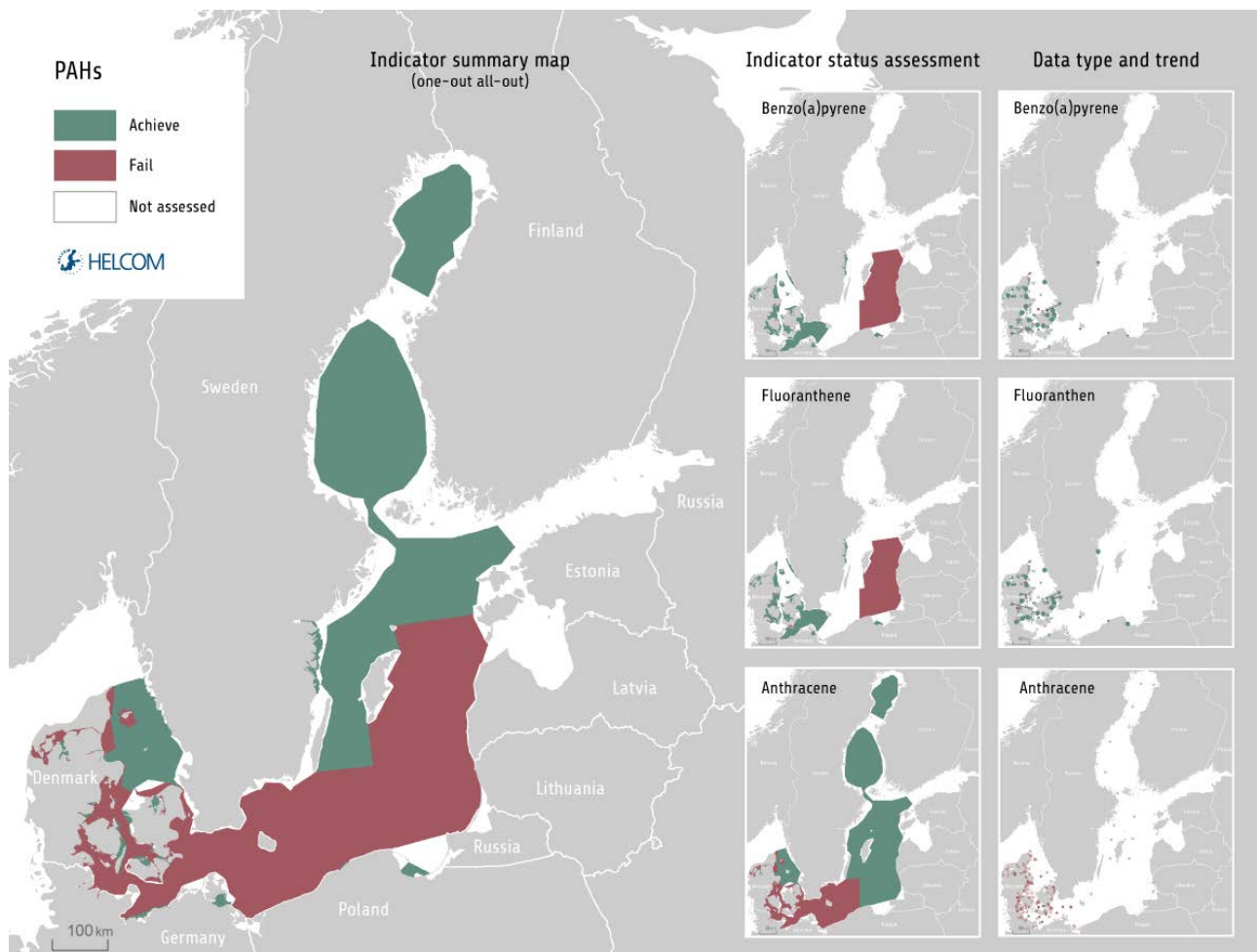# Polyaromatic hydrocarbons (PAHs) and their metabolites

Key Message

The concentrations of benzo(a)pyrene, anthracene and fluoranthene representing the concentration of polyaromatic hydrocarbons (PAH), achieve the threshold value in the open sea assessment units of the Norther Baltic Proper and the Kattegat (Key message figure 1).

Key message figure 1. Status assessment results based evaluation of the indicator 'PAH and metabolites'. One-Out-All-Out (OOAO) method (main figure), benzo(a)pyrene in biota (top inset), fluoranthene in biota (middle inset) and anthracene in sediment (lower inset). The assessment is carried out using Scale 4 HELCOM assessment units (defined in the HELCOM Monitoring and Assessment Strategy Annex 4). **Click here to access interactive maps at the HELCOM Map and Data Service: PAHs.**

The concentrations are below the threshold value in some Danish Fjords (Skive Fjord, Lovns Bredning, Horsens Fjord, outerpart of Vejle Fjord and Isefjord), and some of the coastal areas around Great Belt, Mecklenburger Bucht, Greifswalder Bodden and Bay of Gdansk (POL-006). There are many coastal areas for which data were not available for the evaluated assessment period of 2011-2015 and for which there is currently no evaluation (Key message figure 1).

As there is no commonly agreed threshold value for measuring metabolites available, this report only considers concentrations of PAH.

