.

[3] Imraguen fishermen

Figure 5: quadrant of 50 cm by 50 cm that was used for definite sample station location.

-A core with a surface area of approximately 1/280m^2 was taken and sieved (1 mm mesh size) to obtain a quantitative analyses for the seagrass abundance within the quadrant.
-Penetrability of the soil was determined by launching a cylindrical weight of 325 g through a vertical standing 1.80 m high PVC tube and measuring how deep the cylinder penetrated into the sediment.
Sampling was done during low tide only. From one station accidently only 1 benthos core was taken.

2.3 Lab analyses

All visible benthic life was sorted from the benthos samples (figure 6) and stored on seawater with 3.7% buffered formalin. Identification of the species and determination of the Ash-Free Dry Mass (AFDM) was done at the royal NIOZ (Texel, the Netherlands) and at the Biological centre of the University of Groningen (Haren, The Netherlands). Each individual was identified to species level, (if not possible, genus or family).
AFDM was obtained by incubating the samples at 60°C for a minimum of 72 hours followed by incineration at 550℃ for 5 hours. The samples incinerated at the University of Groningen were done at a temperature of 450°C for five hours.

Figure 6: Jan en Brecht sorting out macrobenthos in the laboratory in Iouik, Mauritania

From the polychaetes and oligochaets, only the first benthos-core was taken from each station for determination of species and AFDM.
All macrobenthic species were measured to the nearest 0.1 mm. Bivalves larger than 8.4 mm were separated from their shells prior to incineration. Smaller bivalves and gastropods were incinerated without separating the animal from the shell.
For these molluscs, correction factors were used to compensate for calcium carbonate condensation during incineration. These correction factors were calculated by multiplying the smaller bivalves with a fixed value in such a way that a regression analysis of smaller and larger bivalves follows the highest possible R^2 (figure 7, Appendix 1)

For the benthos found on each station, the Shannon index for diversity H' (Shannon and Weaver, 1949) and evenness J' (Pielou 1967) was calculated. This method is commonly used among ecological studies as a way to quantify species diversity (e.g. Wijnsma, 1999, Yuwono, 2007).

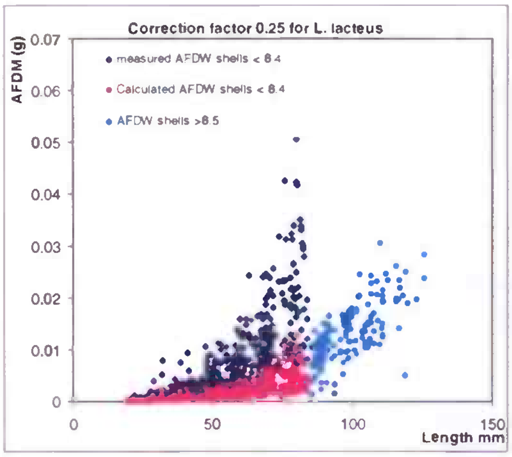

Figure 7: Conversion factors were used to calculate shell-free AFDM from molluscs. The dark blue dots are whole_AFDMs of the bivalve Loripes lacteus. The purple dots are shell-free AFDM's. Light blue dots are uncalibrated weights of specimens separated from their shell.

Fresh seagrass leaves were separated from seagrass roots and dried in paper bags on room temperature. In the laboratory of the University of Groningen, the samples were dried at 60 °C for minimum of 72 hours and incinerated at 520 °C for 3 hours.
The sediment samples with a core length of 10 cm were weighed, dried on room temperature and weighed again to the nearest 0.1 g to determine the moist content.

2.4 Regression analyses

The regression analysis was based on two strategies. 1. Biological model: model building based on biological knowledge. This means that we chose bands from the satellite image that we expected to be related to a physical or biological property of the mudflat which is known to affect the occurrence and abundance of benthic species. We included NDVI, Band6 and distance to water as predictors. NDVI is a proxy for the amount of seagrass, Band6 measures temperature and is therefore related to inundation time and reflects the capacity of the sediment to retain water. Distance to water relates to inundation time. Also the quadratic terms were fitted.

2. Naïve model: regression of all satellite bands including NDVI and distance to water against the biomass of the benthic species (again, also the quadratic terms)

Due to the left-skewed distribution of the macrobenthic biomass (figure 8) we performed a quasipoisson regression that allows for overdispersion on both models. In the first case we wanted to be conservative because the model was going to be used in prediction. Therefore, model selection was based on significance ($p<0.05$) of the parameter estimates. Model selection in the second strategy was based on AIC level of the poisson regression, after which the best linear model was re-estimated with quasipoisson regression including correction for overdispersion.

The best (biological) model for *L. lacteus* was then used to predict the amount of biomass in the unsampled locations in a grid of 50m. Simulation of parameter estimates (Gelman and Hill, 2007) allowed us to perform this calculatation multiple times with varying parameter estimates. This again enabled us to investigate propagation of uncertainty in the parameter estimates in the predicted outcomes of biomass.

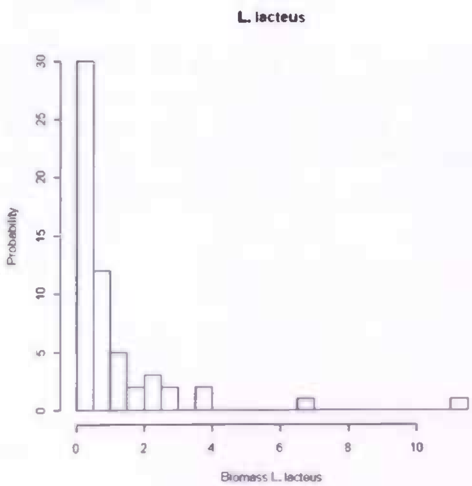

Figure 8: Due to left-skewed distribution of macrobenthos biomass, in this case L. lacteus, a quasipoisson regression, was performed that allows for overdispersion.

