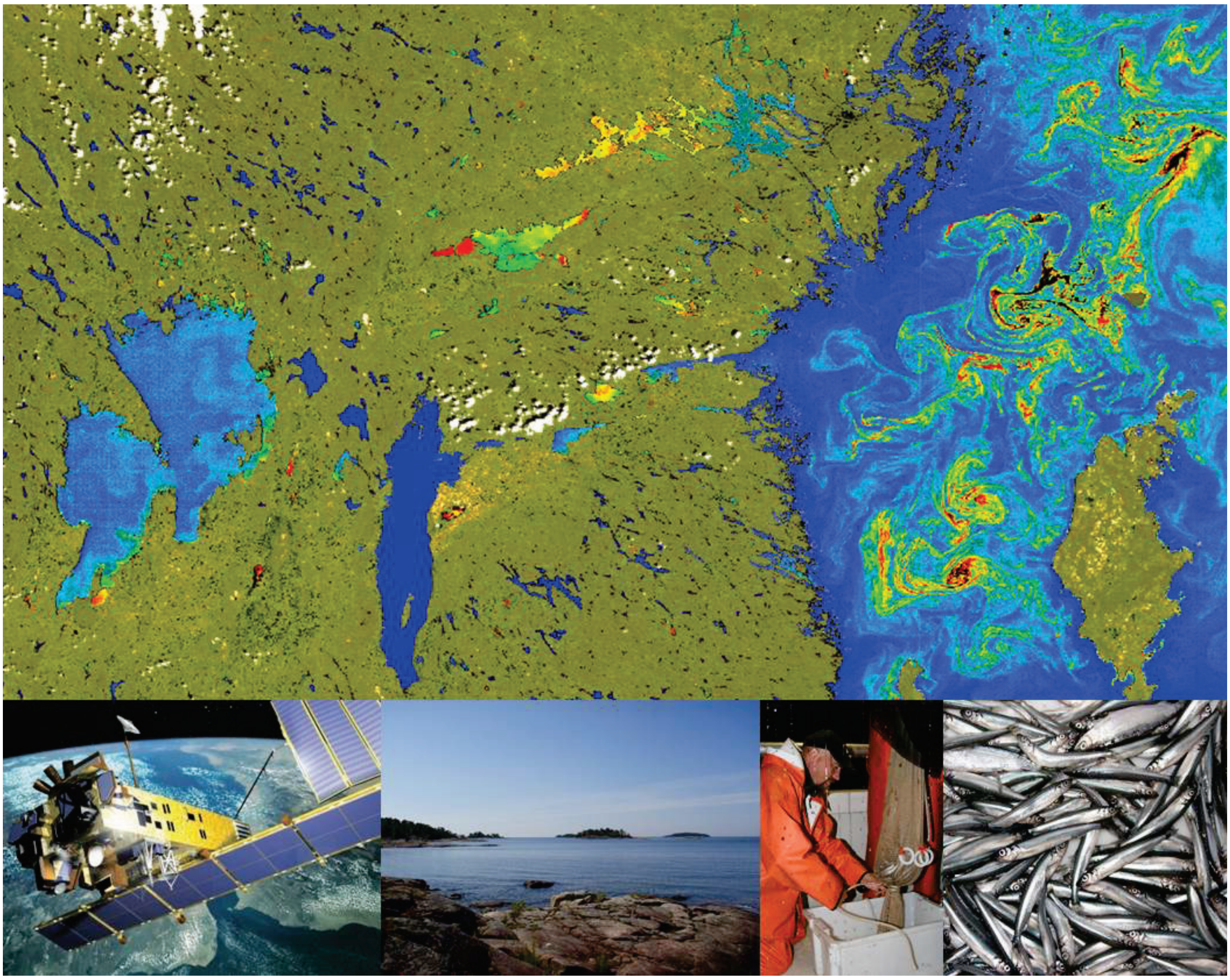
Satellitdata för miljöövervakning och fiskeriförvaltning i Sveriges stora sjöar



SLU

BROCKMANN GEOMATICS SWEDEN AB

Vätternvårdsförbundet

VÄNERNS vattenvårdsförbund

MÄLARENS VATTENVÅRDSFÖRBUND

HJÄLMARENS VATTENVÅRDSFÖRBUND

Titel: Satellitdata för miljöövervakning och fiskeriförvaltning i Sveriges stora sjöar.

Författare: Petra Philipson - *Brockmann Geomatics.* Alfred Sandström, Anders Asp, Thomas Axenrot, Anders Kinnerbäck, Henrik Ragnarsson-Stabo och Willem Dekker – *Sveriges Lantbruksuniversitet SLU.*

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Omslagsfoton:

- Envisat - Världens största satellit för miljöövervakning som samlade in data mellan 2002 och 2012. Ett av instrumenten på Envisat var MERIS – ©ESA
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Förord

Sedan ett antal år tillbaka har forsknings- och utvecklingsprojekt med fokus på satellitbaserad vattenkvalitetsövervakning genomförts för svenska sjöar och kustvatten med ekonomiskt stöd från bland annat Rymdstyrelsen, Vattenmyndigheten och respektive vattenvårdsförbund i sjöarna. Brockmann Geomatics har varit drivande i samtliga av dessa projekt och vattenvårdsförbunden har deltagit som så kallade ”end-users”. Fördelen med satellitbaserad vattenkvalitetsövervakning är att satelliten passerar flera gånger i veckan över Sverige. Detta innebär att det är möjligt att mäta vattenkvaliteten (främst klorofyll, humusämnen, grumling) i flera sjöar och betydligt oftare – uppemot 100 mätdagar per år – än vad som är praktiskt och ekonomiskt möjligt i fält. I stora sjöar såsom Vänern, Vättern, Mälaren och Hjälmaren erhålls, förutom den tidsmässiga upplösningen, dessutom en rumslig kartläggning vilken ökar tolkningen av de mätningar som genomförs som enskilda stickprov i sjöarna. Efter flera års teknik- och metodutveckling kan vi konstatera att det nu är möjligt att använda metoden operativt.

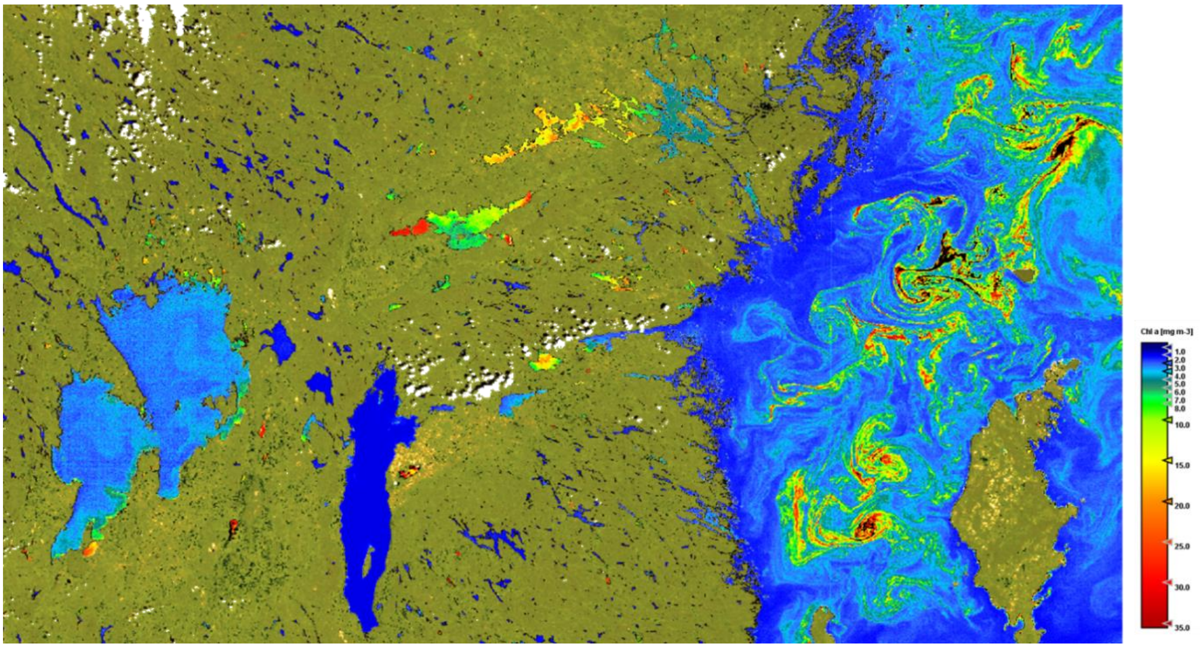
Under 2013-2014 genomförde Brockmann Geomatics och SLU (Sötvattenslaboratoriet) ett samverkansprojekt med syftet att utveckla satellitbaserade indikatorer för vattenkvalitet i de stora sjöarna. Målet är att kunna använda dessa för att förutsäga utbredningen av viktiga och känsliga livsmiljöer, för att bedöma ekologisk status och för att optimera fiskövervakning. Syftet var dessutom att koppla samman informationen över klorofyll och humus från satellitdatat med den fiskövervakningen som görs i sjöarna. Resultaten visar på goda möjligheter att förutsäga fisksamhället i en sjö med hjälp av satellitdata.

Projektet har varit ett samarbete mellan vattenvårdsförbunden för Vänern, Vättern, Mälaren och Hjällmaren samt SLU och Brockmann Geomatics med stöd från Rymdstyrelsen. Brockmann Geomatics har utfört analyserna av satellitdata och SLU har utfört fiskanalyserna.

Sara Peilot, Vänerns vattenvårdsförbund
Måns Lindell, Vätternvårdsförbund
Ingrid Hägermark, Mälarens vattenvårdsförbund
Lotta Carlström, Hjälmarens vattenvårdsförbund
2015-06-25

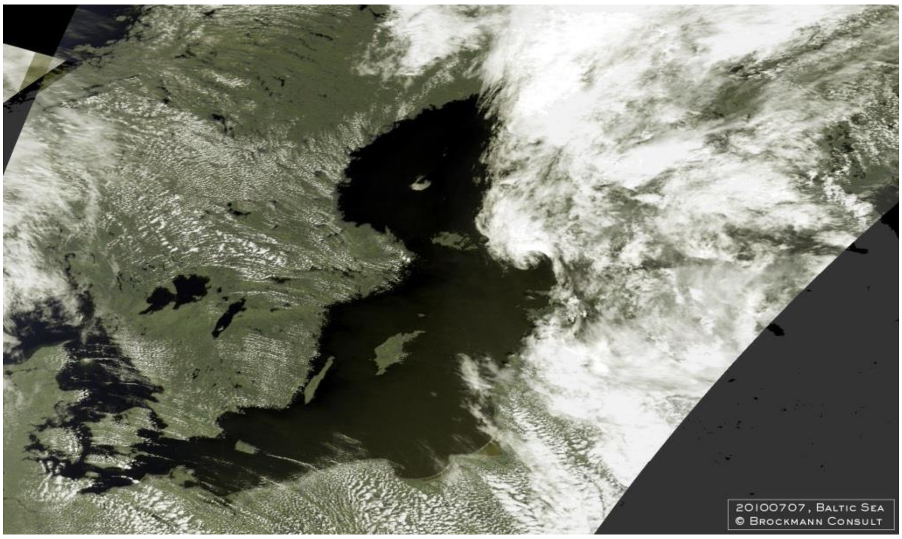
Sammanfattning

EU:s ramdirektiv för vatten samt habitatdirektivet kräver en bedömning av den ekologiska statusen för olika livsmiljöer, inklusive kartläggning av fördelningen av arter och livsmiljöer i svenska sötvatten större än 50 hektar (0,5 km^2), och att åtgärder måste vidtas om inte god eller hög status uppnås. Statusklassningen baseras bl.a. på ett antal faktorer kopplade till växtplankton, makrofyter, bottenfauna och fisk, som tillsammans ska ge en bild av sjöns status. Dessa obligatoriska bedömningar försvåras av storleken på de största sjöarna och det enorma antalet sjöar totalt i Sverige. Budgeten för miljöövervakning av kust och sjöar räcker därmed inte till för att mäta det som krävs för att uppfylla kraven i vattendirektivet. I den senaste utvärderingen från EU klarade inte Sverige att leva upp till kraven och därför behövs det andra mätmetoder som kostar mindre och ger en mer heltäckande bild av vattnens tillstånd. Flertalet primära ekologiska indikatorer (primärproduktion, temperatur, osv.) kan mätas med fjärranalys och uppskattas genom rumslig modellering. Under 2013-2014 genomfördes ett utvecklingsprojekt med syfte att undersöka om och hur satellitbildsbaserad information kan användas för att mäta och övervaka vattenkvaliteten och därmed komplettera den fältbaserade provtagningen. Denna information kan sedan användas för att optimera övervakningsprogram för fisk och andra organismer och för att utvidga deras täckningsområde. Syftet med detta projekt var att utvärdera och demonstrera potentialen av fjärranalys i kombination med fältbaserad övervakningsdata samt att utveckla en strategi för bedömning av ekologisk status i allmänhet och för fiskbeståndens status i synnerhet. Arbetet fokuserades på klorofyll och humus och satellitdata över Vänern, Vättern , Mälaren och Hjälmaren (Figur 1). Projektet var ett samarbete mellan de respektive sjöarnas vattenvårdsförbund, Brockmann Geomatics och SLU:s avdelning för akvatiska resurser. Arbetet finansierades av Rymdstyrelsen och projektdeltagarna.



Figur 1. Översikt av det undersökta området. Bilden visar den beräknade klorofyllkoncentrationen den 24 juli 2008.

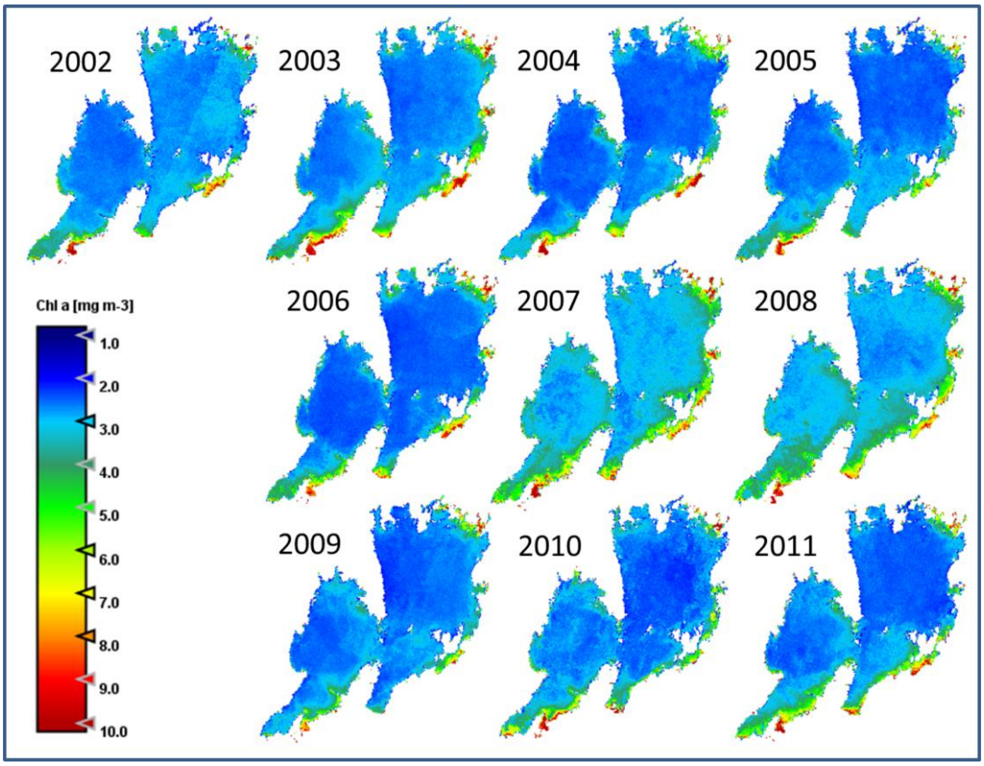
Fjärranalys över sjöar och hav sker genom analys av bilder från satellitburna optiska sensorer. I projektet har vi använt instrumentet MERIS, MEdium Resolution Imaging Spectrometer, som fanns på satelliten ENVISAT. ENVISAT var den största plattformen någonsin utvecklad av ESA, det europeiska rymdorganet, och MERIS var speciellt utvecklat för vatten. Eftersom vatten är mörkt kräver fjärranalys av vatten instrument med andra egenskaper än vad som krävs för att ta bilder över land. Man behöver särskilda ljussensorer som är mycket känsliga och som även kan mäta specifika våglängder av det reflekterade ljuset. Halter av löst och suspenderat material som finns i vattnet avgör mängden och våglängdssammansättningen hos det reflekterade ljuset och därmed vattnets färg. En av de parametrar som kan användas för att mäta statusen för växtplankton är klorofyll. Klorofyll är också en av de parametrar som kan mätas från satellit, eftersom den påverkar färgen på vattnet. Bilderna från MERIS har en upplösning på 300 meter. Upplösningen är ett mått på detaljeringsgraden och innebär i det här fallet att små sjöar och mycket strandnära områden i stora sjöar inte kan övervakas med just det här instrumentet eftersom upplösningen är för grov. Det finns dock andra satellitburna instrument med bättre upplösning (30 meter) som skulle kunna vara ett alternativ. Utveckling pågår för att definiera möjligheterna med dessa satelliter. En stor fördel med MERIS var istället den höga kvaliteten på informationen, den goda täckningen och att data för hela Sverige samlas in under loppet av några minuter. Bilden nedan visar MERIS täckningsområde den 7:e juli 2010. En annan fördel är att satelliten passerar flera gånger i veckan över Sverige, vilket innebär att det är möjligt att mäta vattenkvaliteten betydligt oftare än vad som är praktiskt och ekonomiskt möjligt i fält.



Figur 2. MERIS bild från den 7 juli 2010.

Den av vattnet reflekterade solstrålningen registreras av sensorn och kan sedan via ett omfattande kalibrerings- och processarbete räknas om till koncentrationer av olika vattenkvalitetsparametrar. Bildbehandlingen resulterar i koncentrationskartor för de aktuella parametrarna som sedan kan bearbetas vidare. Områdesspecifika algoritmer för beräkning av vattenkvalitetsparametrarnas koncentrationer har därefter utvecklats och data har analyserats tillsammans med fältbaserad övervakningsdata (vattenkemi och fisk).

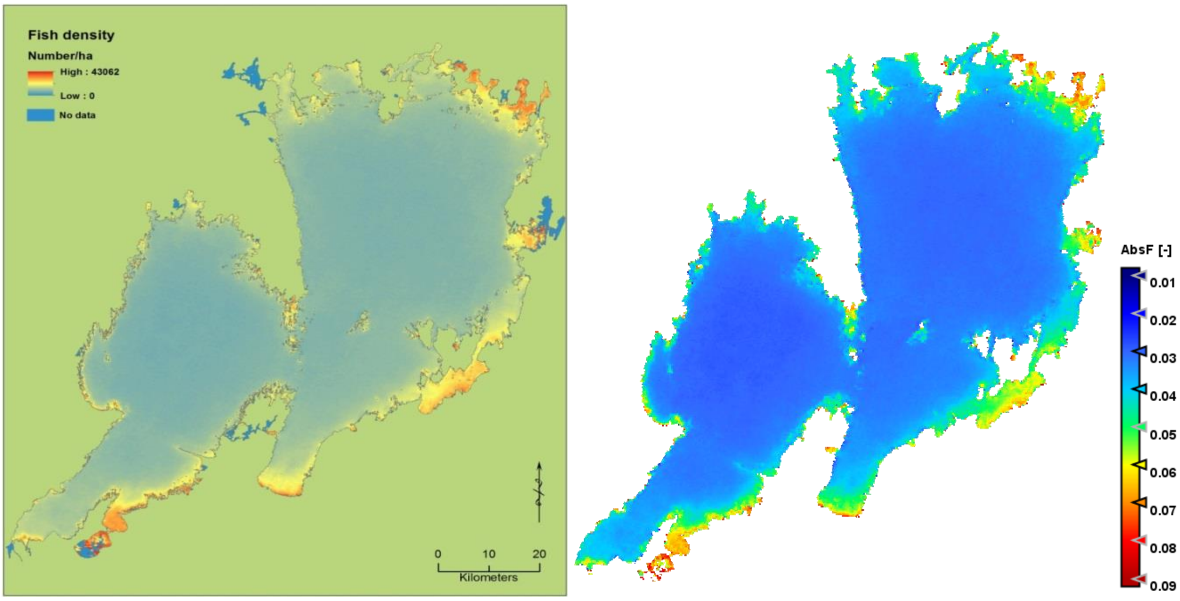
Resultaten visar att satellitbaserade produkter skulle kunna stödja bedömningen av ramdirektivets kvalitetsfaktorer växtplankton, siktdjup och fisk i de undersökta sjöarna. Det var bra överenstämmelse mellan tidsserier baserade på fält- och satellitdata, och en avsevärd förbättring av mätfrekvensen i ett övervakningsprogram kan därmed fås genom kompletterande satellitbaserade mätningar av vattenkvaliteten. Dessutom tillför satellitbaserade produkter information om rumsliga mönster och trender för hela sjöarna. Detta innebär att arbetet med att dela in sjöar i homogena vattenförekomster också kan förenklas. Till exempel kan medelvärden för klorofyll under en viss månad beräknas för en sjöyta för olika år, vilket har exemplifierats för Vänern i Figur 3. Rumsliga och temporala mönster kan åskådliggöras och analyseras för hela sjön.



Figur 3. Vänern, klorofyll, månadesmedel för augusti 2002-2011.

En fördel med det arbetssätt vi har testat är att man kan överlagra den exakta positionen hos de många stationer där man samlar in data på fisk med de kartor som man får via satellitövervakningen. Det ger väsentligt bättre upplösning än att istället försöka göra jämförelser med de få vattenprovtagningsstationer som finns i dagsläget och som i värsta fall kan ligga flera mil från de platser där fiskundersökningarna görs. Det kan också skilja upp till en månad i tid mellan de olika mätningarna. Satellitdata finns från väsentligt fler datum vilket gör det lättare att få en bättre matchning i tidpunkt.

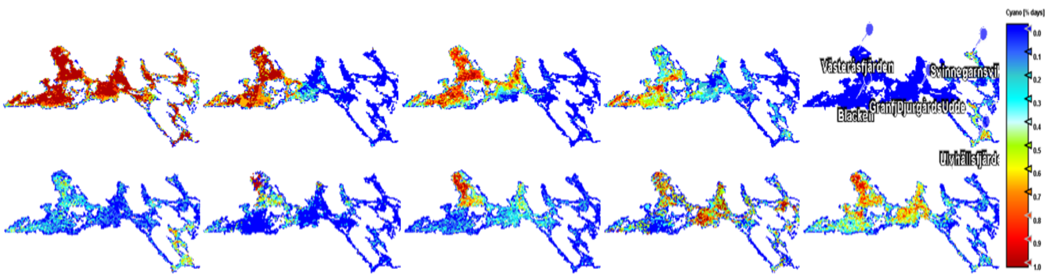
Analysen visade att fjärranalysdata kan användas för att förbättra tolkningen av data som samlats in i fiskövervakningsprogrammen. Särskilt parametrarna klorofyll och humus, som även var starkt korrelerade, kunde på ett bra sätt förklara variationen i fiskövervakningsdata. Särskilt för fisk i den fria vattenmassan, som övervakas med ekolod, kunde data från satelliter bidra till avsevärt bättre tolkningar av fiskförekomsten. I detta fall används redan en slags kartanalys för att koppla de miljontals fiskekon som detekteras i undersökningar till trålundersökningar där man får information om vilka arter och storlekar som finns. Tillgång på satellitdata kan alltså bidra till att man ökar precisionen i skattningen av mängden fisk (Fig. 4). För många av de befintliga fiskarterna var klorofyll och humus tillsammans med djup de viktigaste faktorerna för deras spridning och förekomst i olika områden.



Figur 4. Predikterad fisktäthet (vänster)baserat på satellitmätt absorption av humus (höger).

Tillgången på satellitdata gjorde det också möjligt att på ett bättre sätt än tidigare testa lämpliga indikatorer för att bedöma ekologisk status, i vårt fall framförallt effekter av övergödning. Två av de testade fiskindikatorerna visade på stor potential för bedömning av ekologisk status: andelen karpfiskar när mört utesluts och tätheten av fiskar i den fria vattenmassan. Vår rekommendation är att dessa två indikatorer bör utforskas ytterligare som primära kandidater för bedömning av ekologisk status när övergödningsproblematik föreligger i stora sjöar. Om möjligt bör de kompletteras med en tredje indikator som beskriver fiskens storleks- och åldersstruktur. Kontinuerliga och heltäckande vattenkvalitetskartor kan även användas för att förbättra utformningen av övervakningsprogrammen och för att säkerställa att befintliga livsmiljöer och fisksamhällen är representerade i datainsamlingen för de övervakade systemen.

Förutom klorofyll ingår även ”andel cyanobakterier i biomassan” som en parameter i bedömningen av en sjös status, med avseende på kvalitetsfaktorn ”växtplankton”. En stor andel cyanobakterier är en indikation på näringsrika/övergödda vatten och några arter är dessutom giftiga. Vi har inom ramen för projektet genomfört en första utvärdering av en relativt nypublicerad algoritm för identifiering av områden med dominerande andel cyanobakterier i vattenmassan. Basprodukterna togs fram i det ESA finansierade projektet ”Diversity-II” (www.diversity2.info) där Brockmann Geomatics deltar och har modifierats och utvärderats för de svenska sjöarna i det här projektet (Fig. 5). Det fältbaserade jämförelsematerialet var relativt litet, men resultatet var lovande och vidareutveckling och anpassning av algoritmen pågår.



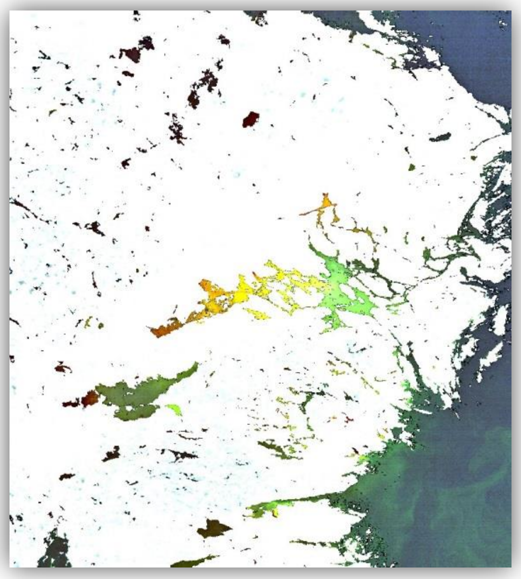
Figur 5. Västra Mälaren 2002-2011. Grön-röda områden indikerar att majoriteten av satellitobservationerna i augusti visade på dominans av cyanobakterier i vattenmassan.

MERIS levererade bilder mellan 2002-2012, men slutade tyvärr att fungera 2012. Konstruktion av nya operationella satelliter för övervakning har pågått sedan flera år tillbaka och den första i en serie av satelliter sköts nyligen (23 juni 2015) upp av ESA (European Space Agency). MERIS första efterföljare planerar ESA att skjuta upp i slutet av 2015. Med flera satelliter i omloppsbana ökar möjligheten till molnfria data och därmed antalet observationer. Målet är att få denna teknik som en etablerad del av svensk nationell och regional miljöövervakning och att kunna bidra till nästa omgång av statusklassningen som sker 2019.

Den fullständiga rapporten är skriven på engelska och har bifogats nedan.

Summary

The report is a full description of the work accomplished within the SNSB user project ”MERIS and hydroacoustic data for fisheries management, assessment of ecosystem status and identification of essential habitats in Sweden's large lakes”.



The project goal was to develop MERIS based water quality indicators for the large lakes and to employ these to predict the distribution of essential and sensitive habitats, to assess ecological status and to optimize fish monitoring. MERIS based water quality products have been developed and the possibility to use these as pressure variables in assessments of ecological quality based on metrics originating from fish monitoring has been investigated.

Our results verify that predictors acquired from MERIS based water quality products can be useful for many purposes. Chlorophyll *a* as well as CDOM (Colored Dissolved Organic Matter), together with depth at the sampling site explained a significant part of the variation in fish assemblage composition. The major changes that normally follow eutrophication, i.e. a dominance shift to cyprinids in benthic fish communities and to young smelt in the pelagic zone, could be successfully predicted using MERIS data. Particularly CDOM and Chl a, which were highly correlated, were both strong predictors. MERIS based data layers could be a useful contribution to model the distribution of individual species and assemblages as well as the characteristics of their habitats. However, since depth in many cases is the single most important environmental factor, bathymetry maps must be markedly improved to enable modelling of the distribution of essential habitats in these systems. Another important factor that could improve the potential to model distributions would be to collect data on fish abundance and presence more evenly along the environmental gradients described by MERIS data. One example is monitoring data from hydro-acoustics that has been focused on the very largest open basins and thus do not cover the entire productivity gradient.

We tested several candidate metrics to describe the influence of eutrophication on fish assemblages in large lakes using MERIS data as proxy pressure variables. In total, we were able to assess the status in thirty-one different water bodies. There were two metrics that appeared to be very promising: the density of pelagic fishes (number per hectare) and the percentage of cyprinids (when roach is excluded). We recommend that these two metrics are further explored as primary candidates for assessment of ecological status when the pressure variable is eutrophication and that the potential of a third candidate metric comprising information on age/size structure of fish communities also is investigated.

To conclude, MERIS based data was a relatively powerful predictor of variation in fish monitoring data. It could be used for modelling distribution and to describe the pressure of eutrophication on water bodies in large lakes. Additionally, since the continuous maps derived from MERIS cover the majority of the lakes surface indicates that they also can be used to improve the design of field based monitoring efforts. The information can be used to ensure that the existing fish assemblages are covered and that data is representatively collected and covers the majority of the existing habitats of the monitored systems.

Contents

Introduction

Internationally coordinated environmental protection programs require the assessment of the ecological status of habitats and the mapping of the distribution of species and habitats in European as well as Swedish freshwaters. These mandatory assessments are hampered today by the size of the largest lakes and the enormous number of lakes in total. However, prime ecological indicators (primary production, transparency, etc.) can be measured by remote sensing and assessed through spatial modeling. This auxiliary information can then be used to optimize fish monitoring programs and to extend their coverage and interpretation potential. Remote sensing can thus provide one key to the implementation of many of the directives and management plans at the desired spatial and temporal coverage. The purpose of this project is to assess and demonstrate the potential of remote sensing in combination with field-monitoring data, and to develop an approach for the assessment of ecological status in general and fish stock status in particular in Sweden's four largest lakes.

Major international, national and regional agreements, directives and management plans aim to protect and monitor freshwater habitats in order to assure a sustainable management of freshwater ecosystems. A fundamental part of this work is to monitor *temporal* variation in order to assure a satisfactory status of water bodies and to assess the *spatial* distribution of the most sensitive and essential habitats requiring long-term protection. Recognizing the importance of protecting and restoring habitats to sustain biodiversity is reflected in many initiatives worldwide, in the EU first and foremost in the Birds- and Habitats Directives.

Beside assessing the distribution of essential habitats (spatial), there is also a need to assess the environmental status of water bodies (temporal), as requested by EU's Water Framework Directive (WFD), the Common Fisheries Policy (CFP) as well as several national and regional management legislations and plans such as the Swedish "Miljömålen" and regional lake- or basin-specific plans, "Vattenplaner". Given the large number of lakes in Sweden (circa 96 000 lakes exceeding 10 hectares) and comparatively large size of many systems compared to the rest of Europe, these directives constitute a heavy financial burden when using traditional monitoring tools. Remote sensing has the advantage of covering large areas and enabling a fast and resource-efficient method to map prime characteristics of aquatic habitats. This project will put particular efforts into using remote sensing in the monitoring and assessment of commercially important as well as endangered species. One such species is eel that due to its low abundance is hard to monitor using conventional methods, while the identification of the most important production areas is vital for its adequate protection. Basic environmental parameters from remote sensing, such as chlorophyll *a* and transparency, can be used to optimise ground-based monitoring and in a longer perspective enable modelling of the distribution of the most important production areas.

User needs

Official legislations have declared the demand for documentation of natural habitats (59) by monitoring temporal variation and spatial distribution of the most sensitive and essential habitats requiring long-term protection. The need to restore and protect water bodies from further degradation has resulted in formulation of the European Union Water Framework Directive 2000/60/EC (WFD). The directive aims to harmonize European legislation on water and member states shall establish a program for monitoring the status of all water bodies larger than 0.5 km^2, in order to ensure future quality and quantity of inland waters. The biological and physical-chemical status and ecological potential should be assessed and action plans for a sustainable management and protection of freshwater resources should be established. In practice, this means that extensive and expensive sampling programs are needed.

Hence, for aquatic environments, the fulfilment of the monitoring requirements is an acknowledged problem due to the size of the largest lakes, the enormous number of lakes in total, the considerable temporal and spatial variability and inaccessibility of many systems. Several countries have received some criticism from EU regarding a number of spatial and temporal shortcomings in their existing monitoring programs. In addition, not all lakes/water bodies are monitored as requested by EU WFD because of the lack of resources. WFD requires systematic monitoring of all inland waters larger than 0.5 km2. This is a very ambitious goal, and cannot be fulfilled without new effective monitoring methods.

The ecological status of a water body can be described by various biological and physical-chemical quality elements and several of these important ecological parameters can be monitored by space based instruments, e.g chlorophyll a concentration and water transparency. Over large lakes, where data is usually available only as spatially and temporally limited point samples, adding remote sensing data to the monitoring system would make a cost-efficient complement to conventional monitoring data. This would enable a fast and resource-efficient method to monitor some of the primary characteristics of aquatic habitats, reach the required spatial coverage, and contribute to enhanced water type classification of water bodies.

Purpose and goal

The purpose of the project was to develop MERIS based water quality indicators for the large lakes, to employ these to predict the distribution of essential and sensitive habitats, to assess ecological status and to optimise fish monitoring. Conventional ecological monitoring methods require excessive efforts to achieve adequate *temporal* and *spatial* coverage, while remote sensing techniques, especially ENVISAT/MERIS (or Sentinel-3/OLCI in the future) cover large areas swiftly and frequently (almost once a day on our latitudes). Our goal was to deliver image based products and data that can be used independently, to support an analysis of the benefit of using satellite data in fish monitoring, to deliver improved indicators of the spatial and temporal distribution of a number of fish stocks and, finally, to discuss potentials of integrated remote and ground-based monitoring programmes in larger areas and smaller water bodies.

Area of investigation

Several of the largest lakes in the European Union are situated in Sweden. The four largest lakes (Vänern, Vättern, Mälaren and Hjälmaren) have a historical, cultural, ecological as well as economic importance. A major part of the Swedish population is living within 100 km distance from these four lakes. These large systems offer many important ecosystem services such as drinking water, navigation, recreation and fisheries. Lake characteristics are indicated in Tab. 1 below. More extreme levels of certain parameters like Secchi depth are exhibited in several sub basins of, primarily, Hjälmaren, Mälaren and Vänern. The size of these four lakes makes them suited for the development of a more efficient monitoring methodology, by including remote sensing data with properties as presented below. We have been actively involved in remote sensing and biological monitoring projects in these areas and these experiences have been beneficial for the current project. Regional expertise and interest in improving the monitoring of these lakes is expressed by the participation in the project of the Water Conservation Societies that are coordinating monitoring and regional governance.

Table 1. Morphological, physical-chemical and optical characteristics of the four lakes.

Lake	Area (km^2)	Mean depth (m)	Secchi depth (m)	*Chl a* (mg m^{-3})	$a_{CDOM}(420)$ (m^{-1})	*TSM* (g m^{-3})
Vättern	1939	39.9	7.8-12.3	0.27-2.8	0.06-1.4	0.01-1.6
Vänern	5648	27.0	3.6-6.7	0.29-7.4	0.89-4.86	0.01-4.48
Mälaren	1140	13.0	0.8-5.0	5.4 -33.2	0.76-3.81	0.8-12.0
Hjälmaren	477	6.1	0.4-4.8	4.0-43.2	1.0-13.0	-

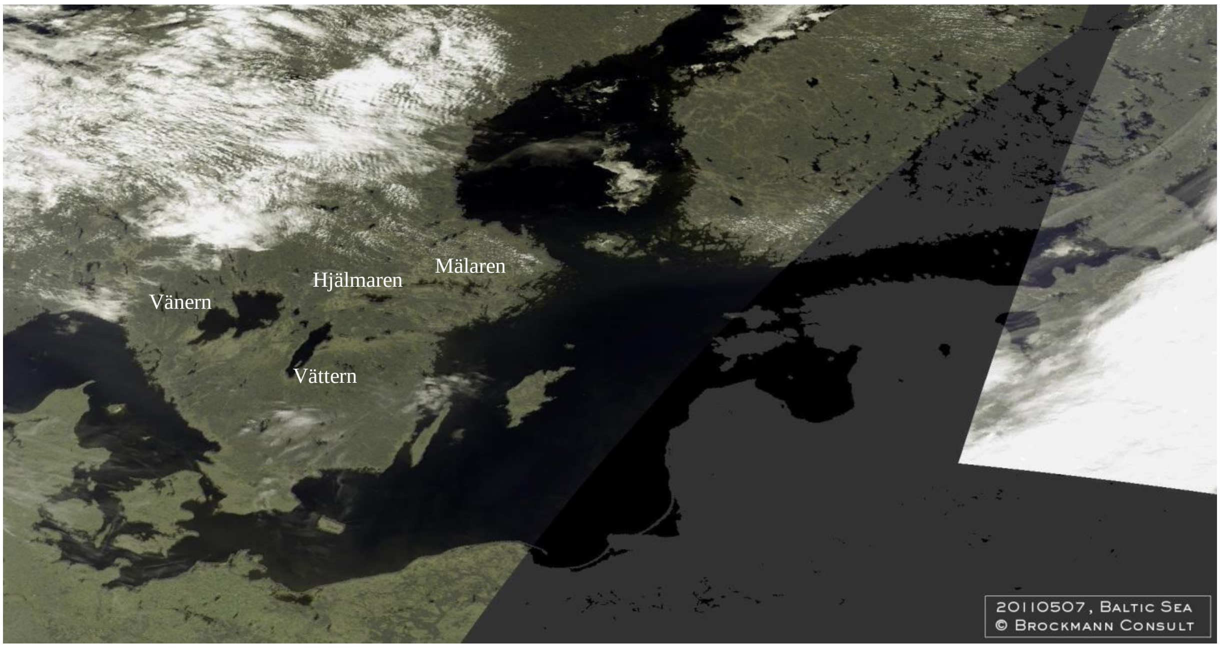


Figure 1. Study area as seen from MERIS on the 7th of May 2011. The whole area is covered within a few minutes.

