Design (and analysis) of marine monitoring and mapping

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Take home messages

- Monitoring is absolutely fundamental as a basis for rational management of the marine environment!
- The design of a sampling or monitoring program matters! It determines the quality of conclusions that can be made from it
- Careful planning BEFORE sampling is needed to avoid confounded conclusions, uncertain measurements and excessive costs
- Always decide upon which statistical analyses and models to use, BEFORE sampling. If possible use pilot data to model ”power” and ”precision” of sampling program.
- The purpose of a sampling or monitoring program influences which type of sampling design is most appropriate (”optimal”)

Five aims for sampling programs

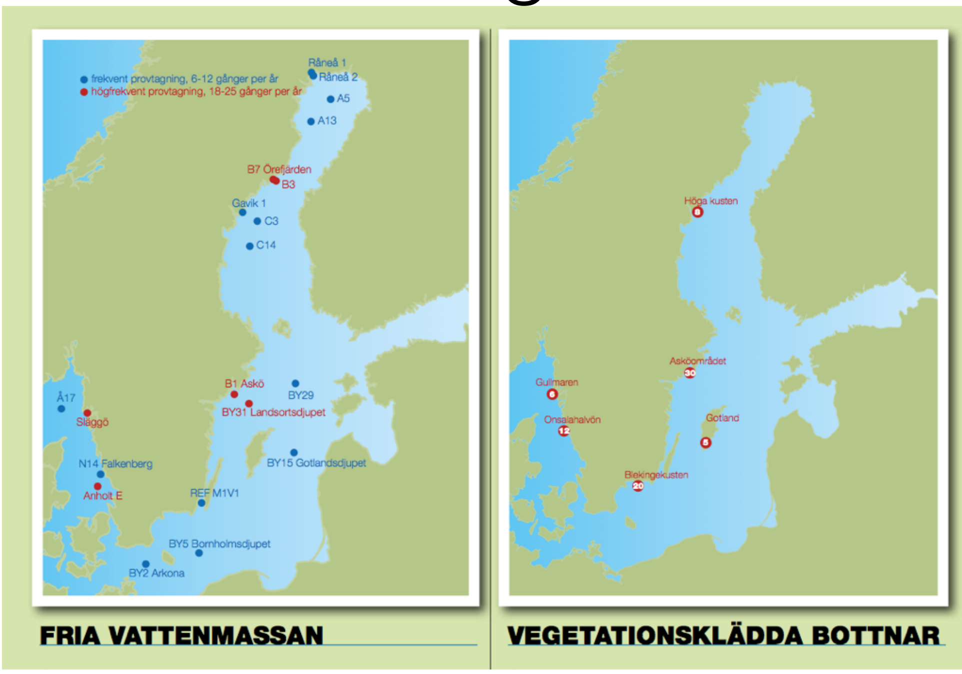
- To detect large-scale environmental changes of the Swedish coast
- To determine if the local industry has a negative effect on the environment
- To assess the environmental status of the drainage area according to a EU Directive
- To determine if a measure has changed the environmental status of the drainage area
- To map the areal distribution of habitat forming species in the area.

One common thing though…

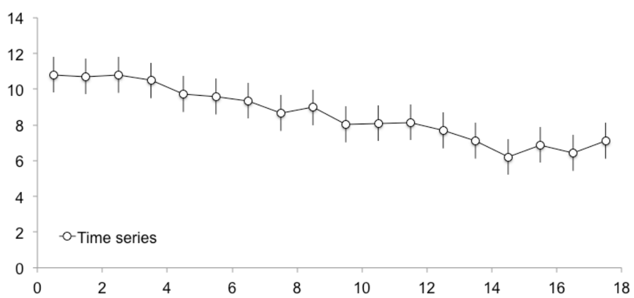
STATISTICAL INFERENCE!

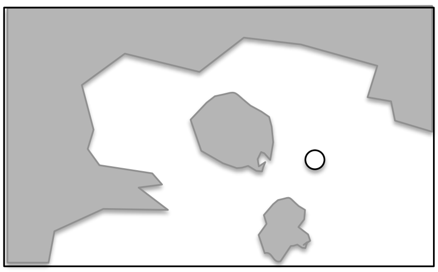
- Why?
- Sampling error. Spatial and temporal variability!
- Are there exceptions?
- Complete sensus vs. Representative sample
- Statistical tools are needed to assess sampling errors, uncertainty and to account for various sources of variability.
- But much of the logic behind monitoring designs can and should be understood conceptually.

”Traditonal monitoring”- Monitoring trends



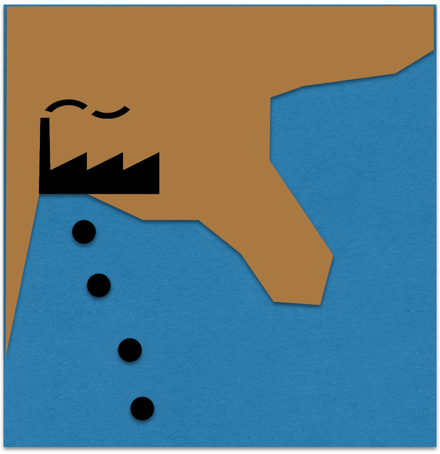
Monitoring trends

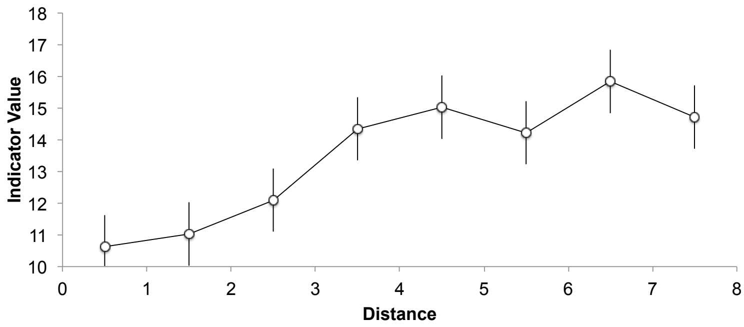




- Detection of changes in time. Monotonic or cyclic ”time series”.
- Typically fixed stations (revisited year after year) to minimise effects of spatial variability.
- Stations not selected to be representative (e.g. ”reference”, ”sensitive” or ”strategic” locations)