The confidence of the indicator evaluation is **high**, and the spatial coverage of available data is currently sufficient to evaluate many areas of the Baltic Sea.

The indicator is applicable in the waters of all countries bordering the Baltic Sea.

Relevance of the core indicator

Polycyclic aromatic hydrocarbons (PAHs) are of concern due to their persistence and potential to accumulate in aquatic organisms, particularly invertebrates such as bivalves and crustaceans. In most vertebrates PAHs are fairly rapidly metabolized, however PAHs and the toxic intermediates that are formed during metabolic degradation can cause harmful effects in fish. PAHs associate with particles in the water accumulate in sediments, and are persistent especially in anaerobic sediments.

Some PAHs are formed naturally, but the majority of PAHs in the marine environment stem from human activity. Sources of PAH include the release of crude oil products into the sea (oil-spills), as well as all types of incomplete combustion of fossil fuels and waste incineration.

Policy relevance of the core indicator

	BSAP Segment and Objectives	MSFD Descriptors and Criteria
Primary link	Concentrations of hazardous substances close to natural levels	D8 Concentration of contaminants - D8C1 Within coastal and territorial and beyond territorial waters, the concentrations of contaminants do not exceed the threshold values
Secondary link	Fish safe to eat	D9 Contaminants in seafood - D9C1 The level of contaminants in edible tissues (muscle, liver, roe or other soft parts, as appropriate) of seafood (including fish, crustaceans, molluscs, echinoderms, seaweed and other marine plants) caught or harvested in the wild (excluding fin-fish from mariculture) does not the exceed threshold values.
Other relevant legislation: EU Water Framework Directive		

Cite this indicator

HELCOM (2018). PAH and metabolites. HELCOM core indicator report. Online. [Date Viewed], [Web link].

Download full indicator report

**[PAHs and their metabolites HELCOM core indicator 2018](#)** **(pdf)**

Results and Confidence

The core indicator is evaluated against specific threshold values in all assessment units where data is available, with aggregated results calculated for each assessment unit (Results table 1). A full evaluation was possible for 13 out of 17 open sea assessment units, missing only Gdansk Basin (SEA-008), Gulf of Riga (SEA-0011), Gulf of Finland (SEA-0013) and the Quark (SEA-016), and 10 coastal assessment units (Results table 1). To carry out a full assessment, a minimum of three years of data per monitoring station is required, though 'initial' data (data series of 2 or less years or containing 'less-than' values) was also included in the assessment (see section Assessment Protocol). Concentrations are available for the primary substance benzo(a)pyrene in biota for three of the evaluated open sea assessment units and a number of coastal assessment units, and the threshold value was achieved in all but two units. It could furthermore be noted that the secondary substance fluoranthene (in biota) was evaluated in a similar selection of assessment units and that a similar status pattern was observed. The secondary substance anthracene, in sediment, however was assessed across a wider spatial area and 6 of the 13 assessed open sea units (and a number of coastal areas failed to achieve the threshold (i.e. not-good status).
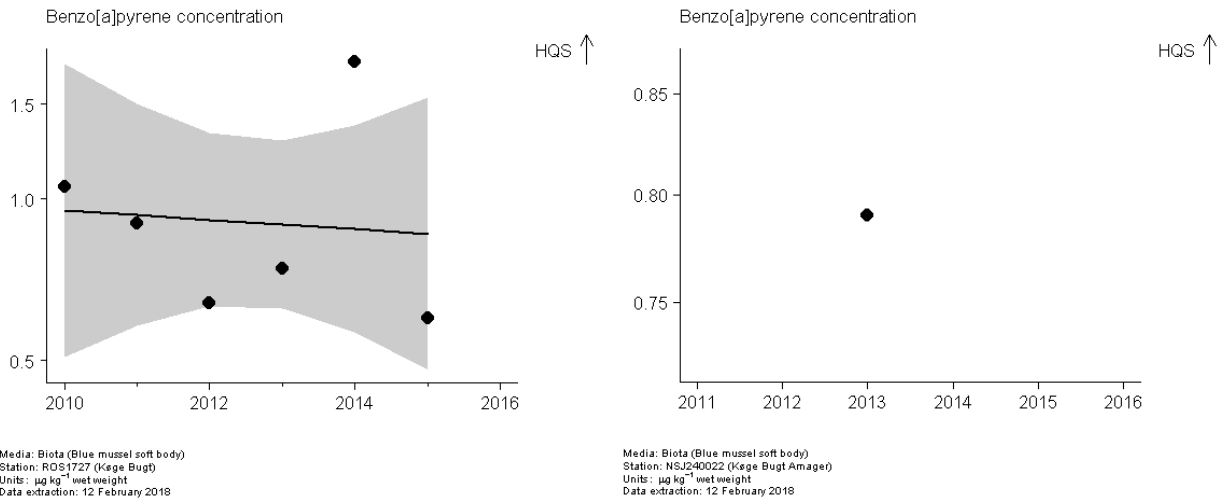
It should be noted that in addition to the data that supports a full assessment using the core indicator assessment protocol, there is also initial status assessment data available meaning that measurements are only available for 1-2 years per station (most sediment stations and some mussel stations). In order to achieve a better spatial coverage and include all available monitoring data, the initial status assessment data are also considered using a precautionary statistical approach.