Satellite data

MERIS

The developments are focused on MERIS FR (Full Resolution) data, with a spatial resolution of 300 meters and spectral properties developed for water targets. Details about the spectral properties are summarized in Tab. 2. An example of the area covered by MERIS from May 7 2011 is shown in Figure 1.

Table 2. Spectral band settings (nm), widths and primary applications for MERIS.

MERIS Bands	Primary application	MERIS Bands	Primary application
412.5 (10)	Yellow substance, turbidity	681.25 (7.5)	Chlorophyll fluorescence
442.5 (10)	Chlorophyll	708 (10)	Atmospheric correction
490 (10)	Chlorophyll, other pigments, Kd	753.75 (7.5)	Oxygen absorption reference
510 (10)	Turbidity, suspended sediments	760 (3.75)	Oxygen absorption
560 (10)	Chlorophyll reference, pigments	775 (15)	Aerosol, vegetation
620 (10)	Suspended sediments	865 (20)	Aerosol correction over ocean
665 (10)	Chlorophyll absorption, atmosphere		

MERIS (http://envisat.esa.int/) was launched 2002 and the first ocean colour instrument in space that was optimised for coastal water. This means waters not only influenced by the primary production, but also by independent sources of humic substances and suspended matter. Five years after its expected lift time, MERIS on ENVISAT stopped sending data in April 2012. MERIS has covered Sweden approximately 4-5 days per week during 10 years, which have generated a unique data set for environmental monitoring and time series analysis. The actual number of useful images is limited by clouds. The complete MERIS FR archive between 2002-2011, covering our area of investigation, has been processed by Brockmann Geomatics Sweden AB and Brockmann Consult Germany GmbH (BC) and has been used in the on-going developments. We have applied latest reprocessing, calibration and correction methodologies, whichare further described below.

In the end of 2015 a new satellite, called Sentinel-3a, will be launched by ESA. This is the first of a series of satellites that have instruments to continue the mission after ENVISAT – MERIS. ENVISAT was an experimental satellite and Sentinels-3 is one of the new series of operational satellites. The new "MERIS" is called OLCI (Ocean and Land Colour Instrument) and is very similar to MERIS but with improved radiometric and spectral properties. One year after the launch of Sentinel-3a, Sentinel-3b is planned for launch. With two satellites in orbit, there will be a daily coverage of MERIS like satellite data over Sweden. Before the estimated lifetime of the initial two satellites has expired, Sentinel-3 c and 3d will be launched, to assure a continuity of data. Successful results from these developments can thus be implemented and used on an operational basis after the launch of Sentinel-3.

Image processing

The source products are MERIS FR Level 1b (L1b) data, which corresponds to Top-Of-Atmosphere radiances. L1b data needs to be transferred to water leaving radiance (L2) by accounting for the atmospheric effects and the apparent optical properties of the light field. Besides the atmospheric correction the L1b to L2 processing includes geo-correction, land-water masking and adjacency effect correction. A general overview of the pre-processing sequence is given in the figure below.

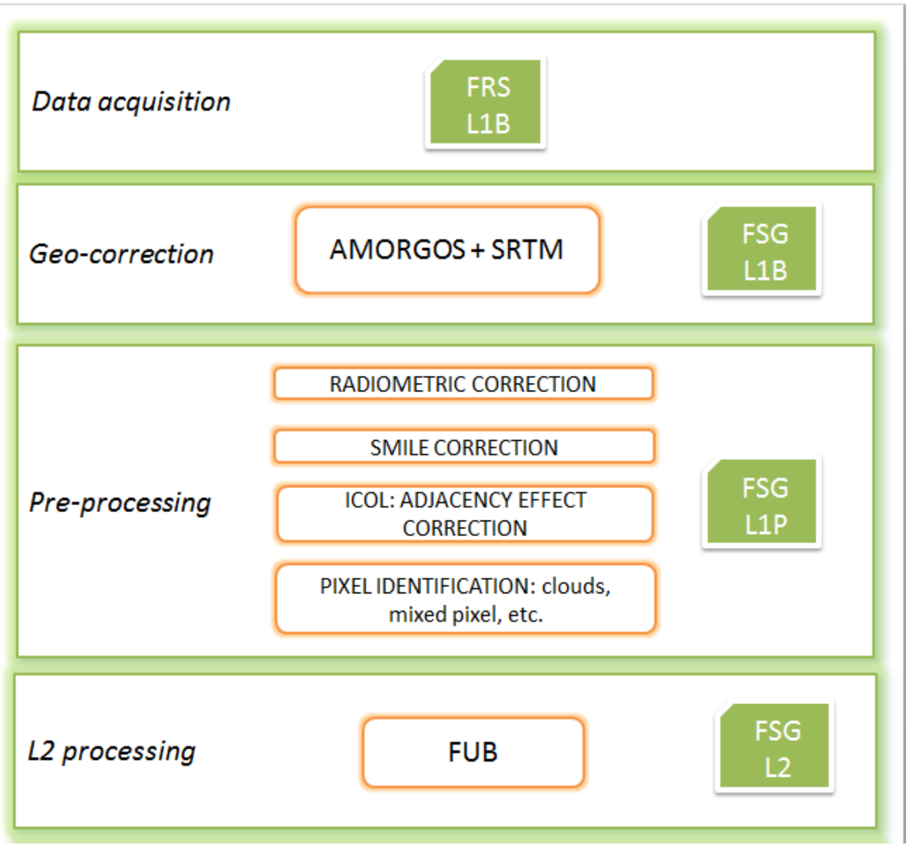


Figure 2. Flow diagram with the processing of the product chain depicting the most important components, algorithms, input and output data.

Geolocation

Small islands and complex shorelines of coasts and lakes, as well as patchy structures in the water, cause a high spatial variability. A high accuracy of the geolocation in the order of sub-pixels is necessary for obtaining good spatial and temporal composites. In addition, this high accuracy is a keystone when looking for matchups of in situ data for validation purposes.

The data used in this project has been geolocated with AMORGOS [50]. AMORGOS (Accurate MERIS Ortho Rectified Geo-location Operational Software), has been developed by ACRI-ST by funding from ESA (European Space Agency). AMORGOS includes a precise orbit determination, instrument pointing and performs an ortho-rectification. We have earlier performed an evaluation of AMORGOS processed data compared to manually geocorrected data, made by definition of Ground Control Points in ortho photo images available in digital format from the Swedish National Land Survey. For most evaluation points, AMORGOS generated slightly better accuracy, and a much better overall quality of the correction was achieved.

Radiometric/SMILE correction

Data needs to be radiometrically calibrated, which initially means that raw data is converted to Top-Of-the-Atmosphere (TOA) calibrated radiances measured in mWm-2sr-1nm-1. In addition, throughout the lifetime of a sensor the detectors are ageing, which needs to be accounted for by applying an updated radiometric model and coefficients.

Additionally, MERIS is composed of 5 cameras and measures the reflected sunlight using CCD technique. Each camera is equipped with a spectrometer and a two-dimensional CCD array. The spectral measurements of each pixel along an image line are made by its own set of CCD sensors. This causes small variations of the spectral wavelength of each pixel along the image that constitute the so-called "smile effect". Even though this variation is small compared to the spectral bandwidth of a band, which is typically 10nm, and can hardly be seen in an image, it can cause disturbances in the processing algorithms, which require very precise measurements, for example the retrieval of chlorophyll. These disturbances can result in a visual artefact, "camera borders", or in a reduced accuracy of the Level 2 products. The radiometric correction aims at eliminating/reducing these effects.

Adjacency Effect Correction

The ICOL (Improve Contrast Between Ocean and Land) algorithm, addresses the so-called adjacency effect and has been applied to the MERIS data after calibration and before atmospheric correction. Described shortly, the adjacency effect means that brighter land in close proximity to darker water gives an apparent increase of reflectance from water due to scattering in the atmosphere. The effect can be seen up to approximately 20 km from land. This processor is very important in order to receive good results in icoastal areas and lakes.

L2 processing

L2 processing consists of atmospheric correction and retrieval of concentrations of the water constituents. Satellites measure water leaving radiance, but also direct and diffuse irradiance from the sun and sky, and radiance reflected from the surface and the environment. The reflected light is scattered and absorbed by the particles and gases in the atmosphere, which makes the atmospheric correction a key procedure in the processing of water colour imagery data. In fact, the main part of the measured signal, over water bodies, in the visible spectrum is due to atmospheric effects. Hence, remote sensing of dark water targets is a challenging task. The surface reflectance is seldom above 1% and the atmospheric contribution to the signal can be several times greater than the actual surface signal. It is therefore critical to perform an area- and time-specific atmospheric correction. Inland waters put particular demands on atmospheric correction methods. These requirements correspond to terrestrial methods as far as ground elevation and aerosol properties are concerned, but require consideration of air-water interface effects as applied for oceanic targets. During the last couple of years, several independent L2 processors have been developed besides the standard MERIS/ESA processors and the results have been improved. Further development is an ongoing important research topic. Today these non-standard processors are widely used and acknowledged by ESA. Some of the most well-known of these independent processors are the Coastal Case 2 Processor (C2R), Boreal Lakes Processor (BOR) and Eutrophic Lakes Processor (EUL), all three from GKSS, Germany, together with the FUB Water Processor from Freie Universitätt Berlin. The first three of these (from GKSS) have identical atmospheric correction algorithms. However, they all have different water quality algorithms, each adapted to certain water types. We have earlier partially evaluated these L2 processors for the Baltic Sea, the Gulf of Bothnia, for Lakes Vänern, Vättern and Mälaren and for smaller lakes in southern Sweden [16, 33-36]. The results showed that the FUB algorithms for water quality estimation [44, 45] generated the best results among the evaluated. The L1b data used in this project has been atmospherically corrected using the FUB processor, producing water leaving reflectance in eight bands and water quality estimates. In the coastal zone and open Baltic Sea, it has been shown that both the FUB chlorophyll and TSM products are in correspondence with existing field data, also in absolute terms. The CDOM product is a threefold underestimating of the true concentration, but this offset has been stable during all evaluations and could therefore be accounted for. For Lakes Vänern, Vättern and Mälaren, FUB has worked well on a relative level but all products are more or less offset for all three lakes in comparison to the available field data [34]. The retrieval is based on an artificial neural network which was trained on the basis of the results of extensive radiative transfer simulations by taking varying atmospheric and oceanic conditions into account [44, 45]. FUB was initially developed for coastal waters with training data of Chl a between 0-50 mg m^{-3}, TSM between 0-50 mg l^{-1} and CDOM absorption between 0-1 m^{-1} (≈0-0.03 AbsF and 0-15 mg Pt/l)). This means that most Swedish lakes are within the valid levels for Chl a and TSM, but that the humic levels in certain areas is way out of its training range and that effect on the estimation must be analysed. FUB has produced estimates that have been significantly correlated to field data, even in more humic lakes. It is, however, most likely an upper limit where the relationship is lost and/or where the retrieval of the other parameters also is affected, due to CDOM absorption of light also at longer wavelengths. For Lakes Vänern. Vättern, Mälaren and Hjälmaren, the FUB performance has been investigated during this project and lake specific calibration algorithms have been developed when necessary.

The maximum peak height algorithm (MPH) for detecting trophic status, cyanobacterial blooms, surface scum and floating vegetation in coastal and inland waters using MERIS data has been evaluated with focus on detection of immersed cyanobacteria [27, 28]. The algorithm is a sequence of conditional arithmetic expressions that allows for the retrieval of Chl a in waters of different trophic states (fluorescence domain, absorption and backscattering domain, floating algae domain). MPH uses the position and magnitude of reflectance peaks around 700 nm in order to differentiate between immersed eukaryotes and cyanobacteria, as well as, surface scums (due to cyanobacteria) and floatingvegetation. Earlier research have indicated that the features of the phycocyanin pigment in cyanobacteria only become clearly visible in the spectra at biomass chl-concentrations greater than 20 mg m^{-3}[24, 29]. As a result, identification of cyanobacteria dominated waters with Chl a < 20 mg m^{-3}, is less reliable that at higher Chl levels. However, ongoing research indicates that cyanobaterial blooms could be detected even in waters with Chl a ≥ 12 mg m^{-3}, which significantly increases the applicability in the investigated Swedish lakes [manuscript in progress]. Initial evaluations of the flag for detection of cyanobacterial dominated waters have been made within the framework of this project.

Masking

A good separation between land and water pixels, as well as pixels partly disturbed by land portions (mixed pixels), is needed. This means that all pixels that do not correspond to optically deep water areas needs to be excluded before statistical analysis of the data. Areas affected by clouds and cloud shadow also need to be masked out. Pixel classification (cloud screening, improved land-sea mask, other pixel attributes) and masking has been performed using CoastColor processing methodology. Remaining issues not completely accounted for, is the identification of shallow areas and to differentiate these from areas with high turbidity/resuspension.

Field data

The investigated lakes are included in national and regional monitoring programs. With respect to water chemistry and phytoplankton data, the majority of the data is extracted from the database hosted by SLU (www.ma.slu.se). SLU are assigned by the Swedish Agency for Marine and Water Management to store data collected from freshwater in the national and regional environmental monitoring programs. With respect to fish, the Department for Aquatic resources at SLU has been running several programmes to monitor fish populations and assess their status in these large lakes during recent years. There is also a unique data set at SLU of hydro-acoustic data with midwater trawling for species apportionment. Additionally, there are fish monitoring programmes that measure the distribution, species composition and age/size structure of focal species and several other extensive monitoring programs in these lakes, coordinated by the Water Conservation Societies. These programs have been running since the late 60s and cover a large number of parameters. All data sets are described in more detail below.

Table 3. Available monitoring data on water chemistry, fish and other biota.

Method	Lakes	Nr of sites/coverage	Years with data	Frequency
Water chemistry and phytoplankton	Vä, Vt, Mä, Hjä*	5**, 2, 11, 4 sites	60ties/ 70ties - present	Annually, 4-7 times/yr
Hydroacoustics and midwater trawling	Vä, Vt, Mä, Hjä	14-16 transects/10-14 trawl hauls	1988-present	Annually except Hjä which has only been surveyed occasionally
Benthic fish monitoring with multimesh gillnets	Vä, Vt, Mä, Hjä	30-300 sites	1973-present	Annually in all lakes
Benthic fauna and zooplankton	Vä, Vt, Mä, Hjä	2-6 sites	1977-present	Zoopl: 2 times/yr, benthos 1 time/yr zoopl. occasionally in Hjä

*Vä=Vänern, Vt=Vättern, Mä=Mälaren, Hjä=Hjälmaren
**Long term control stations

Monitoring data - Water Quality

The water quality has been monitored more or less annually, 4-7 times per year and at several sites in all four lakes. There is data for all investigated parameters, i.e. Chlorophyll a (Chl a), Biovolume(BV), Cyanobacterial BV (CBV), Coloured Dissolved Organic Matter (CDOM), Secchi depth (SD) and total suspended matter (TSM), but in variable amounts. SD is the most frequently occurring observation, while TSM is relatively rare. With reference to the national monitoring program, Lake Mälaren have been sampled frequently at 11 control stations during the life time of MERIS and the data has been used in the analysis and developments (Fig. 3). The corresponding number of stations for Lake Vänern, Vättern and Hjälmaren are 5, 2 and 4 control stations respectively (Fig. 3).

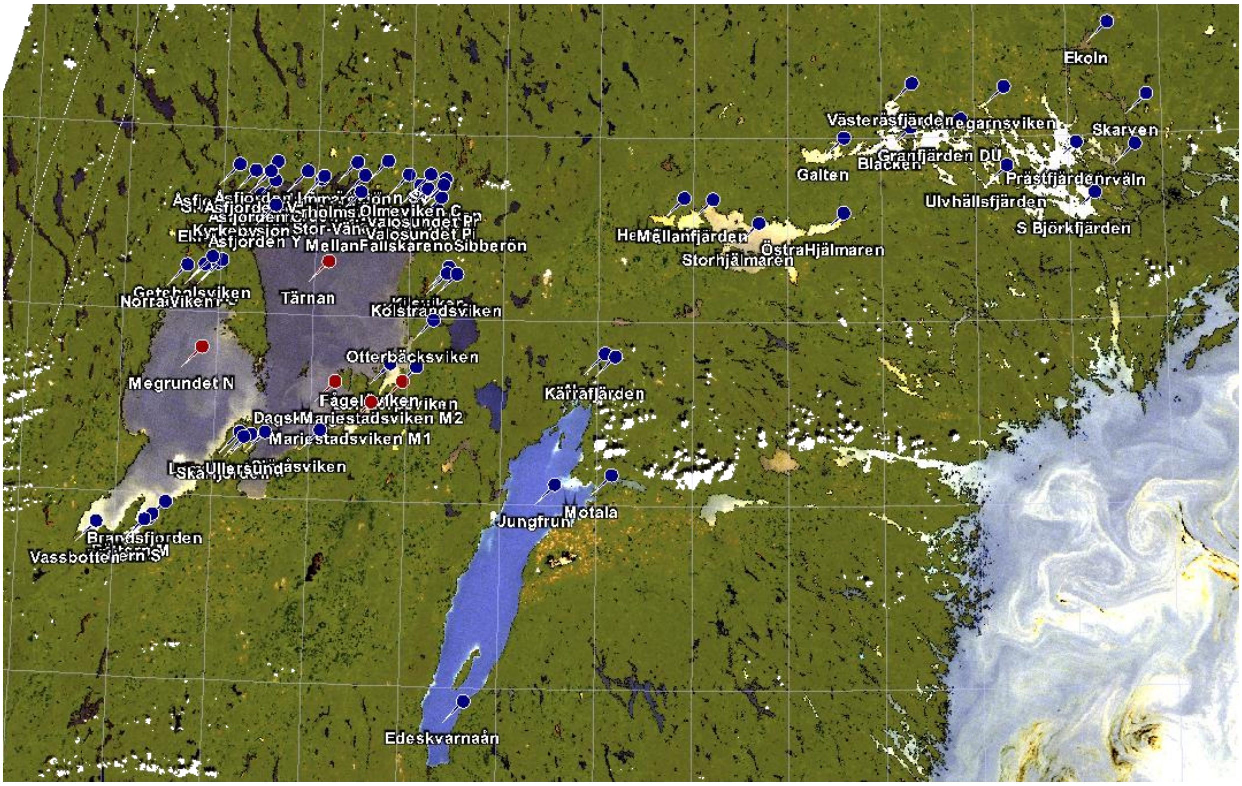


Figure 3. Location of the monitoring stations from which data has been used in the analysis and developments.

In addition, several stations have been sampled within the co-ordinated recipient control program (SRK) or in specific campaigns on the initiative of local/regional actors like the county boards or societies for water conservation. Especially in Lake Vänern, there are a large number of stations that have been sampled during 2002-2011. In Fig. 3 the stations marked in red are the five included in the national monitoring program and the blue are mostly from the recipient control program and/or part of a regional monitoring program. A close up on northern Lake Vänern can be seen in Figure 4 below.

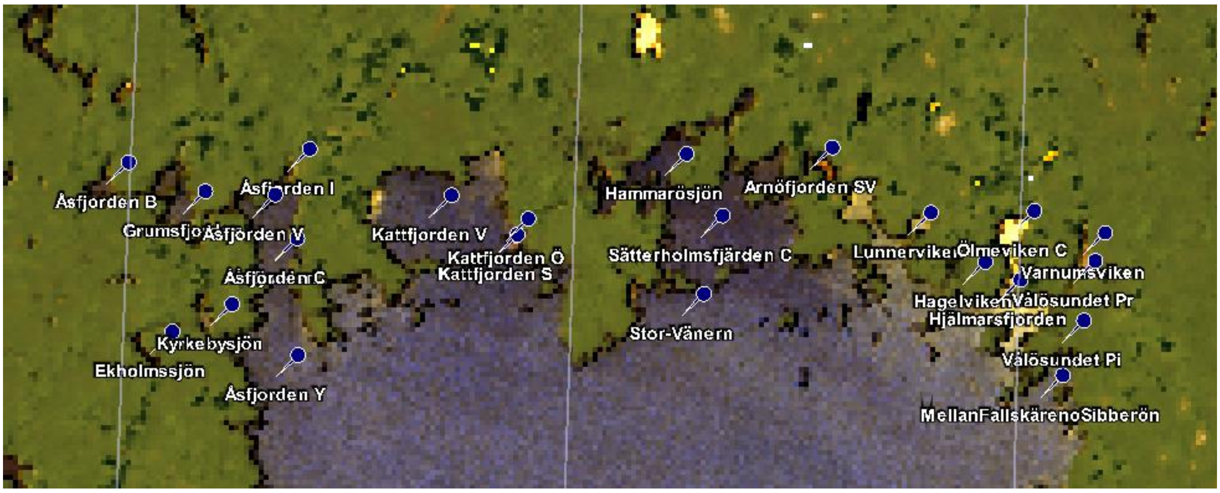


Figure 4. Location of the monitoring stations from which data has been used in the analysis and developments.

However, data from all stations plotted in Figure 1 could not be used in the analysis due to, primarily, the resolution of the satellite data. A MERIS pixel corresponds to 300x300 meters and it is common to use an average of the pixel representing the control station and it closest neighbours. This will limit the effect of the noise present in the data as well as location errors due to small errors in the geometric correction. Based on available maps, sea charts and aerial photos, an assessment regarding the suitability of the station to be analysed together with MERIS data was made. The judgement was based on if 5x5 (1500x1500m) and/or 3x3 (900x900m) pixels centred over the station is located in open waters or close to/over land, in shallow areas or contained islets and rocks that potentially could affect the satellite measurement. As described earlier, the masking procedure aims at removing all pixels that do not correspond to optically deep water, but the result is not perfect and there is no optimal solution for identifying shallow areas and to separate these from areas with high turbidity. Consequently, one needs to be careful as many of these stations are located in narrow shallow bays. The column "Suitability for satellite analysis" in Table 4 indicates, in green, that 5x5 pixels around the station corresponds to deep open water and should be suitable stations to use in the analysis (33 Stn.). For stations marked with orange colour, 3x3 pixels around the station, but not 5x5, corresponds to deep open water, and should be handled more carefully (11 Stn.). Stations marked with red are close to land, includes islet or rock or shallow areas and are most likely inappropriate for analysis together with MERIS data (26 Stn.). Table 4 also gives a first indication for which stations MERIS, and future Sentinel-3 data, could provide complementary data for monitoring and status assessment. Table 4 also includes a comment for all red and orange stations and, in the last column, the median number of pixels on which the stations average concentration is calculated for each available date. This average concentration is referred to as "one observation" in the report. Figure 5 exemplifies a "green", "orange" and "red" station. The green square corresponds to 1x1 km, i.e. approximately 3x3 pixels. Typically, an observation from Grumsfjorden, Svinnegarnsviken and Kärrafjärden corresponds to an average of 9, 7 and 2 pixels respectively.

Figure 5. Example of "Green" (Grumsfjorden, Vn), "Orange" (Svinnegarnsviken, Mn) and "Red" (Kärrafjärden, Vt) stations.

Table 4. Control stations and their suitability for evaluation of MERIs data (300 m resolution).

Lake	Station	Suitability for satellite (MERIS) analysis		Median no. of pixels extracted per image
Hjälmaren	Hemfjärden		Shallow, but SD < depth in general	9
Hjälmaren	Mellanfjärden			9
Hjälmaren	Storhjälmaren			9
Hjälmaren	Östra Hjälmaren		50% land	3
Mälaren	Blacken			9
Mälaren	Ekoln Vreta Udd			9
Mälaren	Galten			9
Mälaren	Granfj. Djurgårds Udde			9

Mälaren	Görväln S			9
Mälaren	Prästfjärden			9
Mälaren	S. Björkfjärden SO			9
Mälaren	Skarven		10-20% land	3
Mälaren	Svinnegarnsviken			7
Mälaren	Ulvhällsfjärden			9
Mälaren	Västeråsfjärden N			9
Vänern	Arnöfjorden SV		Shallow, land, islands etc	3
Vänern	Brandsfjorden		Turbid	9
Vänern	Byviken, centralt		Island east of station	6
Vänern	Byviken, inre		70% land	1
Vänern	Börstorpsviken		40% land	2
Vänern	Dagskärsgrund N			9
Vänern	Dättern		Shallow, but SD < depth in general	9
Vänern	Dättern, middle part		Shallow, but SD < depth in general	9
Vänern	Dättern, south		Shallow, but SD < depth in general	9
Vänern	Ekholmssjön, deepest part		Close to land	3
Vänern	Fågelöviken		Shallow and 10% land	2
Vänern	Gatviken central		10% land	4
Vänern	Getebolsviken inner			7
Vänern	Grumsfjorden			9
Vänern	Hagelviken		Shallow and 50% land	1
Vänern	Hammarösjön		Close to land	5
Vänern	Hjälmarsfjorden		Shallow and close to land	4
Vänern	Kattfjorden, south		Islands	7
Vänern	Kattfjorden, west			9
Vänern	Kattfjorden, eastr		Islands	6
Vänern	Kilsviken		Shallow and close to land	4
Vänern	Kilsviken, south		Shallow and islands	4
Vänern	Kolstrandsviken		Close to land	3
Vänern	Kyrkebysjön, deepest part		Close to land	5
Vänern	Kävelstocken		10% land	3
Vänern	Lomefjorden		Shallow and islands	5
Vänern	Lunnerviken		Land and islands	4
Vänern	Mariestadsviken, M1			9
Vänern	Mariestadsviken, M2			9
Vänern	Megrundet N			9
Vänern	Mellan Fallskären och Sibberön			9
Vänern	Norra Viken		Land and islands	2
Vänern	Otterbäcksviken		Shallow?	9
Vänern	Sjöråsviken		Shallow and 30% land	3

Vänern	Skarefjorden		30% land	2
Vänern	Stor-Vänern, söder Sätersholmarna			9
Vänern	Sätterholmsfjärden, central			9
Vänern	Tärnan SSO			9
Vänern	Ullersund		Land and islands	2
Vänern	Varnumsviken, deepest part		10% land	5
Vänern	Vassbotten		10% land	2
Vänern	Vålösundet Picasso		50% land	1
Vänern	Vålösundet Prästerud		20% land	2
Vänern	Åsfjorden, Borgvikssjön, middle		Island south of station	7
Vänern	Åsfjorden, central			9
Vänern	Åsfjorden, inner		20% land	3
Vänern	Åsfjorden, west		Close to land	7
Vänern	Åsfjorden, outer			9
Vänern	Ölmeviken, central		Shallow, but SD < depth in general	9
Vättern	Jungfrun NV			9
Vättern	Edeskvarnaån NV			9
Vättern	Alsen		Close to land	3
Vättern	Kärrafjärden		Land and shallow	2
Vättern	SRK, Motala ström sjöar		Close to land. Shallow?	7

Data from all stations in Table 4 have been used in the analysis, calibration and evaluation described in chapter "Analysis & Results – Water Quality" below.

Monitoring data - pelagic fish - hydroacoustics and midwater trawling

Data from hydroacoustic surveys combined with midwater trawling has been used to assess the potential of MERIS based predictors to analyse spatial variation in pelagic fishes. In L. Vättern survey data are available from 1988-2014, from L. Vänern from 1995-2014, from L. Mälaren 1995-2014 (except 2006-07) and from L. Hjälmaren only 2009. When comparing detailed acoustic data with remote sensing images we only used the last year available from the time-series when remote sensing data was available, the year 2011. When summarising data to calculate candidate metrics for the various water bodies we used data from the years 2011-2012 to get more robust estimates. More details on survey design are given in [3, 4, 41, 43]. The surveys have been carried out with two vessels. From 1988-2007, R/V Ancylus was used. From 2008 and onward R/V Asterix has been used instead. In 2008, the survey was carried out using both vessels in L. Vänern to assure that there were no vessel-derived differences that could influence the survey data and the time-series comparisons. Acoustic data were collated with the echo-sounder SIMRAD EK60 and transducers Simrad ES 120 7C and ES38B (120 and 38 kHz) at night during dark hours (one hour after sundown till one hour before sunrise) along several parallel transects with sufficient coverage of the larger open basins in the lakes (Fig X). Acoustic operations followed the new CEN guidance on estimation of fish abundance with mobile hydroacoustic methods (EN 15910:2014). Midwater trawling was conducted, to support the hydroacoustic data with species and size composition, using a modified Isaac-kidd trawl. It had a mesh size of 7 mm in the cod end and an extra internal net with 5 mm mesh to separate the catch of small and young-of-the-year fishes from the rest of the catch. The trawl opened 12x5 m. Trawling depth, defined as the distance from the head rope to the surface, was mainly conducted at 5, 12, 22 and 40 metres depth and occasionally down to 60 m depth. Speed during trawling was 2-2.5 knots and the duration of trawling efforts was normally around 20-30 minutes. Trawl samples were evenly distributed over the lakes in a number of sub-areas. Surveys were carried out from mid-August to mid-September. The content of the catch was identified to species, counted, measured to length (TL in mm) and weighed (TW in grams). In hauls with extremely large catches of individual species (mostly smelt that may occur in several thousands), a sub-sample of a minimum of 200 individuals in each mesh size were measured and weighed. A temperature profile was recorded in all surveyed sub-areas.

Monitoring data - benthic fish - multi-mesh gillnets

To analyse patterns for benthic species monitoring data from multi-mesh gillnets has been used. There have been ongoing monitoring programmes in all lakes during the analysed period 2005-2012 (table 5). Two main types of gillnets have been used. In the offshore areas of L. Vänern and Vättern relatively large and deep multi-mesh gillnets have been used to attain a significant catch of commercial species and to be able to avoid the practical problems that influences catch when using short and small gillnets that do not perform well in deep, current-exposed, off-shore areas. These DEEP multi-mesh gillnets were 5 m deep and consisted of five 60 m panels with 20, 30, 35, 43 and 60 mm bar mesh. Inshore areas in L. Vänern and L. Vättern as well as all parts of L. Mälaren and L. Hjälmaren were surveyed using the same NORDIC multi-mesh gill nets as is used along the Baltic Sea coastline. The gill nets are made up of five meter long and 1.8 m deep panels with the mesh sizes 6.25, 8, 10, 12, 15, 19, 24, 30, 38, 48 and 60 mm. Compared to the regular NORDIC multi-mesh gillnets for coastal areas, two additional panels measuring 6.25 and 8 mm in bar mesh size has been added to catch young fishes and small-bodied species. In addition, in some of the smallest and most sheltered basins there has been inventory fishing and other types of studies not included in the national monitoring programs that has been carried out with the NORDIC multi-mesh gillnets used in smaller lakes (CEN, 2005). These are made up of 12 equally sized panels with mesh sizes ranging from 5-55 mm and a height of 1.5 m and a length of 30 meters.

All gillnets were randomly distributed in depth strata covering the existing depth range of the surveyed areas (the depth range varied from 2-95 m). The nets were set in the evening and pulled early in the morning; the duration of one unit of effort was approximately 12 hours. At each sample station, depth was measured at the end points of the gillnet, as well as, the maximum and minimum recorded depth along the gillnet. Depth was measured with a portable echo-sounder (Hummingbird 788 combo CXI). Secchi depth and a temperature profile from the surface to the bottom at a deep site, were measured daily, adjacent to the sampling areas.

Table 5: Number of gillnet nights (all years summarised) and hydroacoustic segments (annual coverage) in the various water-bodies. NORDIC= Nordic multimesh gillnets, DEEP= deep multimesh gillnets, HYAC=hydroacoustics.

	NORDIC	**DEEP**	**HYAC**
Vänern	gillnet nights	gillnet nights	segments
Dalbosjön	72	36	97
Dättern	37		
Gatviken	47		
Getebolsviken	62	49	
Hammarösjön	24		
Kattfjorden	24		
Kolstrandsviken	24		
Sätterholmsfjärden	24		
Varnumsviken	24		

Värmlandssjön	125	96	201
Åsfjorden	24		
Ölmeviken	56		
TOTAL	**543**	**181**	**298**
Vättern			
Alsen	40		
Duvfjärden	54		
Kärrafjärden	40		
StorVättern	201	1198	154
TOTAL	**335**	**1198**	**154**
Mälaren			
Arnöfjärden	31		
Blacken	16		10
Ekoln	106		10
Fiskarfjärden	30		10
Galten	32		
Garnsviken	32		
Granfjärden			8
Oxfjärden	24		
Prästfjärden	131		30
Skarven	16		
Västeråsfjärden	206		
Årstaviken	24		
TOTAL	**733**	**0**	**68**
Hjälmaren			
Mellanfjärden	24		
Storhjälmaren	73		33
Östra Hjälmaren	8		
TOTAL	**105**		**33**

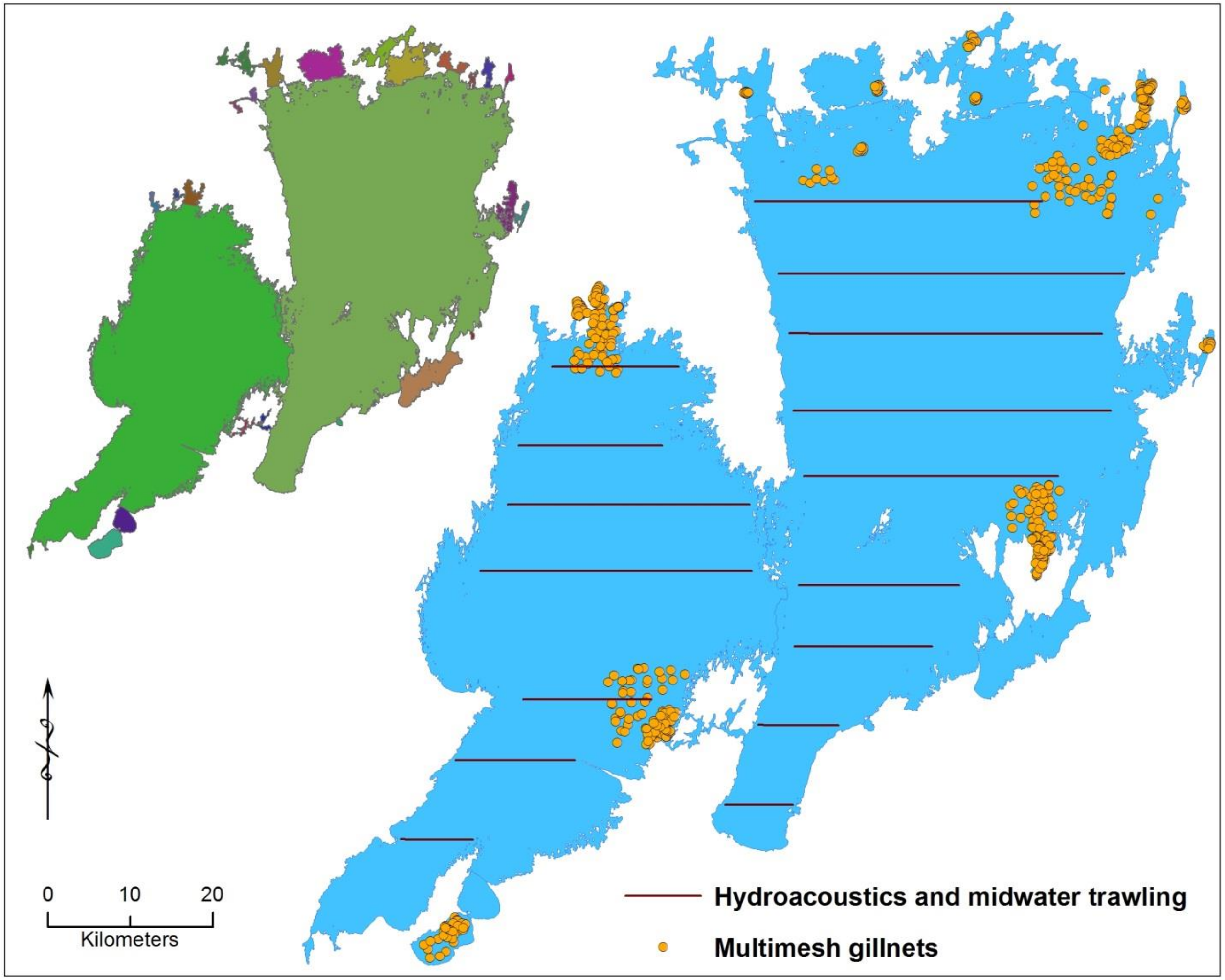


Figure 6. Map of the sampling stations in Lake Vänern. The smaller map at the left corner pictures the location and boundaries of the water-bodies defined to implement EU:s water directive.