3. Results

From the 56 sampling stations visited, 49 were covered with the seagrass *Z. noltii*. Of these stations 12 were mixed with *C. nodosa* and on one station only *C. nodosa* occurred. On 6 sample stations no seagrass was present. The average seagrass density over all the sampling stations is 189 g AFDM per m^2 with a maximum of 498 g m^2. (Figure 9)

The NDVI and seagrass AFDM correlates with $R = 0.51$ and $P < 0.001$.
No difference was found between different seagrass species, when comparing biomass with NDVI values.

Taken the NDVI into account, some outliers in seagrass abundance were encountered in the field. This is due to the small scale of the landsat satellite images (25m by 25m). Some sample locations were unjust classified in expected seagrass abundance, as these sample locations were situated on the border of a seagrass patch. This phenomenon could also be explained by changes of seagrass abundance over time, as the landsat images were not up to date (2003).

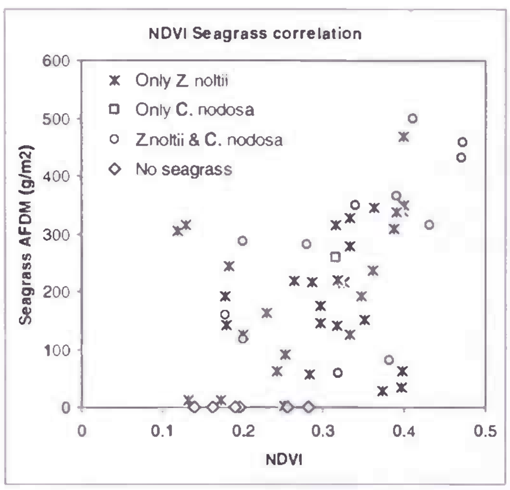

Figure 9 Seagrass abundance and NDVI: asterisks are sample stations with only *Z. noltii*, squares are sample station with only *C. nodosa*, Circles contain both species and diamonds are bare patches.

From the 56 sampled stations sampled, an average of 28.6 g macrobenthic AFDM per m^2 was found of which 20.3 g was attributed to the bivalve A. senilis (figure 10, appendix 2). On the total surface area of 2.014 M^2, 70 species were identified.

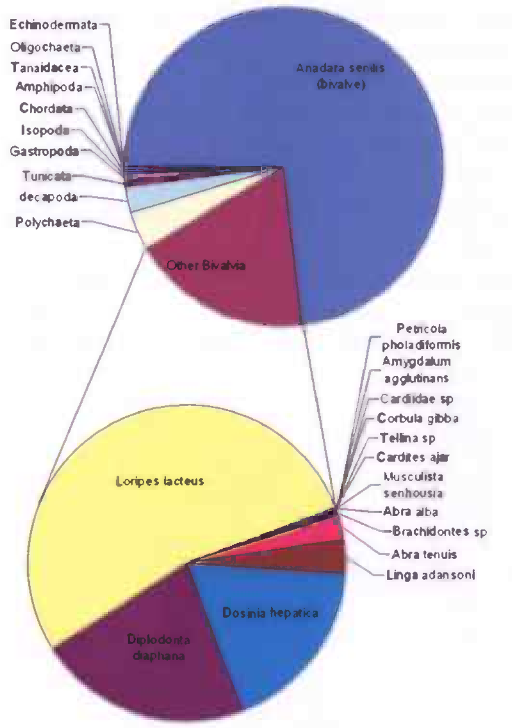

Figure 10: Macrobenthos abundance: The bivalve *A. senilis* has a share of 73 % in AFDM.

In numbers: an average of 2130 specimens were found per m^2 of which the bivalve *A. tenuis* has the biggest share with an average of 761 individuals per m^2 followed by *L. lacteus* (569) and *D. hepatica* (115) (figure 11)

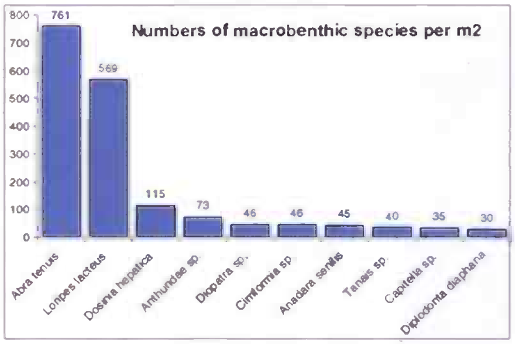

Figure 11: Top 10 in macrobenthos abundance in numbers per m2: *A. tenuis* (761), *L. lacteus* (569), *D. hepatica* (115), *Anthuridae sp.* (73), *Diopatra sp.* (46), *Cirriformia sp.* (46) *A. senilis* (45), *Tanais sp.* (40), *Capitella sp.* (35), and *D. diaphana* (30).

Five bivalve species, three polychaetes and one isopod species were present in more than 25% of the sample stations. For these 9 species, the distribution map is given in figure 13.

Distinguishing between land, water and tidal mudflats with NDVI maps, derived from the landsat 7 satellite proved to be a reasonable method. From the 63 stations visited, only 7 were not situated on the mudflat, but on sebhka (1), in water (5), or on the beach (1)

From the NDVI- and temperature map it was determined which groundparameters appeared to be predictable. Another predictor used was distance to the nearest gully, resembling inundation time. After that, correlations between these groundparameters and macrobenthic abundance were calculated. Also direct correlation between satellite images and macrobenthic characteristics were determined (figure 12, appendix 3).