Benzo(a)pyrene

The results per station show the details of the underlying assessment data, and includes both the stations for which a full and initial data series were possible, visualising the data on which the aggregated results were produced. Of the assessed units one open sea and three coastal assessment unit failed to achieve the threshold value, and in all cases these were based on few sampling stations with short data series (initial data). In the future longer data series (due to ongoing monitoring) and larger spatial coverage will assist with an even more robust assessment.
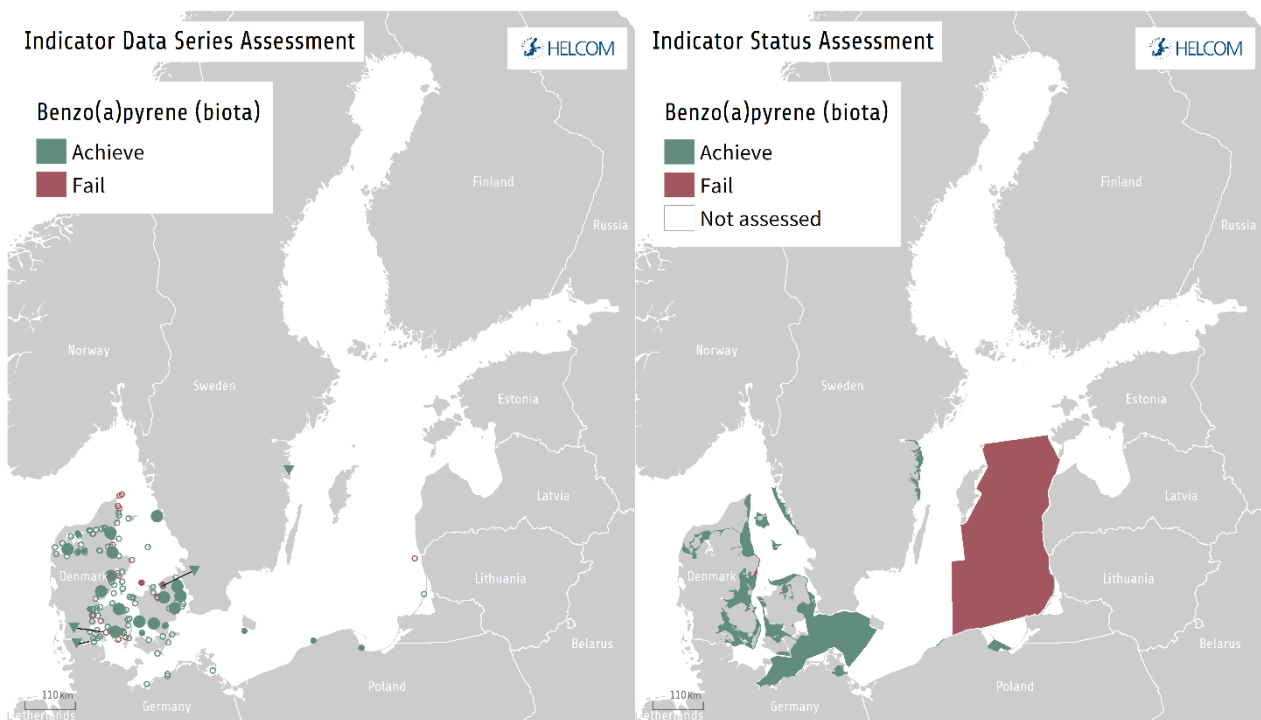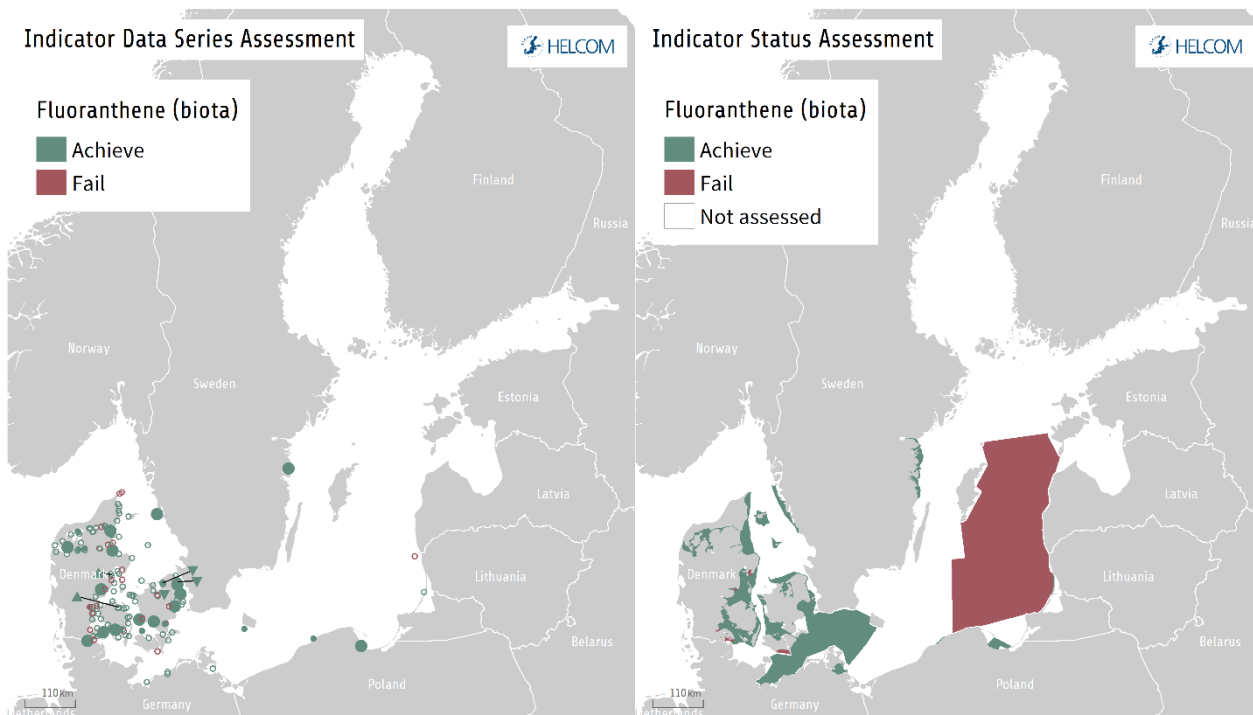