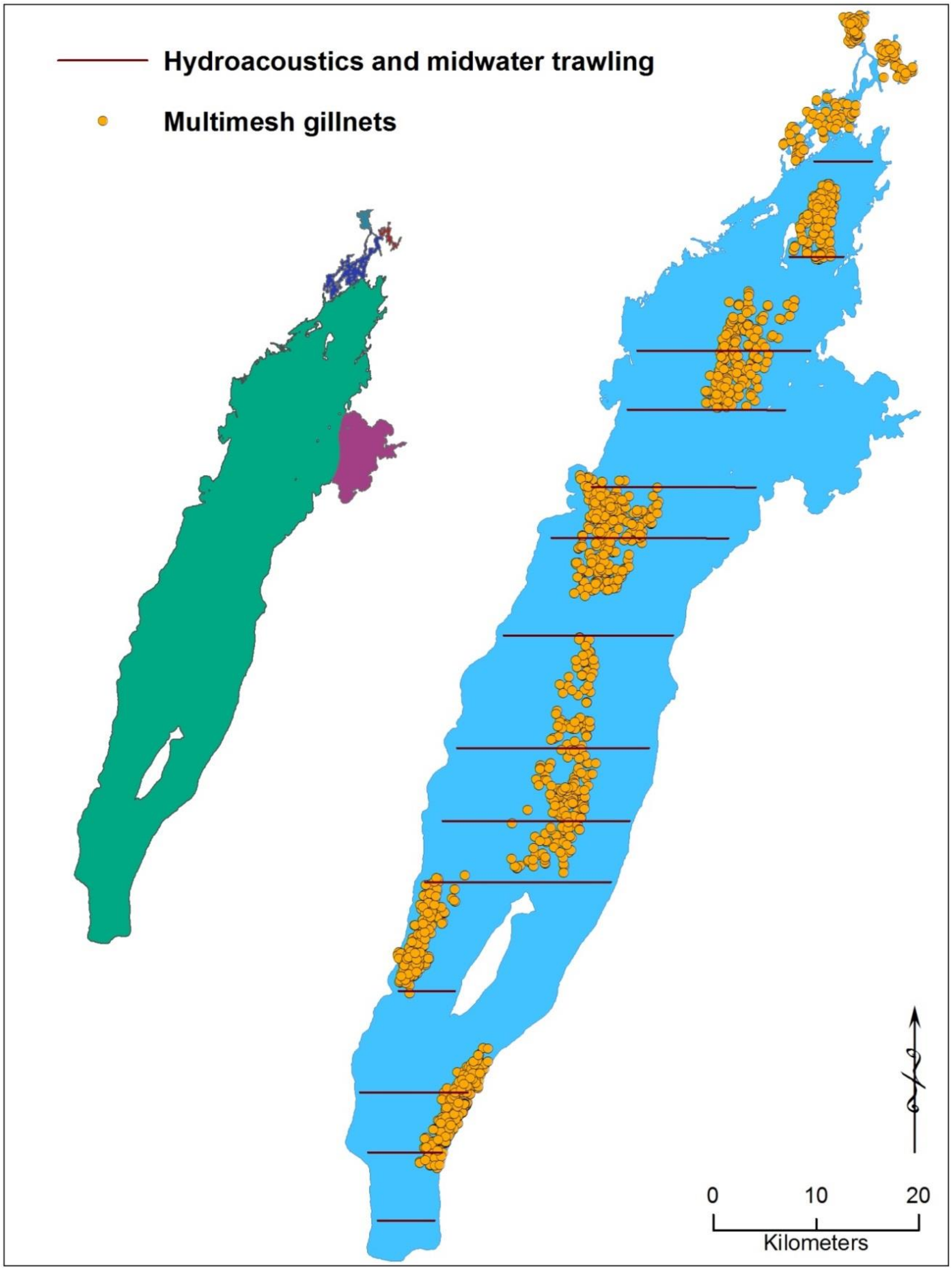


Figure 7. Map of the sampling stations in Lake Vättern. The smaller map at the left corner pictures the location and boundaries of the water-bodies defined to implement EU:s water directive.

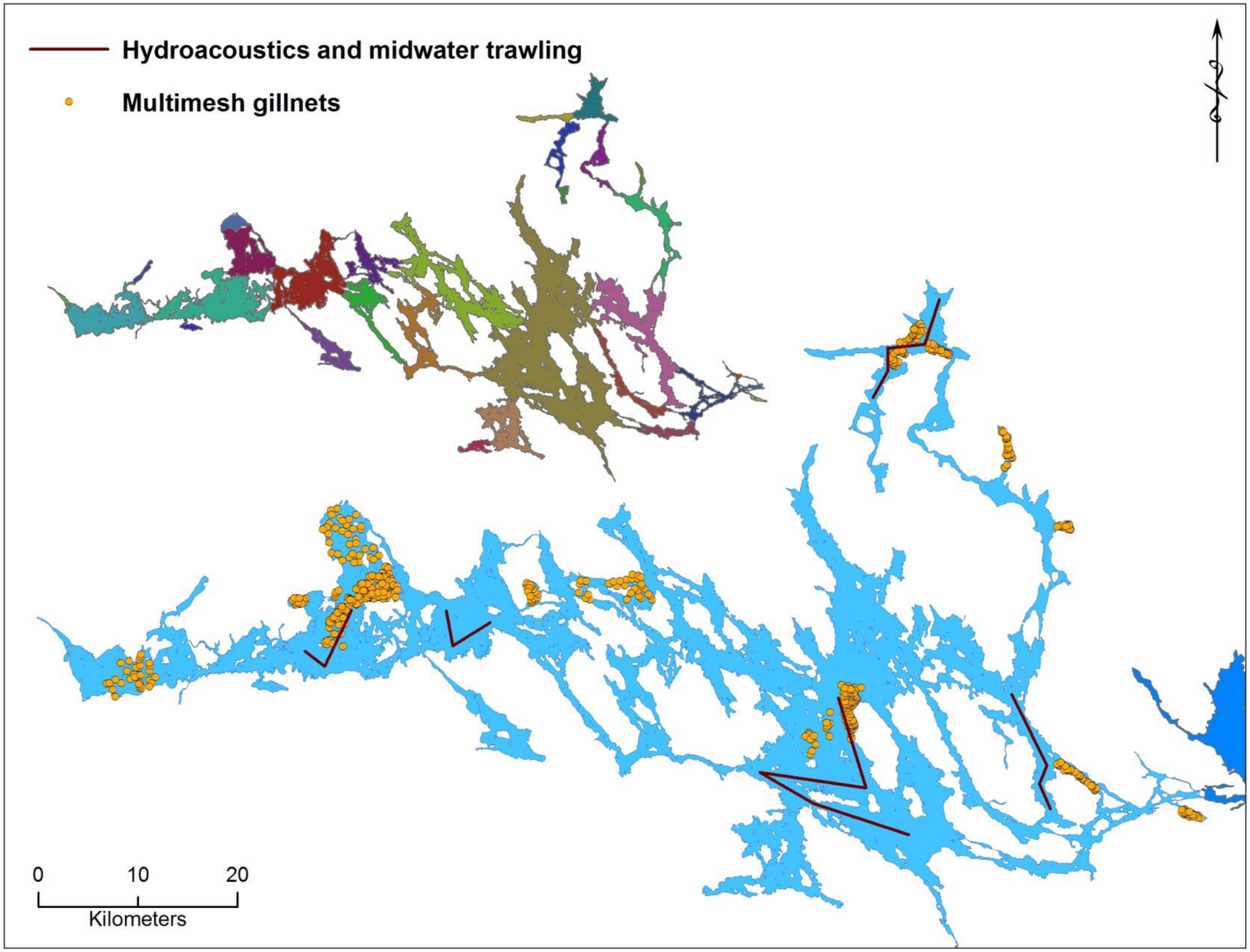


Figure 8. Map of the sampling stations in Lake Mälaren. The smaller map at the left corner pictures the location and boundaries of the water-bodies defined to implement EU:s water directive.

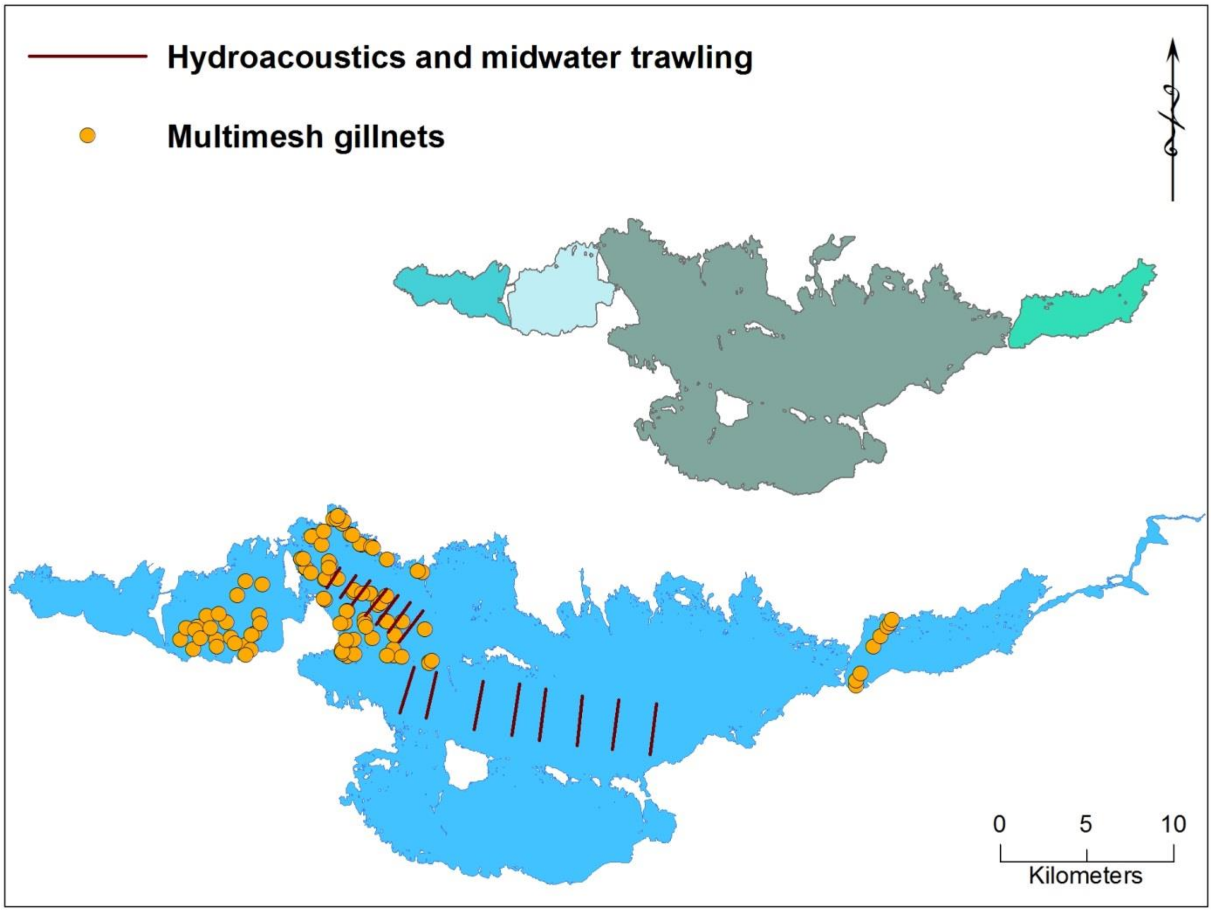


Figure 9. Map of the sampling stations in Lake Mälaren. The smaller map at the top pictures the location and boundaries of the water-bodies defined to implement EU:s water directive.

Figure 10. A DEEP multimesh gillnet with an entangled Arctic charr is lifted on L. Vättern.

Figure 11. Night-time midwater trawling on L. Mälaren. Anders Asp (SLU) and Milan Riha from the Fish Ecology Unit, in the Czech Republic are busy hauling the trawl while implementing the new CEN-guidance for mobile hydroacoustics in lakes.

Analyses & Results – Water Quality

As described in chapter "L2 processing", several algorithms for estimation of water constituents have earlier been evaluated for the Baltic Sea, the Gulf of Bothnia and on a basic level also for Lakes Vänern, Vättern and Mälaren. The results showed that the FUB algorithm [44, 45] for water quality estimation generated the best results among the evaluated algorithms. In the coastal zone and open parts of the Baltic Sea, it has been shown that both the FUB chlorophyll and TSM products are in absolute correspondence with existing field data. The CDOM product was a threefold underestimation of the true concentration, but this offset were stable during all evaluations and could therefore be accounted for. For Lakes Vänern, Vättern and Mälaren, FUB has worked well on a relative scale but all products were more or less offset for all three lakes in comparison to the available field data. FUB was initially developed for coastal waters with training data between 0-50 mg m-3 for Chl a, between 0-50 g/m^{-3} TSM and CDOM absorption between 0-1 m^{-1} (≈0-0.03 AbsF and 0-15 mg Pt/l)). This means that most Swedish lakes are within the valid levels for Chl a and TSM, but that they may exhibit humic levels way out of its training range and that the effect on the estimations had to be further investigated. FUB has produced results that have been significantly correlated to field data in more humic lakes, but it is also most likely that there is an upper limit where the relationship is lost and/or where the retrieval of the other parameters also are affected, due to absorption of light by CDOM also at longer wavelengths [36]. In this project, the main focus of the work related to water quality has been to evaluate the performance, possibilities and limitations of the FUB algorithms for retrieval of Chl a, CDOM and TSM in Lakes Vänern, Vättern, Mälaren and Hjälmaren. Additionally, the relationship between FUB-Chl a and Biovolume, as well as, between FUB-Chl a/CDOM and transparency/Secchi depth has been investigated in order to be able to produce full coverage maps and time series also for these parameters if good correlation could be demonstrated. Earlier developed algorithms for estimation of Secchi depth [1, 15] has also been applied to FUB L2 reflectances and compared to the results from the FUB-CDOM and Secchi depth developments. Finally, an algorithm for detecting areas cyanobacterial dominance [27,28] has been validated.

The chapter starts with a description of the data extraction and data availability for all parameters and all lakes. After that, a match up analysis between field and MERIS data collected on the same day was performed and calibration and estimation algorithms have been established when necessary. Finally, based on the results, time series for all parameters (not CBV) has been produced and compared to available field data in order to further investigate the applicable ranges of each algorithm and the potential for each station to be monitored by MERIS and future Sentinel-3.

Image data - Extraction & Availability

After masking of invalid pixels, an average of a maximum of nine pixels centered on the control station have been extracted and calculated from each date, from all available images, between April-August, 2002-2011. The only exception is 2002, as the data collection by MERIS did not start until June 2002. This station average is referred to as "one observation" and is, together with monitoring data from the control stations, used in the subsequent developments and analysis.

Figure 12a and b shows the number of observations for each control station between May-September, 2002-2011. Additional data is available in April all years, but was not included here due to insufficient screening of sea ice. At least five valid pixels had to be available for calculation of station average, on a specific date, in order to be included as one observation in the graph. For example, only four satellite based observations are available for station "Ekholmssjön" (Fig. 12a). However, the number of observations would be 172 if observations corresponding to an average of 1-4 pixels also would have been included. The maximum number of observations, 408, is obtained for the station "Tärnan" in Lake Vänern, which usually corresponds to an average of nine pixels. The majority of stations with a high number of valid observations were all situated in the large main basins. The color of the bars corresponds to the color used in Table 4 and indicates the suitability of the stations for comparison with MERIS data, mainly with respect to the resolution of the sensor versus the proximity to land and islands for the control station.

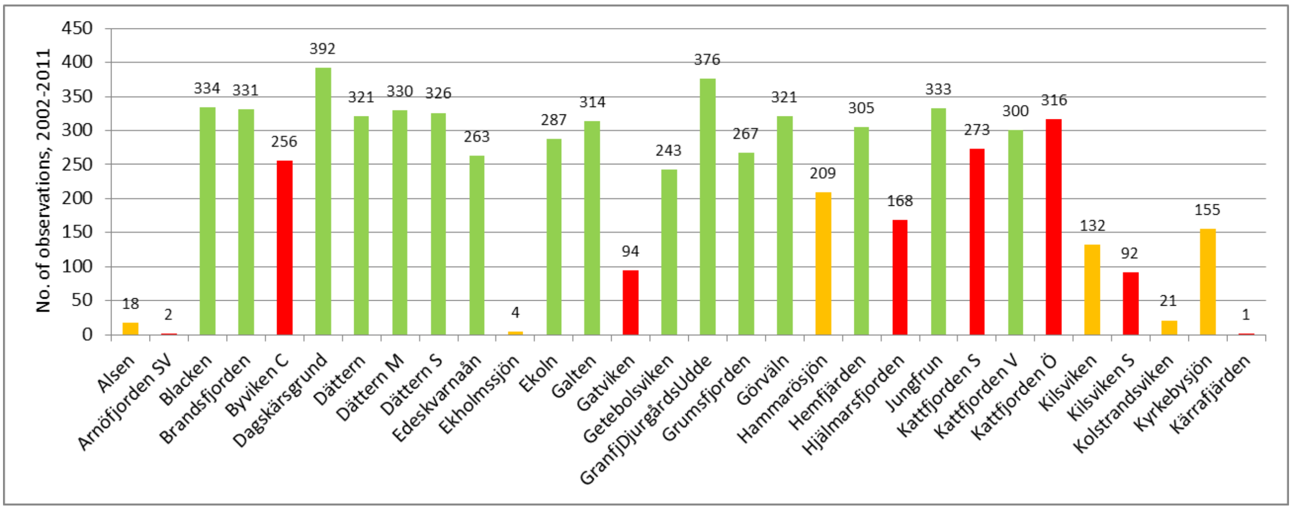


Figure 12a. Number of observations corresponding to an average of 5 pixels or more per observation, collected between May-September, 2002-2011.

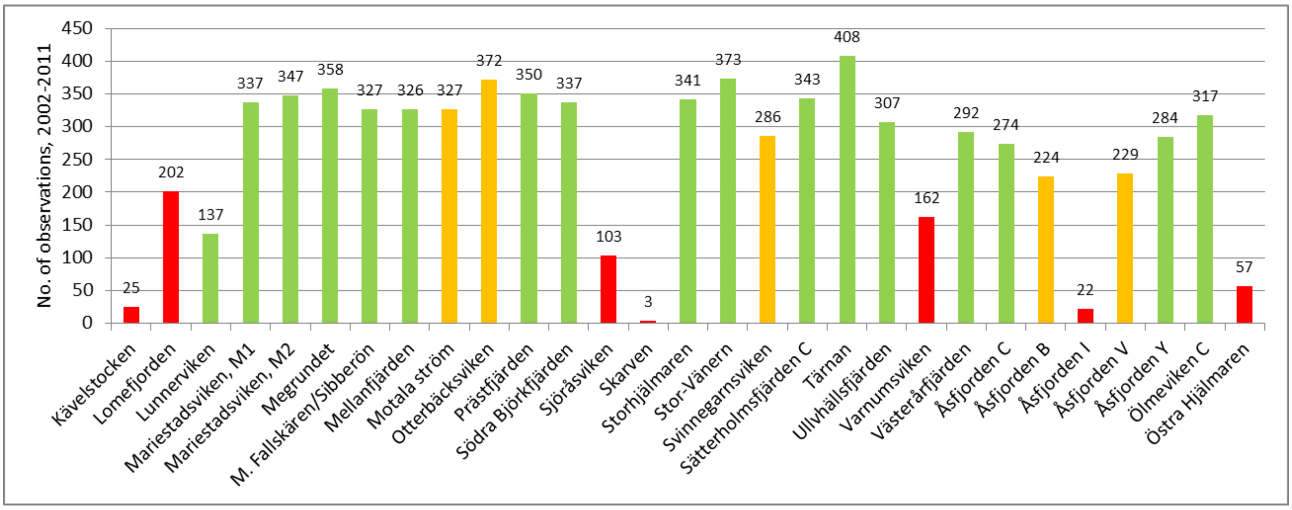


Figure 12b. Number of observations corresponding to an average of 5 pixels or more per observation, collected between May-September, 2002-2011.

Match up analysis & calibration algorithms

The included control stations have been presented earlier and an indication of the availability of MERIS data between 2002-2011, for each station, is shown in Figure 12. The satellite based observations have been used together with the monitoring data in a match-up and time series analysis described below. The main goal of the analysis was to define if good correspondence could be found between the two datasets, merging from two different measurement techniques, and if the concentration levels coincide or if calibration algorithms were needed. The goal was also to investigate the possibilities and limitations of the investigated algorithms for retrieval Secchi depth and of Chl a, CDOM and TSM concentrations.

The availability of MERIS based observations is shown in Figure 12, but the number of field observations is significantly smaller, e.g. 28 compared to 408 for control station "Tärnan". The number of matching (same day) observations for Chl a, Chl a/BM, SD, CDOM/AbsF and TSM) has been summarized in Table 6. The most frequent observation is Secchi depth, which generated 226 same day match-ups taking all four lakes into account. These matching observations have been further analysed and the results of the analysis is presented below.

Table 6. Match ups – Monitoring data

Satellite parameter / Corresponding field parameter	Total	Vänern	Mälaren*	Vättern	Hjälmaren
Chl a	**154**	59	71	15	9
Chl a/Biomass	**66**	23	29	13	1
SD	**226**	128	73	16	9
CDOM/AbsF420	**136**	48	71	16	1
TSM/Turbidity	**38**	8	24	5	1

*Monitoring data from 2004-2006 is missing.

Chlorophyll a

Chl a is one of the pigments in phytoplankton that affects the spectral properties and therefore can be measured with optical satellites. In this analysis the extracted data set was limited to satellite and field data collected on the same date. Taking all available stations into account, the field sampling date matched the image date on 154 occasions, during these ten years (Tab. 6). These match ups has been plotted in Figure 13 below.

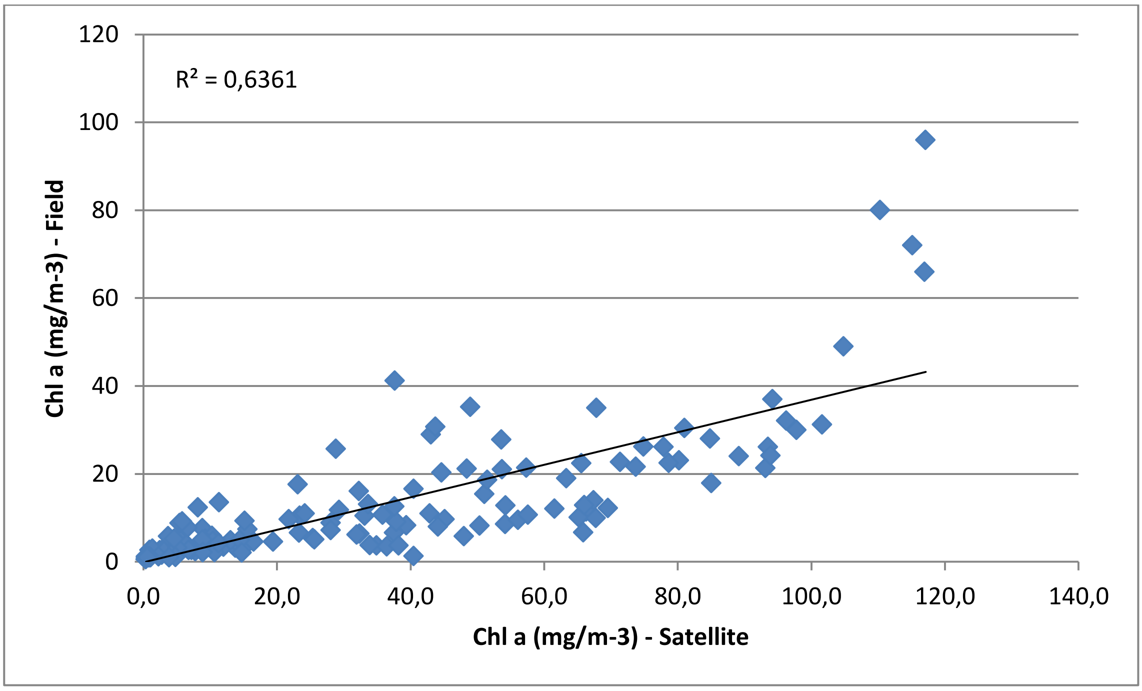


Figure 13. Chlorophyll - Same day match ups between satellite and field data.

There is a clear correlation between the two datasets. The most divergent data points are the four highest concentrations, which correspond to Lake Hjälmaren. The algorithm for Chl a estimation is trained for concentrations between 0-50 mg m-3 and these point are thus out of range. They were therefore excluded in order to capture the general trend as explained by the rest of the data set. The algorithm approximately overestimates the concentrations with a factor three. These results are in line with earlier investigations, based on a limited number of images and data [34]. The remaining variability depends mainly on uncertainties and/or limitations in field sampling methodologies and image pre-processing routines (primarily atmospheric correction) as well as temporal differences between the satellite overpass and the collection of the field sample. One hour might be enough to change the concentration significantly. Winds, water flow and clear skies make the water masses move and algae/cyanobacteria become well mixed in the water column or floating near the surface. In addition to the four points from Lake Hjälmaren, two more points (max overestimation and max underestimation where removed from the final selection (Fig. 14). By removing these points R^2 increases from 0.64 to 0.70.

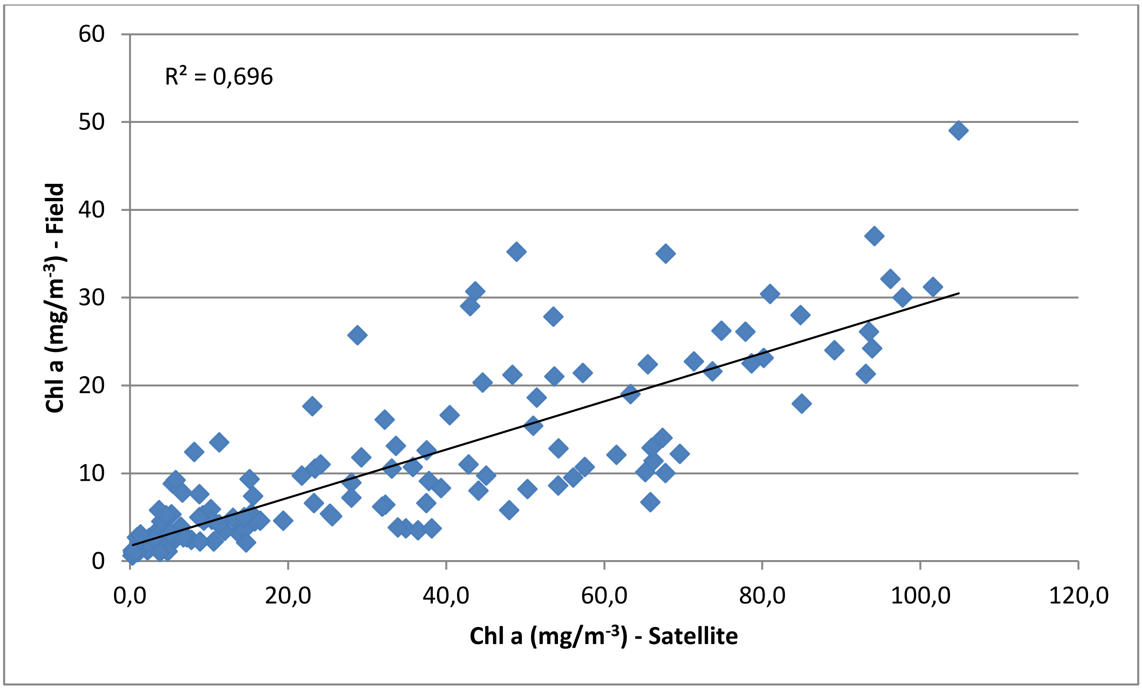


Figure 14. Chlorophyll - Same day match ups between satellite and field data, two outliers and four "out-of-range" concentrations removed.

The variability can be further decreased (R^2 increases from 0.70 to 0.77) if data collected in April is removed from the analysis, but the trend (slope and offset) is not significantly affected. In Figure 15 only data collected in August is included and the variability is much less compared to the initial selection (R^2 = 0.82 instead of 0.7), but again the trend (slope and offset) is not significantly affected. For example, the difference between the relationships derived based on the data plotted in Fig. 14 and 15 would only be 0.15 and 0.55 mg m-3 after calibration of 2 and 10 mg m-3 respectively. This corresponds to an uncertainty much lower than 10%, which is better than what could be expected based on field samples.

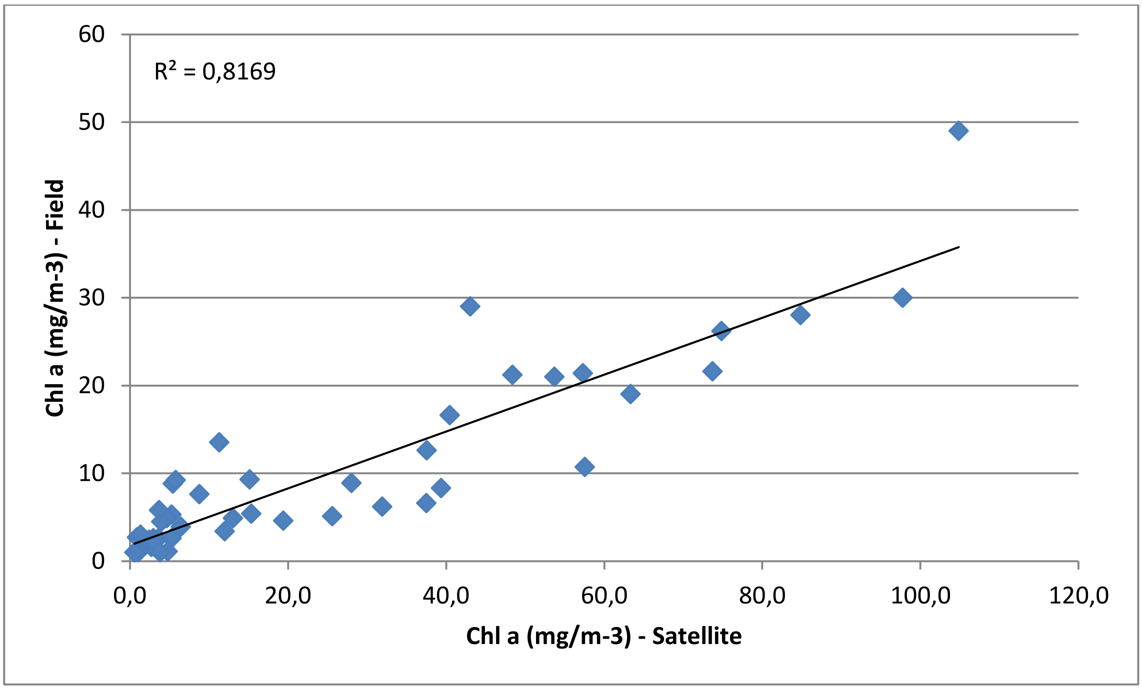


Figure 15. Chlorophyll - Same day match ups between satellite and field data collected in August.

In figure 14 data from all lakes are included, but with a dominating contribution from Lake Mälaren and Lake Vänern. It would not be possible to build stable relationships only using Lake Vättern and Lake Hjälmaren data, due to the few match-up points and small variability in concentrations. All four lakes together exhibit a large range of concentrations, which makes it possible to establish a relationship. The validity will be further evaluated in the time series analysis below. In fact, looking at the data in the lower left corner of the established relationship (Fig. 16), one can see that this relationship is not optimal for the low concentrations measured at control stations "Jungfrun" and "Edeskvarnaån", two clear-water sites in the Lake Vättern, but would double concentrations around 1 mg m-3 (green line in Fig. 16). For Lake Vättern an alternative relationship was created by forcing the regression line in Figure 14 through the cloud of low concentrations corresponding to these two stations (blue line in Fig. 16).

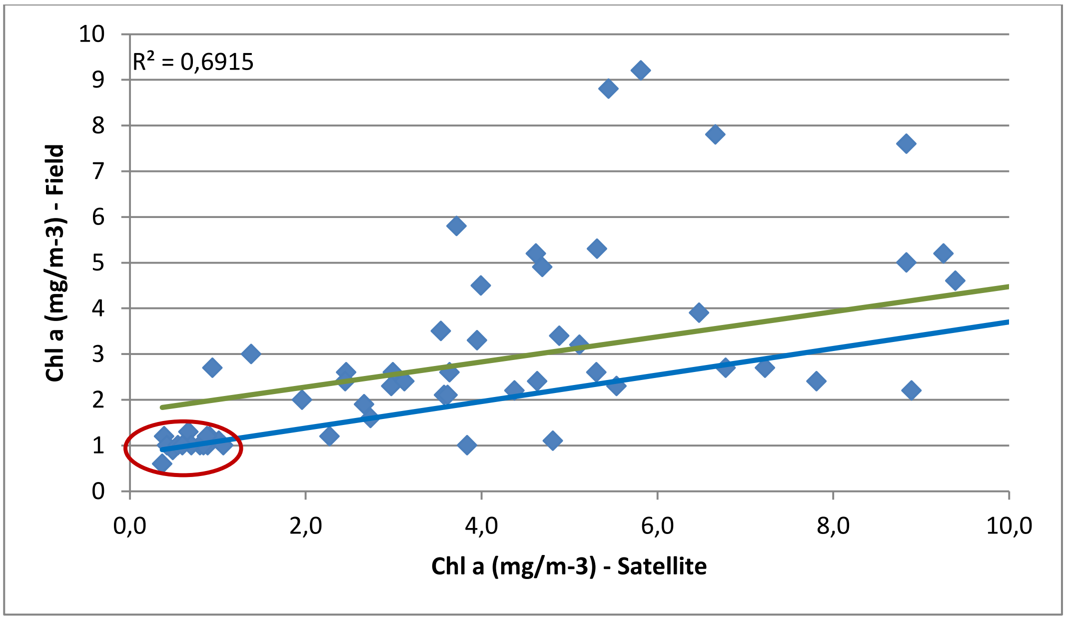


Figure 16. Chlorophyll - Same day match ups between satellite and field data, two outliers and four "out-of-range" concentrations removed. The regression line has been forced through the data cloud representing Lake Vättern.

In order to retrieve data on absolute concentration levels, the relationship established by the observations in Figure 14, for Lake Mälaren and Lake Vänern and 16, for Lake Vättern, has been used in the rest of the analysis and results, to calibrate the observations, produce time series and to further investigate its validity for different stations/water bodies. An example of calibrated data is shown in Figure 17.

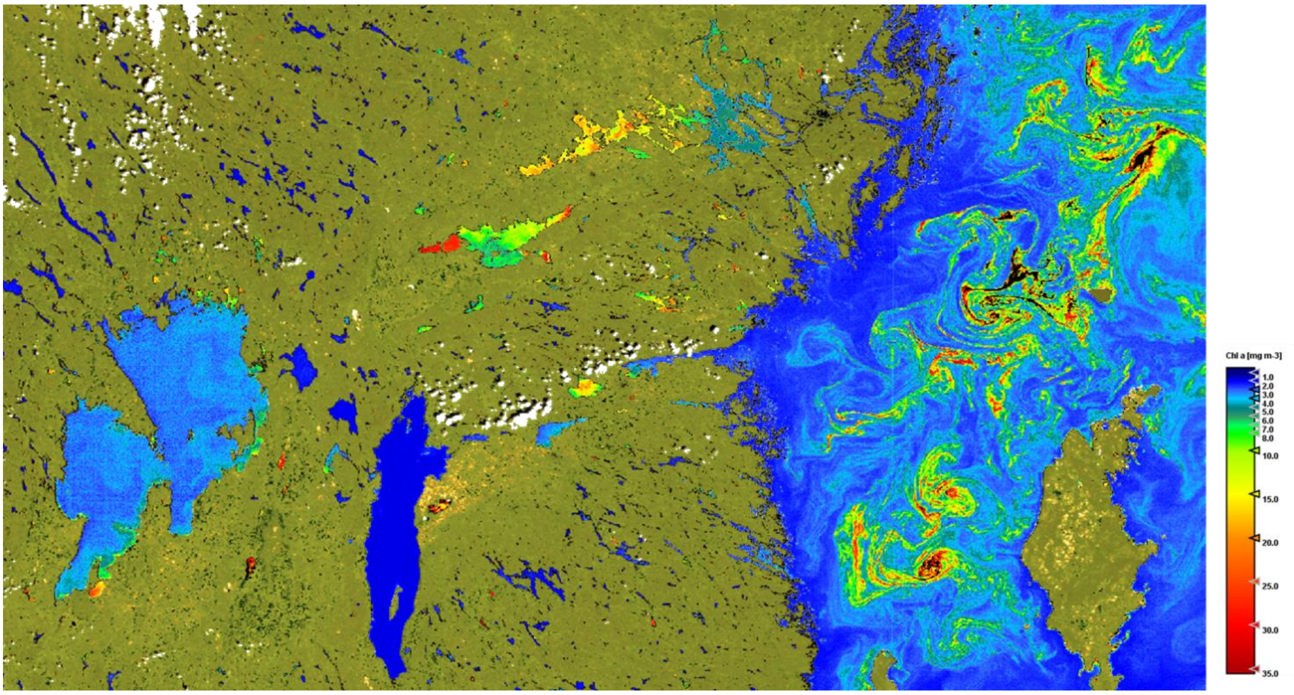


Figure 17. Calibrated Chl a product, 2008-07-24.

Lake Hjälmaren was only represented with one match-up in Figure 14 as most of the observations were out of range for the investigated algorithm. There is too little data available to make any conclusions about calibration algorithms for Lake Hjälmaren, but an experimental alternative was established by fitting an exponential equation to the data in Figure 18 instead of a linear equation (Fig. 13). The established relationship has been used in the rest of the analysis and results to retrieve data on absolute concentration levels for Lake Hjälmaren, and also tested on other extremely turbid and eutrophicated water bodies, e.g. Dättern in Lake Vänern.