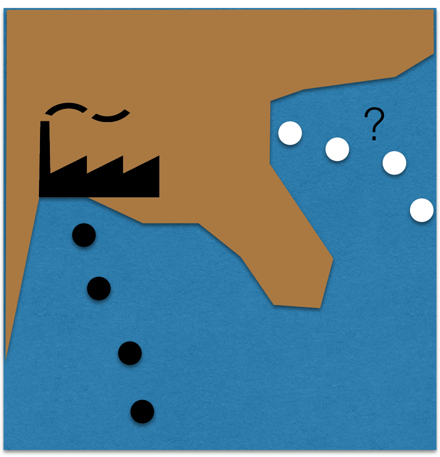
2. Detection of localized impacts

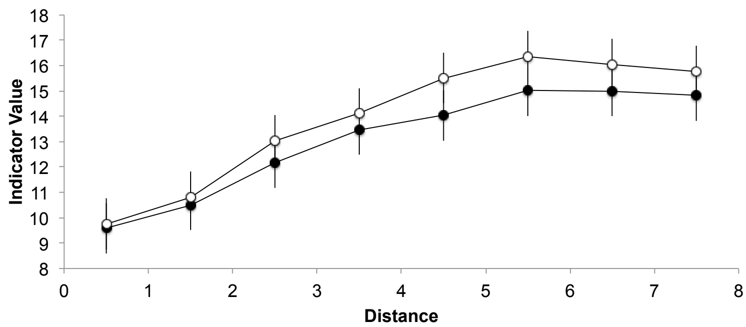




- Impact detected as gradient!
- What about confounding factors?
- Analysis using regression approaches

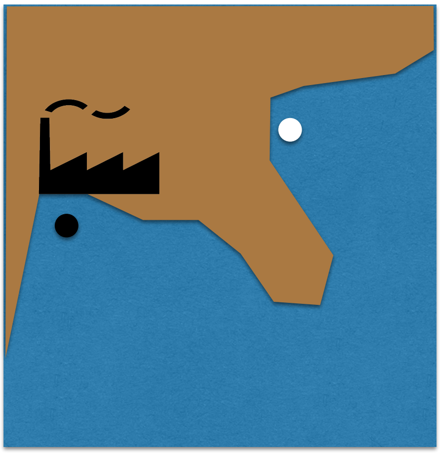
Detection of localized impacts

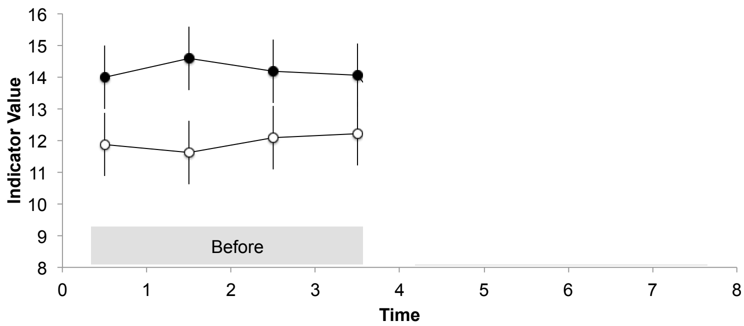




- Impact detected as a difference in gradient between impacted and reference site
- Statistical interaction between site and distance
- Multifactorial analysis of variance (ANOVA) approaches

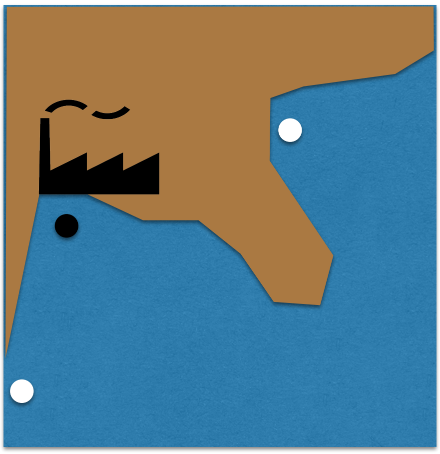
Detection of localized impacts

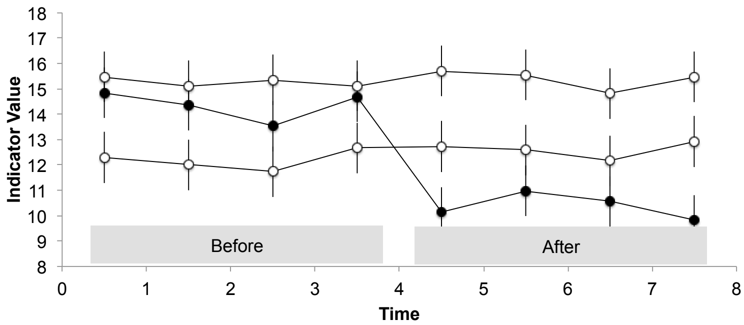




- Before-After-Control-Impact. "BACI-design" Impact detected as an interaction between period and sites.
- Differences in absolute levels no problem
- Shift coincides with onset of pressure. Potential for confounding?