Results figure 1. Benzo(a)pyrene concentration status per station (left) and aggregated assessment unit status assessment (right). Green indicates that the threshold value is achieved and red that the threshold value is failed. Small open circles indicate a status assessment based on only 1-2 years of data (initial data), small filled circles indicate that data is not suitable to assess a trend (treated with initial methodology), large filled circles that no detectable concentration trends can be identified during the whole monitoring period (full data), and the filled arrow indicate that there is a statistically defined upward or downward trend during the monitoring period. **Click here to access interactive maps at the HELCOM Map and Data Service: PAHs.**

Results figure 2. Examples of benzo(a)pyrene concentration in blue mussel (soft body) at two stations in the Arkona Basin selected for illustrative purposes, showing a station with full assessment possible (left) and initial status assessment data (right).

Fluoranthene

Fluoranthene concentration status in biota, as assessed against the relevant threshold, followed a similar pattern to the primary substance benzo(a)pyrene. The results per station show the details of the underlying assessment data, and includes both the stations for which a full and initial data series were possible, visualising the data on which the aggregated results were produced. Of the assessed units five coastal areas an done open sea area failed to achieve the threshold value and these were in general assessments based on on few sampling stations with short data series (initial data). In the future longer data series (due to ongoing monitoring) and larger spatial coverage will assist with an even more robust assessment (Results figure 3).

Results figure 3. Fluoranthene concentration status per station (left) and aggregated assessment unit status assessment (right). Green indicates that the threshold value is achieved and red that the threshold value is failed. Small open circles indicate a status assessment based on only 1-2 years of data (initial data), small filled circles indicate that data is not suitable to assess a trend (treated with initial methodology), large filled circles that no detectable concentration trends can be identified during the whole monitoring period (full data), and the filled arrow indicate that there is a statistically defined upward or downward trend during the monitoring period. **Click here to access interactive maps at the HELCOM Map and Data Service: PAHs.**