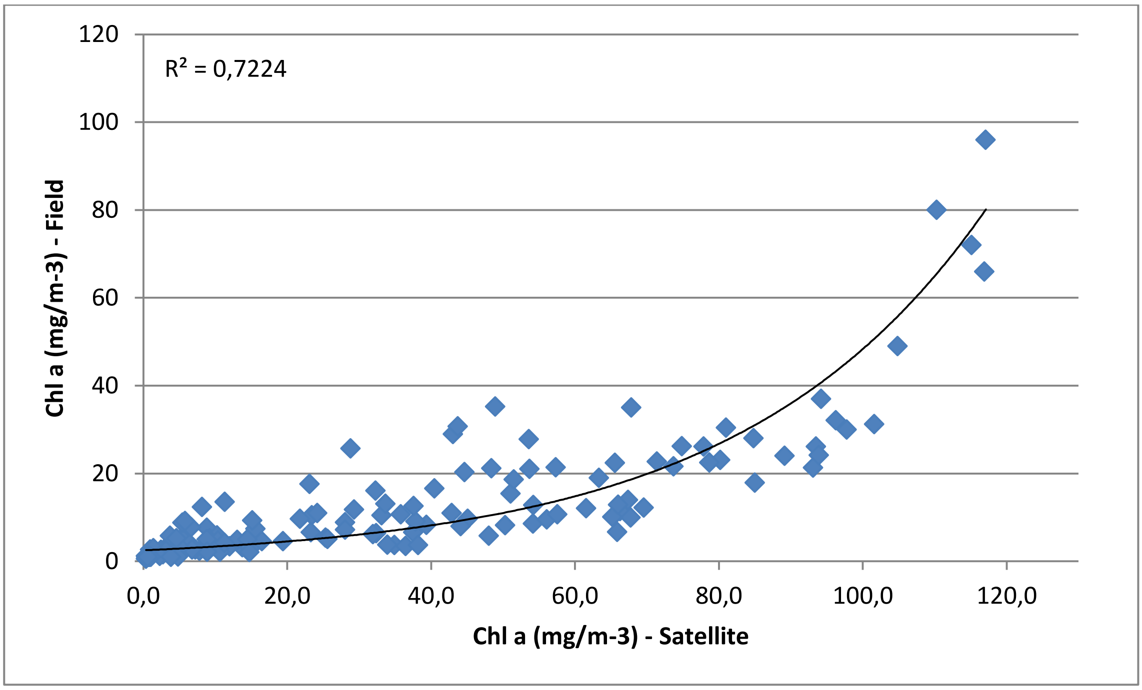


Figure 18. Chlorophyll - Same day match ups between satellite and field data, two outliers removed.

Biovolume

Chl a is one of the pigments in phytoplankton that affects the spectral properties and therefore can be measured with optical satellites. Biomass, or biovolume (BV), is not a spectral water component, but is often strongly correlated to Chl a. However, different phytoplankton species and species compositions contains different Chl a concentrations. In addition, the same species can produce different amounts of Chl a, as an adaption to prevailing light conditions in the area. Poor light availability, due to e.g. high CDOM absorption, can trigger higher Chl a production. The objective of the work with BV was to investigate if the Chl a concentration is related to the biomass in the investigated lakes. If a strong correlation can be observed, it would suggest that the species composition is stable and that Chl a products could be used as a proxy for biomass and full coverage biomass products/time series could be derived. As above, the extracted data set was limited to image and field data collected on the same date. Taking all available stations into account, the field sampling date matched the image date on 66 occasions, during these ten years (Tab. 6). These match-ups have been plotted in Figure 19 below. However, this data is not very representative for the entire lakes as the data points only correspond to eleven stations (Dagskärsgrund, Megrundet, Tärnan, Jungfrun, Edeskvarnaån, S.Björkfjärden, Görväln, Ekoln, Granfjärden, Galten and Storhjälmaren), compared to 32 different stations for Chl a.

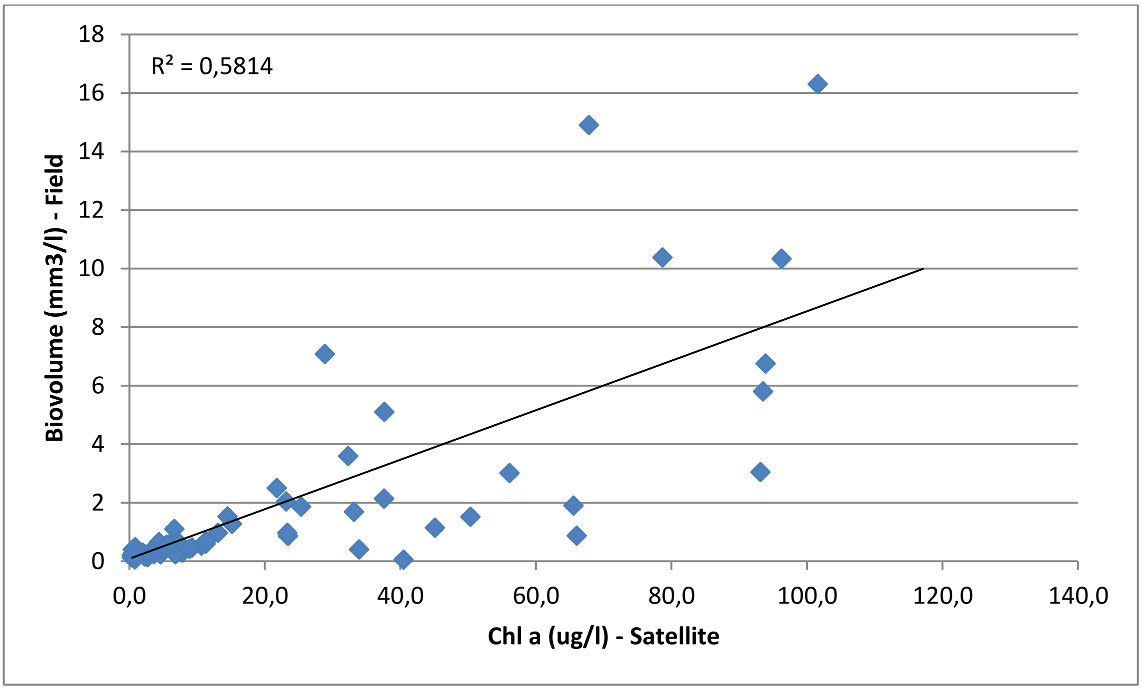


Figure 19. Same day match ups between satellite (uncalibrated Chl a) and field data (BV).

A relatively good correlation and alignment around the trend line can be seen for lower concentrations (<20 mg m^{-3}), while the variability exhibited by the higher concentrations is very large. All data points >20 mg m-3 corresponds to samples from Lake Mälaren and all data points >60 mg m-3, except one, were collected at control station "Galten". As described earlier, some of the variability can be attributed to uncertainties and/or limitations in field sampling methodologies and image pre-processing routines (primarily atmospheric correction) as well as temporal differences between the satellite overpass and the collection of the field sample. Most of the data points >20 mg m^{-3} that are the furthest from the trend line is collected in spring, April-May. If these turbid months are excluded from the analysis, the variability is significantly decreased, as can be seen in Figure 20.

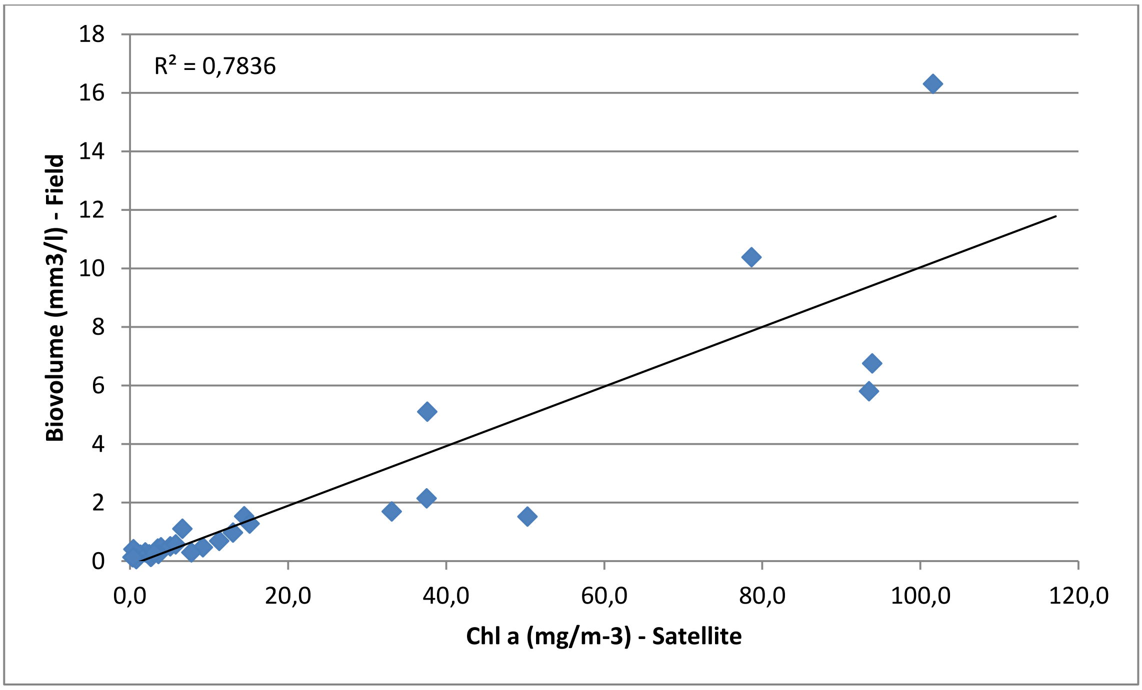


Figure 20. Same day match ups between satellite (uncalibrated Chl a) and field data (BV) after removal samples collected in April and May.

In Figure 20, data from all lakes is included, but with a dominating contribution from Lake Mälaren and Lake Vänern. It would not be possible to build stable relationships only using Lake Vättern and Lake Hjälmaren data, due to the few match-up points and small variability in concentrations. All four lakes together exhibit a larger range of concentrations, which makes it possible to establish a relationship. The validity will be further evaluated in the time series analysis below. In a similar manner as for Chl a the relationship in Fig. 20 is not optimal for the lower concentrations, which can be seen in Fig. 21. Based on this relationship, lowest concentrations would correspond to negative biovolume. An alternative relationship was created by only including concentrations <20 mg m-3(Fig. 22).

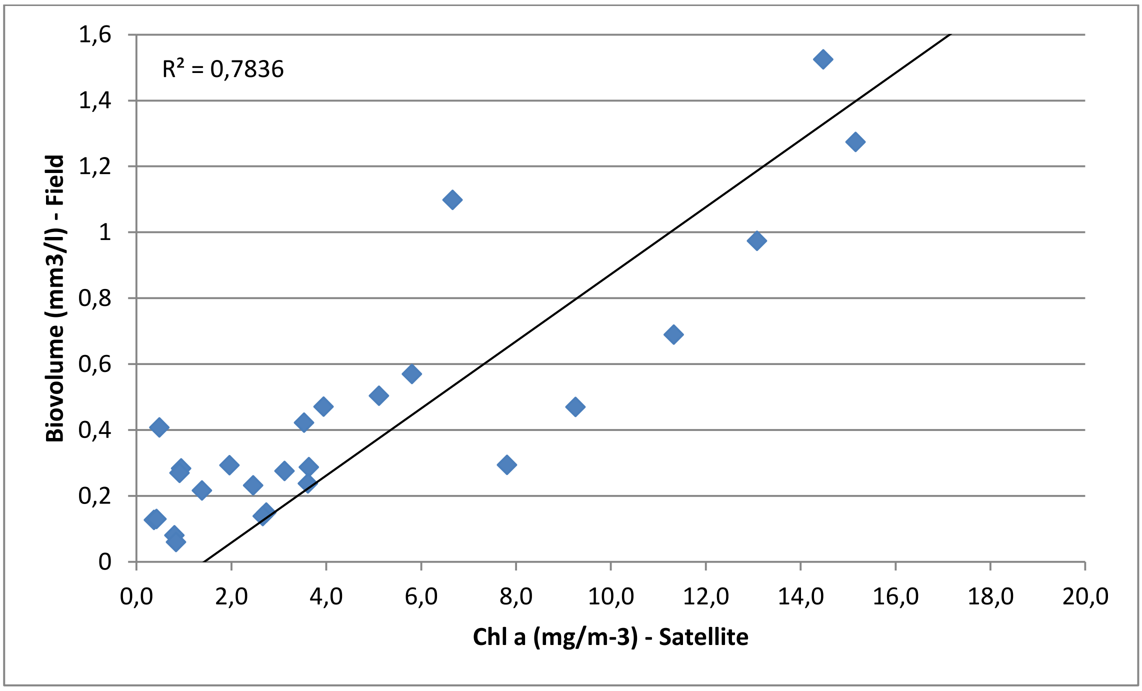


Figure 21. Same day match ups between satellite (uncalibrated Chl a) and field data (BV), with focus on Chl a concentrations between 0-20 mg m-3.

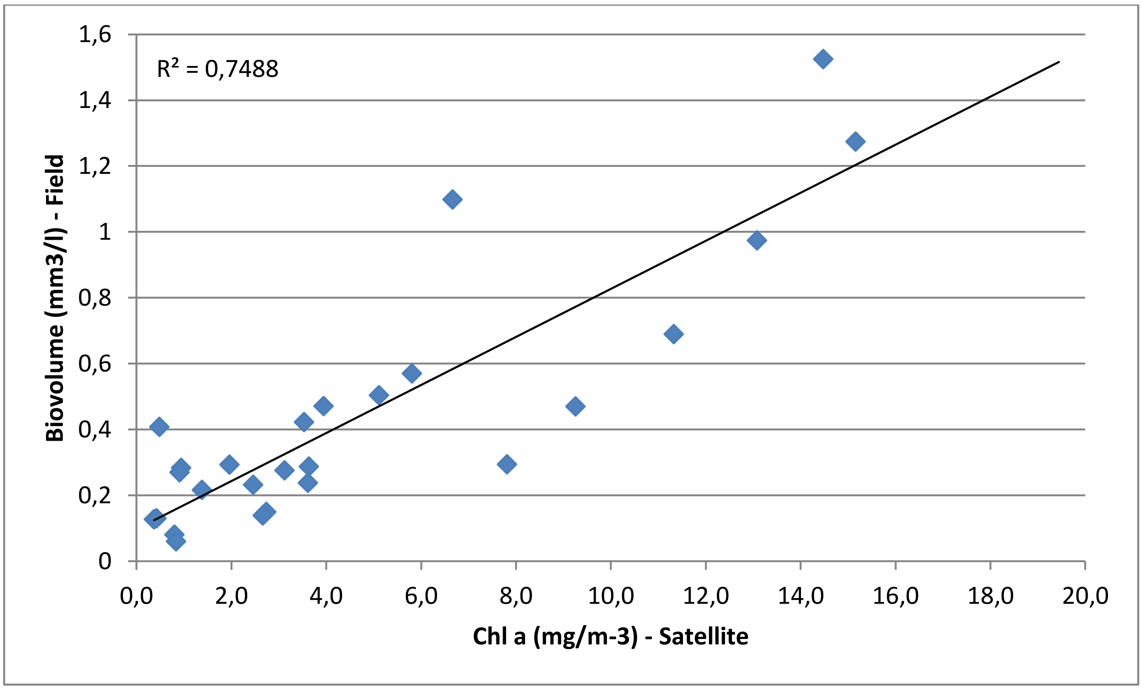


Figure 22. Same day match ups between satellite (uncalibrated Chl a) and field data (BV), only including Chl a concentrations between 0-20 mg m-3.

This relationship fits much better to the lower concentrations, but would generate an underestimation of higher biomasses if generally applied. The offset in the relationship above is 0.0976. In order to retrieve time series of biovolume data, the relationship established by the observations in Figure 22, will be used for control stations <20 mg m-3 and the relationship in Figure 20 for control stations >20 mg m-3 after replacing the negative offset with 0.0976 in order to not produce negative biovolumes for occasionally occurring low concentrations.

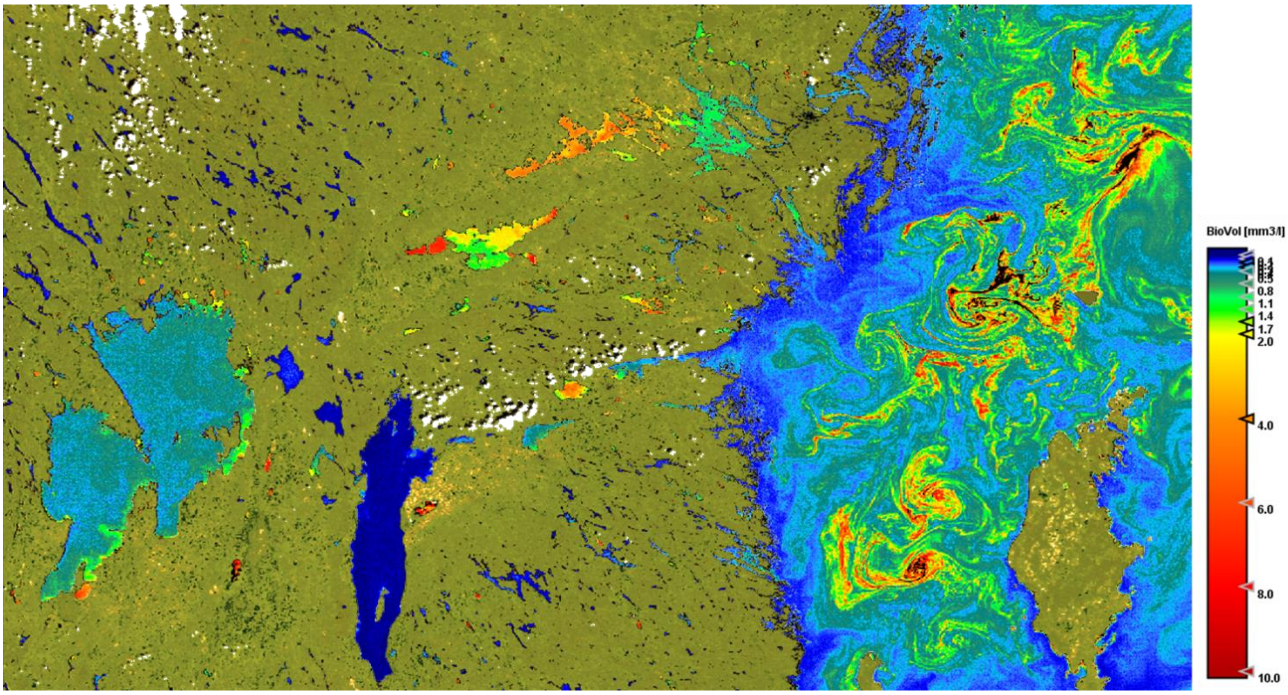


Figure 23. Biovolume, 2008-07-24.

CDOM – Coloured Dissolved Organic Matter

The amount of humic substances in surface water can be measured in different ways. Observations of water color and measurements of water absorbance based on field samples are examples of two methodologies that areused. From satellite, the level of humic substances is measured in terms of absorption by Coloured Dissolved Organic Matter (CDOM), i.e. the coloured fraction of DOC. In the analysis, MERIS based estimations of absorption by Coloured Dissolved Organic Matter (CDOM) at 443 nm (aCDOM(443) m-1) is compared to field based measurements of filtered absorbance (AbsF) at 420 nm (Abs._F 420nm/5cm). In natural waters, these parameters mainly reflect the content of humic substances, but certain iron and manganese compounds could also affect the absorption. The measurement of absorbance is made with a spectrophotometer using a filtered water sample in a 5 cm cuvette. Abs._F 420nm/5cm can be converted to aCDOM(443) and vice versa. The extracted data set was limited to satellite and field data collected on the same date. Taking all available stations into account, the field sampling date matched the image date on 136 occasions, during these ten years (Tab. 6). These match ups has been plotted in Figure 24 below.

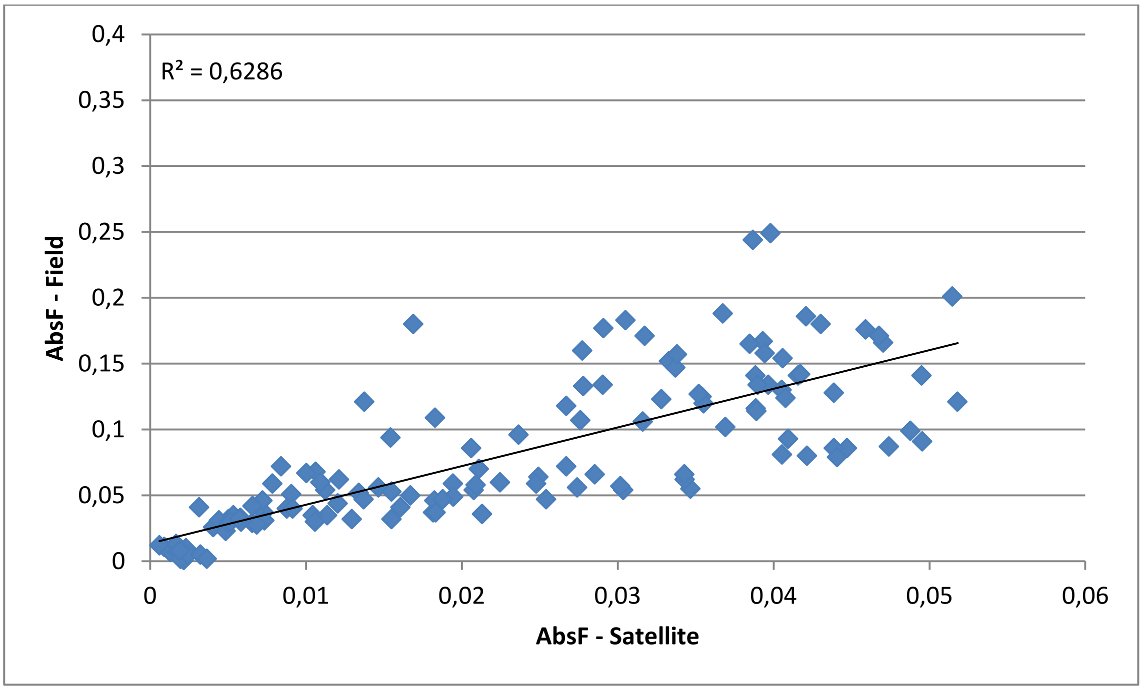


Figure 24. Same day match ups between satellite (CDOM converted to AbsF) and field data (AbsF).

There is a correlation between the two datasets, but variability increases with higher concentrations. A majority of the data points in the upper "cloud" corresponds to stations in Lake Mälaren. The middle group made up mainly of observations from Lake Mälaren and Lake Vänern. The dense cloud of observations in the lower end corresponds to the two Lake Vättern stations. There is only one data point representing Lake Hjälmaren. In total, data from 25 different stations is plotted in Fig. 24. The algorithm underestimates the concentrations with approximately a factor of three. These results are in line with earlier investigations, based on a limited number of images and data [34, 35]. Some of the variability depends on uncertainties and/or limitations in field sampling methodologies and image pre-processing routines (primarily atmospheric correction) as well as temporal differences between the satellite overpass and the collection of the field sample. However, as discussed earlier, the mentioned CDOM algorithm is developed with training data of CDOM absorption between 0-1 m^{-1} (≈0-0.03 AbsF and 0-15 mg Pt/l)). This means that most of these control stations exhibits humic levels out of its training range. Nevertheless, the algorithm has still produced results that are significantly correlated to field data also in more humic waters [36], but it is also likely that there are limits to its applicability. Initial conclusions about these limitations are made based on the time series produced for all control stations, and are described below.

As for the other parameters, the variability is decreased (R^2 increases from 0.63 to 0.72) if data collected in the usually more turbid months, April and May, is removed from the analysis (Fig. 25).

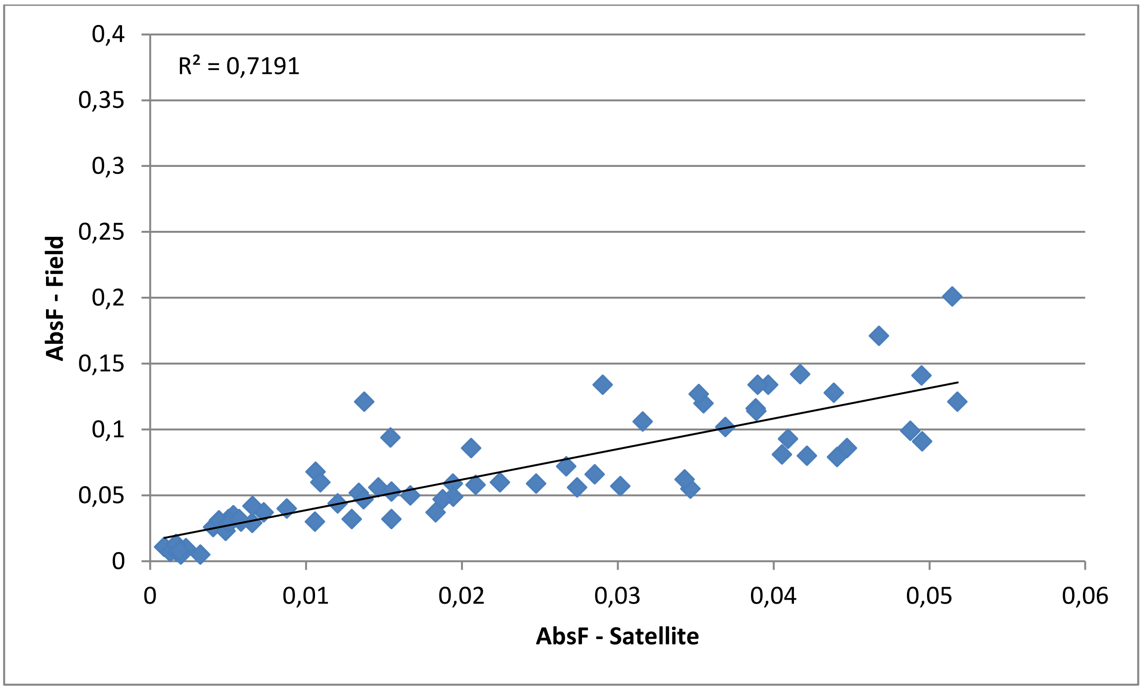


Figure 25. Same day match ups between satellite (CDOM converted to AbsF) and field data (AbsF) after removal samples collected in April and May.

In Figure 25 data from all lakes are included, but with a dominating contribution from Lake Mälaren and Lake Vänern. When pooled, the four lakes exhibit a considerable range in concentrations, which makes it possible to establish a relationship. The validity will be further evaluated in the time series analysis below. In a similar manner as for Chl a this relationship is not optimal for the low concentrations measured at the clear water control stations "Jungfrun" and "Edeskvarnaån"in Lake Vättern. For Lake Vättern stations an alternative relationship was created by forcing the regression line in Figure 25 through the cloud of low concentrations corresponding to these two stations.

In order to retrieve data on absolute concentration levels, the relationship established by the observations in Figure 25, has been used for all stations/lakes, except Lake Vättern, in the rest of the analysis and results, to calibrate the observations, produce time series and to further investigate its validity for different stations/water bodies (Fig. 26). For Lake Vättern the algorithm with adjusted offset has been used.

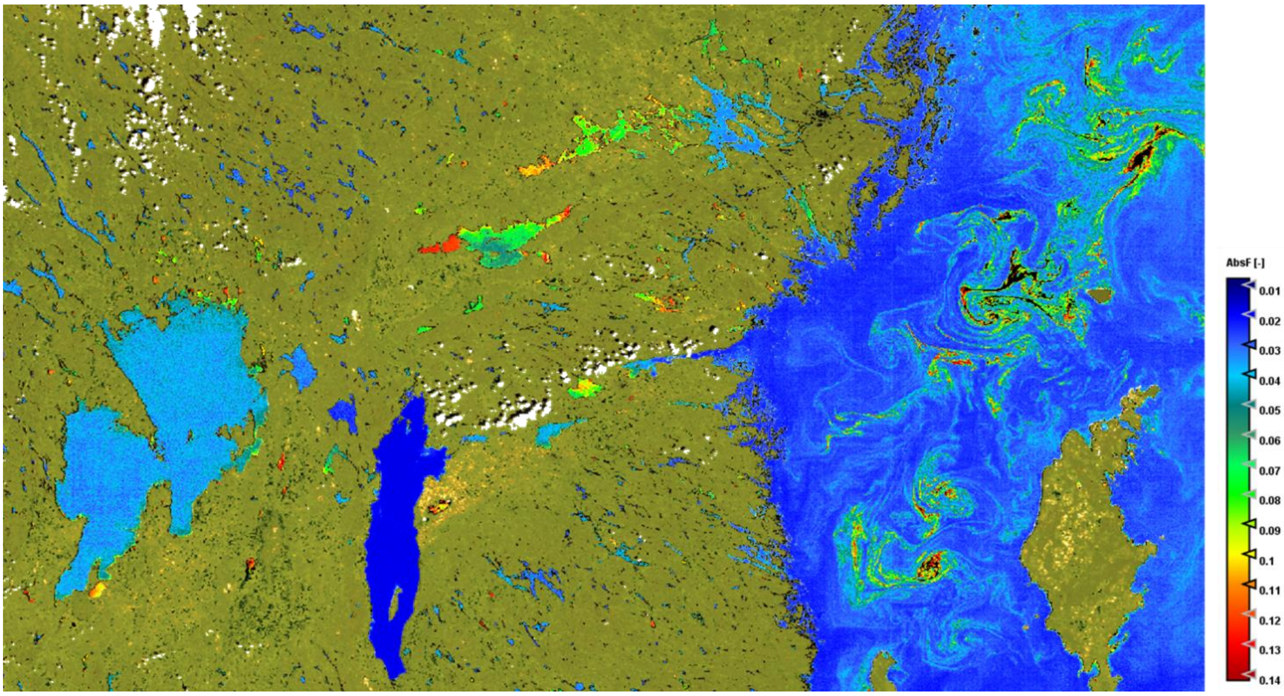


Figure 26. Calibrated AbsF product, 2008-07-24.

SD – Secchi Depth

Secchi depth is a measure of the transparency of the water. Depending on the properties and abundance of water constituents (phytoplankton, humic substances and suspended matter), Secchi depth can be a function of any or all of these parameters. However, in lakes, the absorption of light by humic substances is usually pronounced and dominating the influence on the transparency. Observations of SD are conducted by measuring the depth at which a continuously lowered white disc is not seen by the eye. The extracted data set was limited to satellite and field data collected on the same date. Taking all available stations into account, the field sampling date matched the image date on 226 occasions during these ten years (Tab. 6). For SD three different algorithms has been evaluated [1, 15]. Two are applied to FUB-Rrs spectra and one is established using the FUB-CDOM product as a basis. These match-ups have been plotted in Figure 27 below.

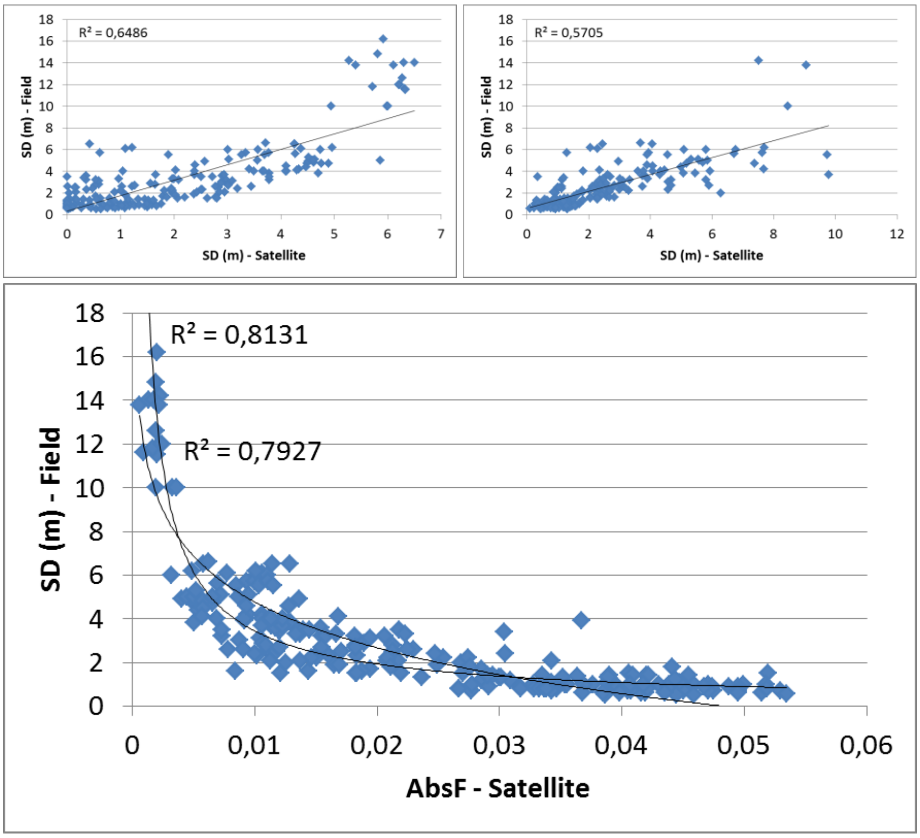


Figure T27a-c. Same day match ups between satellite (SD or AbsF) and field data (SD) based on two already developed algorithms (a, b) and one regression analysis based on the FUB-CDOM product (c).

The algorithm applied in Fig. 27a was developed based on SD, absorption and scattering properties measured in the coastal waters near Himmerfjärden, south of Stockholm [15]. It has been evaluated earlier and the conclusions, which are further confirmed here, is that it a bit insensitive to low Secchi depths and that it reaches an asymptote between 6-7 meters. It works well between 2-6 meters, and was suitable for a large part of the coastal zone, but it is not optimal for the lakes, which often exhibits lower transparency. The algorithm applied in Fig. 27b was developed based on a dataset collected in 14 Estonian and 7 Finnish lakes [1]. The upper limit seems to be a bit higher, but the variability in derived Secchi depths is significantly increased. Similarly to the first algorithm, the sensitivity to lower Secchi depths do not seem to be optimal for the lakes, which often exhibits lower transparency. The relationship between satellite based AbsF and SD is relatively strong (Fig. 27c) and SD does not decrease linearly with increasing CDOM absorption, the relationship instead is rather logarithmic (R^2 = 0.79) or a power function (R^2 = 0.81). Using this relationship for estimation of SD, would make it possible to derive Secchi depths outside the 2-7 meters range. The variability can be further decreased (R^2 increases from 0.81 to 0.83) if data collected in April and May is removed from the analysis, but the trend is not significantly affected. In Figure 27c data from all lakes is included, but with a dominating contribution from Lake Mälaren and Lake Vänern. In total, data from 41 different stations is plotted in Fig. 27c. It would not be possible to build stable relationships only using Lake Vättern and Lake Hjälmaren data, due to the few match-up points and small variability in concentrations. All four lakes together exhibit a large range of concentrations, which makes it possible to establish a stronger relationship. The validity will be further evaluated in the time series analysis below.

A detailed look at the AbsF range between 0.005-0.03 in Figure 27c is shown in Figure 28a, and it seems like there is a division of the data set into two groups. One upper group better fitted to the logarithmic function and one lower that are better described by the power function. Further investigation of the data points reveals that all samples from a certain control station, in most cases, are closer to one of two trend lines. E.g.

data point corresponding to control station “Grumsfjorden”, “Görväln”, “Kattfjorden” and “Åsfjorden” belongs to the upper group, while data points corresponding to control stations “Tärnan”, “Prästfjärden”, “Mariestadsviken” and “Stor-Vänern” are found in the lower group. In Fig. 28b stations associated to the upper group have been filtered out and a power function is fitted to the remaining data points ((R^2 = 0.87). In a similar manner, the data points associated to the lower group was filtered out instead and a logarithmic function is fitted to the remaining data points (R^2 = 0.90).

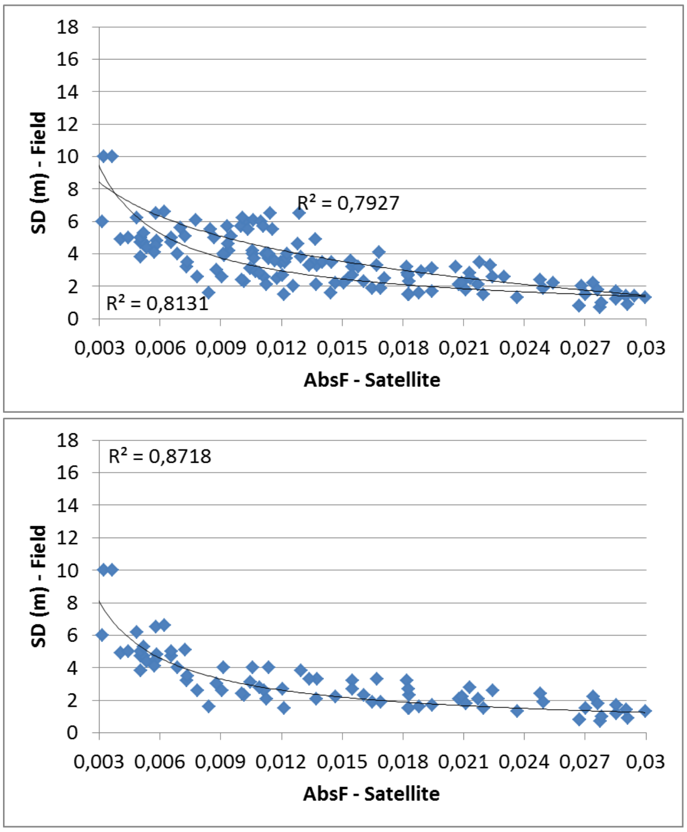


Figure 28a and b. Same day match ups between satellite (AbsF) and field data (SD) for absorbance values = 0.003-0.03.