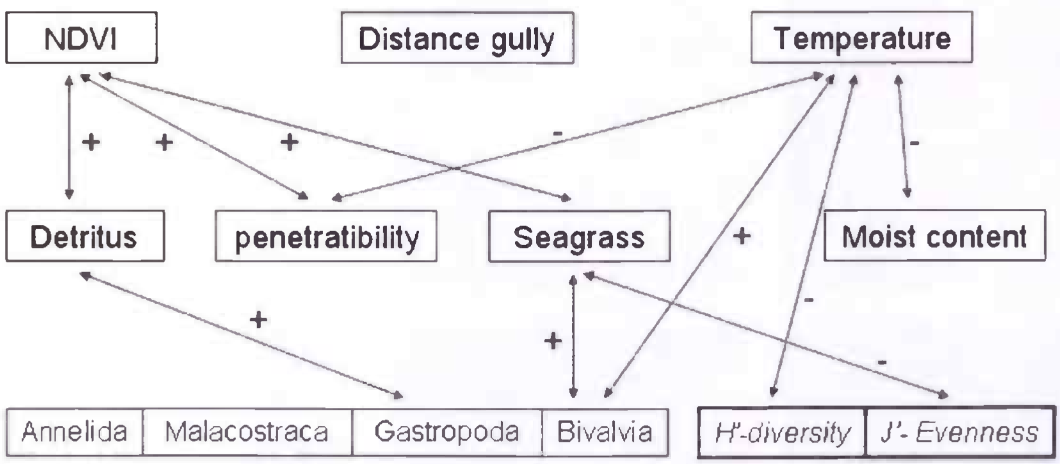

Figure 12: correlations between the different levels of approaching the system: Remote sensing, physical parameters, benthic abundance and diversity. Arrows indicate significant correlations ($P < 0.05$). + and – symbols indicate the direction of the correlation.

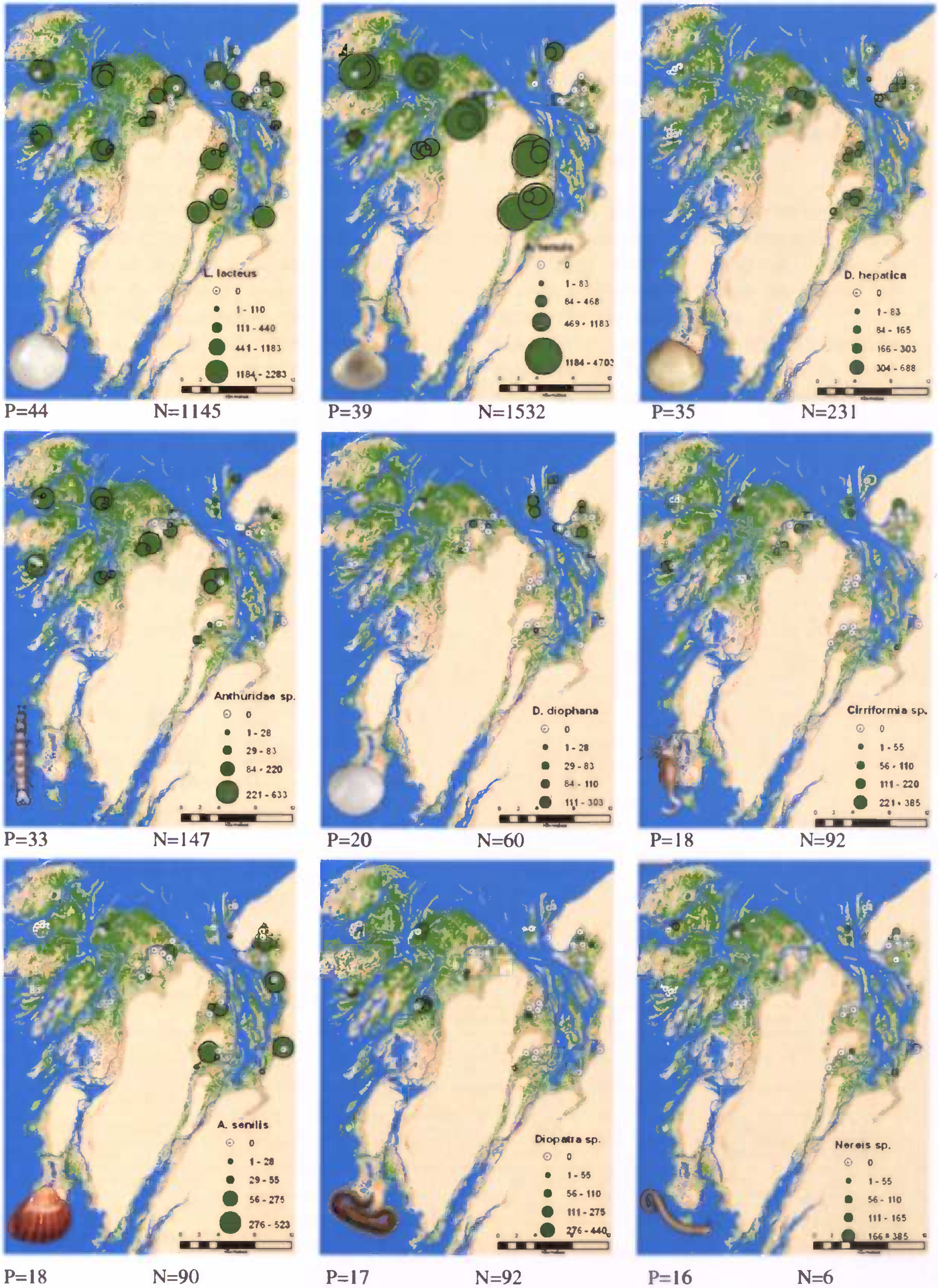

Figure 13: Abundance of macrobenthos in the research area in numbers per m^2. Averages were taken over 56 sample stations. P = Number of stations were the species was found. N = Total number per m^2.

The top three of both preferable and accessible food items for the knot *Calidris canutus* are the bivalve species: *Loripes lacteus, Abra Tenuis* and *Dosinia hepatica.* Only those specimens are selected that live in the top 4 cm of the bottom and therefore are available as prey item. Whether prey items are eaten depends on their size, principally circumference. Following Zwarts and Blomert (1992 A), this leads to the acceptance as prey for all specimens of *A. tenuis* and *L. lacteus* and *D. hepatica* specimens that are smaller than 13.4 mm. (Appendix 4) Taken the average over the sampling stations this leads to an availability of 1.22 g AFDM per m^2. This is 93% of the total available bivalve prey for *C. canutus* (Figure 14). *L. lacteus* alone is responsible for 69 % of total available bivalve prey items.