Anthracene

Anthracene is monitored in sediments and across a wide spatial area. The sampling strategies for sediments are commonly less frequent that those for biota or water and this data is generally treated with the methodologies applied to 'initial' data (see Assessment Protocol below). The results per station show the details of the underlying assessment data, and includes both the stations for which a full and initial data series were possible, visualising the data on which the aggregated results were produced (Results figure 4). Seven of thirteen open sea assessment units achieved the threshold value (good status) and coastal assessment units, where assessed, generally failed the threshold value (not good status).
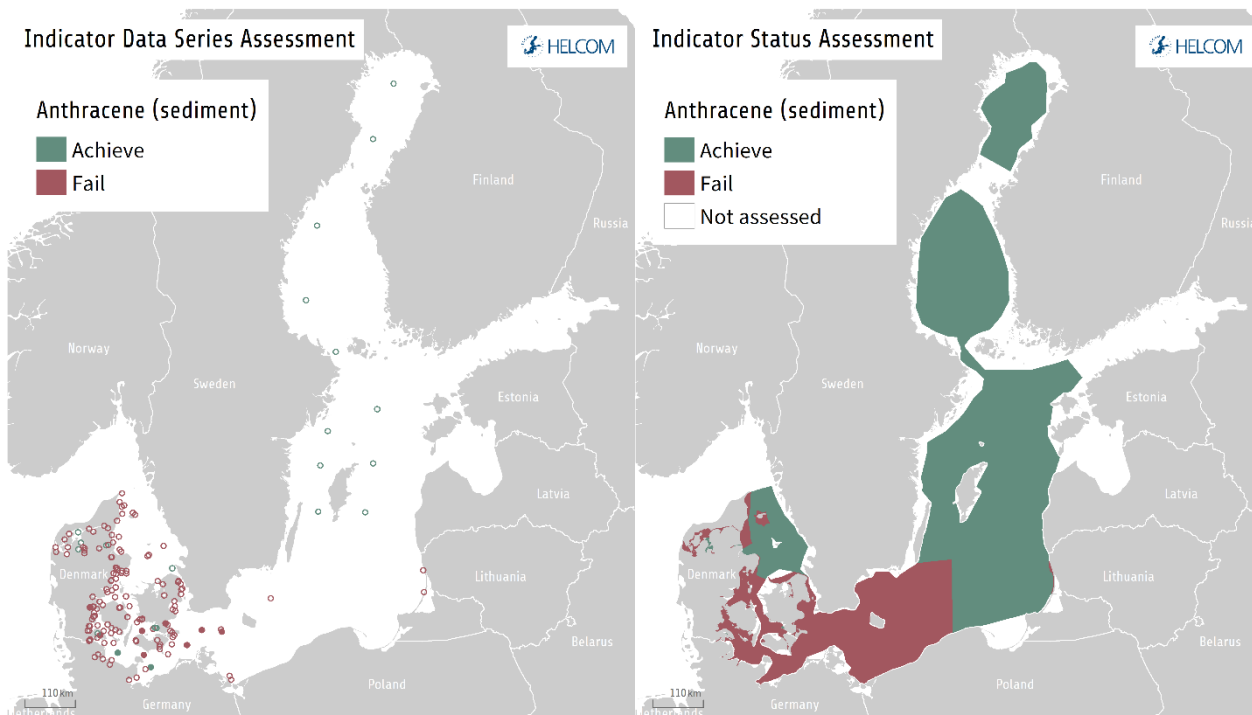
Results figure 4. Anthracene concentration status per station (left) and aggregated assessment unit status assessment (right). Green indicates that the threshold value is achieved and red that the threshold value is failed. Small open circles indicate a status assessment based on only 1-2 years of data (initial data), small filled circles indicate that data is not suitable to assess a trend (treated with initial methodology), large filled circles that no detectable concentration trends can be identified during the whole monitoring period (full data), and the filled arrow indicate that there is a statistically defined upward or downward trend during the monitoring period. **Click here to access interactive maps at the HELCOM Map and Data Service: PAHs.**

Confidence of the indicator status evaluation

Confidence in the indictor evaluation for the assessment units where a full assessment was possible is evaluated to be **high**. Further monitoring data in the future will elongate the data series available and strengthen the confidence further. Certain assessment areas, where relevant, could further benefit from wider spatial monitoring of these substances.

Even if PAH metabolites are not included in the present version of this report it should be noted that they are potentially valuable HELCOM core indicators and could be included in environmental assessment as soon as agreed threshold levels are available. Many countries in Europe including Germany and Poland can provide long term monitoring data on PAH metabolites and this aspect would further strengthen this indicator and status assessment. The analytical methods are quality assured, well documented and PAH metabolites can be turned into a proper environmental assessment as soon as there is agreement on the threshold.

The data used in this assessment are considered to be reliable and the evaluation accurate, indicating a high confidence in the evaluation. The threshold value is based on an EU Environmental Quality Standard (EQS) which is considered to have a high confidence.

Thresholds and Status evaluation

Good status is evaluated for the core indicator 'Polyaromatic hydrocarbons (PAHs) and their metabolites' by comparing the measured concentrations of benzo(a)pyrene in the matrix biota (shellfish soft body) against the EU Environmental Quality Standard (EQS) of 5 µg/kg wet weight (Thresholds figure 1). The threshold value is an EQS derived for the protection goal of human health via consumption of fishery products.
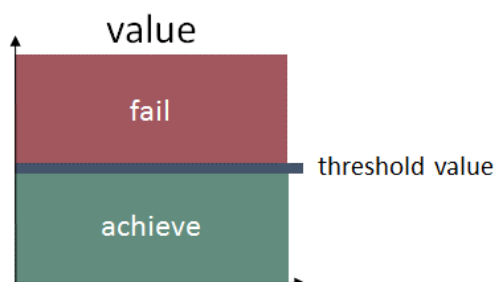
Thresholds figure 1. Schematic representation of the threshold value for which the measured concentration of the primary substance benzo(a)pyrene, or the secondary substances fluoranthene and anthracene, should be lower than the threshold value concentration in order for the threshold value to be achieved.

The threshold value for benzo(a)pyrene concentration is matrix sensitive, and only applicable if the concentrations are measured in the appropriate matrix. For historical reasons, the Contracting Parties around the Baltic Sea have differing monitoring strategies and as a pragmatic approach secondary threshold values for secondary substances have also been agreed to be used to evaluate assessment units where no measurements are available for the primary substance and threshold value. The threshold values were agreed at HELCOM HOD 50-2016 (outcome para 4.47).

Thresholds table 1. Threshold value for the primary substance benzo(a)pyrene and the two secondary substances fluoranthene and anthracene.

Substance	Threshold value	Reference
Benzo(a)pyrene	5 µg/kg wet weight crustaceans and molluscs	EQS biota human health
Secondary substance fluoranthene	*30 µg/kg wet weight crustaceans and molluscs*	*EQS biota human health*
Secondary substance anthracene	*24 µg/kg dw sediment (Normalized to 5% TOC)*	*QS*

The EU directive on environmental quality standards (2008/105/EC), Article 3, states that also long-term temporal trends should be assessed for substances that accumulate in sediment and/or biota.