For most control stations, the power function established by the observations in Fig 28b has been used for Secchi depth estimation, production of time series and to further investigate its validity for different stations/water bodies (Fig. 29). For a limited number of stations, where the time series indicated an underestimation of the Secchi depth, the corresponding logarithmic function is used instead, e.g. “Grumsfjorden”, “Görväln”, “Kattfjorden” and “Åsfjorden”.

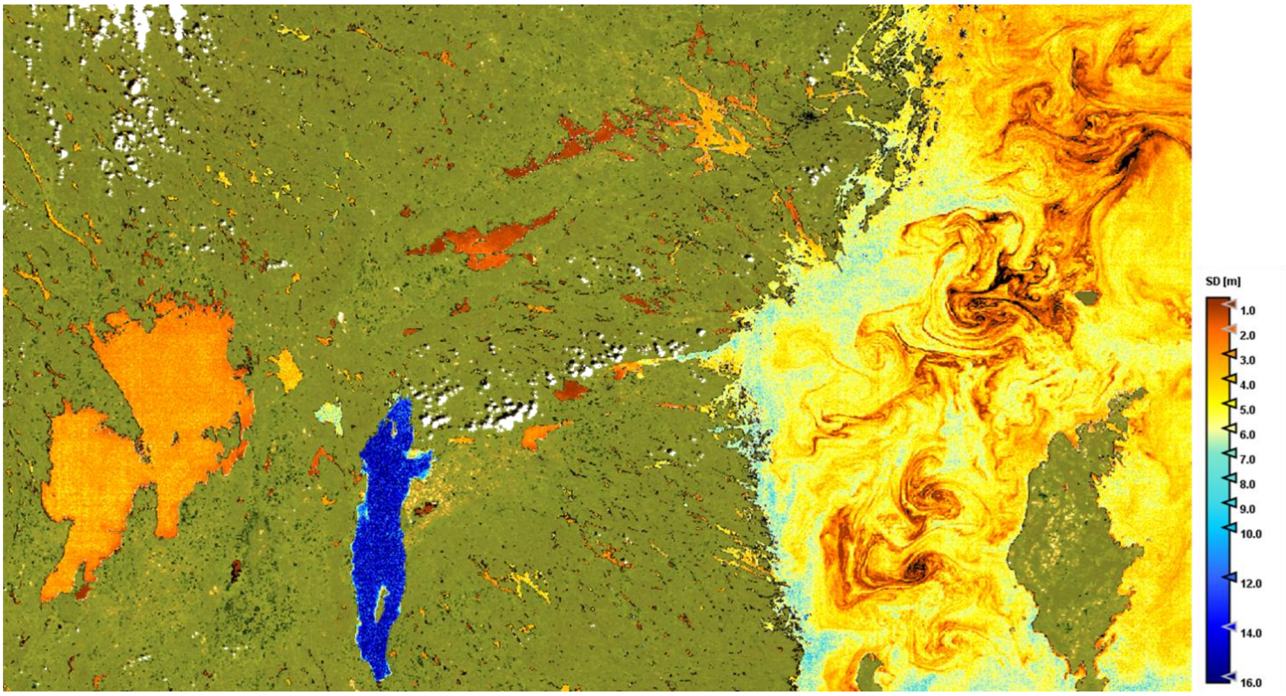


Figure 29. Secchi depth, 2008-07-24.

TSM – Total Suspended Matter

TSM has been compared to measurements of turbidity. Turbidity measures reflects how much of the incident light that deviates from its straight path when it passes through a water sample, which for surface water is largely due to the reflection at the particle surfaces, and is therefore a measure of the concentration of particles in the water. The unit is FNU (Formazine Nephelometric Unit), which expresses how the signal is related to that obtained from a standardized formazin suspension. Turbidity have rarely been measured in laboratory/field and only 14 and 38 match-ups, respectively, where available (Fig. 30). The extracted data set was limited to satellite and field data collected on the same date and focused on turbidity as more match-ups were available for this parameter. As mentioned above, the field sampling date matched the image date on 38 occasions, during these ten years (Tab. 6).

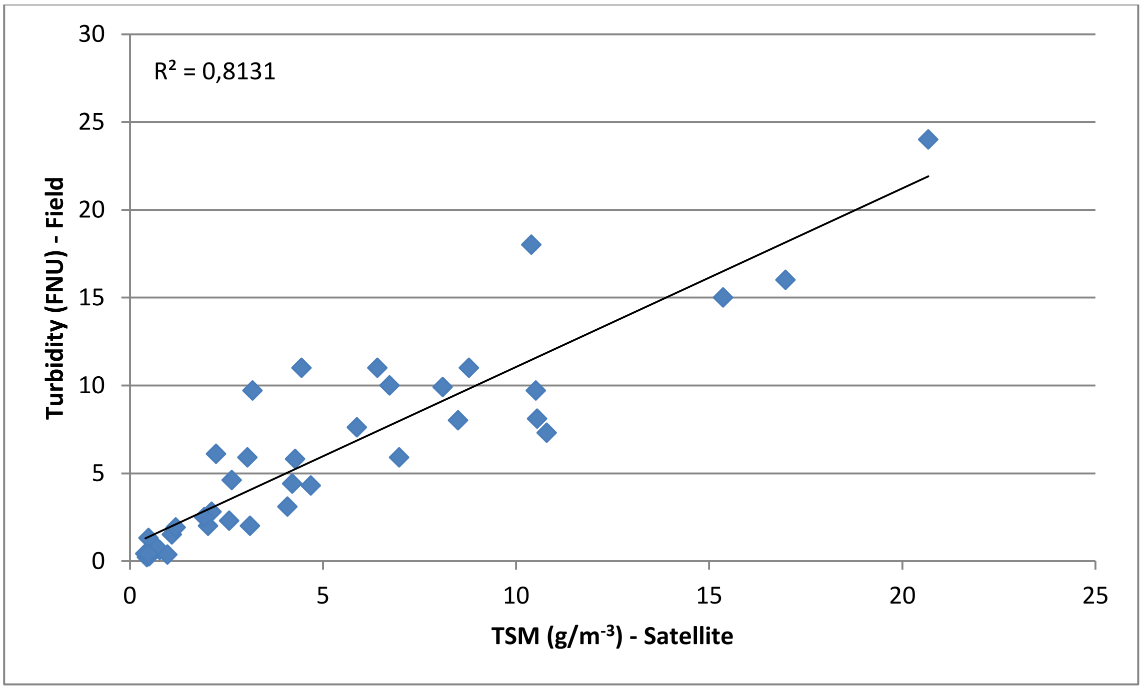


Figure 30. Same day match ups between satellite (TSM) and field data (Turbidity).

The data points plotted in Figure 30 correspond to 16 stations, but only one located in Lake Hjälmaren, and there is a strong correlation between the two parameters. Although the parameters have different units, TSM and turbidity more or less exhibits a 1:1 relationship and earlier investigations have indicated that FUB-TSM products are in correspondence with field based TSM data, also in absolute terms [34, 35]. Removing spring (April) samples excludes the highest concentration, but the trend (slope and offset) is not significantly affected. The relationship in Fig. 30 could be adjusted to better fit also lower concentrations, by replacing the offset with "0" (Fig. 31), but it should be emphasized that FUB-TSM, most likely, do not need calibration to become comparable to field based TSM. 0-offset has also been used in the time series.

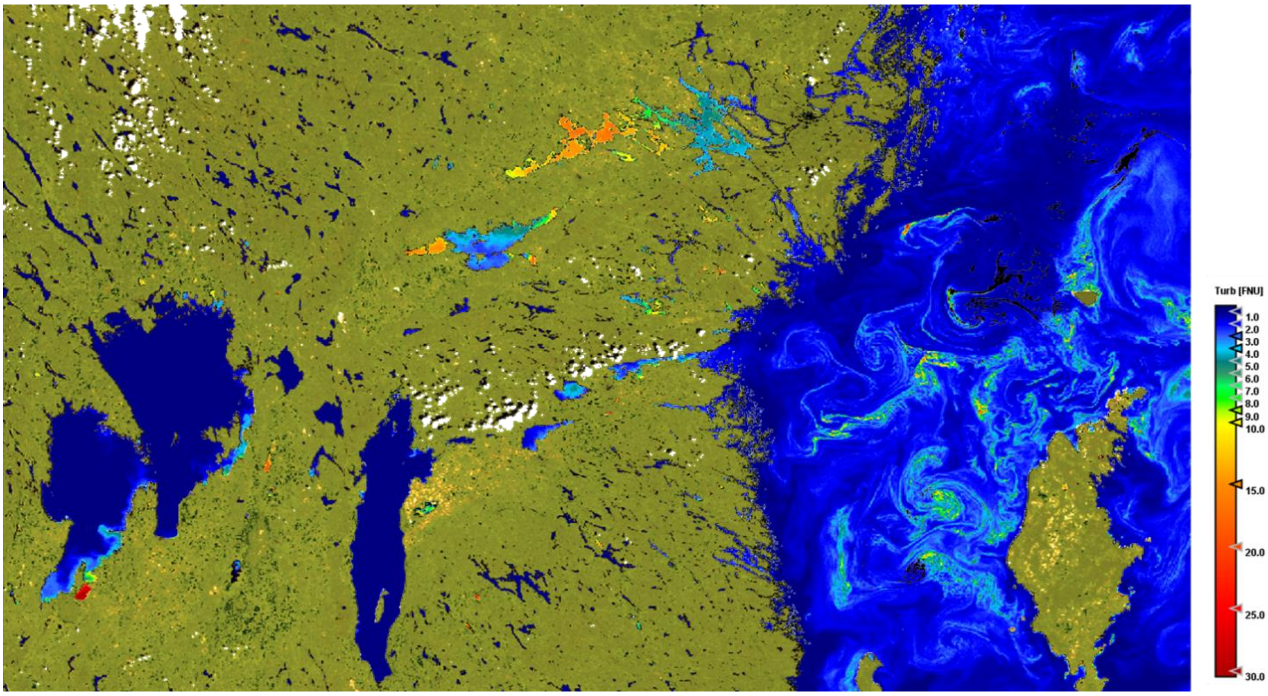


Figure 31. Turbidity, 2008-07-24.

Cyanobacteria

The maximum peak height algorithm (MPH) for detecting trophic status, cyanobacterial blooms, surface scum and floating vegetation in coastal and inland waters using MERIS data has been evaluated with focus on detection of immersed cyanobacteria [27, 28]. When applied to MERIS data, the resulting image consists of "0" or "1", where 1 indicate that the cyanobacterial dominance flag has been raised (Fig. 32).

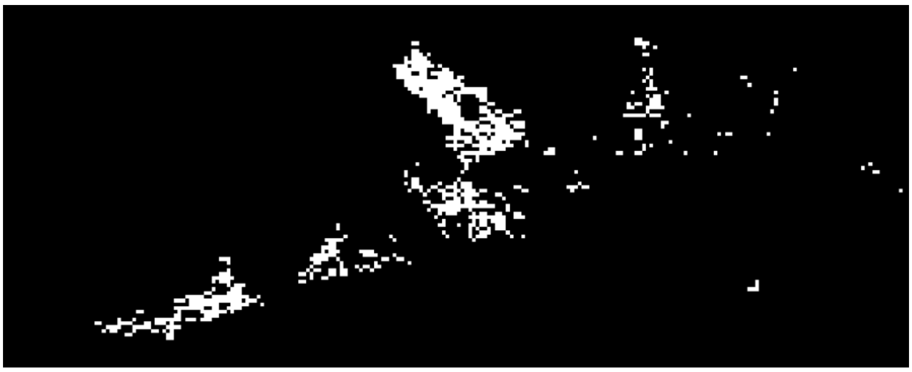


Figure 32. MPH result in western Mälaren, 2010-07-14. White pixels are flagged for cyanobacterial dominance.

After processing of all images, the number of valid pixels per month at a certain position, e.g. a control station, is counted. In the next step, the number of pixels flagged for cyanobacterial dominance is counted and divided by the total number of valid pixels. Hence, in the final monthly product each pixel has a value between 0-1, where 0 indicates that none of the valid pixels where flagged and 1 that all valid pixels where flagged. The monthly products of immersed cyanobacteria has been produced within the framework of "Diversity II, supporting the Convention on Biological Diversity" supported by the European Space Agency (www.diversity2.info) (ESRIN/Contract No. No. 4000106622/12/I-LG) and has been further evaluated within the framework of this project. A number of examples are given below for each lake.

Vänern

There are 176 field samples of biovolume and portion cyanobacteria available from Lake Vänern between 2002-2011. 142 of these are samples taken on monthly basis from the open water control stations "Tärnan", "Megrundet" and "Dagskärsgrund". On average, the cyanobacteria portion at these stations is between 10-15% of the total biovolume, with slightly higher portion (20%) based on data collected in August and Chl a < 20 mg m^{-3}. The cyanobacteria portion never exceeds 50% based on these samples. The MERIS based monthly cyanobacteria products from August, 2002-2011, do not indicate any dominant abundance of floating or immersed cyanobacteria in the open parts where these stations are located (Fig. 33). Figure 34 shows the available number of MERIS observations in August, 2002-2011, which the cyanobacteria product is related to.

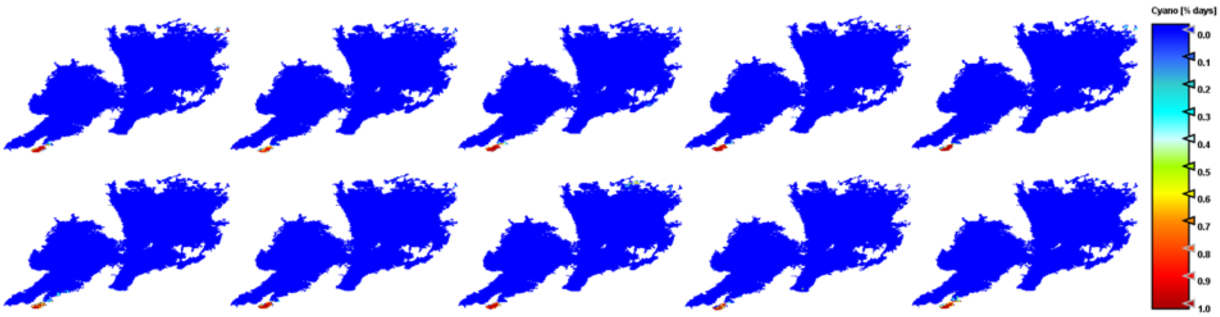


Figure 33. Lake Vänern 2002-2011. Green-red areas indicates that a majority of the observations in August are flagged for cyanobacteria dominance in the water mass.

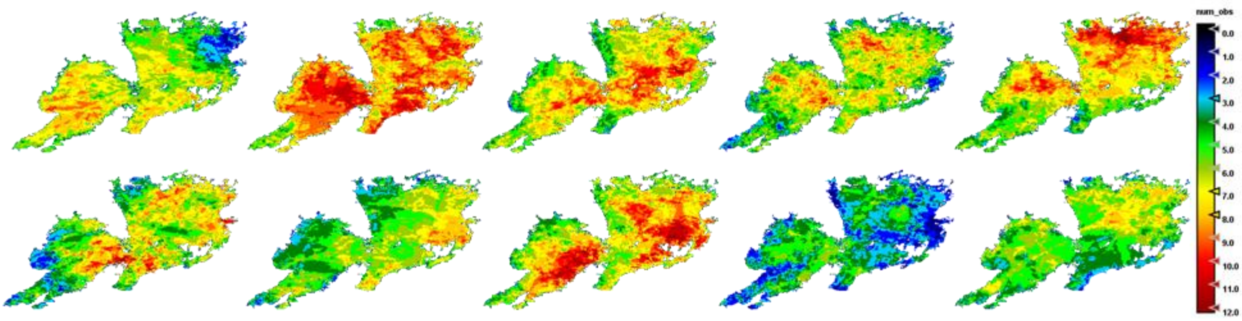


Figure 34. Number of observations per pixel in August, 2002-2011.

The only area in Figure 33, with frequently occurring majority of days in August, dominated by cyanobacteria, is the shallow and turbid Dättern in southern Lake Vänern (Fig. 35). Dättern is characterized by high Chl a concentration (40-50 mg m^{-3}), but the two available field samples cannot confirm cyanobacteria dominance in the total biovolume. These samples were taken 2008-08-28 and 2009-08-27.

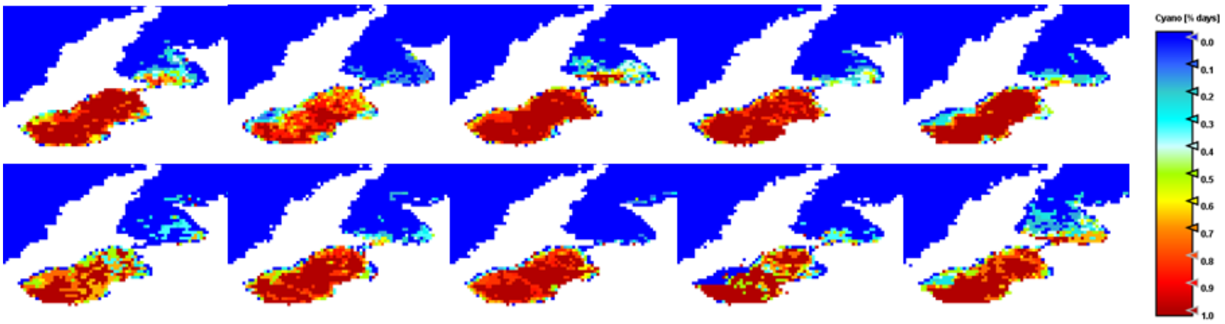


Figure 35. Lake Vänern, Dättern, 2002-2011. Green-red areas indicates that a majority of the observations in August are flagged for cyanobacteria dominance in the water mass.

In addition to Dättern, the MERIS based monthly cyanobacteria product corresponding to Ölmeviken, which is located in the northwestern part of Lake Vänern, indicates cyanobacteria dominance during a few years (2002 and 2005). Chl a sometimes exceeds 20 mg m^{-3}in Ölmeviken. However, these years are also the ones that are based on the fewest satellite observations (1-4). There is no field data of cyanobacterial biovolumes available to confirm the results.

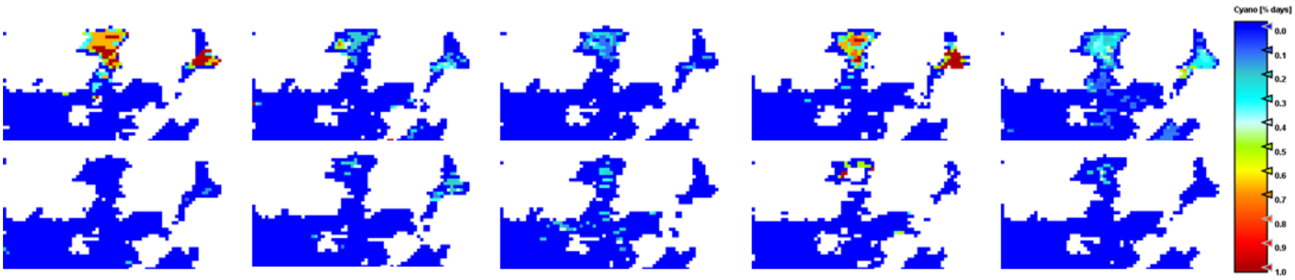


Figure 36. Lake Vänern, Ölmeviken, 2002-2011. Green-red areas indicates that a majority of the observations in August are flagged for cyanobacteria dominance in the water mass.

Among the available 176 field samples of biovolume and portion cyanobacteria only one showed cyanobacteria dominance (77%). That sample was collected in Arnöfjorden 2009-08-25. According to the MERIS based cyanobacteria products, a majority of the days with satellite observations were flagged for cyanobacteria dominance in the area around Arnöfjorden during the same time period. Actually, the same area is flagged for cyanobacteria dominance during almost the whole season 2009 (May-August), but not always for a majority of observations (Fig. 37 and 38).

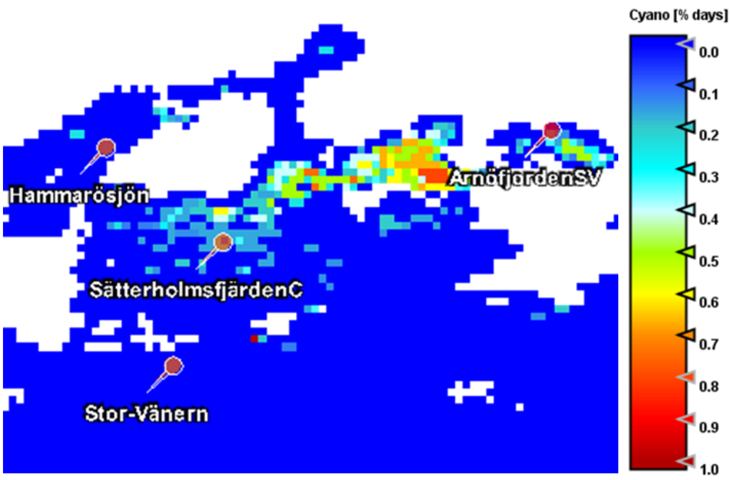


Figure 37. Lake Vänern, Arnöfjorden, August, 2009. Green-red areas indicates that a majority of the observations in August are flagged for cyanobacteria dominance in the water mass.

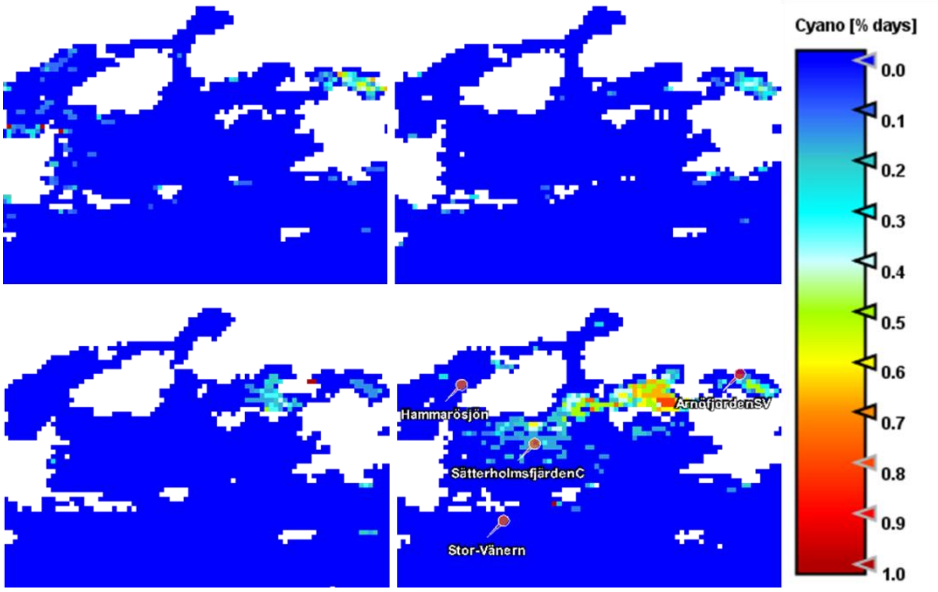


Figure 38. Lake Vänern, Arnöfjorden, May-August, 2009. Green-red areas indicates that a majority of the observations in August are flagged for cyanobacteria dominance in the water mass.

In the sample taken one year before (2008) at the same station, the cyanobacteria proportion is 6% and the total biovolume lower. The MERIS based monthly cyanobacteria products from May-September, 2008, do not indicate any dominant abundance of floating or immersed cyanobacteria either.

It is not possible to make good quantitative evaluations based on field data where the cyanobacteria proportion does not exceed 50% as the MERIS based product requires this abundance in order to flag for cyanobacteria dominance. As MERIS data is more frequently available, a summary of all months and all stations where more than half (>0.5) of the available observations are flagged for cyanobacteria dominance, is listed in Table 7. Months that only correspond to one observation are not included. In addition to these, the cyanobacteria flag is always, with a few exceptions, raised in Dättern (Fig. 35). The exceptions are May 2003, 2006 and 2007 and June 2003.

Table 7. Months and stations flagged for cyanobacteria dominance in Lake Vänern.

Name	Year-month	No. of observations	Immersed cyano (% observations)	Chl a (mg m^{-3})
Brandsfjorden	2002-08	6	0.67	-
Brandsfjorden	2004-08	5	1	-
Brandsfjorden	2008-04	9	0.67	-
Brandsfjorden	2010-08	3	0.67	-
Varnumsviken	2002-08	2	1	7.8
Varnumsviken	2004-07	4	0.75	51
Ölmeviken	2002-08	3	0.67	9.8
Ölmeviken	2005-08	4	0.75	25
Ölmeviken	2006-07	7	0.57	18

In Brandsfjorden in south-western L. Vänern there are two field samples where the proportion cyanobacteria intotal biovolume are available (August 2008 and 2009). None of these samples indicate cyanobacteria dominance (22%, 16%) and corresponding pixels are not flagged in MERIS based products either. The measured Chl a concentration is only 10 mg m-3 (2008) and 6 mg m-3 (2009) and according to the MERIS based time series of Chl a, only a few observations >20 mg m^{-3}. However, slightly higher concentrations prevails in 2002-04, 2005, 2008 and 2010, which includes the years listed in Table 7. In Varnumsviken in north-east L. Vänern Chl a concentrations >20 mg m^{-3} are common, with higher than average values in 2004-06, including an extreme level (52 mg m^{-3}) in July 2004. Field samples from July 2002 indicated higher concentrations, but the sample in August only measured 7.8 mg m-3 . Ölmeviken is situated close to Varnumsviken and is flagged for cyanobacterial dominace during the same months as field samples indicates Chl a > 20 mg m-3, but not otherwise. As mentioned above, cyanobacteria dominated waters with Chl a < 20 mg m^{-3}, is much less reliable that at higher Chl levels, which means that cyanobacterial dominance might prevail in Ölmeviken, but is not flagged for. However, ongoing research indicates that cyanobacterial blooms could be detected even in waters with Chl a ≥ 12 mg m^{-3}[manuscript in progress].

Mälaren

There are 175 field samples of biovolume and the proportion of cyanobacteria are available from Lake Mälaren between 2002-2011. These samples were collected at control stations “Södra Björkfjärden”, “Görväln”, “Ekoln”, “Granfjärden”and “Galten” on a monthly basis. Unfortunately, “Galten” and “Ekoln” were not included in the products generation within Diversity II, which leaves 105 samples for evaluation. On average, the cyanobacteria proportion at these three stations is between 8-17% of the total biovolume, with higher proportions (14-42%) based on data collected in August. According to the MERIS based monthly cyanobacteria products cyanobacteria very seldom dominates the total biovolume in the western and middle part of Lake Mälaren and the general pattern over the investigated years is similar to the one exhibited in 2011 as shown in Figure 39. However, the Chl a concentrations at control stations “Görväln”, “Södra Björkfjärden” and “Prästfjärden” only occasionally exceeds 20 mg m^{-3}, which means that the detection of possible cyanobacterial dominance is less reliable. The average Chl a concentration between 2002-2011, at stations “Svinnegarnsviken” and “Ulvhälsfjärden”, is 21 mg m^{-3} and 17 mg m^{-3} respectively, which is on the detection limit. Chl a concentration > 20 mg m^{-3}, is more frequent at stations “Granfjärden” and “Blacken” and relatively common at station “Västeråsfjärden”. Average concentrations are 13, 11 and 22 mg m^{-3} respectively.

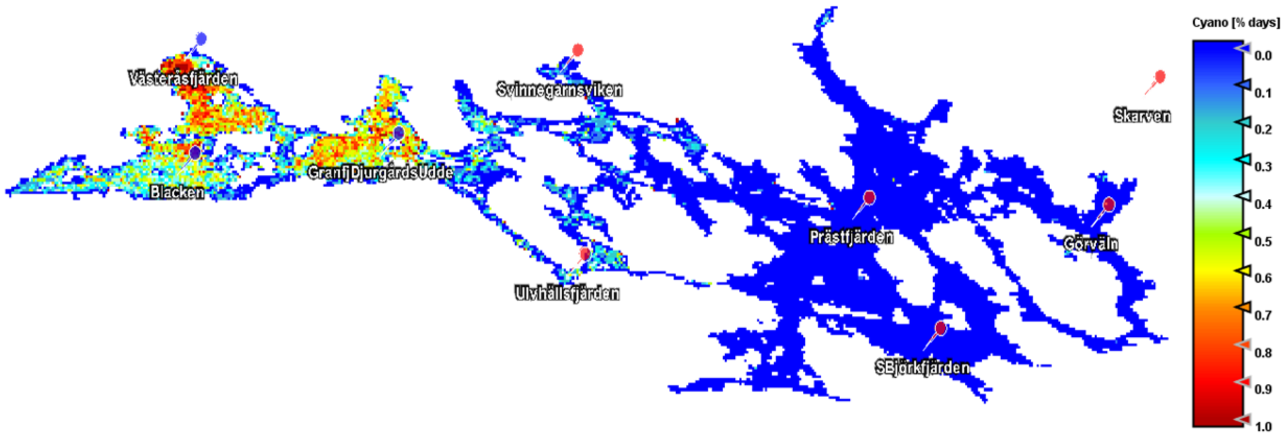


Figure 39. Lake Mälaren, August, 2011. Green-red areas indicates that a majority of the observations in August are flagged for cyanobacteria dominance in the water mass.

Compared to the pattern exhibited in Fig. 39, the most divergent years are August 2002, 2007 and 2010 (Fig. 40), where the flag for cyanobacterial dominance has been raised during a few days also in the middle and eastern parts of Lake Mälaren. Chl a concentrations at stations “Södra Björkfjärden” and “Prästfjärden” do not exceed 20 mg m^{-3} in 2007, but are still flagged for cyanobacterial dominance. As mentioned before, ongoing research indicates that cyanobacterial blooms could be detected even in waters with Chl a ≥ 12 mg m^{-3}[manuscript in progress].

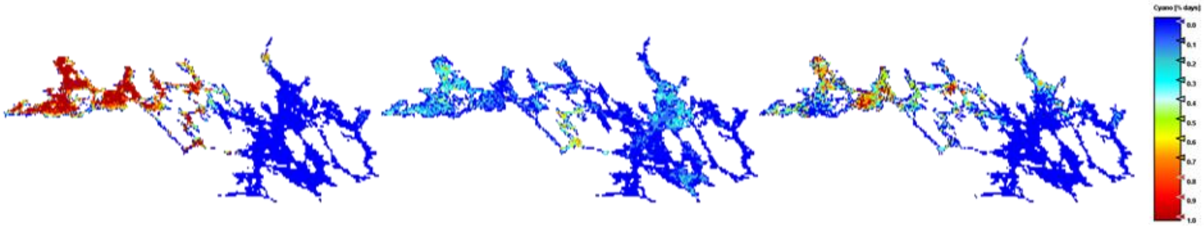


Figure 40. Lake Mälaren 2002, 2007 and 2010. Green-red areas indicates that a majority of the observations in August are flagged for cyanobacteria dominance in the water mass.

An overview of the products for eastern Lake Mälaren, east of Ulvhällsfjärden and Svinnegarnsviken, is shown in Fig. 41a. Figure 41b shows the available number of MERIS observations in August, 2002-2011, which the cyanobacteria product is related to.

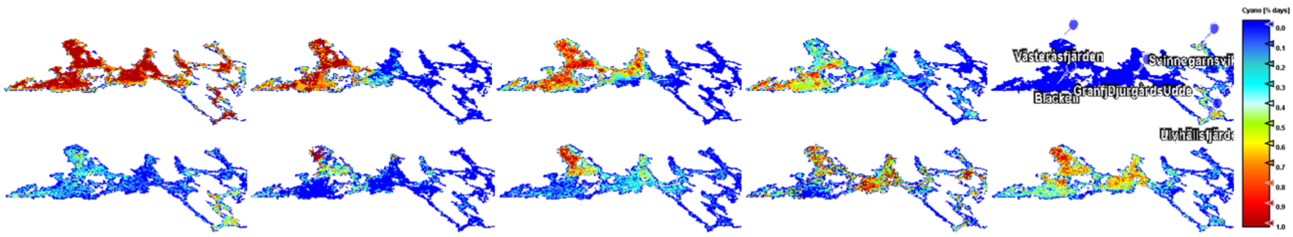


Figure 41a. West Lake Mälaren 2002-2011. Green-red areas indicates that a majority of the observations in August are flagged for cyanobacteria dominance in the water mass.

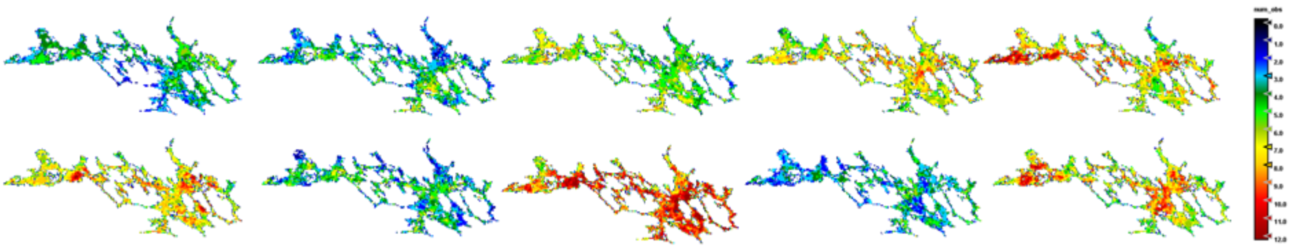


Figure 41b. Number of observations per pixel in August, 2002-2011.

According to the available field data, the cyanobacteria proportion exceeded 50% on five occasions during these years. Three samples were taken in Granfjärden and one in Södra Björkfjärden and Görväln respectively. The sample from Södra Björkfjärden was collected 2007-08-14 and indicated that the proportion of cyanobacteria was 60% of the total biovolume. Looking at the MERIS based monthly cyanobacteria products between 2002-2011 the flag for cyanobacteria dominance is only raised once and that was in August 2007. In total, nine valid observations are available for control station "Södra Björkfjärden in August 2007 and on one of these nine dates the flag for immersed cyanobacteria dominance was raised (Fig. 42). The field sample collected in August 2007 measured a Chl a concentration of 7.8 mg m^{-3}. The sample from Görväln was also collected 2007-08-14 and indicated 51% cyanobacteria in the total biovolume. Looking at the MERIS based monthly cyanobacteria product from Görväln there is no indication of cyanobacteria dominance in August 2007. The field sample collected in Görväln in August 2007 measured a Chl a concentration of 10.8 mg m^{-3}.

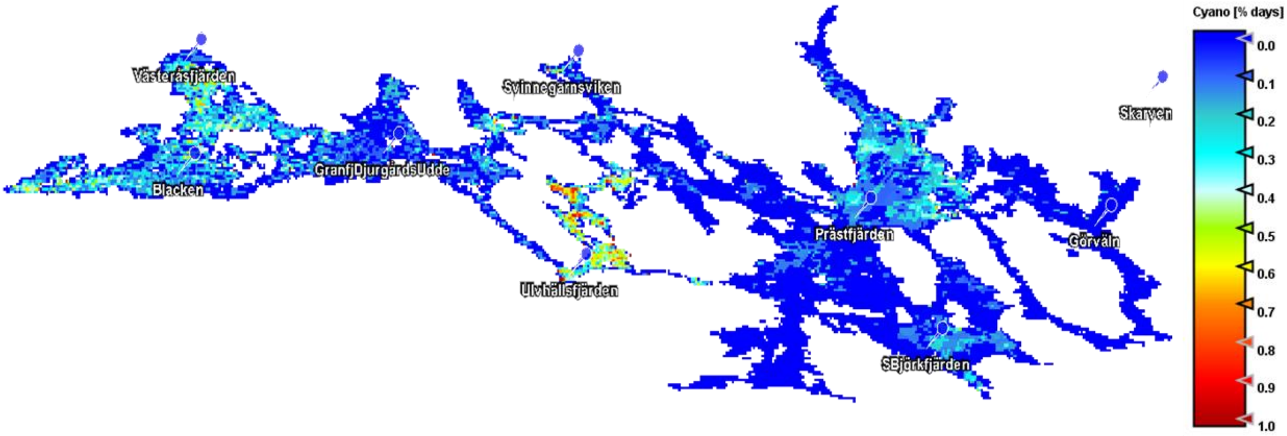


Figure 43. Lake Mälaren, August, 2007. Infrequent indications of temporally limited cyanobacteria dominance in eastern Lake Mälaren.

The samples from Granfjärden were collected in July, August and September 2002 and indicated 56%, 92% and 56% cyanobacteria in the total biovolume respectively. Looking at the MERIS based monthly cyanobacteria product from Granfjärden during the same months, the cyanobacteria flag is raised for 100%, 100% and 50% of the available observations (Fig. 44). However, only one valid observation was available in July 2007. The field samples collected in Granfjärden in 2002 measured Chl a concentrations of 43.4, 27.8 and 14.9 mg m^{-3} respectively.