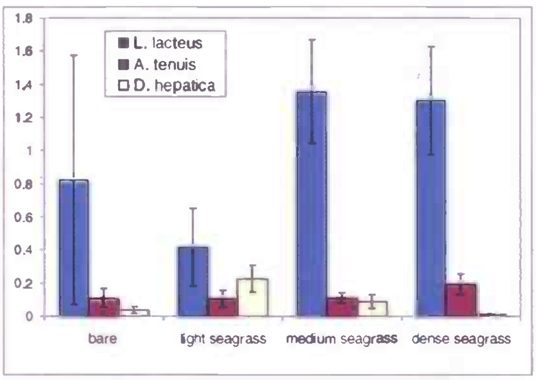

Figure 14: The top 3 of available bivalve AFDM for *C. canutus* separated over four classes of seagrass cover.

Values derived from satellite images: distance to gully, temperature and NDVI have significant correlations on the AFDM of available prey, in particular on the most important prey item: *L. lacteus.* The groundparameters: seagrass, penetrability and detritus content are also correlated with available prey items, in particular *D. hepatica* (table 1)

Regression analysis was performed based on two strategies: 1. Naïve modelling (table 2), finding best fit using all layers. 2. Biological modelling (table 3), based on proxies that we understand.
A lot of the variation in the models could be explained by NDVI and distance to water. Naïve modelling generated a higher fit.

Table 1: Correlation coefficients (R) with ground parameters and remotely sensed data versus AFDM of available prey for *C. canutus.* Numbers displayed in red are significant correlations.

	Abra tenuis	Dosinia hepathica	Loripes lacteus	Total
NDVI	.4144	-.2677	.6201	.6361
Temperature	.4645	.1554	-.2242	-.0937
Distance to gully	-.0576	-.3459	.5518	.4664
C. nodosa present	-.2009	-.4609	-.1053	-.1742
Only Z. noltii	.2830	.4542	.2004	.2783
Total seagrass AFDM	.6112	-.2542	.5034	.5725
Detritus in substrate	.2324	-.5161	.3065	.2914
Penetrability of the substrate	.0286	-.5314	.3811	.3147

Table 2: Naïve model - quasipoisson regression analysis (allowing for overdispersion) to predict the AFDM of five bivalve species: Lor = *L. lacteus*, Dos = *D. hepatica*, Abr = *A. tenuis*, Ana= *A. senilis*, Dlp= *D. Diaphana*. All bands of the landsat7 satellite were used as predictors, including distance water and NDVI. Coefficients ending in .s are quadratic terms.

	Lor	Dos	Abr	Ana	Dip
Coefficients					
(Intercept)	−61.49	2212.35	−70.15***	5235.65**	13210.75
	(49.13)	(2546.81)	(13.42)	(1756.97)	(91025.51)
NDVI	51.29	373.89*			
	(71.95)	(171.58)			
dwater	12.03**				
	(4.24)				
B3.031	0.63	−4.16			
	(0.62)	(3.46)			
B4.031	−0.08	2.21			
	(0.18)	(2.11)			
B5.031	−0.48	0.62			
	(0.36)	(0.83)			
B7.031	0.63	−2.40	−0.13*		
	(0.79)	(1.47)	(0.06)		
NDVI.s	−12.50	−210.04*			
	(29.79)	(103.21)			
dwater.s	−13.77**				
	(5.02)				
B3.031.s	−0.01	0.02	0.00		
	(0.00)	(0.02)	(0.00)		
B5.031.s	0.01	−0.02			
	(0.01)	(0.02)			
B61.031.s	0.00	0.16	0.00***	0.72**	1.70
	(0.00)	(0.17)	(0.00)	(0.24)	(11.32)
B62.031.s	−0.00			−0.31*	−0.67
	(0.00)			(0.13)	(4.58)
B7.031.s	−0.02	0.09			0.03
	(0.03)	(0.06)			(0.18)
B8.031.s	0.00		−0.02**		0.01
	(0.00)		(0.01)		(0.07)
B61.031		−38.86		−175.44**	−410.99
		(41.93)		(57.99)	(2733.21)
B1.031.s		0.00			
		(0.00)			
B4.031.s		−0.01			
		(0.01)			
B8.031			1.49**		
			(0.48)		
B2.031				0.12**	9.09
				(0.03)	(70.96)
B62.031				82.25*	174.84
				(34.17)	(1195.48)
B2.031.s					−0.12
					(0.87)
Summaries					
McFadden R-sq.	0.74	0.63	0.60	0.47	0.69
Cox-Snell R-sq.	0.56	0.31	0.12	1.00	0.24
Nagelkerke R-sq.	0.84	0.69	0.62	1.00	0.73
phi	0.43	0.47	0.09	61.81	79.87
Likelihood-ratio	44.9	20.1	7.1	1852.7	15.0
p	0.00	0.09	0.22	0.00	0.06
Deviance	15.5	12.0	4.8	2068.4	6.8
N	54	54	54	54	54

Table 3: Biological model- poisson regression analysis (allowing for overdispersion) , based on proxies that we understand, to predict the AFDM of five bivalve species: Lor = *L. lacteus*, Dos = *D. hepatica*, Abr = *A. tenuis*, Ana= *A. senilis*, Dip= *D. Diaphana*. Predictors are: Dwater = distance to water (inundation time) B62 = Temperature (water retainment), and NDVI (seagrass abundance).

	Lor	Dos	Abr	Ana	Dip
Coefficients					
(Intercept)	−0.68	648.61	−21.97***	17.08**	32.48
	(3.35)	(831.28)	(5.74)	(5.08)	(20.36)
dwater	14.34***	12.03		−3.79	
	(3.93)	(8.81)		(2.23)	
NDVI.s	3.52***	−138.70			
	(0.60)	(77.49)			
dwater.s	−16.00**	−15.73			
	(4.95)	(11.33)			
B62.031.s	−0.00*	0.05	0.00***		
	(0.00)	(0.05)	(0.00)		
NDVI		364.38		−10.56*	
		(203.00)		(4.16)	
B62.031		−13.67			−0.26
		(12.95)			(0.16)
Summaries					
McFadden R-sq.	0.58	0.41	0.24	0.29	0.12
Cox-Snell R-sq.	0.48	0.22	0.05	1.00	0.05
Nagelkerke R-sq.	0.71	0.48	0.26	1.00	0.14
phi	0.52	0.94	0.19	94.80	0.84
Likelihood-ratio	34.8	13.2	2.8	1129.2	2.6
p	0.00	0.04	0.09	0.00	0.11
Deviance	25.5	18.9	9.0	2791.8	19.3
N	54	54	54	54	54

Based on the amount of variance explained by the biological model, we felt confident enough to predict the available *L. lacteus* meat for *C. canutus*. Hence a prediction map was created (figure 16). On certain areas no fair predictions could be made as predictor-values in these areas fell outside the range of values observed in the sample stations.