Assessment Protocol

Assessment units are evaluated using the primary substance benzo(a)pyrene concentration measured in crustaceans. If no evaluation is possible using the primary substance, then the secondary substances can be used to develop an evaluation for an assessment unit.

Sediment measurements were normalized to 5% total organic content (TOC) before being evaluated against the threshold value.

Assessment methodology for contaminants in biota, sediment and water

The assessment protocol is structured in three main parts, 1) changes in log concentrations over time are modelled, 2) check for compliance against threshold value and evidence for temporal change of contaminant concentration per station and 3) a spatial aggregation of status per assessment unit.

It should be noted that the assessment protocol makes the assumption that monitoring data stems from the same monitoring stations during consecutive years. The stations used by the protocol are defined in the ICES Station Dictionary. Stations with similar station name are grouped together, but it is also possible to define a group of stations with different names to be defined as the same station in the Station Dictionary. Usually a station is defined in the Station Dictionary with coordinates and a valid box around these coordinates, but coordinates outside of the box will only give a warning when reporting the data, and are not used in the actual data extraction.

All initial data is handled in a highly precautionary manner to further ensure that the risk of false positives is minimalised. For all initial data the 95% confidence limit on the mean concentration, based on the uncertainty seen in longer time series throughout the HELCOM area, is used. Applying a precautionary approach, the 90% quantile (psi value, Ψ) of the uncertainty estimates in the longer time series from the entire HELCOM region are used. The same approach is used for time series with three or more years of data, but which are dominated by less-than values (i.e. no parametric model can be fitted). The mean concentration in the last monitoring year (meanLY) is obtained by: restricting the time series to the period 2011-2016 (the last six monitoring years), calculating the median log concentration in each year (treating 'less-than' values as if they were above the limit of detection), calculating the mean of the median log concentrations, and then back-transforming (by exponentiating) to the concentration scale. The upper one-sided 95% confidence limit (clLY) is then given by: exp(meanLY + qnorm(0.95) * Ψ / sqrt(n)), where n is the number of years with data in the period 2011-2016 (HELCOM 2018).

Assessment units

The core indicator evaluation is carried out on the HELCOM assessment unit scale 4, including 17 open sea assessment units delimitated by the so called 1 nautical mile boundary from the baseline, and with the coastal areas split into WFD waterbodies or –types. The assessment units are defined in the HELCOM Monitoring and Assessment Strategy Annex 4.

Relevance of the Indicator

Hazardous substances assessment

The status of hazardous substances is assessed using several core indicators. Each indicator focuses on one important aspect of the complex issue. In addition to providing an indicator-based evaluation of PAHs and their metabolites, this indicator will also contribute to the overall hazardous substances assessment along with the other hazardous substances core indicators.

Policy relevance

Benzo(a)pyrene, benzo(b)fluoranthene, benzo(g,h,i)perylene, benzo(k)fluoranthene, indeno(1,2,3-cd), anthracene, pyrene, fluoranthene and naphthalene are identified as priority substances by European Commission (Directive 2008/105/EC).

The maximum levels of benzo(a)pyrene, and also a sum of benzo(a)pyrene, benz(a)anthracene, benzo(b)fluoranthene and chrysene, are regulated in food stuff according to the Commission Regulation (EC) No 835/2011.

Role of PAH and their metabolites in the ecosystem

Polycyclic aromatic hydrocarbons (PAHs) are of concern due to their persistence and potential to accumulate in aquatic organisms, particularly invertebrates, such as bivalves and crustaceans. In most vertebrates, PAHs are fairly rapidly metabolized, but they and their toxic intermediates that emerge during metabolic degradation, can cause deleterious effects in fish.

The PAH compounds identified as priority pollutants include low-molecular-weight PAH compounds, two-ring compounds (naphthalene) and three-ring compounds (acenaphthylene, acenaphthene, fluorene, phenanthrene, anthracene) that are acutely toxic to a broad spectrum of marine organisms. The compounds also include high-molecular-weight PAHs with four-ring compounds (fluoranthene, pyrene, benzo(a)anthracene, and chrysene), five-ring compounds (benzo(a)pyrene, benzo(b)fluoranthene, benzo(k)fluoranthene, and dibenz(a,h)anthracene), and six-ring compounds (indeno(1,2,3-c,d)pyrene, benzo(g,h,i)perylene) that are less toxic but have greater carcinogenic potential (Kennish 1997).

Indeno(1,2,3-c,d)pyrene and chrysene have been shown to cause carcinogenic effects in experiments on animals (IARC class 2b), and benzo(a)pyrene to cause cancer in humans (IARC class 1). Weakly- or non-carcinogenic PAHs can modify the carcinogenic activity of other PAHs in complex mixtures (Marston et al. 2001). Therefore, synergistic effects of PAHs can be larger than the total levels of PAHs would indicate. Also, PAHs are transformed in the marine environment, e.g. when exposed to sunlight, the mechanism known as phototoxicity is involved, producing reactive and toxic photomodification products (HELCOM 2010). Thus, evaluating the overall environmental status based on PAHs has to take this complexity into consideration.