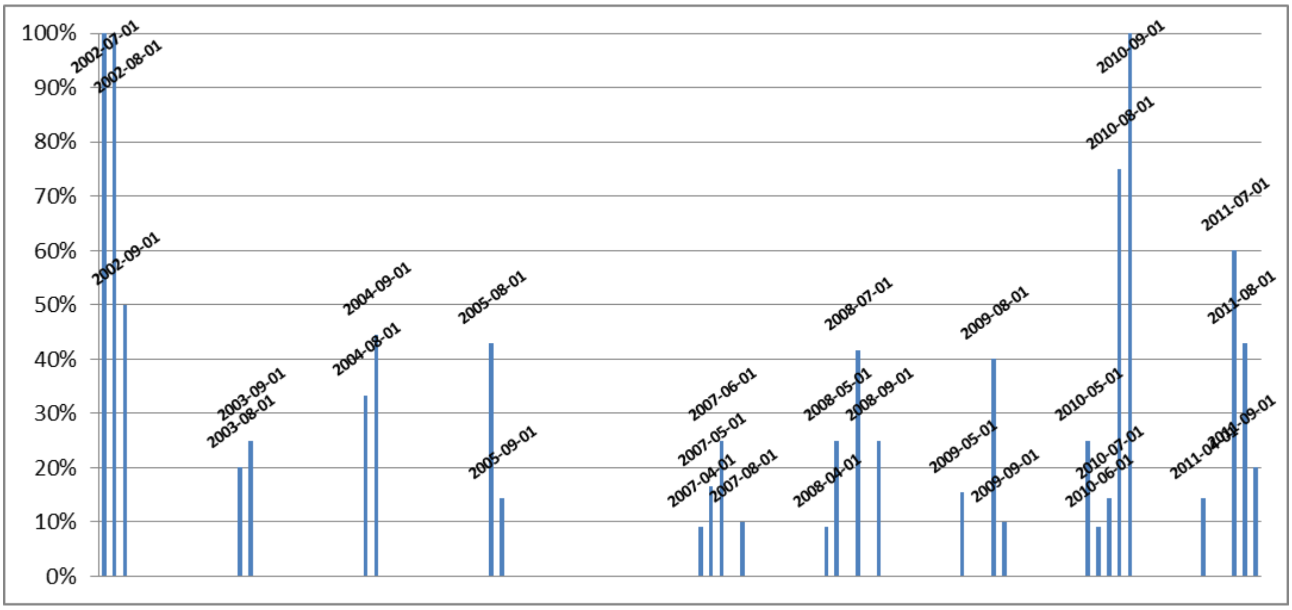


Figure 44. The percentage of all valid observations available for each month, where the cyanobacteria dominance flag has been raised at control station "Granfjärden". For example, in August 2002, five valid observations (No. not in graph) were available for control station "Granfjärden". For all of these (100%) the "immersed cyanobacteria" flag was raised. In September 2002, two valid observations (No. not in graph) were available for control station "Granfjärden". For one of these (50%) the "immersed cyanobacteria" flag was raised.

Fig. 44 show that the proportion of cyanobacteria was elevated also in 2010. The MERIS based monthly cyanobacteria product from July, August and September 2010 is based on seven, four and three observations respectively at the control station "Granfjärden", and the cyanobacteria flag is raised in one (14%), three (75%) and three (100%) of these products. The field sample from July was collected 2010-07-13 and indicated 28% cyanobacteria in the biovolume. The closest (in time) MERIS product 2010-07-14 is not flagged for dominance of cyanobacteria either, which indicates that the cyanobacteria dominance most likely occurred earlier. Image data is available between 3rd to 16th of July. The field sample from August and

September was collected 2010-08-17 and 2010-09-14 and indicated 9% and 7% cyanobacteria in the biovolume, i.e. not dominating the biovolume. The MERIS based monthly cyanobacteria products indicates higher abundance but the included image dates are collected between mid-August and early September, i.e. after and before these samples were collected. The field samples collected in Granfjärden in 2010 measured Chl a concentrations of 10.5 (July), 12.8 (Aug) and 10.8 (Sept) mg m^{-3}.

It is not possible to make good quantitative evaluations based on field data where the cyanobacteria portion does not exceed 50% as the MERIS based product requires this abundance in order to flag for cyanobacteria dominance. As MERIS data is more frequently available, a summary of all months and all stations where more than half (>0.5) of the available observations are flagged for cyanobacteria dominance, is listed in Table 8. A few months only corresponds to 1-2 observations, which should be considered in the interpretation of the data. Corresponding field based concentrations of Chl a is listed when available.

Table 8. Months and stations flagged for cyanobacteria dominance in Lake Mälaren.

Name	Year-month	No. of observations	Immersed cyano (% observations)	Chl a (mg m^{-3})
Blacken	2002-07	1	1	16.7
Blacken	2002-08	5	1	26
Blacken	2003-08	3	1	18.5
Blacken	2004-08	7	0.57	8.3
Blacken	2005-08	8	0.63	26
Blacken	2007-06	9	0.56	-
Blacken	2010-09	1	1	15.5
Granfjärden	2002-07	1	1	43.4
Granfjärden	2002-08	5	1	27.8
Granfjärden	2010-08	4	0.75	12.8
Granfjärden	2010-09	3	1	10.8
Granfjärden	2011-07	5	0.6	14.6
Svinnegarnsviken	2002-08	5	0.8	60
Svinnegarnsviken	2005-09	5	0.6	20
Svinnegarnsviken	2009-09	5	0.8	22.5
Ulvhällsfjärden	2002-08	3	1	17.1
Ulvhällsfjärden	2010-08	3	0.67	30.3
Västeråsfjärden	2002-07	1	1	27.7
Västeråsfjärden	2002-08	4	1	98.2
Västeråsfjärden	2003-08	2	1	50.8
Västeråsfjärden	2004-08	9	0.78	32
Västeråsfjärden	2004-09	9	0.78	7.6
Västeråsfjärden	2005-09	7	0.86	19
Västeråsfjärden	2007-05	6	0.67	19.5
Västeråsfjärden	2009-08	7	0.57	21.4
Västeråsfjärden	2009-09	5	0.8	20.6
Västeråsfjärden	2010-07	6	0.67	27.8
Västeråsfjärden	2010-08	3	1	17.6
Västeråsfjärden	2011-07	4	1	17.2
Västeråsfjärden	2011-08	6	0.67	52.2

Published reports from Lake Mälaren Society for water conservation identifies Galten, Granfjärden and Ekoln as dominated by diatoms and cyanobacteria, while the cryptophytes usually dominate in Görväln and Södra Björkfjärden [www.malaren.org]. Unfortunately, as mentioned above, Galten and Ekoln were not included in the products generated within Diversity II. Field data for Svinnegarnsviken and Västeråsfjärden indicates presence of cyanobacteria at both stations and increased levels in July-August. However, the ratio could not be calculated as total biovolume was not available.

Vättern

The monthly cyanobacteria products from August, 2002-2011, do not indicate significant abundance of floating or immersed cyanobacteria in Lake Vättern. A few occasional pixels are flagged for cyanobacteria near the shorelines. Looking at available field data cyanobacterial dominace (57%) is measured in one sample during these years. That sample was taken at control station Alsen in August 2009. There is no valid data produced in Alsen in the monthly cyanobacteria product from August 2009. However, the time series for biovolume indicates an increase in biomass in August 2009 (Fig. 45). In addition, four field samples collected at stations Jungfrun (2010-07-27 and 2011-07-28) and Edeskvarnaån (2006-04-27 and 2011-07) showed that 30-50% of the biovolume consisted of cyanobacteria, but according to the corresponding satellite products no cyanobacteria dominance was flagged, which indicates that the portion never exceeded 50%. However, as mentioned above, cyanobacteria dominated waters with Chl a < 20 mg m^{-3}, is most likely not detected.

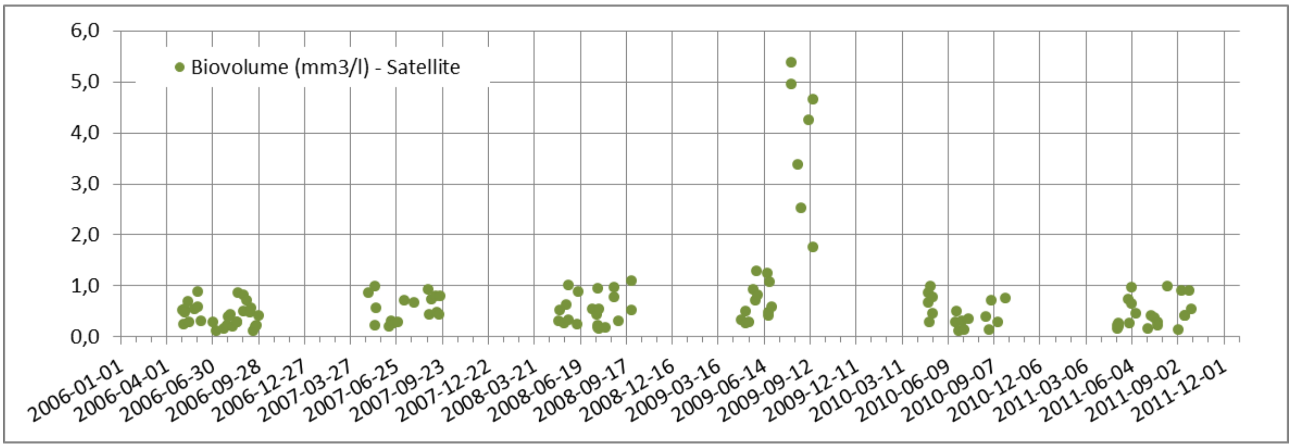


Figure 45. Alsen – Estimated biovolume between 2002-2011.

Hjälmaren

There are eight field samples where the biovolume and proportion of cyanobacteria is available from Lake Hjälmaren between 2010-2011. These samples were collected at control stations "Hemfjärden", "Mellanfjärden", "Storhjälmaren" and "Östra Hjälmaren" in August. Unfortunately, "Hemfjärden" was not included in the products generated within Diversity II, which leaves six samples for the evaluation. On average, the cyanobacteria proportion at these four stations is between 30-71% of the total biovolume. The Chl a concentrations at these stations usually exceeds 20 mg m^{-3}, except for station "Storhjälmaren", which varies between 4-41 mg m^{-3} over the years. The average Chl a concentration between 2002-2011, at station "Storhjälmaren" is 18.6 mg m^{-3}, which is close to the detection limit. According to the MERIS based monthly cyanobacteria products cyanobacteria usually dominates the total biovolume in some part of the lake (Fig. 46). Figure 47 shows the number of MERIS observations in August, 2002-2011, which the cyanobacteria product is based on

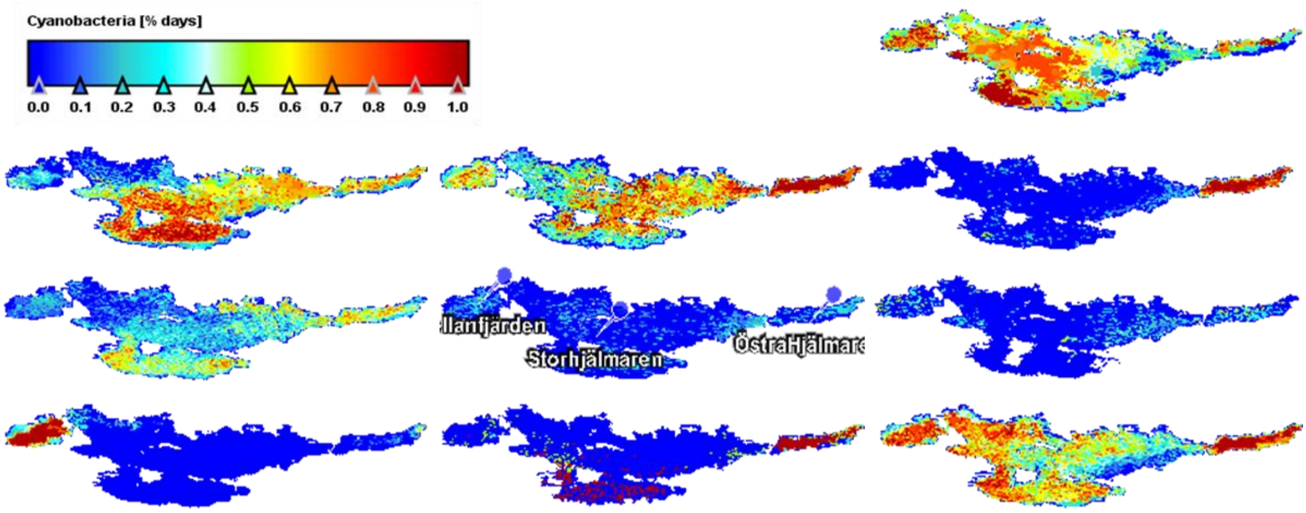


Figure 46. Lake Hjälmaren 2002-2011. Green-red areas indicates that a majority of the observations in August are flagged for cyanobacteria dominance in the water mass.

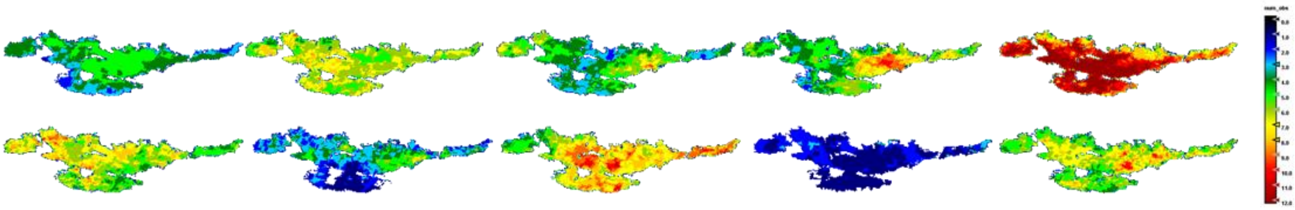


Figure 47. Number of observations per pixel in August, 2002-2011.

According to the available field data, the cyanobacteria proportion exceeded 50% on four occasions during these two years. One of these samples was taken in Mellanfjärden, one in Storhjälmaren and two at station "Östra Hjälmaren". The sample from station "Mellanfjärden" was collected 2011-08-25 and indicated 89% cyanobacteria in the total biovolume and a Chl a concentration of 115 mg m^{-3}. Looking at the MERIS based monthly cyanobacteria product, 5 out of 6 (83%) available observations are flagged for cyanobacterial dominance. The sample from station "Storhjälmaren" was collected 2011-08-30 and indicated 54% cyanobacteria in the total biovolume and a Chl a concentration of 41 mg m^{-3}. Looking at the MERIS based monthly cyanobacteria product, 2 out of 7 (29%) available observations are flagged for cyanobacterial dominance. The samples from station "Östra Hjälmaren" were collected 2010-08-10 and 2011-08-23 and indicated 54% and 86% cyanobacteria in the total biovolume and Chl a concentrations of 37 mg m^{-3} and 59 mg m^{-3} respectively. Looking at the MERIS based monthly cyanobacteria product, there are no products available in August 2010, but 2 of 4 (50%) available observations are flagged for cyanobacterial dominance in 2011. The available number of observations for station "Östra Hjälmaren" is usually low, as it is located very close to land and often excluded in the land-water/mixed pixel masking process.

It is not possible to make good quantitative evaluations based on field data when the cyanobacteria portion do not exceed 50% as the MERIS based product requires this proportion in order to flag for cyanobacteria dominance. As MERIS data is more frequently available, a summary of all months and all stations where more than half (>0.5) of the available observations are flagged for cyanobacteria dominance, is listed in Table 9. Months that only correspond to one observation are not included.

Table 9. Months and stations flagged for cyanobacteria dominance in Lake Hjälmren.

Name	Date	No. of observations	Immersed cyano (% observations)	Chl a (mg m^{-3})
Mellanfjärden	2002-08	4	1	41
Mellanfjärden	2003-07	6	0,67	-
Mellanfjärden	2003-09	6	0,67	-
Mellanfjärden	2004-06	6	0,83	-
Mellanfjärden	2004-08	6	0,83	55 (2004-07-29)
Mellanfjärden	2008-07	10	0,6	-
Mellanfjärden	2009-05	8	0,75	-
Mellanfjärden	2009-07	3	0,67	-
Mellanfjärden	2009-08	5	1	40
Mellanfjärden	2009-09	9	1	-
Mellanfjärden	2010-05	8	0,75	-
Mellanfjärden	2010-06	13	0,85	-
Mellanfjärden	2011-05	9	0,56	-
Mellanfjärden	2011-08	6	0,83	115
Mellanfjärden	2011-09	8	0,75	-
Storhjälmaren	2002-08	5	0,8	33
Storhjälmaren	2003-08	7	0,71	22
Storhjälmaren	2004-08	2	1	16 (2004-07-29)
ÖstraHjälmaren	2004-08	2	1	44 (2004-07-29)
ÖstraHjälmaren	2005-08	2	1	31

Summary & Error assessment

The selected algorithms for calibration of MERIS data to field based levels/parameters are shown in chapter "Match up analysis & calibration algorithms" for Chl a, BV, CDOM, SD and TMS respectively. Initially, the Mean Absolut Error (MAE) and Root Mean Square error (RMSE) has been calculated for each algorithm in order to describe the overall difference between the two techniques. The error is given in the same unit as the variables have been measured, e.g. mg m^{-3}. Usually, these measures are used to calculate errors in a modelled variable expressed as the difference compared to the corresponding observation. In this case, it is important to point out that there are natural differences in what these two methods measure and that a certain degree of the differences (errors) is due to this and not to errors in the established models capability to predict these concentrations. For example, the laboratory measurement is based on a few liters of water, while the averaged satellite concentration represents several hundreds of thousands cubic meters of water, depending on the transparency of the water and the number of pixels included in the observation average. There are (different) measurement errors attributed to both techniques and the target measured is not identical, especially in turbid/eutrophic waters.

The MAE measures the average magnitude of the errors for continuous variables. The MAE is a linear score which means that all the individual differences are weighted equally in the average. The RMSE is a quadratic scoring rule. Since the errors are squared before they are averaged, the RMSE gives a relatively high weight to large errors. This means the RMSE is most useful when large errors are particularly undesirable, but it might not be an optimal measure in this case as large errors usually occur for natural reasons (bloom events), and when it is of more interest to describe the general differences rather than these few, sometimes large, differences. However, the MAE and the RMSE can be used together to indicate the variation in the differences in the measurement. The RMSE will always be larger or equal to the MAE and the greater the difference between them, the greater the variance in the individual errors in the sample. If the RMSE=MAE, then all the errors are of the same magnitude.

In Table 10, the MAE and RMSE are reported in %, which for MAE is called MNE (Mean Normalised Error), i.e. the difference is normalized relative to the value of the field observation. This is a better description of the differences as values of very different magnitude can be compared. The correlation coefficient, r, is also included in Table 10. These errors comprise all lakes, but are in general smaller for less turbid stations, e.g. only 11% based on data from station "Jungfrun" and "Edeskvarnaån".

Table 10. Minimum, Maximum and Mean concentrations of the field data included in the final calibration algorithms. Differences between field and satellite based estimations reported as MNE and RMSE.

	Chl a	Biovolume (Chl <20)	Biovolume (Chl >20)	AbsF	SD	TSM
MIN	0,6	0,06	1,5	0,005	0,5	0,21
MAX	49	1,52	16,3	0,201	16,2	24
MEAN	10,1	0,44	6,2	0,066	3,0	6,2
r	0.83	0.87	0.88	0.85	> -0.90	0.89
MNE (%)	42	43	74	27	27	39
RMSE (%)	63	61	98	37	27	54

Table 11. Reported uncertainty for laboratory measurements [55].

	Chl a	BV	AbsF	AbsF	SD	Tubidity	Tubidity
MIN	>0,5	-	0,010	0,100	-	0,2	5
MAX	-	-	0,100	1,0	-	5	20
Uncertainty	16%	-	17%	5%	-	0,33 FNU	5%

Time series

Time series for all parameters and all stations has been produced based on the results described above. All MERIS observations between June 2002 and September 2011 have been included in the time series, except those that only corresponds to one valid pixel. Satellite based estimations from April is not included due to insufficient screening of sea ice. Particularly in some sheltered basins in L. Vänern the duration of ice cover some years can expand into April (50). Additional filtering could be made based on the standard deviation of the averaged pixels corresponding to one observation, in order to mask out potentially erroneous estimations, not identified in the initial pre-processing of the data. Available field data is included for each control station and few examples are included below. Decadal time series for control station Megrundet, Södra Björkfjärden, Storhjälmaren and Jungfrun, annual detailed time series of Chl a for 2005, 2007, 2009 and 2011, as well as, detailed time series for all parameters in 2011, is shown in figures 48-75.

Megrundet

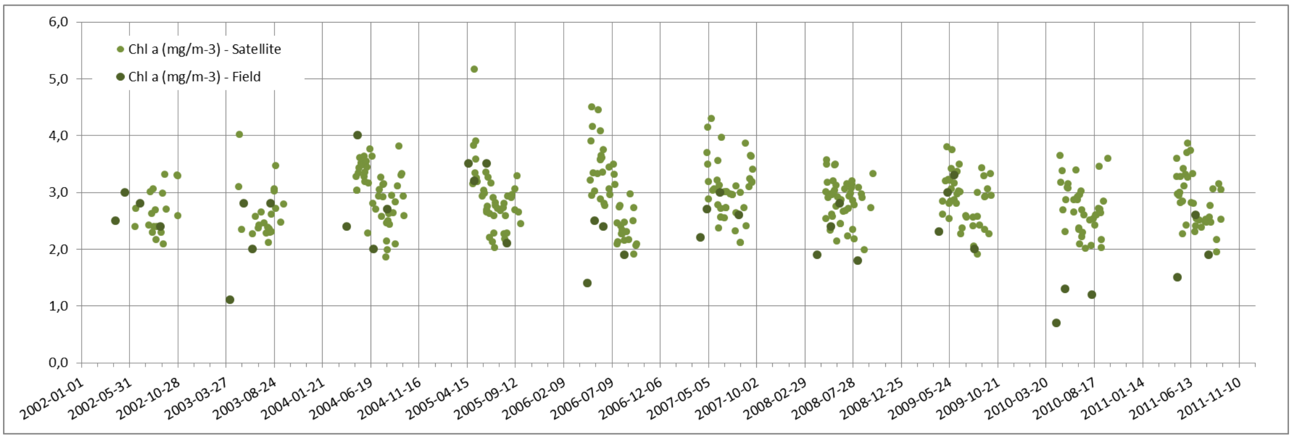


Figure 48. Megrundet – Estimated Chl a concentrations between 2002-2011.

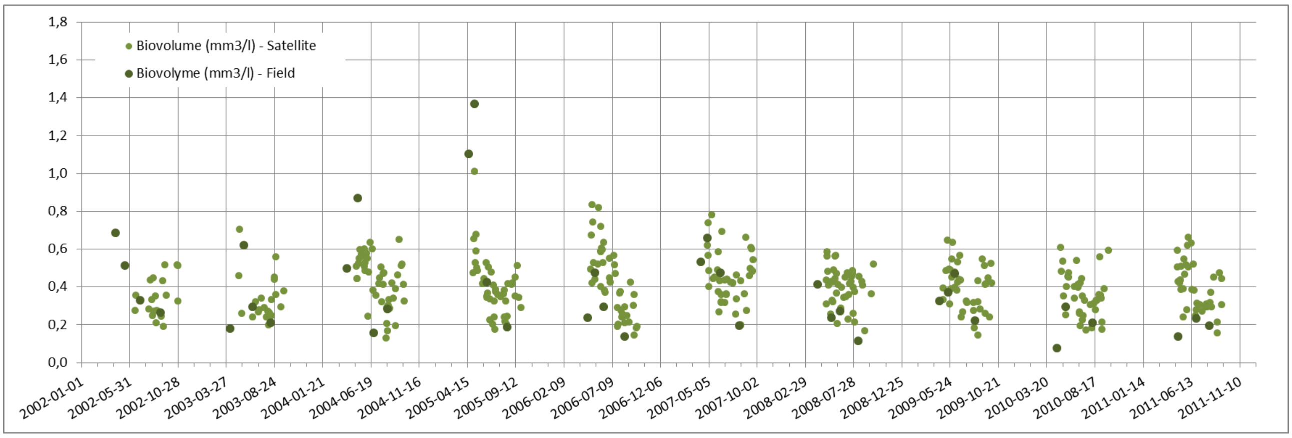


Figure 49. Megrundet – Estimated biovolume between 2002-2011.

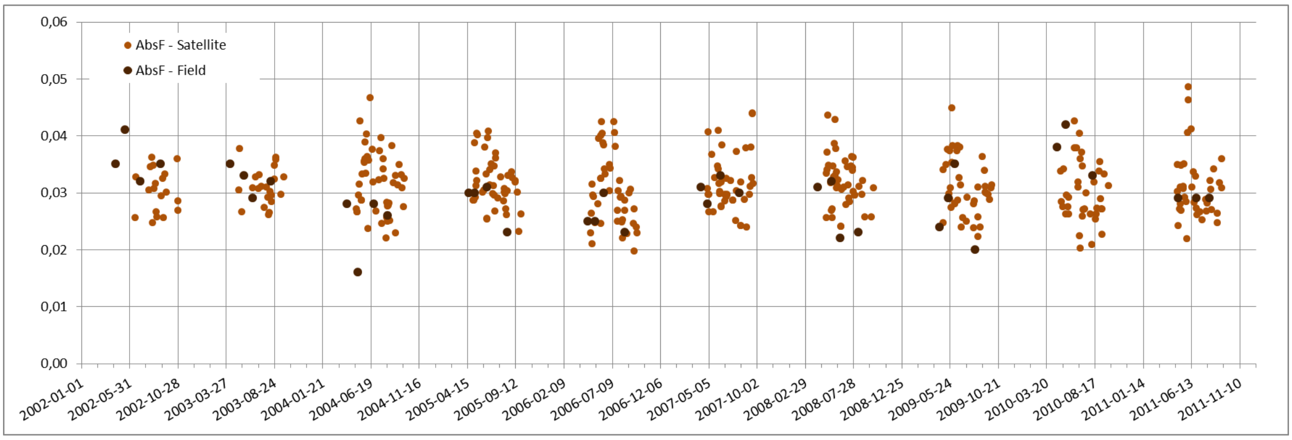


Figure 50. Megrundet – Estimated AbsF between 2002-2011.

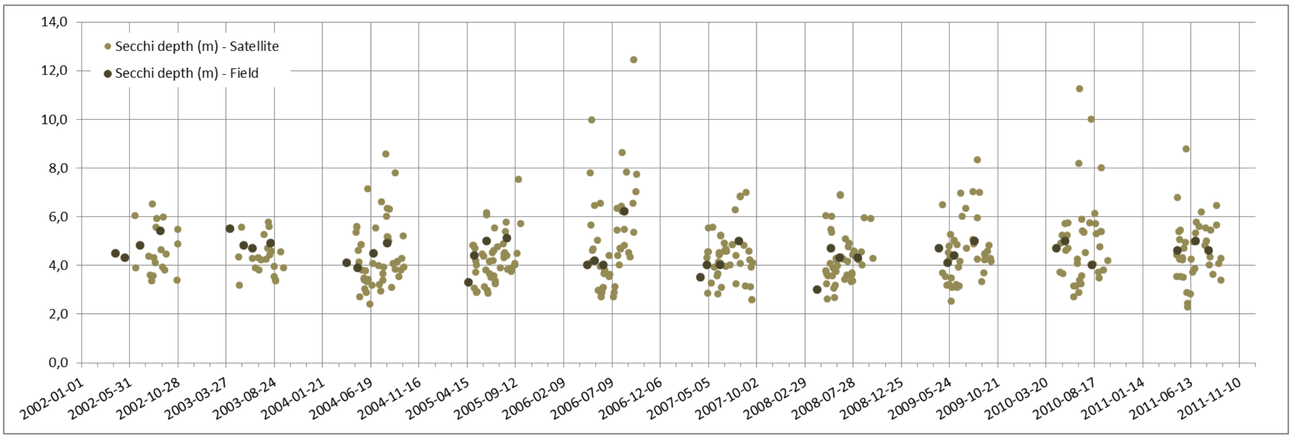


Figure 51. Megrundet – Estimated Secchi depth between 2002-2011.

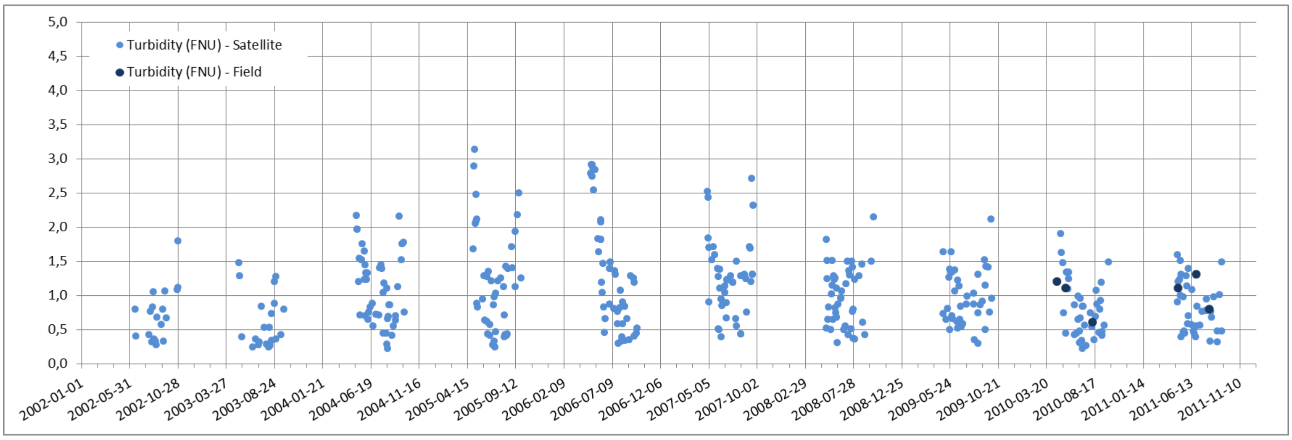


Figure 52. Megrundet – Estimated turbidity between 2002-2011.

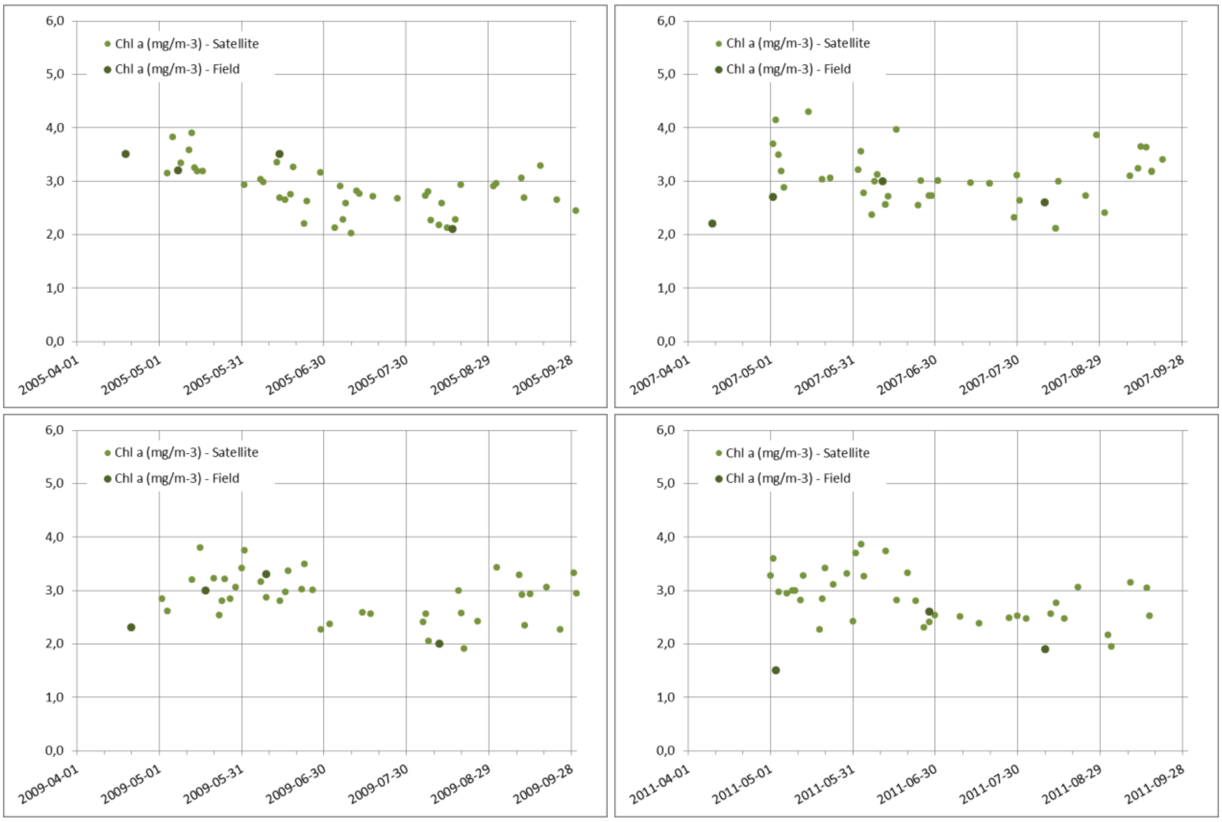


Figure 53. Megrundet – Detail of estimated Chl a concentrations during 2005, 2007, 2009 and 2011.

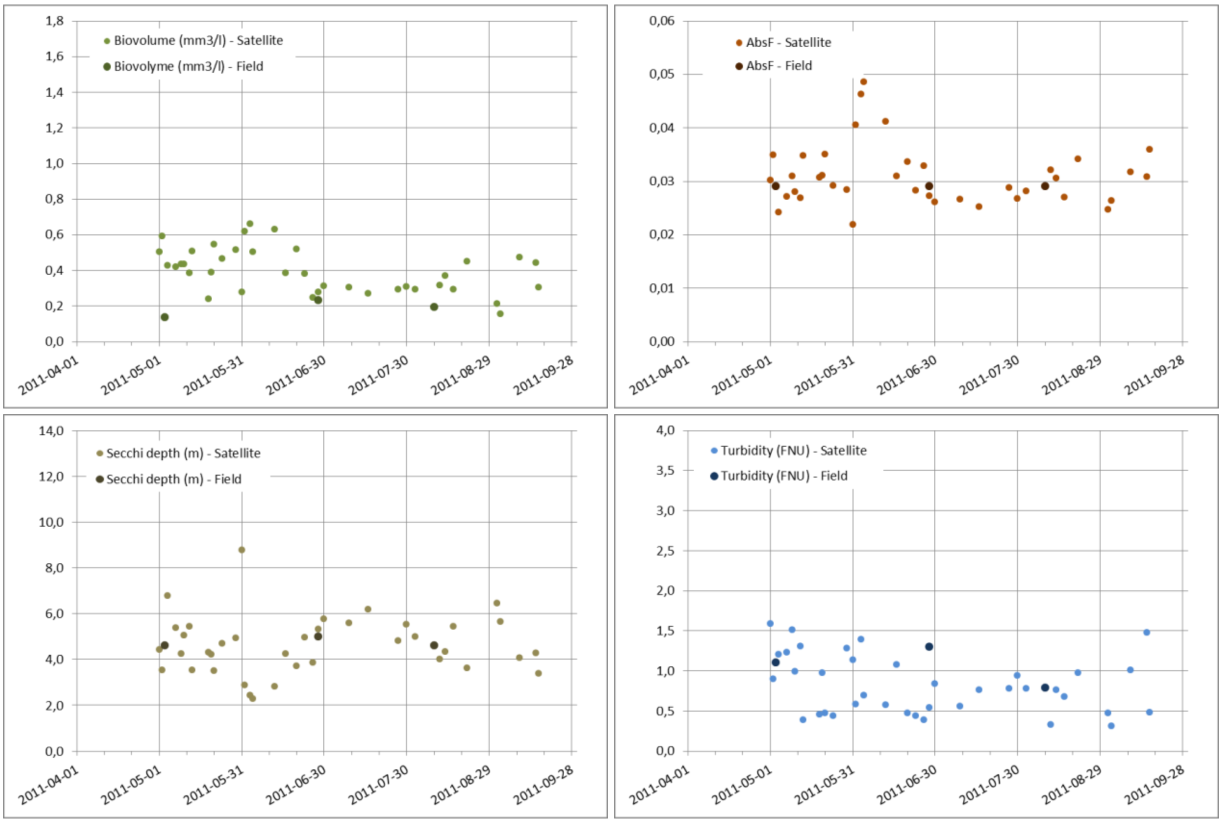


Figure 54. Megrundet – Detail of estimated water quality parameters during 2011.

Södra Björkfjärden

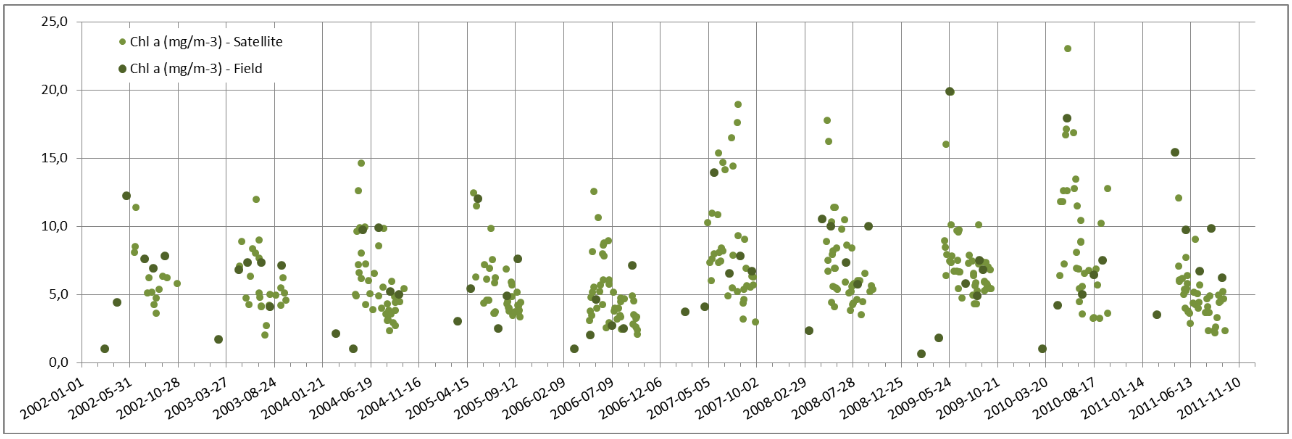


Figure 55. Södra Björkfjärden – Estimated Chl a concentrations between 2002-2011.