A variance map was created to see how the uncertainty of our parameter estimates propagated in our predictions (figure 17).

Simulations ran over the model predicted an outcome of on average 0.79 g AFDM per M^2 available *L. lacteus* meat for *C. canutus* with confidence intervals of 0.44g and 1.20 g. (figure 15)

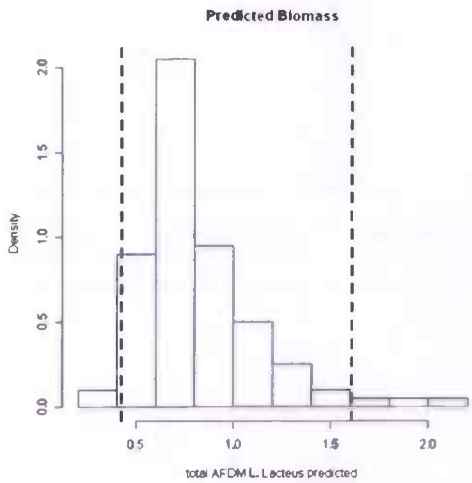

Figure 15: Reliability in the *L. lacteus* meat predictions available for *C. canutus*. Height of bars represent plausibility on outcome of the simulation ran over the model. The average outcome of available *L. lacteus* meat is 0.79 g AFDM, with confidence intervals of 0.44 and 1.20 g AFDM.

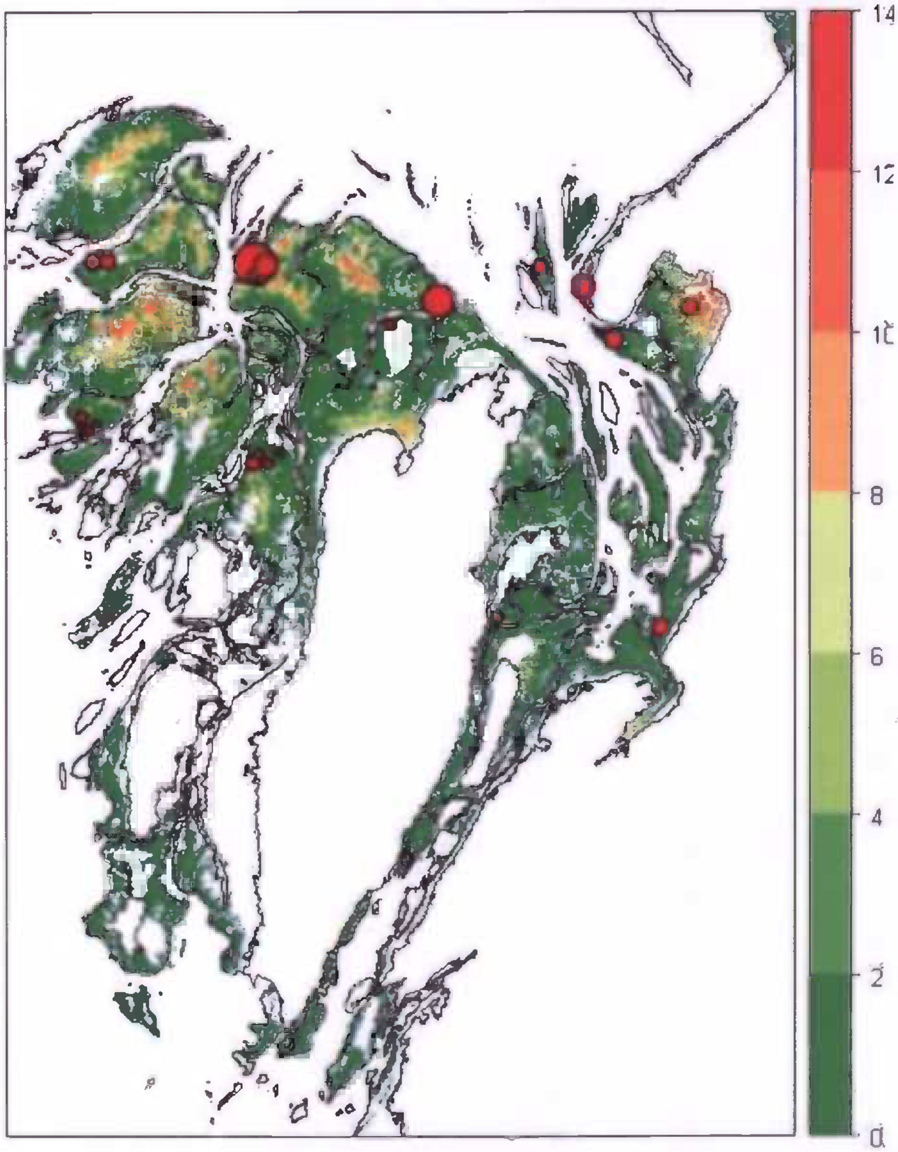

Figure 16: Predicted *L. lacteus* meat for *C. canutus*, based on the biological explainable quasipoisson regression model. The size of red dots represent the amount of observed *L. lacteus* meat. In some areas, no fair predictions could be made as predictor values in these areas fell outside the range of values observed in the sample stations.