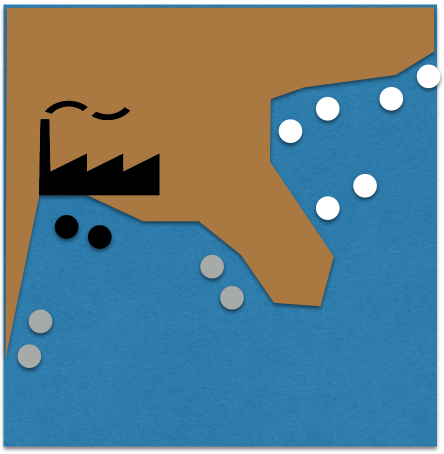
Detection of localized impacts



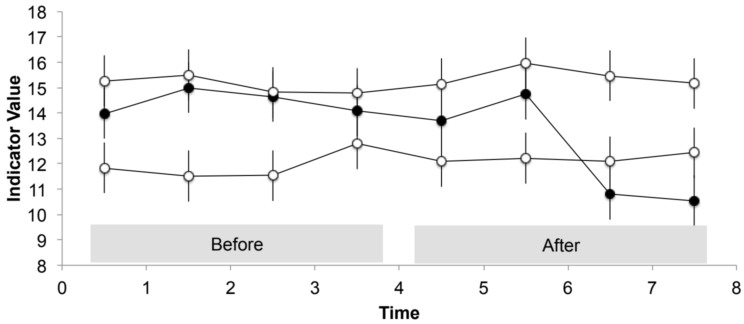


- Shift coincides with onset of pressure and there is a systematic difference between control and impact.
- Asymmetric design! ANOVA with planned contrasts.
- Scale of impact?

Detection of localized impacts

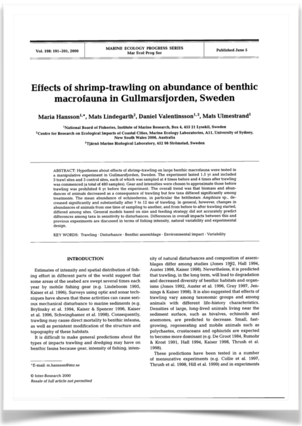


- Small scale impact ● vs ●
- Large scale impact ●● vs ○
- What if impacts are not consistent in time? Transient impacts. Individual times.
- ”Beyond BACI”. Multiple controls and hierarchical sampling.



A practical example

Source	df	Polychaetes		Echinoderms	
		MS	p	MS	p
B/A	1	1.903	nt	2.633	<0.001***c
Tr	1	0.403	nt	0.969	>0.822b
S(Tr)	4	1.025	<0.000***	16.765	<0.000***
Ti(B/A)	6	0.124	>0.074	0.069	>0.611
B/A × Tr	1	0.225	nt	0.481	<0.020*a
B/A × S(Tr)	4	0.373	<0.001**	0.016	>0.950
Tr × Ti(B/A)	6	0.122	>0.079	0.077	>0.555
S(Tr) × Ti(B/A)	24	1.055	>0.109	0.092	>0.167
Residual	432	0.040		0.071	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Effects of shrimp-trawling on abundance of benthic macrofauna in Gullmarsfjorden, Sweden

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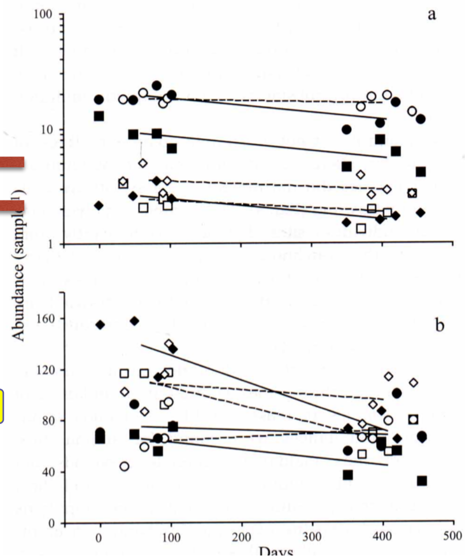
ABSTRACT: Hypotheses about effects of shrimp-trawling on large benthic macrofauna were tested in a manipulative experiment in Gullmarsfjorden, Sweden. The experiment lasted 1.5 yr and included 3 trawl sites and 3 control sites, each of which was sampled at 4 times before and 4 times after trawling was commenced (a total of 480 samples). Gear and intensities were chosen to approximate those before trawling was prohibited 6 yr before the experiment. The overall trend was that biomass and abundances of animals decreased as a consequence of trawling but few taxa differed significantly among treatments. The mean abundance of echinoderms, in particular the brittlestars *Amphiura* sp., decreased significantly and substantially after 7 to 12 mo of trawling. In general, however, changes in abundances of animals from one time of sampling to another, and from before to after trawling started, differed among sites. General models based on size and feeding strategy did not accurately predict differences among taxa in sensitivity to disturbances. Differences in overall impacts between this and previous experiments are discussed in terms of fishing intensity, natural variability and experimental design.

KEY WORDS: Trawling · Disturbance · Benthic assemblage · Environmental impact · Variability

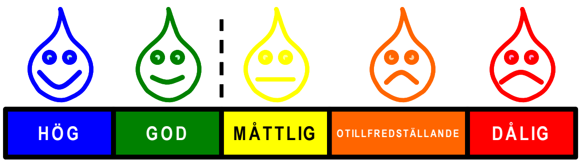
INTRODUCTION

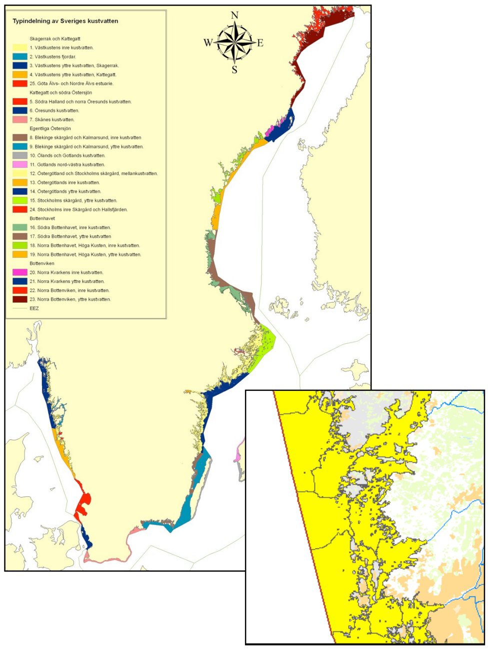


- Large variability among sites
- Echinoderms change consistently among impacted sites
- Polychaetes respond differently among sites