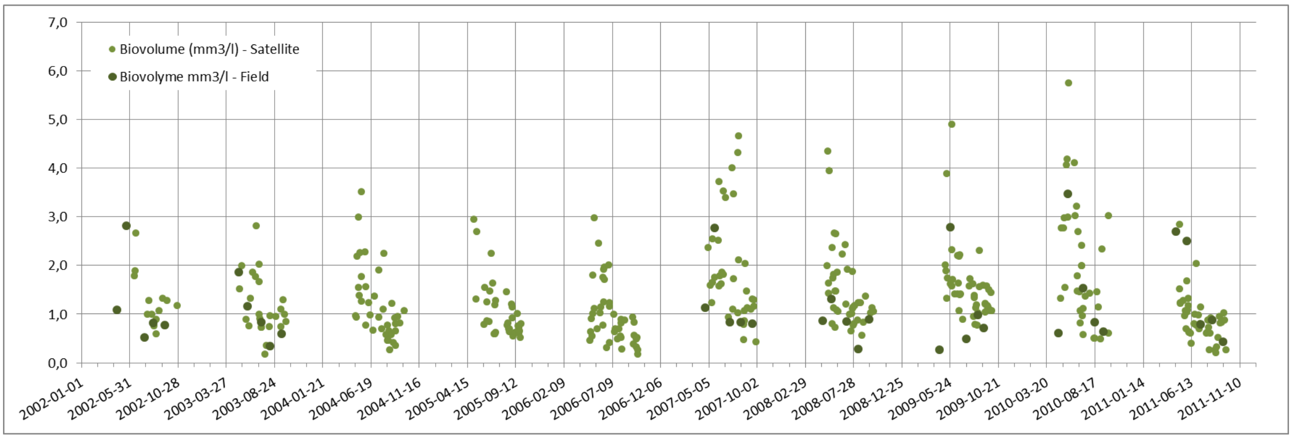


Figure 56. Södra Björkfjärden – Estimated biovolume between 2002-2011.

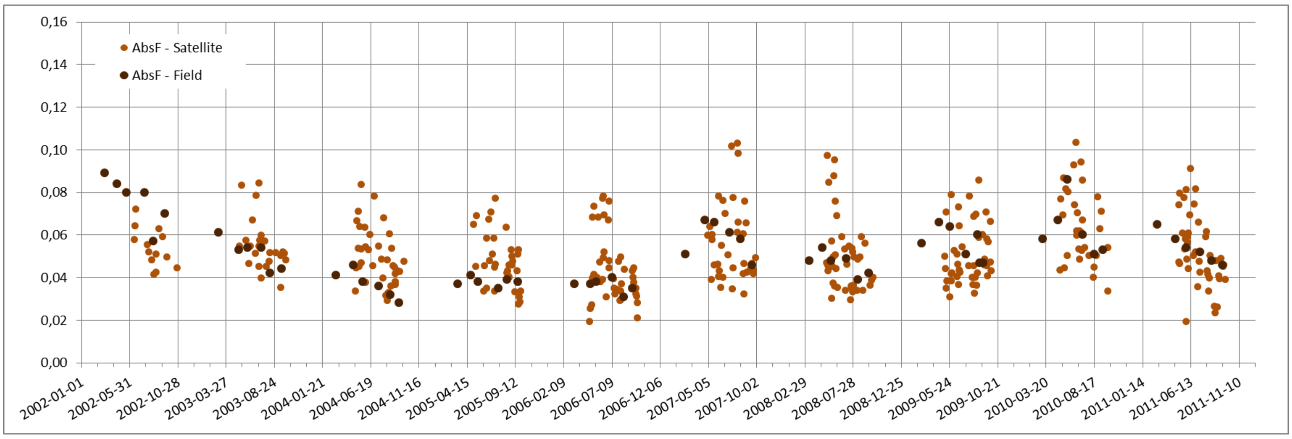


Figure 57. Södra Björkfjärden – Estimated AbsF between 2002-2011.

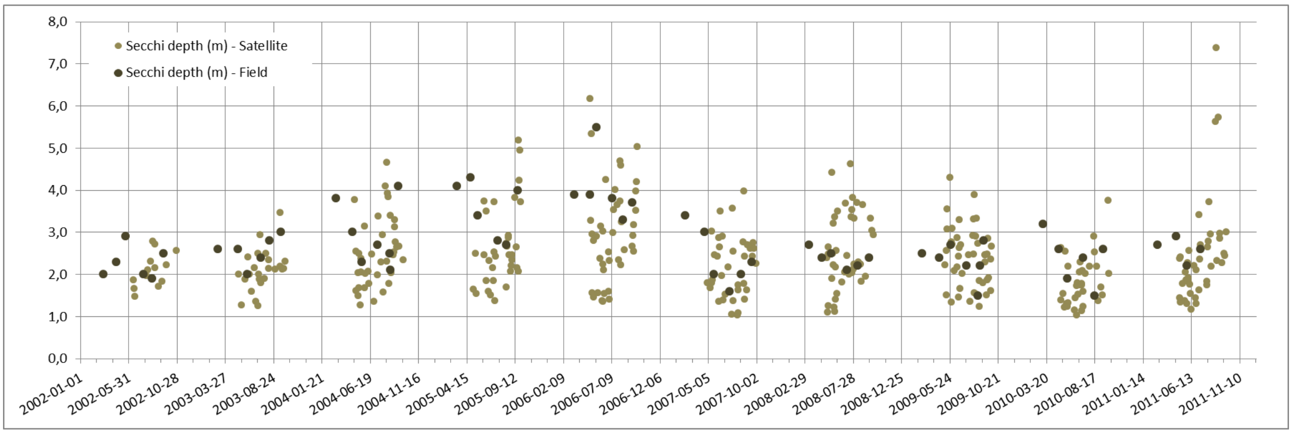


Figure 58. Södra Björkfjärden – Estimated Secchi depth between 2002-2011.

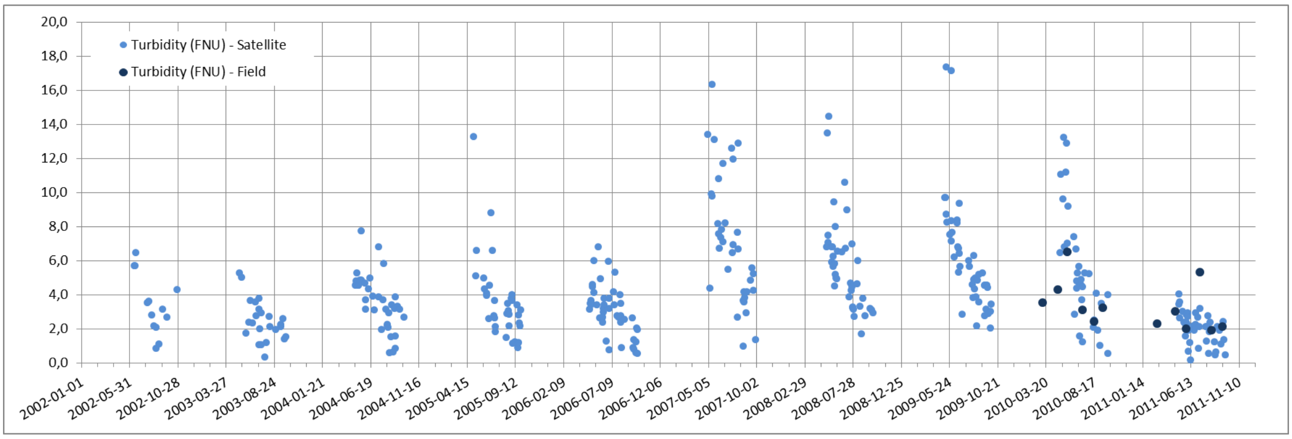
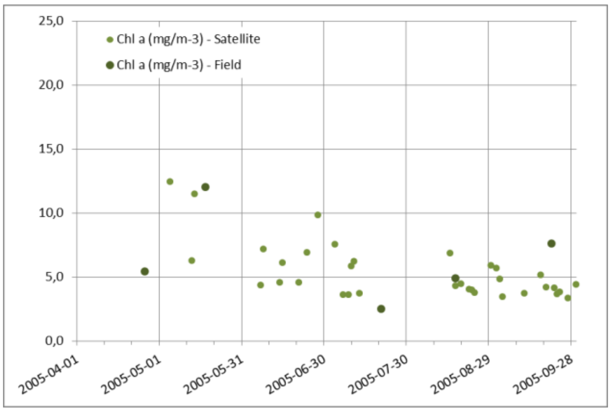
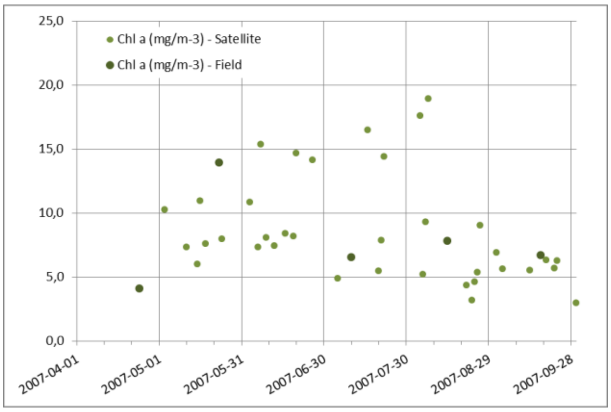


Figure 59. Södra Björkfjärden – Estimated turbidity between 2002-2011.





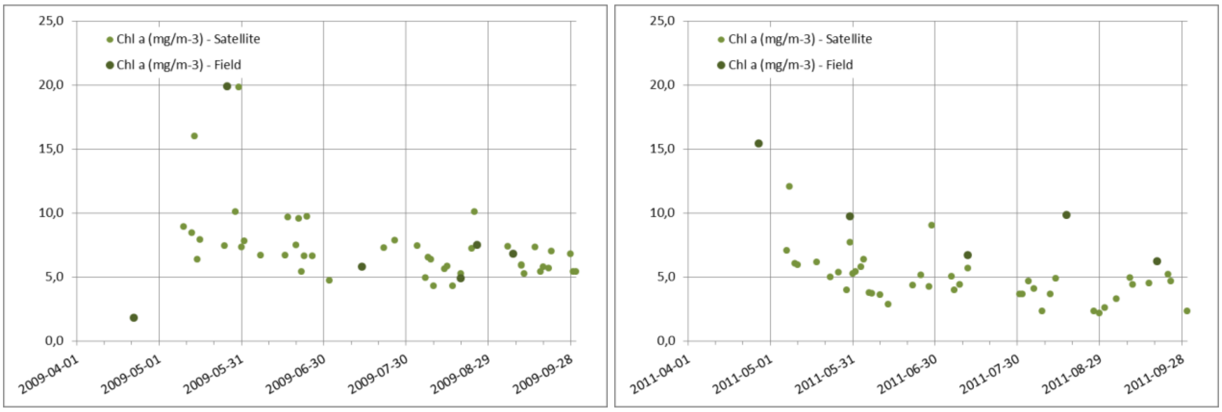


Figure 60. Södra Björkfjärden – Detail of estimated Chl a concentrations during 2005, 2007, 2009 and 2011.

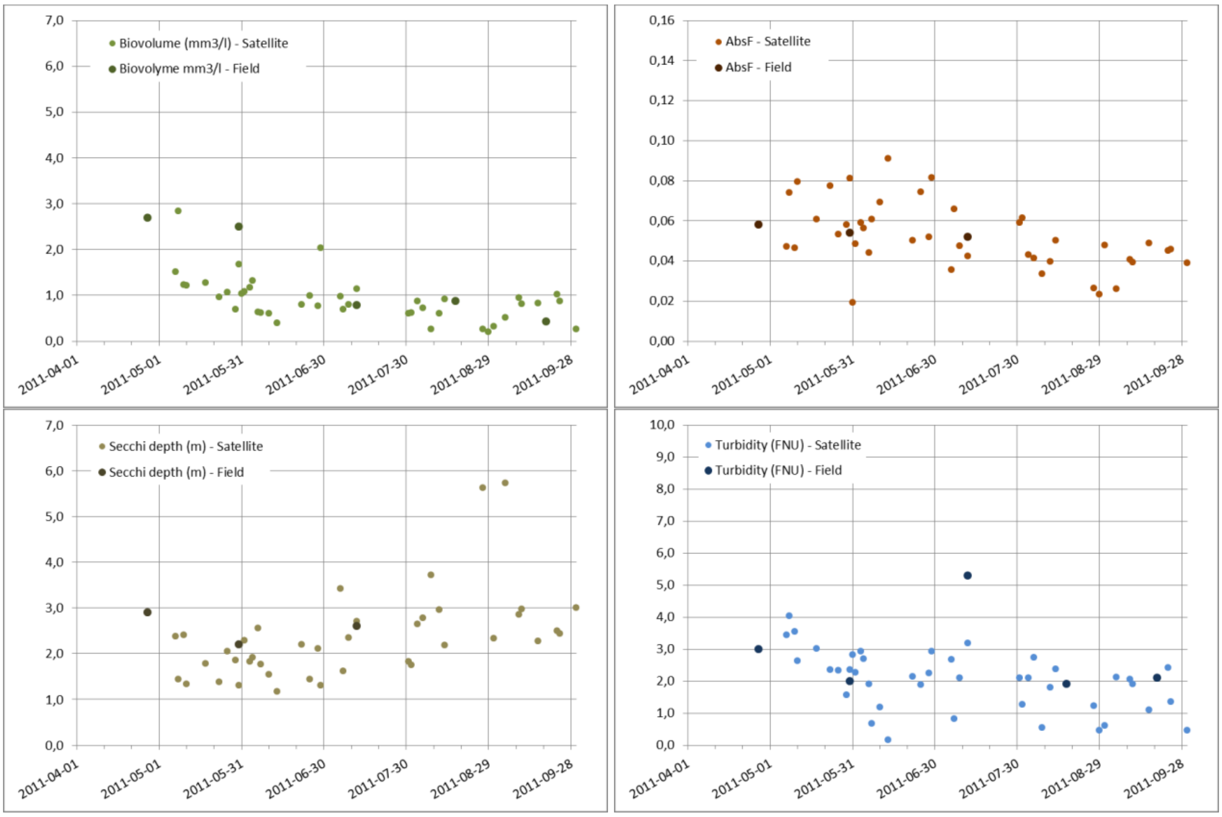


Figure 61. Södra Björkfjärden – Detail of estimated water quality parameters during 2011.

Storhjälmaren

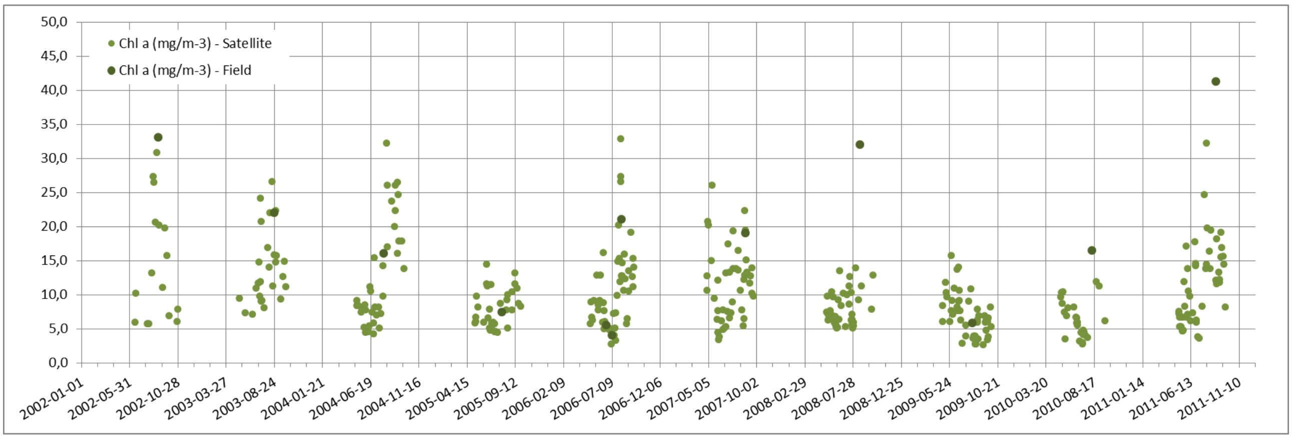


Figure 62. Storhjälmaren – Estimated Chl a concentrations between 2002-2011.

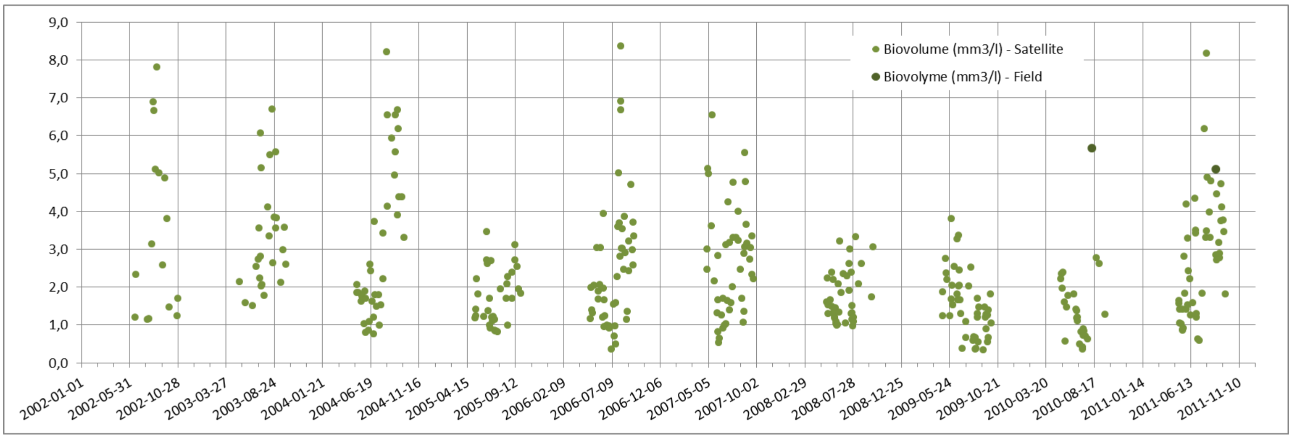


Figure 63. Storhjälmaren – Estimated biovolume between 2002-2011.

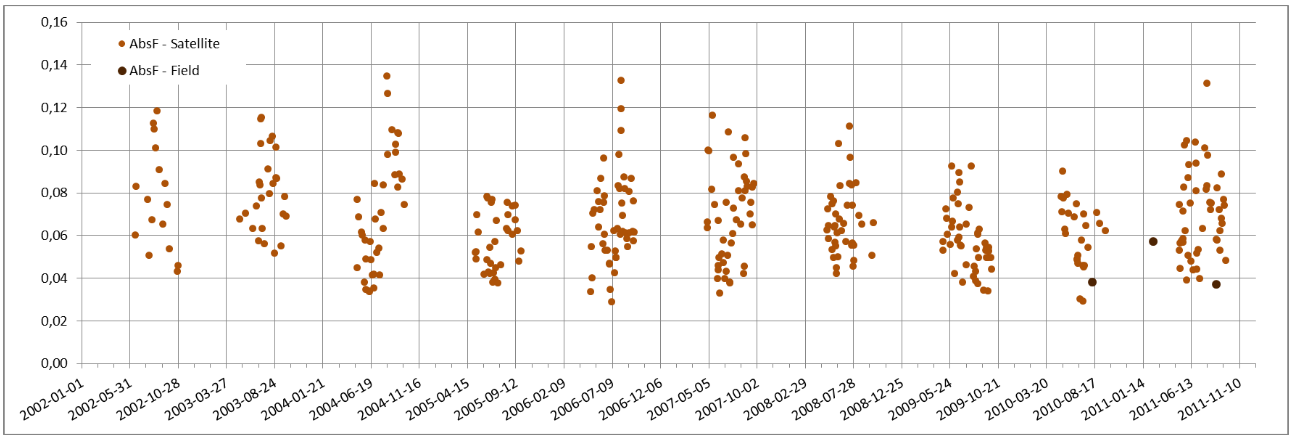


Figure 64. Storhjälmaren – Estimated AbsF between 2002-2011.

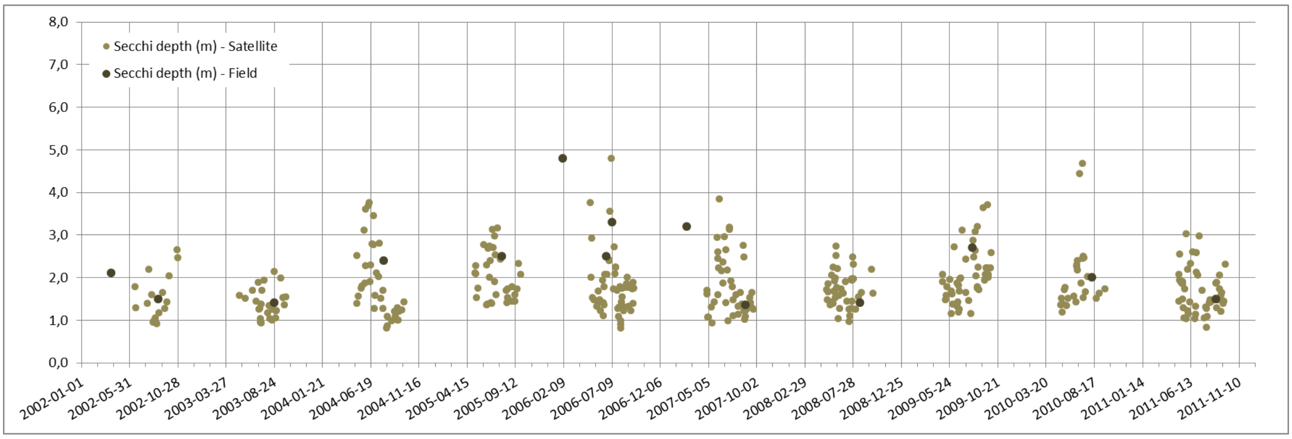


Figure 65. Storhjälmaren – Estimated Secchi depth between 2002-2011.

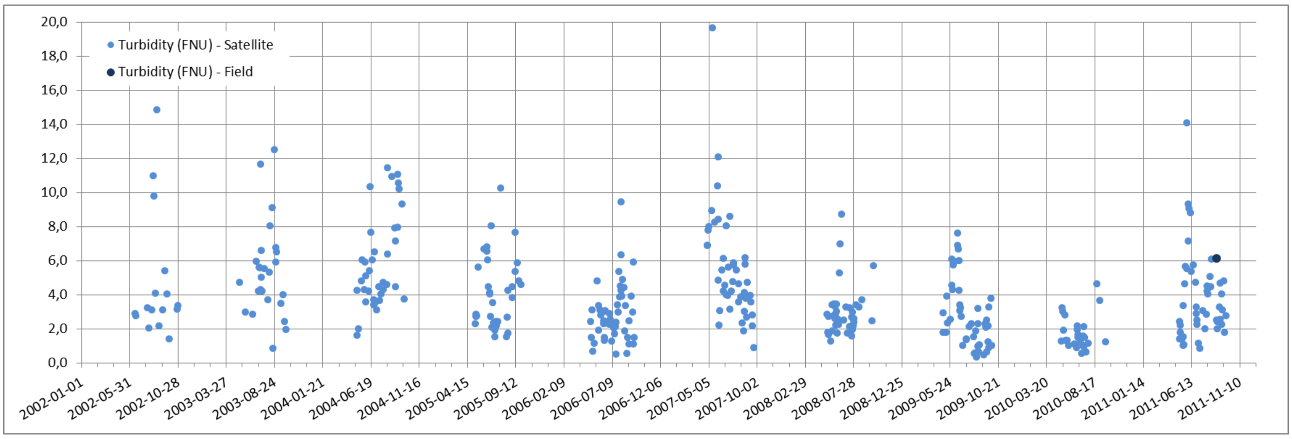


Figure 66. Storhjälmaren – Estimated turbidity between 2002-2011(above).

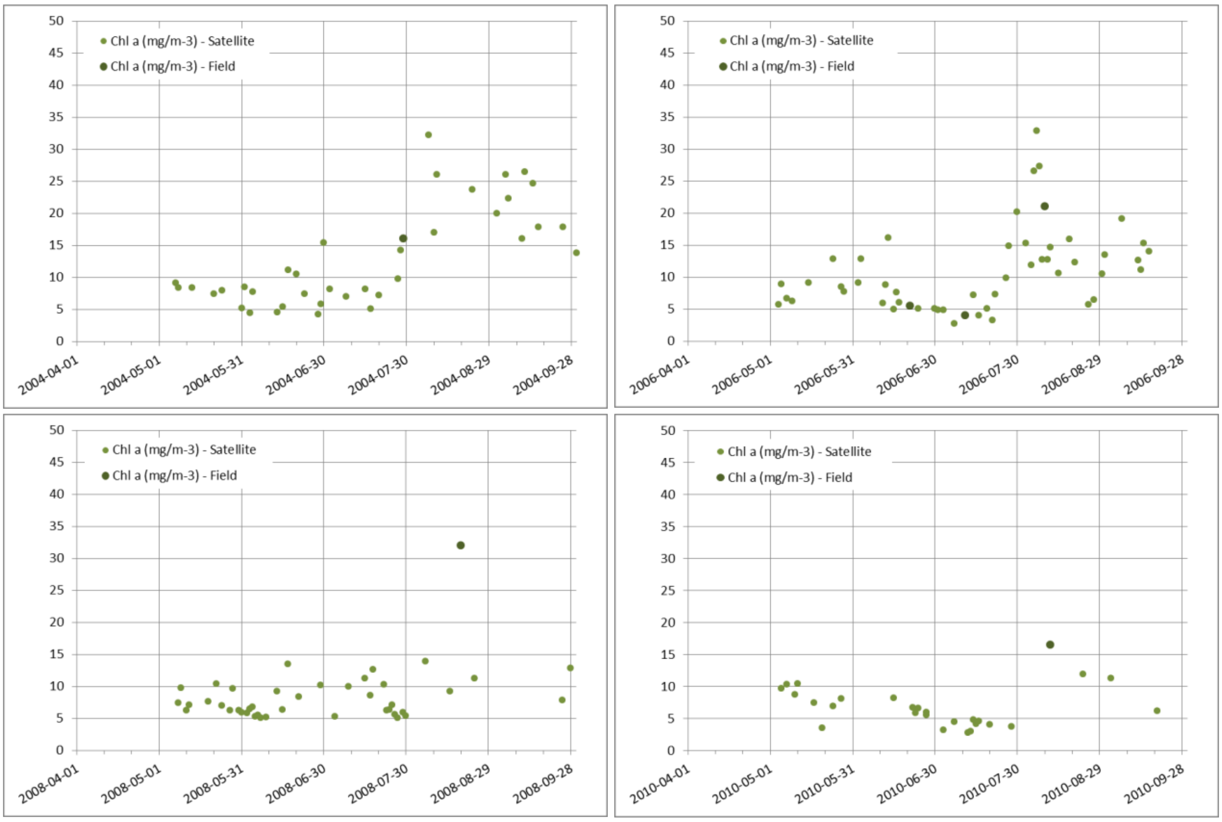


Figure 67. Storhjälmaren – Detail of estimated Chl a concentrations during 2004, 2006, 2008 and 2010.

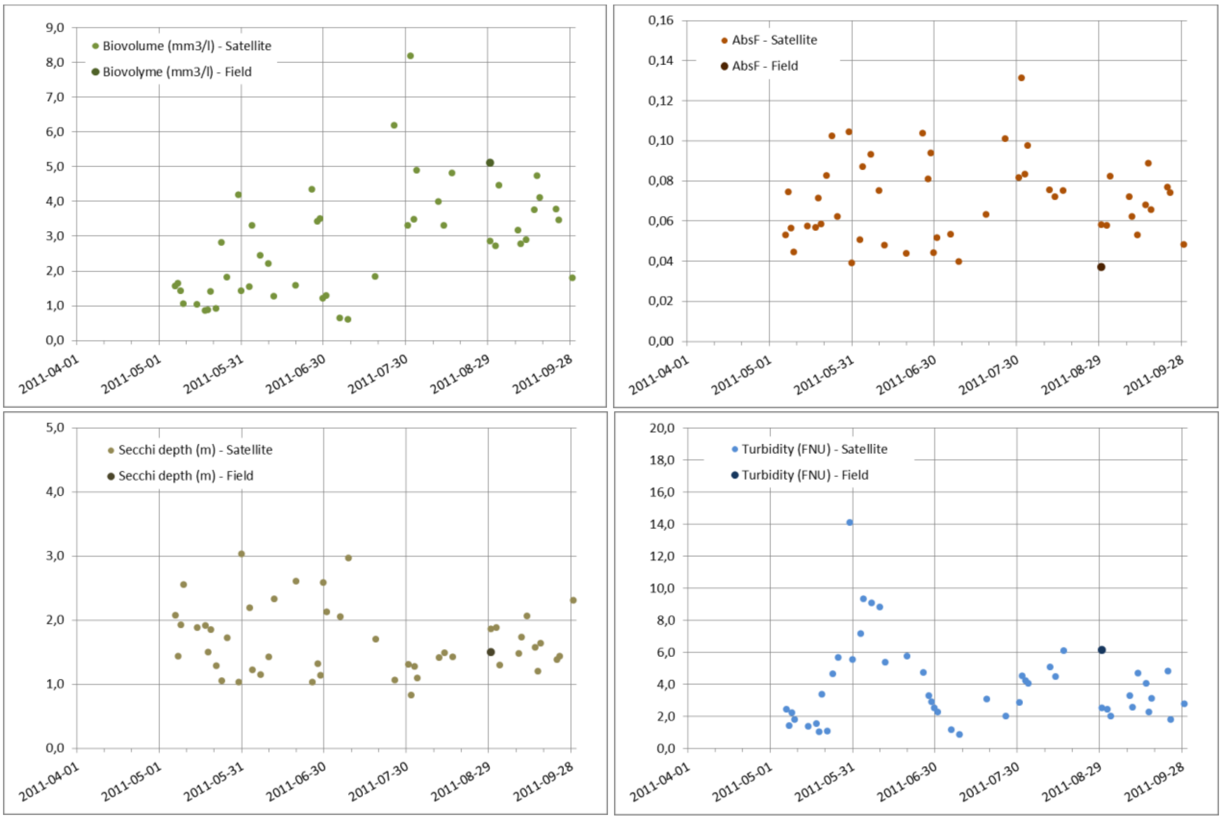


Figure 68. Storhjälmaren – Detail of estimated water quality parameters during 2011.

Jungfrun

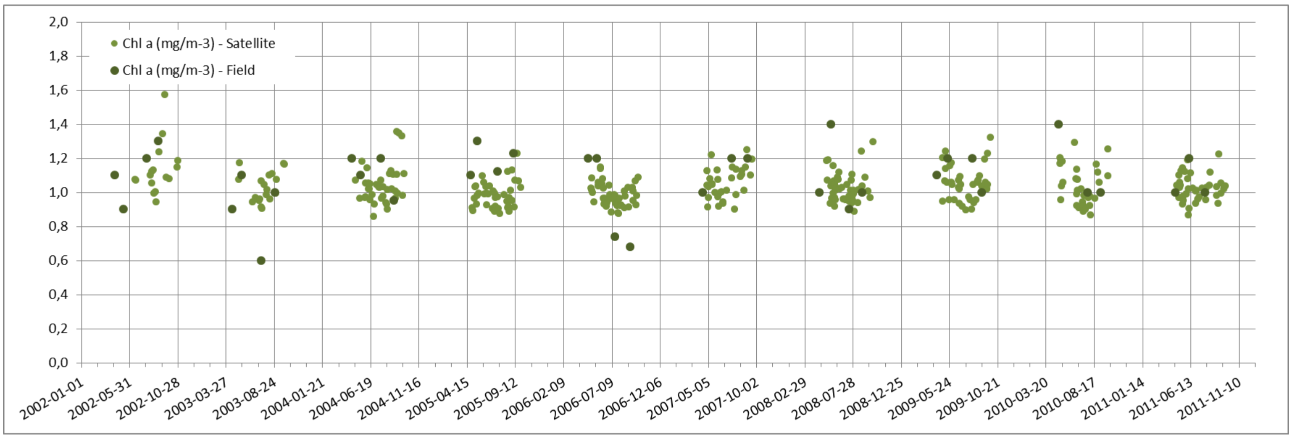


Figure 69. Jungfrun – Estimated Chl a concentrations between 2002-2011. Note! Many of the field samples are defined as, e.g. "<1 mg m-3" in the protocol.

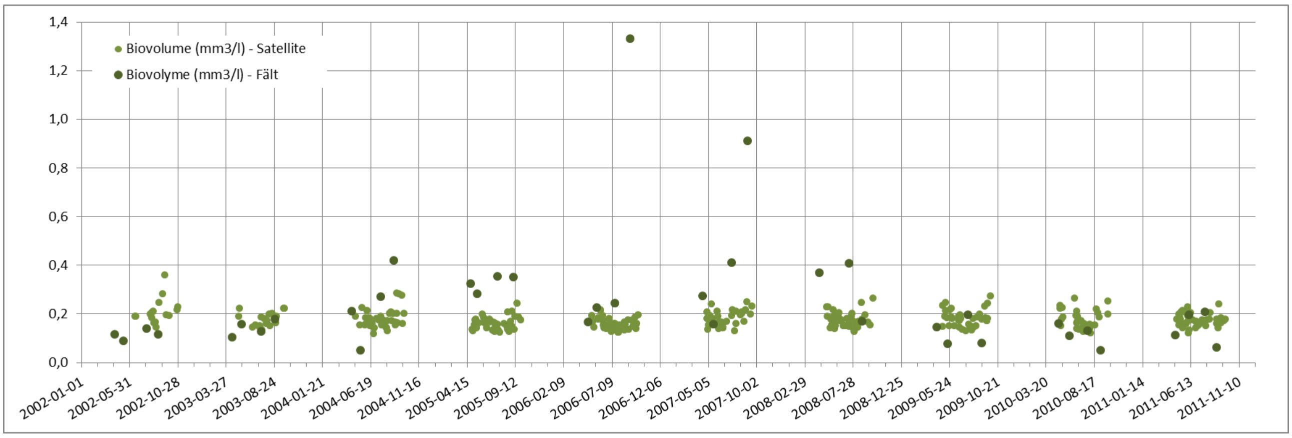


Figure 70. Jungfrun – Estimated biovolume between 2002-2011.

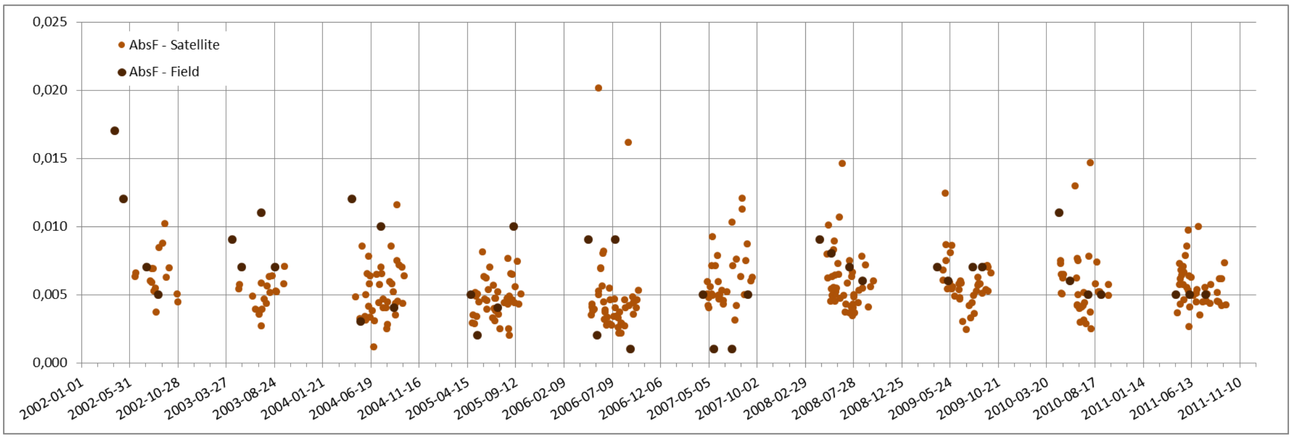


Figure 71. Jungfrun – Estimated AbsF between 2002-2011.

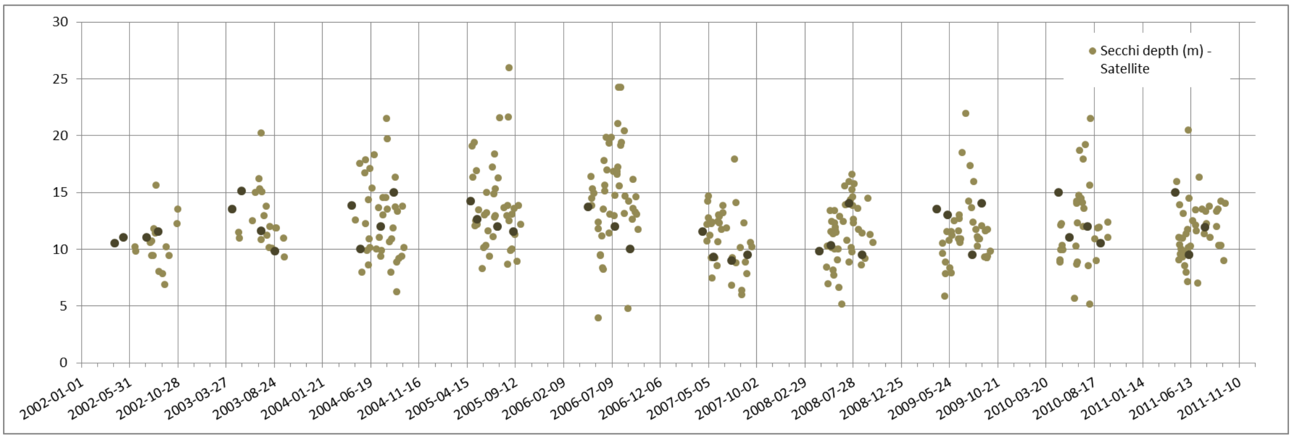


Figure 72. Jungfrun – Estimated Secchi depth between 2002-2011.