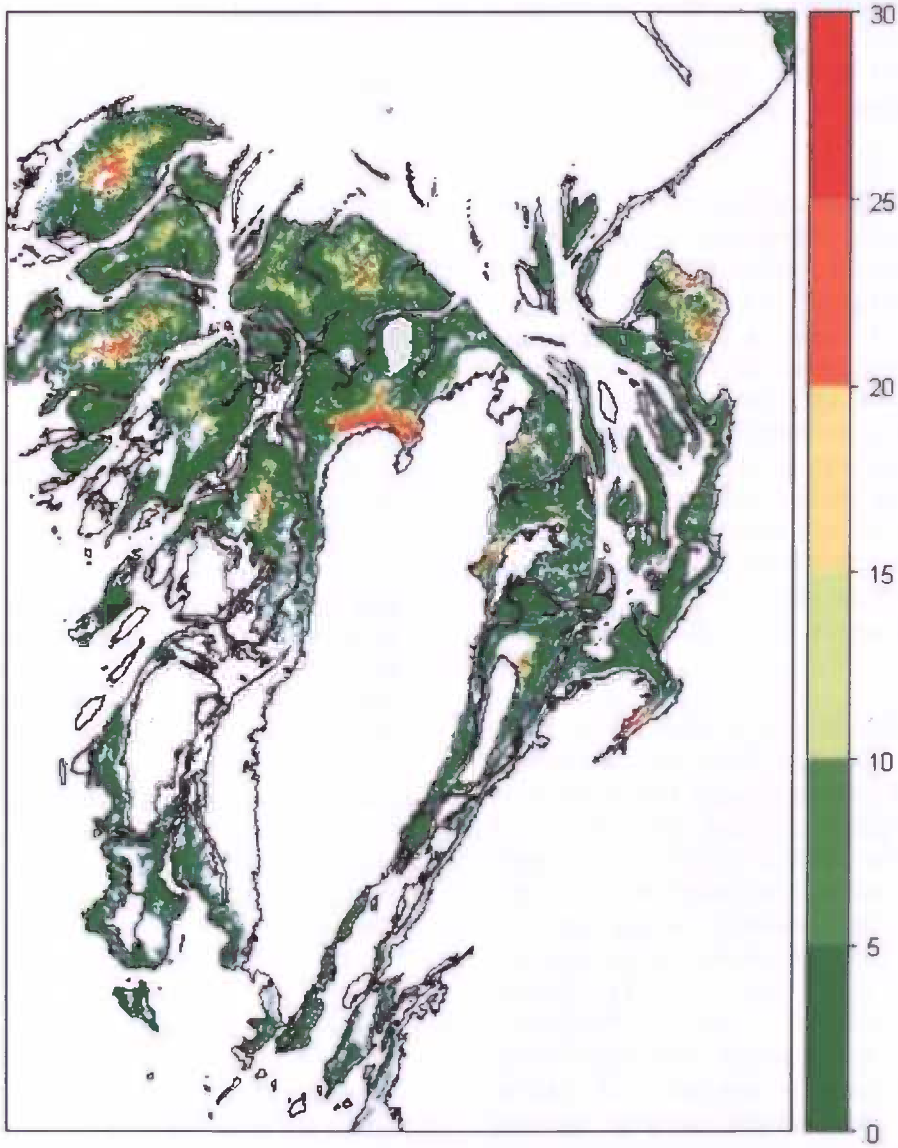

Figure 17: Variance map of available *L. lacteus* meat for *C. canutus*. Variance was determined by running the quasipoisson regression model for a number of times using varying parameter estimates.

4. Conclusion and discussion

Remote sensing as indicator of physical properties and as benthos prediction tool.

Multiple physical and biological properties of the tidal areas in the Banc d'Arguin were adequately quantified by the use of spectral satellite images. Specifically NDVI turned out to be a good measure for the abundance of seagrass. The thermal band was strongly related to sediment characteristics such as moist content and penetrability (which in its turn is related to grain size). Also groundparameters which are not so clearly visible from the surface, such as detritus and moist content relate to these images.

Furthermore, macrobenthic spread was strongly related to the satellite images or its derivatives. The calculated NDVI for instance is a measure of greenness, caused by seagrass. Seagrass occurrence changes the habitat drastically for macrobenthos in terms of food availability (detritus, epiphytes) and sediment (seagrass covered sites tend to be softer). Therefore the (biological) link between NDVI and macrobenthos spread is straightforward (WOTRO-project 10/01/2006 – 11/30/2010[4]).

Other spectral bands that cause significant improvement on the regression model are less easy to explain by a valid biological cause. Correlation coefficients of the model used for extrapolating data over the whole area goes up to as much as a (McFadden) r^2 of 0.74(!) when using a full model (using all spectral bands) in *L. lacteus*. but we loose biological causality. Apparently other processes, play an important role that have an influence on macrobenthos spread and can in some way indirectly be detected by spectral landsat images.

Mechanistic understanding of the functional relationships between benthos and physical properties that are determined with the satellite images requires two levels of investigation. One should be focused on the relationship between electromagnetic reflection and properties of the mudflat. The second should focus on the relationship between the physical properties and benthos.

However, without understanding the details of the underlying mechanisms, this research shows that it is possible to predict the amount of biomass of single species rather adequately, given a good fit of the regression model. This can be directly used in inference about ecology in the next trophic level. The prediction made about the available prey items for *C. canutus* can help us predict the carrying capacity of the area in terms of food. But care is necessary when using outcomes of statistical models for prediction as we only partly understand the processes that play a role in macrobenthos distribution.

A lot of variation in the samples is not adequately explained by both physical parameters and spectral satellite bands. In the full model for instance, predictors for *A. senilis* explain only 30 % of the variation. By visual inspection one can see that *A. senilis* is more spatial correlated to the bay. Perhaps other processes (e.g. salinity, spatfall, predation etc.) play a more important role here. A combination with spatial regression analyses and remotely-sensed data regression analyses would possibly give a higher yield. Another possibility is that the spatial distribution of *A. senilis* is hampered by dispersal limitation or predation.

Overall distinguishing between land water and mudflats with NDVI maps works well, but in some cases, causes inconsistencies: thick dead algal mats on sebhka and dead organic material washed on the beach are sometimes misinterpreted as seagrass beds. Some sample stations appeared to be in deeper (50 cm+) not easy accessible water. The area between mudflats and seawater are sometimes unjust classified as seagrass-covered mudflats (personal observation). The small resolution of the

[4] http://www.nwo.nl/projecten.nsf/pages/2300132307

maps (25m) and heterogeneity of the area also complicates this distinguishing. Possible dynamics in intertidal habitats and differences in tidal regime are other possible causes of faulty classified habitat types.