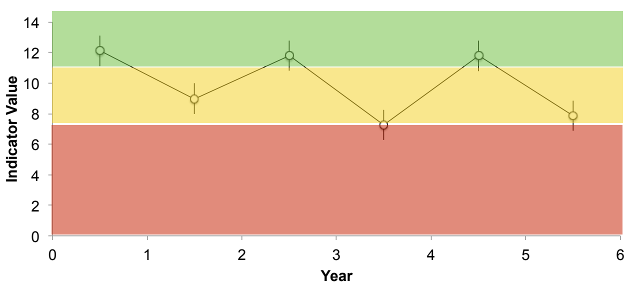
3. Assessment of status

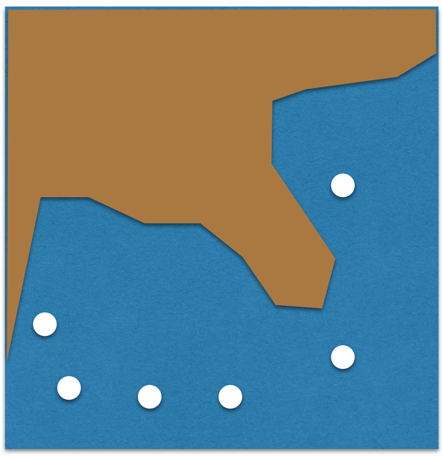
- Indicator reflecting ”health” , status. Responsive to relevant pressures
- Standardised scale of measurement. Classification of health status.
- Assessment units.
  - WFD: Water bodies and 6-yr assessment periods
  - MSFD: Coastal seas and 6-yr assessment periods
- Estimate the mean level of indicator in relation to class boundaries!
- Requires representativity!





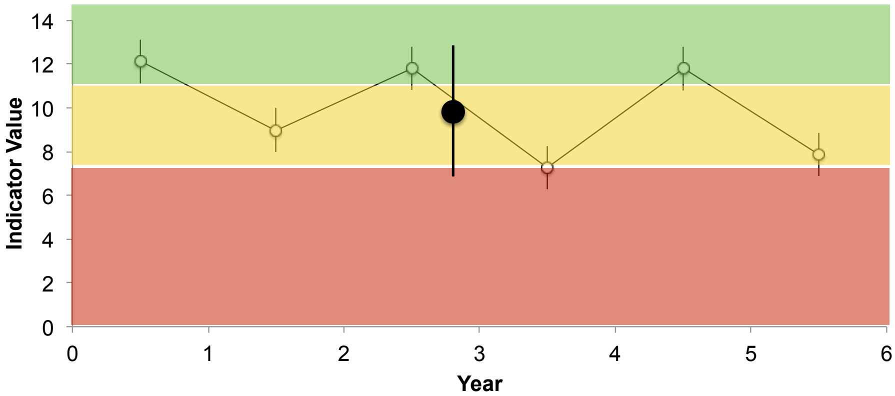
Assessment of status





- Temporal representativity. Not only one year!
- Spatial representativity. Account for spatial variability!
- Random ≈ representative.
- Random ≠ anywhere or any time!
- Regular may also be a good option with small sample sizes.

Assessment of status



- Estimation rather than hypothesis testing.
- Precision of estimated mean! Error / Uncertainty (SE)
- Confidence interval! (95% CI)
- Confidence in classification!
- We must estimate parameters of statistical distributions

Assessment of status

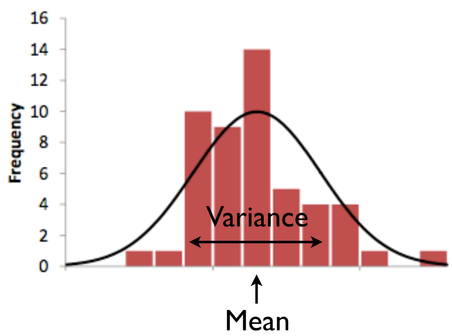
Population
("true" parameter)

Sample
(estimated parameter)

$$\mu = \frac{\sum x_i}{n}$$

$$\sigma^2 = \frac{\sum (x_i - \mu)^2}{n}$$

$$\sigma = \sqrt{\sigma^2}$$



$$\bar{x} = \frac{\sum x_i}{n}$$

$$s^2 = \frac{\sum (x_i - \bar{x})^2}{n - 1}$$

$$s = \sqrt{s^2}$$

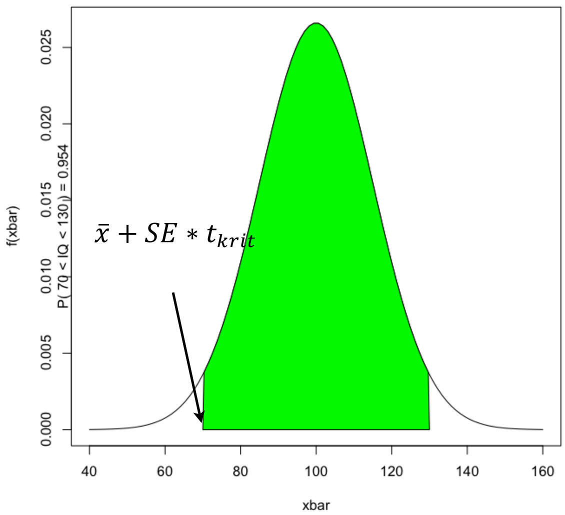
Assessment of status

- SE (of the mean) is a measure of uncertainty. How much does an estimated mean on average deviate from the true mean.