PAHs tend to associate with particulate material due to their low water solubility and hydrophobic nature. Deposition of these particles can lead to an accumulation of PAHs in the sediment. PAHs are persistent,

especially in anaerobic sediments, with the higher molecular weight PAHs being more persistent than the lower molecular weight compounds (Kennish 1997; Webster et al. 2003).

Bioaccumulation of PAHs in marine organisms from sediments is dependent, thermodynamically, on the ratio between adsorption capacity of the sediment and absorption capacity of the organism. Different profiles of contaminants have been observed in organisms of different trophic levels that have been attributed to a partial biotransformation of the contaminants in the organisms of higher trophic levels (Baumard et al. 1998b). Increased levels of neoplastic aberrations or tumors have been found in fish exposed to PAH contaminated sediments. High concentrations of PAHs are also harmful to reproduction of fish and can damage cellular membrane structures (Knutzen 1995). Oxidised PAHs in an organism are known to bind to DNA and/or cause mutations which may lead to cancer.

To evaluate effects of PAH exposure on fish, concentrations of the main metabolites such as 1-hydroxypyrene, 1-hydroxyphenanthrene and 3-hydroxybenzo(a)pyrene can be determined in bile by HPLC with fluorescence detection (HPLC-F), by synchronous fluorescence scanning, gas chromatography with mass selective detection (GC/MS) and also by UPLC/MS/MS (Ariese et al. 2005). PAH metabolites in fish bile reflects the level of exposure during the last few days before sampling, varying to some degree depending on the feeding activity of the fish.

Human pressures linked to the indicator

	General	MSFD Annex III, Table 2a
Strong link	PAH introduced to the marine environment through spills of petrochemical substances and emissions from fuel consumption and maritime activities	Substances, litter and energy - Input of other substances (e.g. synthetic substances, non-synthetic substances, radionuclides) – diffuse sources, point sources, atmospheric deposition, acute events
Weak link	Atmospheric deposition may be a significant pathway	

Some polyaromatic hydrocarbons (PAHs) are formed naturally, but the majority of PAHs in the marine environment stem from anthropogenic activity. Anthropogenic PAH sources in the marine environment include the release of crude oil products (petrogenic source) and all types of incomplete combustion of fossil fuels – coal, oil and gas or wood and waste incineration (pyrolytic sources) (Neff 2004).

Each source generates a characteristic PAH pattern enabling distinction of the sources in a sample by analyzing the concentration relationships of individual PAH compounds (Baumard et al. 1998, Sicre et al. 1987, Yunker et al. 2002). The PAH contamination in the Gulf of Finland and some areas in the western Baltic Sea (Sound, Belt Sea and Kattegat) have been identified as having a significant contribution of petrogenic PAHs, compared to the rest of the Baltic Sea where pyrolytic sources predominate. PAHs from pyrolytic sources may be introduced through atmospheric deposition, however no reliable information is available on the airborne deposition of PAHs to Baltic Sea surface waters (Pikkarainen 2004). In the areas where petrogenic PAHs are identified as a significant source, PAH contamination is likely to originate from atmospheric deposition combined with shipping activities.

PAH compounds are pervasive in the Baltic Sea. Anthracene has been detected in fish from Swedish monitoring stations selected to reflect reference conditions. Anthracene has also has been measured in sediment from the Stockholm area (with concentrations falling inversely with distance from central Stockholm) and homogeneous coastal samples, indicating small local impact. It has also been measured in detectable concentrations in water areas sampled with the use of passive sampling devices. Fluoranthene is frequently present in fish from Swedish background stations, and also found in sediment and sludge. It has been found in all water samples from Sweden taken by means of passive sampling devices, and it is detectable in groundwater samples (Swedish EPA 2009).

With distance of point sources there are no temporal trends of PAH contamination, mirrored as PAH metabolites detectable in dab and flounder from the North Sea and the western Baltic Sea caught during 1997 and 2004 (Kammann 2007). Lower values than in North Sea (dab, cod, flounder, haddock) and Baltic Sea (flounder, cod, herring, Vuorinen et al. 2006; eelpout) have been detected in Barents Sea (cod) and near Iceland (dab). Higher concentrations are present in fish caught in harbour regions or in coastal areas (eelpout, Kammann and Gercken 2010).

Monitoring Requirements

Monitoring methodology

HELCOM common monitoring of relevance to the indicator is documented in the on-line **HELCOM Monitoring Manual in the sub-programme: Contaminants in biota** and **sub-programme: Contaminants in sediment**.

Monitoring guidelines on the determination of persistent organic compounds in biota are currently documented in the HELCOM COMBINE manual, and are under review.

Current monitoring

The monitoring activities relevant to the indicator that are currently carried out by HELCOM Contracting Parties are described in the **HELCOM Monitoring Manual**

Sub-programme: monitoring concepts table for biota and the **monitoring concepts table for sediment**.

PAHs are monitored in biota in Denmark, Poland and Sweden and in sediments in Denmark, Poland and Sweden.