A combination of different sources of remote sensing could increase the accuracy of such interpretations. Also realistic bathometric maps and more knowledge of the local tidal regime could increase reliability.

Comparison with earlier studies on benthos distribution and density.

Studies that are done in the same area and similar season are that of Altenburg et al. (1982) and Wolff (1993), who obtained an AFDM (*A. Senilis* left out) of respectively 2.9 g m^{-2} and 8.9 g m^{-2}. The latter study is more towards the 8.3 g AFDM m^{-2} found in this study.

Due to extreme densities it is unrealistic to make fair comparisons between studies for *A. senilis*: On one sample location the density of this bivalve reached 533 g AFDM m^{-2} Furthermore it is also unjust to compare studies carried out in only subsamples of the area because the distribution pattern of macrobenthos is highly clustered for some species (Figure 11). In such a case the chosen stratification scheme strongly influences the estimation of biomass densities.

Nevertheless, in the study of Wolff (1993) and this study both the most abundant and the second most abundant in terms of AFDM are *A. senilis* and *L. lacteus* respectively. The numbers three, four and five differ. In the study of Wolff these are formed by the polychaetes *M. sanguinea* and *P. terricola*, and the bivalve *T. turulosa*. In this study numbers three, four and five are formed by the bivalves *D. diaphana* and *D. hepathica* and a member of the *Xantho* family.

Differences in methodology make it also difficult in comparing macrobenthic live. Wijnsma et al. (1999) found an annelid: bivalve ratio (in numbers) of 4.82:1 versus a ratio of this study of 0.20:1 (!) in the same time of the year. During that expedition smaller cores were used (internal diameter of 10 cm), the cores were taken deeper (40-45 cm) and all the material was sieved over a 0.6 mm sieve.

It is not unlikely that a lot of annelids were lost over the 1 mm sieve. Reish (1959) shows a loss of annelid specimens of 72 % when using a 1 mm sieve compared to a loss of only 28 % when sieving over a 0.59 mm mesh, based on 100% retrieval over 0.15 mm mesh sized sieve.

We partly understand the relation between remotely sensed data, physical parameters of the mudflat and macrobenthos abundance. Understanding more about processes that play a role in the spread of macrobenthos and how they relate with remotely sensed data is important.

If we know how dynamic the system is in its "natural" state we can use satellite images as a baseline, from where we can pick up signals of change in the ecosystem and in this way contribute to the protection of the area.

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Appendix 1

For molluscs that were incinerated as a whole (Bivalves < 8.4 and all gastropods), correction factors were used to compensate for calciumcarbonate condensation during incineration.

Large bivalves were seperated from their shell before incineration, so no calciumcarbonate was lost.

The length of large and small bivalves was plotted against AFDM in the same graph.
Then bivalves that were incinerated as a whole were multiplied with a fixed value, to obtain the highest correlation coefficient over the whole range of the graph.

For mollusks of which there were insufficient large specimens to determine the slope of the graph (AFDM vs. Length), the average over the other species was used (0.19)

Species	Correction factor	R2
A. senilis	0.38	0.985
Brachiodontes sp.	0.55	0.983
D. hepatica	0.29	0.900
L. lacteus	0.25	0.864
D. diaphana	0.14	0.937925
A. agglutinans	0.19	-
C. ajar	0.19	-
A. alba	0.19	-
Cardiidae sp.	0.19	-
C. gibba	0.19	-
L. adansoni	0.19	-
Tellina sp.	0.19	-
A. tenuis	0.19	-
All gastropods	0.19	-

Appendix 2:

Biomass (AFDM), number and frequency of macrobenthos found over all sample stations (2.014 m2)*

Species	Tax Group	Weight	Number	Frequency
Anadara senilis	Bivalvia	40,9109	91	32,1
Loripes lacteus	Bivalvia	5,3279	1145	78,5
Diplodonta diaphana	Bivalvia	2,1473	60	35,7
Dosinia hepatica	Bivalvia	1,7466	231	62,5
Xantho sp.	Decapoda	1,2767	10	10,7
Petaloproctus sp.	Polychaeta	1,0288	24	7,1
Lumbrineris sp.	Polychaeta	0,892	24	19,6
Linga adansoni	Bivalvia	0,3466	3	5,3
Tunicata sp. 1	Tunicata	0,3156	47	16
Marphysa sp.	Polychaeta	0,4874	18	8,9
Abra tenuis	Bivalvia	0,239	1532	69,6
Diopatra sp.	Polychaeta	0,4598	92	30,3
Maldanidae sp.	Polychaeta	0,2862	38	25
Anthuridae sp.	Isopoda	0,1424	147	58,9
Naineris sp.	Polychaeta	0,2478	40	14,2
Goniada sp.	Polychaeta	0,211	10	8,9
Polychaeta sp.	Polychaeta	0,204	24	16
Palaemon sp.	Decapoda	0,0839	6	5,3
Notomastus sp.	Polychaeta	0,152	2	1,7
Cirriformia sp.	Polychaeta	0,1344	92	32,1
Amphipoda sp.	Amphipoda	0,0552	36	17,8
Conus sp.	Gastropoda	0,0545	2	3,5
Gibbula umbilicalis	Gastropoda	0,0514	16	16
Nereis sp.	Polychaeta	0,0918	60	28,5
Brachidontes sp.	Bivalvia	0,0438	9	7,1
Idotea sp.	Isopoda	0,0437	24	25
Tanais sp.	Tanaidacea	0,0421	80	17,8
Tunicata sp. 2	Tunicata	0,0379	1	1,7
Callianassa sp.	Decapoda	0,0374	1	1,7
Anaitides sp.	Polychaeta	0,0662	4	3,5
Mesalia mesal	Gastropoda	0,0306	8	10,7
Asterina gibbosa	Echinodermata	0,0286	1	1,7
Capitella sp.	Polychaeta	0,0556	70	23,2
Bulla Adansoni	Gastropoda	0,0248	4	5,3
Amphipholis squamata	Echinodermata	0,0206	4	1,7
Oligochaeta sp.	Oligochaeta	0,0406	26	12,5
Prunum amygdala	Gastropoda	0,0189	4	5,3
Crepidula Porcellana	Gastropoda	0,0188	28	17,8
Haminea sp.	Gastropoda	0,0183	18	23,2
Hydrobia ulvae	Gastropoda	0,0151	38	12,5
Scoloplos sp.	Polychaeta	0,0298	34	17,8