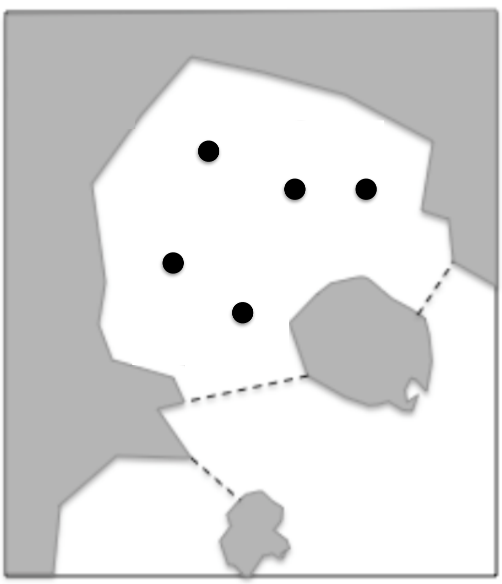
$$SE = \sqrt{\frac{s^2}{n}}$$

- The confidence interval is a measure of the boundaries in which the true mean is located with a given certainty

$$KI = \bar{x} \pm SE * t_{krit}$$



A very simple case



$$\bar{x} = \frac{\sum x_i}{n}$$

$$s^2 = \frac{\sum (x_i - \bar{x})^2}{n-1}$$

$$SE = \sqrt{\frac{s^2}{n}}$$

Assessment of status

$$y = \mu + YEAR + STATION + YEAR * STATION + PATCHINESS$$

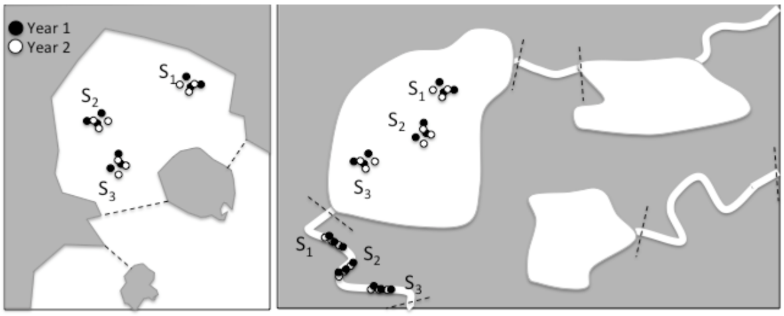


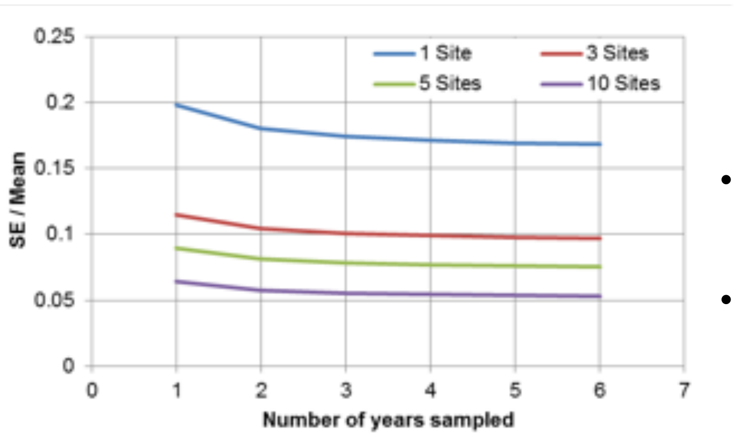
FIGURE 3.1
Illustration of crossed monitoring designs in a coastal water body (left) and in a lake and stream (right). In the examples, *a* = 2 years, *b* = 3 stations, and *n* = 3 replicates.

$$V[\bar{y}] = \frac{s_Y^2 * (1 - \frac{a}{Y})}{a} + \frac{s_S^2}{b} + \frac{s_{Y*S}^2}{ab} + \frac{s_e^2}{abn}$$

Assessment of status

The variance components used in calculating the overall uncertainty of the status of benthic invertebrates in a coastal water body within a single year and over a 6-year assessment period.

	Source	West Coast	Baltic Proper	Gulf of Bothnia
Variation among years	s_Y^2	0.03	0.13	0.16
Variation among stations	s_S^2	2.59	2.15	1.71
	s_{Y*S}^2	0.63	0.59	0.19
Variation among samples	s_e^2	0.64	1.06	1.24



$$V[\bar{y}] = \frac{s_Y^2 * (1 - \frac{a}{Y})}{a} + \frac{s_S^2}{b} + \frac{s_{Y*S}^2}{ab} + \frac{s_e^2}{abn}$$

- Optimise precision by sampling many sites
- Number of years / period and samples per site less important"

more sites are better than more years

A nested monitoring design

$$y = \mu + YEAR + SITES(YEAR) + PATCHINESS$$

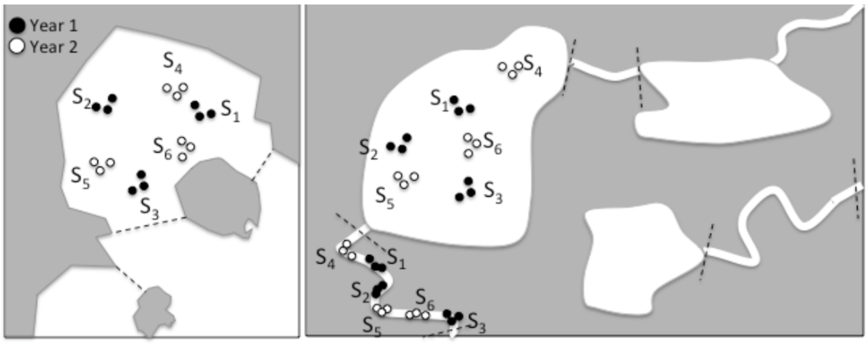
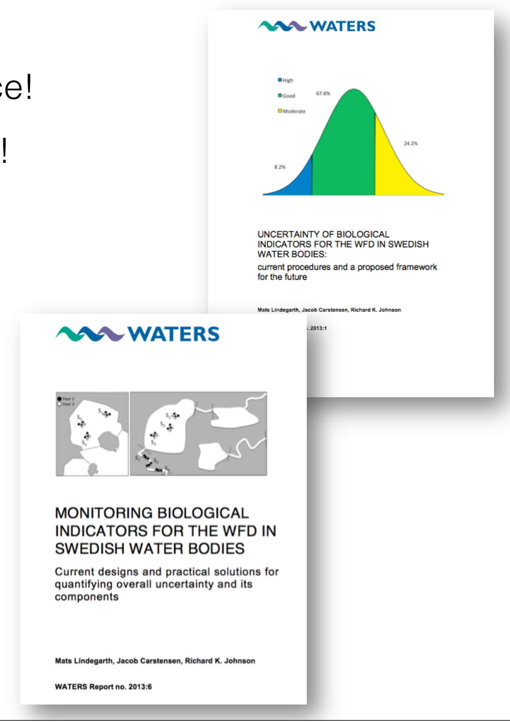