PAH metabolites in fish bile are regularly monitored by Denmark, Germany and Poland. Pre-monitoring stage of PAH metabolites investigations exist in Finland and Poland.

Description of optimal monitoring

PAHs or their metabolites are not monitored adequately in the eastern parts of the Baltic Sea. Especially, the lack of monitoring in Gulf of Finland is noteworthy.

Data and updating

Access and use

The data and resulting data products (tables, figures and maps) available on the indicator web page can be used freely given that the source is cited. The indicator should be cited as following:

HELCOM (2018) PAH and metabolites. HELCOM core indicator report. Online. [Date Viewed], [Web link].

ISSN 2343-2543

Metadata

Result: Polyaromatic hydrocarbons (PAH) and their metabolites

Data: Polyaromatic hydrocarbons (PAH) and their metabolites sediment data

Data: Polyaromatic hydrocarbons (PAH) and their metabolites biota data

The core indicator evaluation is based on an extraction of data from the HELCOM COMBINE database, hosted by ICES. The database contains data from regular environmental monitoring carried out by the Contracting Parties of HELCOM.

The dataset has been used to evaluate the assessment period 2011-2016 for the purposes of the 'Status of the Baltic Sea' report.

Contributors and references

Contributors

HELCOM Expert Network on Hazardous Substances

Archive

This version of the HELCOM core indicator report was published in July 2018:

PAHs and their metabolites HELCOM core indicator 2018 (pdf)

Earlier versions of this indicator are available at:

HOLAS II component - Core indicator report – web-based version July 2017 (pdf)

References

Ariese F, Beyer J, Jonsson G, Porte Visa C, Krahn MM (2005) Review of analytical methods for determining metabolites of polycyclic aromatic compounds (PACs) in fish bile. ICES Techniques in Marine Environmental Sciences No. 39

Baumard P., Budzinski H., Garrigues P. (1998a). PAHs in Arcahon Bay, France: origin and biomonitoring with caged organisms. Marine Pollution Bulletin, 36 (8): 577–586.

Baumard, P., H. Budzinski & P. Garrigues (1998b): Polycyclic aromatic hydrocarbons in sediments and mussels of the western Mediterranean Sea, Environ. Toxicol. Chem. 17:765–776.

HELCOM (2010). Hazardous substances in the Baltic Sea – An integrated thematic assessment of hazardous substances in the Baltic Sea. Balt. Sea Environ. Proc. No. 120B.

Kammann U (2007) PAH metabolites in bile fluids of dab (Limanda limanda) and flounder (Platichthys flesus) – spatial distribution and seasonal changes. Environ Sci Pollut Res 14(2): 102–108.

Kammann U, Gercken J (2010) PAK-Metaboliten in Aalmuttern (Zoarces viviparus) aus der Wismar-Bucht. Umweltwiss Schadst Forsch. 22(5): 541–546.

Knutzen J., (1995), Effects on marine organisms from polycyclic aromatic hydrocarbons (PAH) and other constituents of waste water from aluminium smelters with examples from Norway. Sci.Total.Environ., 163: 107–122.

Marston Ch.P., Pereira C., Ferguson J., Fischer K., Hedstrom O., Dashwood W-M., Baird W., (2001), Effect of a complex environmental mixture from coal tar containing polycyclic aromatic hydrocarbons (PAH) on the tumor initiation, PAH_DNA binding and metabolic activation of carcinogenic PAH in mouse epidermis, Carcinogenesis, 22: 1077–1086.

Neff, J.M. (2004): Bioaccumulation in marine organisms. Effect of contaminants from oil well produced water, Elsevier, Amsterdam, London, Tokio, 241–318 pp.

Pikkarainen, A.-L. (2004): Polycyclic aromatic hydrocarbons in Baltic Sea sediments. Polycyclic Aromatic Compounds, 24:667–679.

Sicre, M. A., J.C. Marty & A. Saliot (1987): Aliphatic and aromatic hydrocarbons in different sized aerosols over the Mediterranean Sea: occurrence and origin. Atmosphere and Environment 21:2247–2259.

Swedish EPA, 2009. Swedish Pollutant Release and Transfer Register [online: 2011-01-15].

Vuorinen PJ, Keinänen M, Vuontisjärvi H, Baršienė J, Broeg K, Förlin L, Gercken J, Kopecka J, Köhler A, Parkkonen J, Pempkowiak J, Schiedek D (2006): Use of biliary PAH metabolites as a biomarker of pollution in fish from the Baltic Sea. Mar Pollut Bull 53(8–9):523–537

Webster L., Twigg M., Megginson C., Walsham P., Packer G., Moffat C. (2003). Aliphatic hydrocarbons and polycyclic aromatic hydrocarbons (PAHs) in sediments collected from the 110 mile hole and along a transect from 58o58.32'N 1o10.38'W to the inner Moray Firth, Scotland. Journal of Environmental Monitoring, 5: 395–403.

Yunker, M.B., R.W. Macdonald, R. Vingarzan, R.H. Mitchell, D. Goyette & S. Sylvestre, (2002): PAHs in the Fraser River basin: a critical appraisal of PAHs ratios as indicators of PAH source and composition. Organic Geochemistry 33:489–515.