Species	Tax Group	Weight	Number	Frequency
Petricola pholadiformis	Bivalvia	0,0144	3	5,3
Spionidae sp.	Polychaeta	0,0272	18	10,7
Cardiidae sp.	Bivalvia	0,0111	4	5,3
Nassarius cuvierii	Gastropoda	0,0105	4	5,3
Heteromastus sp.	Polychaeta	0,0192	22	8,9
Muricopsis sp.	Gastropoda	0,009	3	1,7
Crustacea sp.	Crustacea	0,0084	4	7,1
Bittium sp.	Gastropoda	0,0076	13	8,9
Terebellidae sp.	Polychaeta	0,0146	12	10,7
Gibberula oryza	Gastropoda	0,0072	10	12,5
Tellina sp.	Bivalvia	0,0059	3	3,5
sphaeromatidae sp.	Isopoda	0,0055	7	3,5
Caridea sp.	Decapoda	0,005	1	1,7
Syllidae/Hesionidae sp.	Polychaeta	0,0078	40	8,9
Calyptraea chinensis	Gastropoda	0,0026	6	7,1
Amyclina pfeifferi	Gastropoda	0,0023	1	1,7
Prunum ameliensis	Gastropoda	0,0022	1	1,7
Turritella torulosa	Gastropoda	0,0021	1	1,7
Abra alba	Bivalvia	0,002	6	1,7
Cardites ajar	Bivalvia	0,002	2	1,7
Clavatula bimarginata	Gastropoda	0,0019	1	1,7
Clavatula sp.	Gastropoda	0,0015	1	1,7
Jujubinus sp.	Gastropoda	0,0015	2	1,7
Musculista senhousia	Bivalvia	0,0015	1	1,7
Corbula gibba	Bivalvia	0,0006	1	1,7
Amygdalum agglutinans	Bivalvia	0,0005	1	1,7
Hesionidae sp.	Polychaeta	0,0008	8	1,7
Syllidae sp.	Polychaeta	0,0008	8	1,7
Corophium sp.	Amphipoda	0,0003	1	1,7

*Macrobenthos samples were taken in duplo. Polychaet and oligochaet samples were taken singular For this reason, polychaet and oligochaet species in the number and weight column are multiplied by 2

Appendix 3:

Correlations (R) between different levels of the system. Significant correlations are displayed in red

Variable	detritus	Seagrass total AFDW	penetratibility	moist content
NDVI	.3409	.5367	.3093	.2675
	p=.015	p=.000	p=.029	p=.060
Dist_gully	-.1671	-.1135	-.0893	-.0064
	p=.246	p=.432	p=.537	p=.965
temperature	-.0802	-.1366	-.3603	-.4275
	p=.580	p=.344	p=.010	p=.002

Variable	annelida per m2	malacostraca per m2	bivalvia per m2	Gastropoda per m2	J' evenness	H' diversity
NDVI	.1426	.0311	.1924	.0976	-.2456	.1535
	N=56	N=56	N=56	N=56	N=56	N=56
	p=.295	p=.820	p=.155	p=.474	p=.068	p=.259
Dist_gully	.2073	.0646	.0855	-.0182	-.0801	-.0349
	N=56	N=56	N=56	N=56	N=56	N=56
	p=.125	p=.636	p=.531	p=.894	p=.557	p=.798
temperature	-.0599	.1016	.3038	-.2228	-.2169	-.3112
	N=56	N=56	N=56	N=56	N=56	N=56
	p=.661	p=.456	p=.023	p=.099	p=.108	p=.020

Variable	annelida per m2	malacostraca per m2	bivalvia per m2	Gastropoda per m2	J' evenness	H' diversity
detritus	-.1563	-.0902	.1235	.3577	-.2497	-.0597
	N=53	N=53	N=53	N=53	N=53	N=53
	p=.264	p=.521	p=.378	p=.009	p=.071	p=.671
Seagrass total AFDW	.0950	.1197	.3824	-.1197	-.3430	-.0168
	N=56	N=56	N=56	N=56	N=56	N=56
	p=.486	p=.379	p=.004	p=.380	p=.010	p=.902
penetratibility	-.0750	.0658	.0690	.1087	-.2629	.1562
	N=53	N=53	N=53	N=53	N=53	N=53
	p=.593	p=.640	p=.624	p=.439	p=.057	p=.264
moist content	-.0474	.1135	.0595	.2567	-.2576	.1346
	N=55	N=55	N=55	N=55	N=55	N=55
	p=.731	p=.409	p=.666	p=.059	p=.058	p=.327

Appendix 4

Circumference as a function of length, where circumference = 1.55 * (width+height), following Zwarts & Blomert (1992-A)

L. lacteus: N = 836

Average height : width ratio:	1 : 0.544	SEM: 0.00136
Average length : width ratio:	1 : 1.10	SEM: 0.00183
Critical length:	**14.0 = all**	SEM: 0.0193

D. hepatica: N = 143

Average height : width ratio:	1 : 0.574	SEM: 0.00418
Average length : width ratio:	1 : 1.07	SEM: 0.00578
Critical length:	**13.4**	SEM: 0.0607

A. tenuis: N = 10*

Average height : width ratio:	1 : 0.501	SEM: 0.0127
Average length : width ratio:	1 : 1.24	SEM: 0.0144
Critical length:	**16.3 = all**	SEM: 0.227

*N is only 10 for A. tenuis as only 10 shell heights were measured, because the shell of A. tenuis is very fragile.