FIGURE 3.2
Illustration of nested monitoring designs in a coastal water body (left) and in a lake and stream (right). New sites are selected each year, so sites are nested within years. In the examples, *a* = 2 years, *b* = 3 sites, and *n* = 3 replicates. Reproduced from Lindegarth et al. (2013)

$$V[\bar{y}] = \frac{s_Y^2 * (1 - \frac{a}{Y})}{a} + \frac{s_{S(Y)}^2}{ab} + \frac{s_e^2}{abn}$$

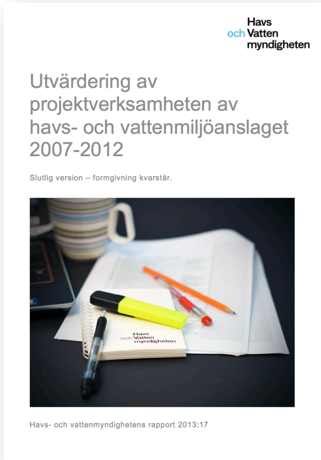
Assessment of status

- Representativity in time and space!
- Assess against class boundaries!
- Confidence in estimation and classification!
- Sampling design AND natural variability determines confidence!

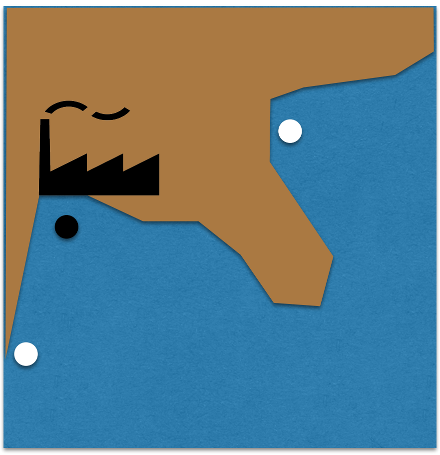


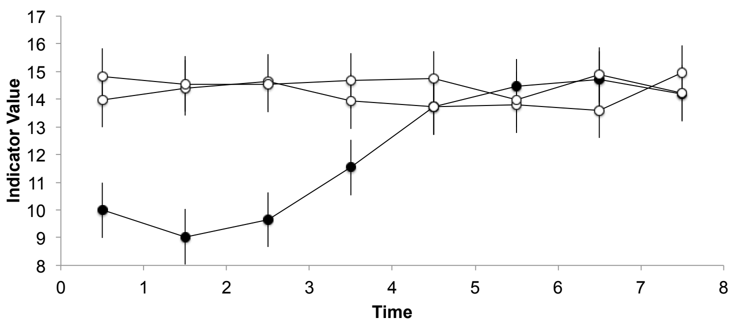
4. Effects of actions and programs of measures

- Important for adaptive management and rational use of resources.
- Incorporated in WFD and MSFD
- Effects are often NOT evaluated properly!
- Similar logic as determination of localized impacts.



Effects of actions and programs of measures

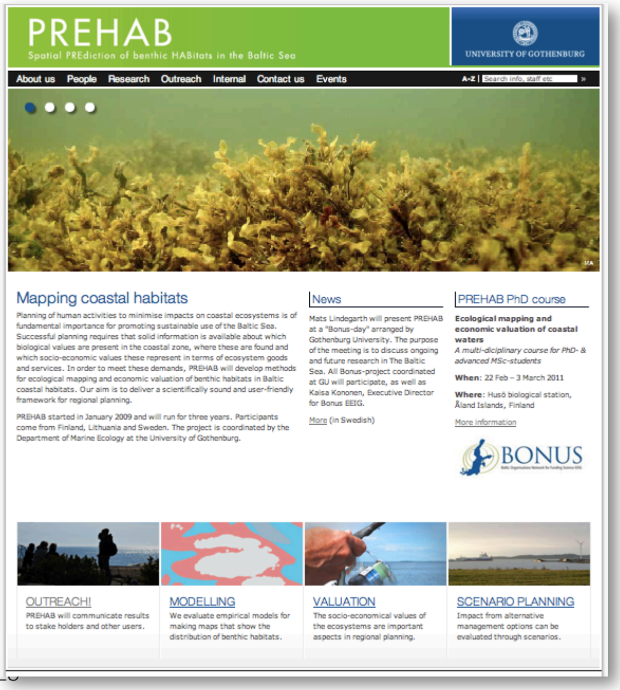




- Effects detected as an interaction between times and sites.
- When have we achieved full recovery?
- Shift coincides with onset of action.

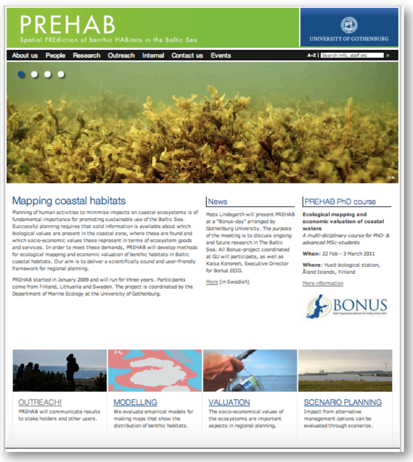
5. Mapping of areal distribution and extent of species and habitats

- Important for MSFD and habitats directive!
- Marine spatial planning! MSP
- Not in traditional monitoring!
- Limited by cost, lack of methods etc.
- Complete sensus vs sampling methods.
- Remote sensing
    - shallow vegetation (eelgrass?, filamentous algae), phytoplankton
- Sampling surveys (representative or otherwise)
    - deeper flora and fauna, biodiversity, particular species, habitats/communities, fish?
- European project PREHAB 2009-2012



Mapping of areal distribution and extent of species and habitats

- Sampling surveys!
- Often ”visual methods”, photo, video
- ”Top-down” strategy - requires knowledge about important environmental factors (e.g. depth, substrate,…).
    - Estimation of mean within strata
    - Representative sampling within strata.
- ”Bottom-up” strategy. Representative sampling in the whole target area. ”No prior knowledge”.
    - Estimation of overall mean or total cover in the area using standard statistical methods.
    - Estimation of detailed map of distribution using predictive modelling (with or without covariates). Interpolation.

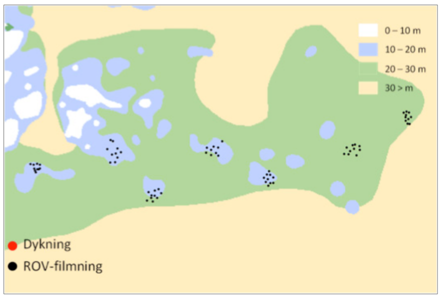


Mapping of areal distribution and extent of species and habitats

- Survey of off-shore banks.
- Representative clustered sampling of cover of algae and substrate using video and ROV.
- Estimates of cover (m^{-2}) and occurrence (frequency of photographs) of dominant and visible taxa.

Tabell 5. Täckningsgrad och förekomst med 95 % konfidensintervall (KI) av de tio mest täckande och de tio mest förekommande taxonomiska enheterna på videobilderna från Svaberget.

SVABERGET	Täckningsgrad		Förekomst	
Art/artgrupp	**%**	**95% KI**	**%**	**95% KI**
Alcyonium digitatum	10.1	3.6	70.7	4.1
Phycodrys rubens	7.5	5.9	28.8	4.0
Flustra foliacea	5.4	2.8	25.8	3.9
Rhodophyta	4.8	2.5	44.9	4.4
Laminaria hyperborea	3.5	6.8	-	-
Nemertesia SPP	3.4	1.9	30.1	4.1
Krustabildande bryozoa (på alger)	3.2	4.8	-	-
Delesseria sanguinea	2.4	3.2	13.6	3.1
Brongniartella byssoides	2.1	2.6	-	-
Metridium senile	1.5	2.5	-	-
Caryophyllia smithii	-	-	24.3	3.8
Serpulidae	-	-	16.6	3.3
Krustabildande bryozoa (på hårdbotten)	-	-	14.7	3.2
Hydroida	-	-	13.7	3.1



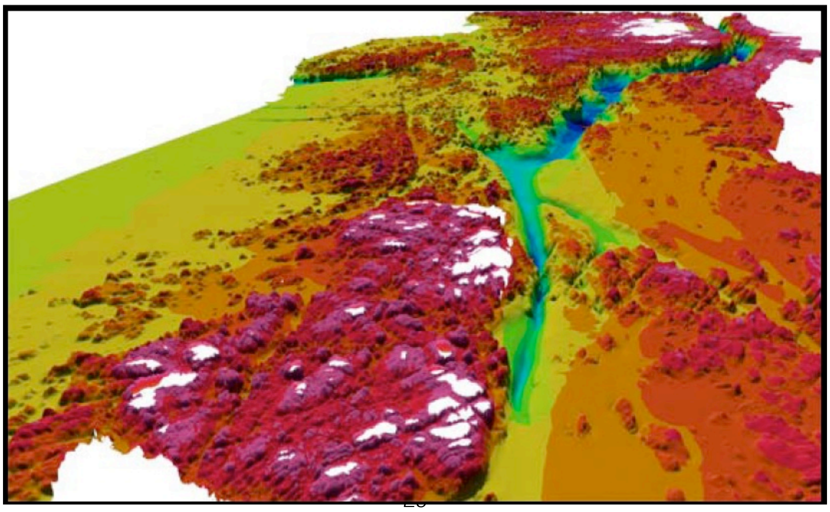
Figur 12. Genomförd provtagning vid Makrillbåden.

Mapping of areal distribution and extent of species and habitats

- Often using sophisticated statistical methods but based on traditional empirical relations between species and environment!

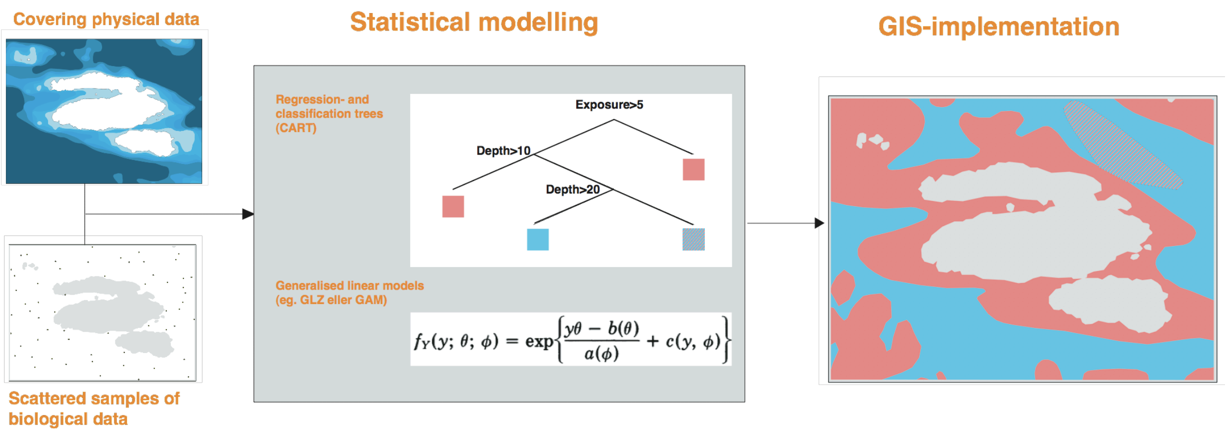
Mapping of areal distribution and extent of species and habitats

- Requires good ecological data (response variable)!
- Complete and detailed coverage of powerful environmental data (predictor variables)
- Strong mechanistic (direct or indirect) links between response and predictors



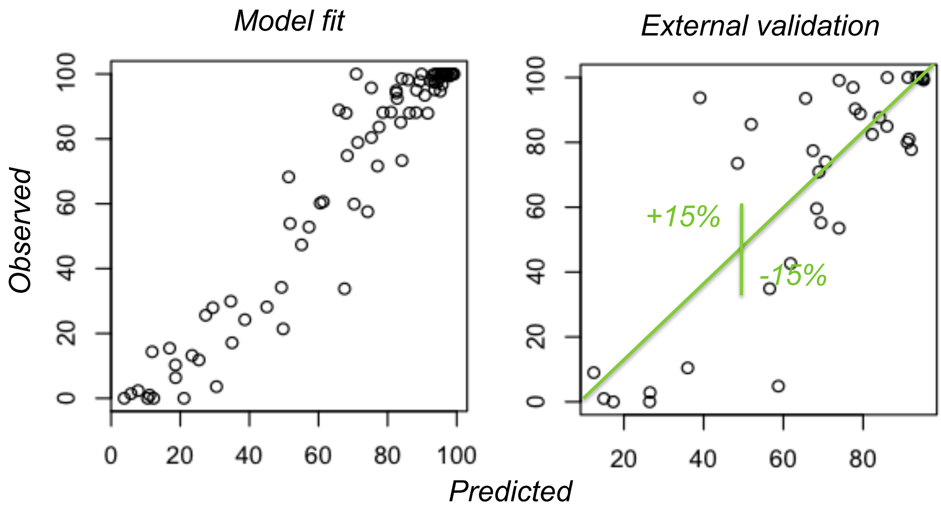
Mapping of areal distribution and extent of species and habitats

- General methodology!
- Many different types of modelling techniques for estimation and prediction of abundance or occurrence.
- Can handle complex relationships and interactions among factors.
- Too flexible?

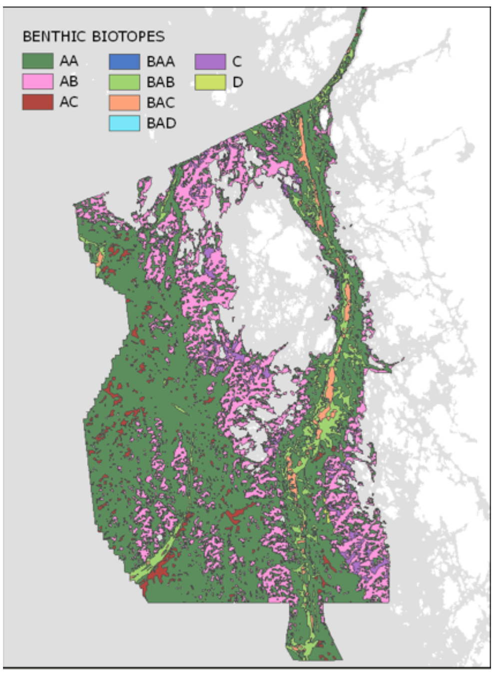


Mapping of areal distribution and extent of species and habitats

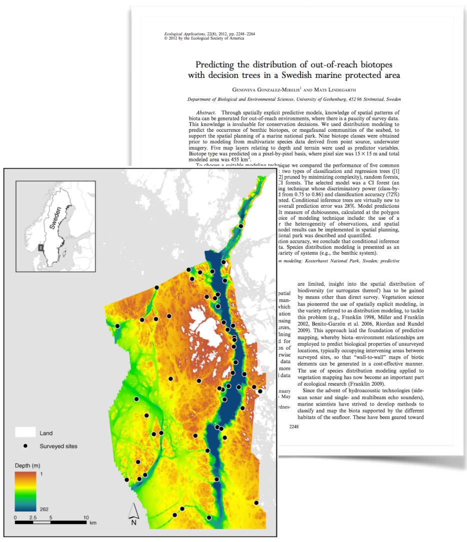
- We can not assume that the model gives a good fit or that it predicts well!
- Prediction ≠ Model fit!
- Use external (test) data to test model fitted by training data!



Mapping of areal distribution and extent of species and habitats



- Modelling of habitats / communities in Kosterhavet national park



Mapping of areal distribution and extent of species and habitats

- Mapping of areal distribution is not represented in traditional monitoring to a large degree (but data are used for mapping anyway)
- Sorely needed as indicators in the MSFD, HD and MSP!
- If complete surveys can not be made representative sampling in space (and time!) is needed in ”top-down” or ”bottom-up”
- New sampling methods and programs need to be developed using combinations of sampling and remote sensing techniques.

Final comments

- Monitoring and mapping is the method for getting information about the state of the environment. We cannot manage the marine environment rationally without it!
- Methods and programs for monitoring is undergoing large changes as a consequence of new policies and technological developments!
- The resources for monitoring are not likely to increase drastically, so we need to be better at optimising and coordinating activities such as monitoring for the directives and mapping.