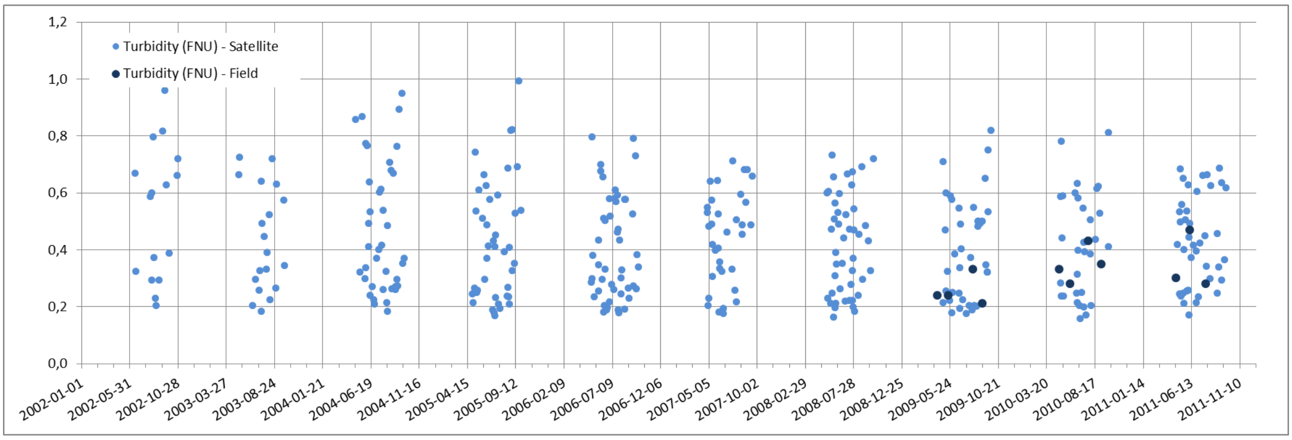


Figure 73. Jungfrun – Estimated turbidity between 2002-2011.

Figure 74. Jungfrun – Detail of estimated Chl a concentrations during 2005, 2007, 2009 and 2011.

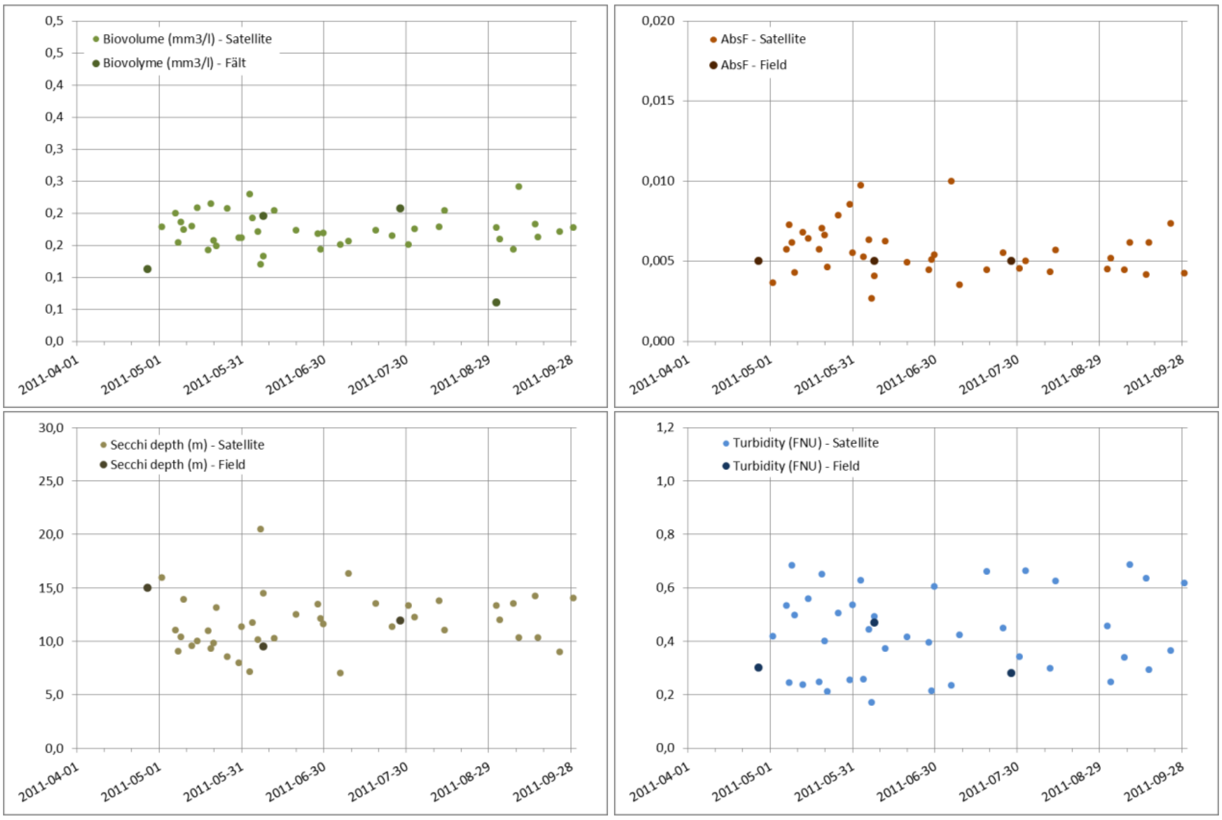


Figure 75. Jungfrun – Detail of estimated water quality parameters during 2011.

All time series, for all control stations, could not be included in the report, but have been thoroughly analyzed in order to investigate the applicable ranges and limitations of the algorithms. The results are summarized below.

Applicability of algorithms

The Chl a range between 1-30 mg m^{-3} was sufficiently represented by the available field data and there was a strong linear relationship between field and remote sensing measurements (R^2 = 0.70). For Chl a levels above 35 mg m^{-3} the available field data was very sparse and above 50 mg m^{-3} the existing data points do not fit to the general linear trend. The FUB algorithm was trained on concentrations up to 50 mg m^{-3}, and field data > 50 mg m^{-3} was therefore excluded in the development of a calibration algorithm. This means that the established calibration algorithm will not be valid for concentrations above approximately 30 mg m^{-3}. A brief investigation of Chl products/images from Lake Hjälmaren between 2005-07-25 – 2005-08-05, when extreme concentrations (110-130 mg m^{-3}) were measured in field, showed that the maximum existing value was 118. Based on the established algorithm, "118" would produce a Chl a concentration of 34.1 mg m^{-3} in the calibrated data, which is a clear underestimation. To conclude, the FUB-Chl a algorithm could not produce values higher than "118" in these waters and values between 100-118, no longer follows the linear trend, but corresponds to a large variability of high concentrations. In general, in low-moderate humic waters (see below), the calibration algorithm should be able to produce accurate Chl a concentrations up to approximately 30 mg m^{-3}, but will then saturate around 33-34 mg m^{-3}. Hence, a concentration of 34 in a time series, will correspond to a field based concentration of 34 mg m^{-3} or higher. With respect to the lower end, realistic time series for clear water stations "Jungfrun" and "Edeskvarnaån" (0.8-1.2 mg m^{-3}) have been produced. Concentrations <0.8 mg m^{-3} could not be produced, but are also on the detection limit for laboratory measurements. In fact, many field observations are specified as <1 mg m^{-3} in the protocol, where the image data still exhibit realistic variability.

Biovolume data has been produced by establishing an algorithm based on the FUB-Chl a product. The good correlation suggests that the species composition is stable and that Chl a products could be used as a proxy for biomass and full coverage biomass products/time series could be derived. The available field data was limited, but the range between 0-1.6 mm^3/l was sufficiently represented by the available field data and the correlation between datasets exhibited a positive linear trend ($R^2 = 0.75$). Higher volumes, mainly represented by control stations in more turbid parts of Lake Mälaren, exhibited a large variability, especially for samples collected in April-May. As the relationship is built on FUB-Chl a, the constraints discussed above also apply to the biovolume products and time series. However, with reference to the available field data, we can assume that the algorithm should be able to produce accurate biovolumes, up to approximately 2 mm^3/l. This corresponds to FUB-Chl a values between 0-20, which is far from the saturation level around 118. Based on the established algorithm for biovolume, "118" would produce a biovolume of of 11.7 mm^3/l in the calibrated data. To conclude, the FUB-Chl a algorithm could not produce values higher than "118" in these waters, andwill saturate around 11 mm^3/l. Regarding biovolumes between 2-11 mm^3/l, there is very few match ups to base conclusions upon. However, realistic time series for stations "Södra Björkfjärden" and "Granfjärden" (0.5-6 mm^3/l) have been produced, which indicates that the upper limit is above 2 mm^3/l. With respect to the lower end, the field based observations for clear water stations "Jungfrun" and "Edeskvarnaån" (0.05-0.5 mg m^{-3}) are occasionally in line with the produced time series, but more often scattered around it (±0.1 mm^3/l). However, the uncertainty of the field based estimations is unclear.

The AbsF range between 0-0.15 was sufficiently represented by the available field data, but the variability was relatively large at higher humic levels. The relationship was improved by excluding spring values and there was a linear trend between datasets ($R^2 = 0.71$). For AbsF levels above 0.15 the available field data was very sparse (two data points), but seemed to fit to the general linear trend. This indicates that that the established calibration algorithm could be valid for AbsF levels between 0-0.15, but with a larger uncertainty for higher humic levels. A brief investigation of AbsF products/images over the most humic water bodies were made, which showed that the maximum existing value was 0.054. Based on the established algorithm, "0.054" would produce an AbsF level of 0.14 in the calibrated data, which is below the level exhibited by several water bodies in the investigated lakes. In general, the calibration algorithm should be able to produce accurate AbsF levels up to approximately 0.13-0.14, but will then saturate. Hence, AbsF levels of 0.14 in the time series will correspond to field based levels of 0.14 or higher. With respect to the lower end, realistic time series for clear water stations "Jungfrun" and "Edeskvarnaån" (0.002-0.01) have been produced. Field data is in line with the produced time series for most data points and only occasionally more scattered around it (±0.003). However, the uncertainty of the field based estimations is most likely >20% at these low levels.

SD data has been produced by establishing an algorithm based on the FUB-CDOM/AbsF product. The SD range between 1-7 was well represented by the available field data, while the larger Secchi depths between 10-16 m, representing Lake Vättern, were less numerous. Despite the lack of field data between 7-10 meter there was a strong correspondence between satellite derived SD and field measurements. The best fit was with a power function ($R^2 = 0.81$). The data between 2-6 meters naturally divided in two groups and a logarithmic trend was established as an alternative for one of these groups. 1-16 m is a good representation of the total Secchi depth range in these lakes, which means that the established calibration algorithm should be valid for most of the investigated water bodies. However, there are a few very turbid water bodies that exhibit SD between 0.2-0.8. These low SD could not be produced as the established power function saturates just below 0.8 meters. To conclude, the SD algorithm could not produce SD lower than 0.8 in these waters. Hence, a Secchi depth of 0.8 m in a time series, will correspond to a field based observation of 0.8 m or lower. With respect to the upper end, realistic time series for clear water stations "Jungfrun" and

"Edeskvarnaån" (9-17 m) have been produced. Due to the properties of the power function there is a risk for over estimation of high SD, but this is not shown in the existing time series.

The turbidity range between 0.5-12 FNU was sufficiently represented by the available field data and there was a linear trend between datasets (R^2 = 0,80). For turbidity levels above 12 FNU the available field data was very sparse, but still fitted well to the general linear trend. In general, the evaluations indicate that the calibration algorithm should be able to produce accurate turbidity estimates between, at least 0-20 FNU. However, realistic time series for stations "Västeråsfjärden" and "Hemfjärden" (8-24 FNU) have been produced, which indicates that the upper limit is above 20 FNU.

The MPH algorithm for detection of cyanobacterial dominated waters is of a completely different character, and initial evaluations have been made within the framework of this project. Reasonable products have been generated, but quantitative evaluations were difficult. The analysis could be enlarged by looking at single image products rather than monthly products and by compiling more field data collected within local/regional monitoring programs. At this point, the conclusion is that the results are promising. Earlier research have indicated that cyanobacteria phycocyanin pigment related features only clearly become visible in the spectra at biomass chl-concentrations greater than 20 mg m^{-3}[24, 29]. As a result, identification of cyanobacteria dominated waters with Chl a < 20 mg m^{-3}, is much less reliable than at higher Chl levels. However, ongoing research indicates that cyanobaterial blooms could be detected even in waters with Chl a ≥ 12 mg m^{-3}, which significantly increases the applicability in the investigated Swedish lakes [manuscript in progress].

Analysis & Results – Fish Metrics

Statistical analyses and data processing

Several analyses were conducted to test the potential of remote sensing data as predictor of fish monitoring data.

1. The importance of remote sensing data to understand and predict the assemblage composition of fish communities in large lakes has been analysed.
2. Remote sensing data has been utilized to test the possibility to predict the distribution of certain important species and life-stages and to test the importance of remote sensing data to explain the variation in abundance of individual benthic and pelagic fish species in Swedish large lakes.
3. Data on fish assemblages has been summarised across a subset of the existing water bodies (31 out of 73) defined within EU:s water framework directive, to test how certain selected candidate metrics respond to remote sensing data as a pressure variable.

Monitoring data on fish - hydroacoustics and midwater trawling

Acoustic density estimates were obtained by post-processing the collected datasets with the software Sonar 5® to identify and count individual fish tracks [6]. The threshold for the volume of backscattering was selected to avoid inclusion of backscattering from other organisms than fish that might appear in high densities like *Mysis relicta* and *Chaoborus larvae* [38, 56]. Target strength of single echo detections was set according to the echo sounder technical resolution abilities and the chosen S_v threshold, i.e. low, from -60 dB or slightly higher. Acoustic densities were averaged over segments and summarised for subareas and whole lakes. Segment length was approximately 1000 m.

Trawl catch composition, species and size structure is apportioned to acoustic densities using a classification approach, see e.g. Yule et al. (2014) (54) for details. This approach has been used since 2011 and makes it possible to derive density and biomass of individual species, size classes and cohorts in each segment along the transects and thus also enables to assess the precision of the measures of species abundance and biomass when summarized for an entire lake or subarea.

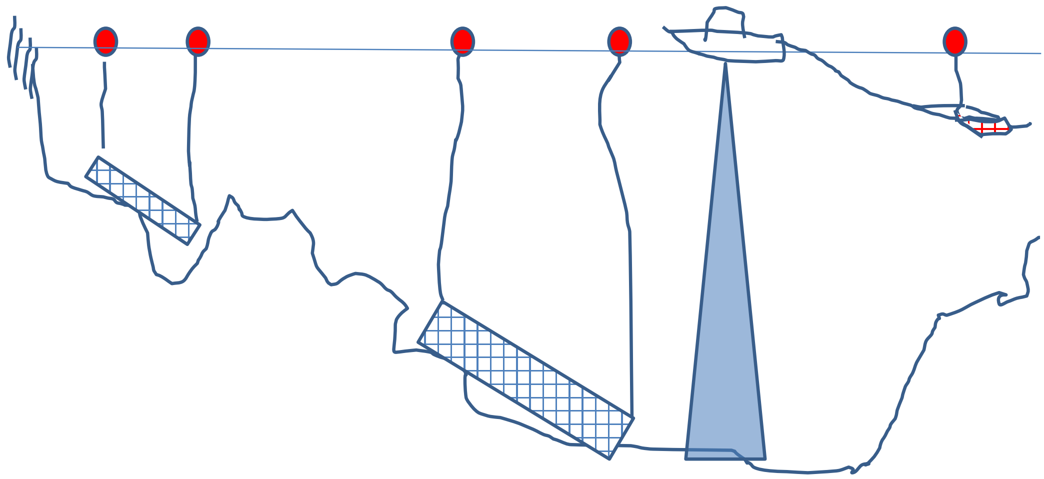


Figure 76. Conceptual description of monitoring design.

Monitoring data on fish - multi-mesh benthic gillnets

All data on catches were extracted from NORS, the Swedish database for multi-mesh gillnet monitoring data (Kinnerbäck, 2014). The catches of each gillnet (biomass and number of individuals) were given for each species. In order to make catches from different types of gears more comparable we used the number and/or biomass per 100 m^2 net area. For certain species (sander for example) the catch of young-of-the-year fish was also summarized for each gillnet. We extracted data from the period 2005-2012. In analyses when several different gillnet types were used, gear type was used as a nominal factor.

Spatial processing, data assembling and statistical analyses

The data-sets from NORS and hydroacoustics combined with midwater trawling were linked to remote sensing data from corrected and interpreted satellite data. The mean position of each gillnet and/or acoustic transect segment was overlaid with predictor layers derived from remote sensing. For these positions with fish data collection sites the mean of the nine most adjacent pixels in the remote sensing grid layers was calculated as well as the number of accepted pixels and the standard deviation among these approved pixels. The various fish data was linked to spring (mean of the May measurements), summer (August means) and annual means (the period from ice-break to 30 September). The fish sampling occasions were always coupled to the closest corresponding time period with remote sensing data. Besides environmental predictors we also used other predictor variables, that were accessible as continuous map layers. These were: depth at the sampling site and distance to the shoreline. Distance was calculated using a cost-distance approach thus calculating the closest water distance for a fish to migrate and not the closest linear distance. A grid with mean distance to closest shoreline was created to perform a cost-distance analysis using all shorelines except islands and skerries under 100 ha in size (map of shoreline from Fastighetskartan, resolution 1:50000 m).

The response variables describing fish communities were often transformed prior to statistical analyses, mainly by log (+1) transformation in the case of abundance and biomass data.

Table 12. Intervals of major explanatory variables covered with various fish monitoring methods. Maximum and minimum levels are given. As a comparison we also show the environmental envelope in the studied environments, e.g. the aggregated max and min levels. NEAR DIST=Nearest distance to shoreline.

	Chl a	CDOM	TSM	DEPTH	NEAR DIST
NORDIC	0.1-100.6	0.1-1.6	0.1-39	1.8 - 85	0 - 9000
DEEP	0.2-8.5	0.1-0.7	0.1-1.5	5 - 92	100 - 13000
Hydroacoustics	0.9-8.5	0.1-0.9	0.1-25.7	8 - 110	200 - 20000
Environment	0.1-130	0.1-25	0.05-36	0- 126	0 – 22410

Assemblage composition analyzed with a multivariate approach

The analysis was conducted in several steps. Firstly, we analyzed the general relationships among the many various predictor and response variables using a CCA based on species proportions of total biomass.

The dataset was then divided into three parts, one dataset was obtained from the two types of Nordic multi-mesh gill nets, one part from the deeper and longer multi-mesh gillnets used for monitoring of commercial species in offshore areas and the last data set from hydroacoustics. We thus covered the three main habitats in large lakes: the near-shore (NORDIC gillnets), the offshore benthic (DEEP gillnets) and the offshore pelagic (hydroacoustics combined with midwater trawling). For these datasets we explored and analyzed fish assemblage composition using multivariate regression trees (11, 53). Multivariate regression trees form groups of data by repeatedly splitting data into clusters minimizing variation within groups and maximizing variation between groups. The method is particularly useful when analyzing complex ecological relationships and non-linear relationships. Proportional species-specific catch measured as biomass or acoustically estimated biomass per hectare, of individual species were used as response variables when building trees. Several continuous explanatory variables were used: the three MERIS-derived predictors: chlorophyll a, TSM and CDOM in spring, summer and annual means and also the depth at the sampling point and the mean distance to the nearest shoreline. All exist as comprehensive GIS-layers covering the lakes. When constructing trees for inshore areas we also added gear type as a categorical predictor variable.

Multivariate regression trees were constructed using Brodgar´s Interface 3.7.4 linked to the mvpart package ran in R version 3.1.4. The trees were pruned using the approach in Zuur et al. 2007 (53). The sizes of the trees were optimized using the complexity parameter (cp) and relative error in predictions obtained by cross-validation. Leaf numbers were set with the "one standard error rule", cp cut values were set to 0.1. The trees were evaluated using estimates of deviations, species variance (%) explained by tree splits and whole tree and cross-validation mean value for the largest tree and the total standard error of the tree.

In order to test specifically for the importance of remote sensing data we created one tree using all predictor variables, one without the remote sensing predictors, one tree using only the remote sensing predictors and one tree using the remote sensing variables combined with nearest distance to shoreline. The habitat categorizations obtained by the tree analysis were used to create GIS-layers in order to visualize the distribution of different assemblages in the studied lakes and water bodies. Due to the lack of bathymetry data from shallow areas we only conducted this on Lake Vänern as an illustration of the approach. Habitat categories were obtained using the Query tool in ArcGis10. Habitats outside the range of environmental parameters in the tree analysis were visualized by a layer called "unknown".

Many of the remote sensing derived explanatory variables were correlated to each other. This was particularly evident for Chl a and CDOM that were strongly positively correlated to each other (Pearson's correlation coefficient 0.89, p<0.001). The relationship between these two parameters was more logarithmic than linear. In many of our analyses we only selected one of these variables. We chose to use CDOM, since it appeared to explain more of the variation in the fish datasets. It must be emphasized however, that since these predictors are strongly correlated they are both valuable predictors that seem to capture the same biological signal. Chl a is in many senses a more intuitive proxy for eutrophication pressures and it can be easily exchanged with CDOM with relatively similar results in many cases. The relationships with CDOM and fish indicators also should be interpreted with care particularly when moving outside the investigated CDOM interval or when analysing fish communities in other lake systems.

Patterns in assemblage composition

In total, thirty-three different species was present in the aggregated datasets used in our study (Tab. 16). Thirty-two species was present in the catch with multi-mesh gillnets in the four study lakes (Tab. 16) Twenty-nine in the NORDIC gillnets and twenty-three in the DEEP gillnets. The dominating species were ruffe, perch and roach that were present in all the investigated four lakes and in all of the thirty water bodies investigated within them. Ruffe was the most common, with the highest overall prevalence. Some species like eel, river lamprey, nine-spined stickleback, Alpine bullhead and Crucian carp occurred in very low numbers. The total number of species caught in midwater trawling was seventeen. Smelt was by far the dominating species in all lakes and water bodies, followed by vendace, bream, three-spined stickleback, whitefish and sander.

The high species diversity in the Swedish four largest lakes combined with pronounced environmental gradients makes them suitable for studying assemblage composition patterns. Our multivariate analyses showed that depth was the main predictor explaining assemblage composition but that the predictors derived from remote sensing analyses also explained a considerable part of the variations in the studied fish communities. There was one main environmental gradient that explained the variation along the first axis of the CCA. Areas (Fig. 77) with high *Chl a* and high CDOM are mainly situated in shallower areas closer to the shoreline. The variation among fish species resembles earlier studies on assemblage composition in Swedish lakes (Ragnarsson, 2008). These four lakes in a sense encapsulate the same patterns that can be seen on a national scale.

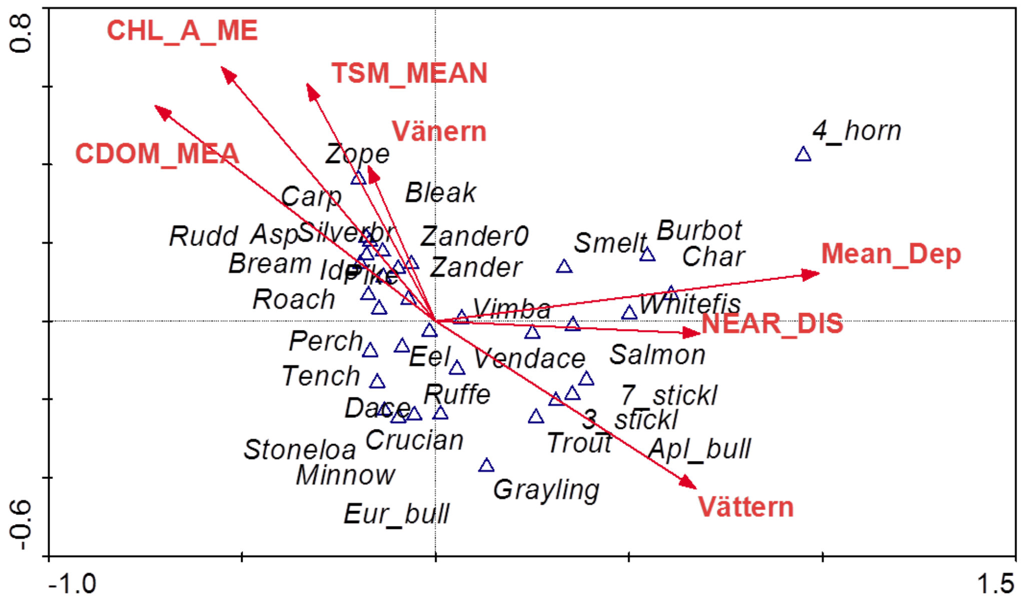


Figure 77. A CCA on gillnet data. The blue triangles indicate individual fish species and the red arrows indicate the major predictor variables influencing species composition. The longer the arrow the more influential is the predictor.4-horn= four-horn sculpin.

Multivariate trees – benthic fish assemblages

There was an apparent depth-dependent shift in species composition at the median position of the thermocline indicated by the first split in all multivariate trees (Tab. 16, Fig 78-80). Typical warm-water species were more common above the thermocline and cold-water species below it. The shift, as indicated with multivariate trees, occurred at different depths in the open basins of L. Vättern and L. Vänern compared to inshore areas and the comparatively smaller basins of L. Mälaren and L. Hjälmaren. The splits at 20.9 (offshore) and 12.2 meters (inshore), respectively, nicely follows the median position of the thermocline in different areas. Temperature has been investigated using vertical measurements at all fish monitoring occasions. Next primary splits were mainly based on remote sensing parameters, mainly CDOM but one split on a lower branch was also based on TSM.

Multivariate trees – inshore benthic areas

In inshore areas (surveyed with NORDIC gillnets) the splits and leaves on the trees indicate the presence of characteristic and clearly differentiated fish assemblage groups (Fig 78). Seven distinct groups were identified. Two groups were identified in the deeper areas below the thermocline. The first one with CDOM levels below 0.32 is dominated by sampling stations in L. Vänern and L. Vättern and is made up mainly by salmonids such as whitefish, vendace and Arctic char. Four-horned sculpin, although only occurring in low numbers, is a characteristic species, unique to this group. The next group of fish assemblages from sites below the thermocline is situated in more productive areas of L. Mälaren, L. Hjälmaren and certain parts of L. Vänern. This group instead was dominated by burbot, smelt and percids. The rest of the leaves were situated on the second branch, made up of sampling stations from above the thermocline. The first group at this branch consisted of an assemblage found in areas with very low CDOM, thus it is mainly consisting of sites in the littoral areas of L. Vättern. Dominating species in this group were ruffe, perch and roach. As a contrast to other assemblage groups, salmonids were a significant part of this group. One such species was grayling that occurred in low numbers, a unique and characteristic species for this group that only inhabits L. Vättern. The next leaves on this branch were characterized by sample stations also above the thermocline but with higher levels of CDOM. Sites with CDOM levels between 0.12 and 0.76 were split into two groups based on the depth of the sampling sites, under and over 8.3 meter in mean depth. The first leaf with depth between 8.3 and 12.2 meter was highly dominated by perch. The second leaf with mean depth below 8.3 m was instead dominated by roach. Dace and ide were also characteristic species, unique to this group. The remaining branch was made up of sites with CDOM levels over 0.76 and was split in two groups based on the distance to the shoreline. One group with sites further away from the shoreline than 500 m was made up mainly of white bream, bleak, sander and bream. The last group, sites closer to the shoreline than 500 m was dominated by perch, bream and roach. The characteristic species of this group were asp, zope, rudd and bleak.

The tree had a relatively low root node error and the full tree with six splits had an overall error that was 69 % of the root node error (Tab. 13). The inclusion of remote sensing parameters decreased overall relative errors of the inshore fish assemblage tree with about 23 % (relative error in last split was 0.85 compared to 0.69). In a situation where bathymetric maps not are available and depth thus is omitted from the analyses, remote sensing layers can still contribute to valid multivariate trees with similar errors as if depth was included, particularly if a GIS-derived parameter such as distance to shoreline can act as a proxy substitute for depth in the analysis (relative error in last split then increases from 0.83 to 0.80).

Table 13. Summary statistics of a multivariate regression tree analysis on inshore fish assemblages. CP is the complexity parameter, N split is the number of the split, Rel error is the relative error, X error is the mean value of the errors of the cross-validations and X std is the standard deviation of the cross-validations. The root node error was 53.77/1631=0.033.

Nr	CP	N split	Rel error	X error	X std
1	0.110	0	1.000	1.001	0.017
2	0.108	1	0.890	0.937	0.016
3	0.030	2	0.782	0.848	0.015
4	0.030	3	0.752	0.829	0.015
5	0.015	4	0.722	0.801	0.014
6	0.015	5	0.707	0.791	0.014
7	0.010	6	0.693	0.770	0.014

Multivariate trees – offshore benthic areas

This dataset only captured a limited part of the existing productivity gradient, thus limiting the potential to construct a multivariate tree using remote sensing data as explanatory variables. There were six distinct assemblage groups in the benthic offshore areas in L. Vänern and L. Vättern, that were the only lakes monitored using DEEP multi-mesh gillnets (Fig. 79). The first split was based on depth, splitting the data in two branches, over and under 20.9 meters depth. This position of the split is highly correlated to the median thermocline depth at off-shore areas in L. Vänern and L. Vättern thus splitting the dataset in one branch above and one below the thermocline. The first branch, consisting of sites deeper than 20.9 m, was first split based on CDOM (over and under 0.17). The group with CDOM under 0.17 was also split based on the distance to the shoreline (closer and further away than 1830 m) and the group consisting of sites close to the shoreline was split into one group with TSM levels under 0.38 and one group of sites with TSM levels over 0.38 . The group on this branch with CDOM under 0.13 and sites situated more than 1830 m from the shoreline was dominated by sites from L. Vättern and species like Arctic charr, four-horned sculpin and whitefish. The second group with CDOM under 0.17, closer to the shoreline than 1830 m and TSM below 0.38 consisted of sites from both L. Vänern and L. Vättern. This group was dominated by whitefish. The third group on this branch (under the thermocline) consisted of sites with CDOM under 0.32, closer the shoreline than 1830 m and TSM over 0.38. This group was mainly comprised of sites from L. Vänern and was dominated by burbot. The last group on the branch under the thermocline consisted of sites with CDOM over 0.32 and was mainly made up of sites from the most productive parts in L. Vänern. This group was dominated by smelt and vendace. The second branch was made up of sites above the thermocline and was split into two based on CDOM. The first group of sites with CDOM under 0.19 was dominated by perch, whitefish, ruffe and roach. Other characteristic species were trout, grayling, bullheads and certain cyprinids.

The root node error of the tree for offshore assemblages was relatively high compared to the other two trees and the relative error of the full tree was higher than in the other two cases (Tab. 14). The inclusion of remote sensing parameters decreased overall relative errors of the inshore fish assemblage trees with about 10 % (relative error in last split was 0.75 compared to 0.84). A tree built only on remote sensing variables could not contribute to as robust results as in the case with pelagic or inshore benthic assemblages (relative error was 0.90). Combining remote sensing predictors and nearest distance to the shoreline only lead to a very limited improvement in the relative error of the resulting tree. Thus, depth appeared to be a more important predictor in offshore benthic assemblages compared to remote sensing parameters.

Table 14. Summary statistics of a multivariate regression tree analysis on offshore fish assemblages. CP is the complexity parameter, N split is the number of the split, Rel error is the relative error, X error is the mean value of the errors of the cross-validations and X std is the standard deviation of the cross-validations. The root node error was 381.9/1375=0.277.

Nr	CP	n splits	rel error	xerror	Xstd
1	0.145	0	1.000	1.002	0.021
2	0.068	1	0.855	0.861	0.019
3	0.040	2	0.786	0.799	0.020
4	0.014	3	0.746	0.762	0.020
5	0.013	4	0.732	0.759	0.020

Multivariate trees – pelagic fish assemblages

The dataset based on acoustics and midwater trawling is less optimal for building multivariate trees. Firstly, there is an inherent difficulty using acoustic data due to the apportionment process, where species composition from trawl hauls are apportioned to the discrete acoustic densities. Secondly, the dataset is limited to the pelagic zone of the main basins of the lakes, leading to more limited gradients in remote sensing predictors. The pronounced differences between the more productive basins in L. Mälaren compared to L. Vänern and L. Vättern thus drives the majority of splits between groups of observations. The pelagic zone is highly dominated by two species, smelt and vendace, making multivariate analyses less powerful. We tried to solve this problem by dividing the datasets on smelt and vendace into adults and young-of-the-year. The tree based on acoustics was still relatively sparse compared to those obtained from multi-mesh gillnets and only consisted of five leaves (Fig. 80). The first and major split of observations was based on CDOM levels, splitting the data into two main branches, below and under CDOM levels of 0.14. The branch with CDOM under 0.14 consisted mainly of sites from L. Vättern). This branch was split in two groups, segments over and under 39.4 m bottom depth. The first group on this branch (deeper sites) was characterized by species such as Arctic charr, four-horned sculpin and bream and the other group with more shallow sites was characterized by a higher biomass of whitefish. The second branch originating from the first split with CDOM higher than 0.14 and was dominated by segments from L. Mälaren. This branch was first split into two groups consisting of sites over and under 40 m depth. The group made of sites from shallower areas was split in two more groups based on TSM levels. The group with shallow sites (less than 40 m) and TSM above 0.39 was dominated by sander, white bream, perch and smelt. The group with shallow sites and TSM levels under 0.39 was dominated by smelt. The group with shallow deep sites was dominated by adult vendace.

Despite some inherent shortcomings, remote sensing predictors were particularly important for constructing multivariate trees for pelagic assemblages (Tab. 15). Trees based only on remote sensing predictors were almost as good as trees based on a combination of all predictors. Trees obtained with a combination of nearest distance to shoreline and remote sensing parameters were even slightly better than trees obtained with all predictors combined. Trees built only using depth and nearest distance to shoreline had significantly larger relative error than trees built using some kind of remote sensing information indicating that remote sensing variables are particularly important predictors for pelagic fish assemblages.

Given that the predictor variables are available as continuous maps it is possible to map the distribution of the different assemblages specified by the multivariate tree analysis. We chose to illustrate our results bu portraying the distribution of fish assemblage groups in Lake Vänern. It must be emphasised however that the quality of the depth layer is limited, particularly in shallow areas.

Table 15. Multivariate results 2. Summary statistics of a multivariate regression tree analysis on offshore fish assemblages. CP is the complexity parameter. N split is the number of the split. Rel error is the relative error. X error is the mean value of the errors of the cross-validations and X std is the standard deviation of the cross-validations. The root node error was 108/478=0.226.

Nr	CP	n splits	rel error	xerror	xstd
1	0.157	0	1.000	1.005	0.032
2	0.125	1	0.843	0.854	0.032
3	0.048	2	0.718	0.740	0.035
4	0.034	3	0.670	0.701	0.035
5	0.031	4	0.635	0.680	0.036
6	0.029	5	0.605	0.669	0.037

Table 16. Occurring species listed after their prevalence (%) in NORDIC multimesh gillnets. Commercial catch in tonnes (mean of the years 2011-2012), redlisted species and Natura 2000 typical species are also given.

SPECIES	LATIN	NORDIC MULTIMESH	DEEP MULTIMESH	HYDRO-ACOUSTICS	CATCH (tonnes)	RED-LISTED?	Natura 2000?
Ruffe	*Gymnocephalus cernuus*	91,9	76,1	66,2	0,0		
Perch	*Perca fluviatilis*	75,9	32,0	14,4	87,0		
Roach	*Rutilus rutilus*	68,4	9,1	6,9	1,0		
White bream	*Blicca bjoerkna*	67,6	3,1	3,5	0,0		
Bream	*Abramis brama*	49,3	4,0	17,0	31,0		
Sander	*Sander lucioperca*	42,2	4,4	25,4	434,0		
Bleak	*Alburnus alburnus*	35,1	0,0	2,4	0,0		
Smelt	*Osmerus eperlanus*	27,0	68,5	100,0	0,5		
Vendace	*Coregonus albula*	12,1	18,5	93,0	315,0		
Rudd	*Scardinius erythropthalmus*	6,3	0,0	0,0	0,0		
Whitefish	*Coregonus maraena*	5,9	94,9	60,1	27,0		
Pike	*Esox lucius*	5,6	1,5	0,0	95,0		
Zope	*Abramis ballerus*	4,0	0,0	0,0	0,0		
Asp	*Aspus aspus*	3,7	0,0	0,0	2,5	NT	X
Burbot	*Lota lota*	3,0	47,5	5,9	31,0	NT	
Tench	*Tinca tinca*	2,3	0,0	0,0	0,0		
Dace	*Leuciscus leuciscus*	1,0	0,0	0,0	0,0		
Four-horned sculpin	*Myoxocephalus quadricornis*	0,9	10,3	0,0	0,0		
Minnow	*Phoxinus phoxinus*	0,5	0,0	0,0	0,0		
Ide	*Idus idus*	0,4	0,0	0,0	0,0		
Vimba	*Vimba vimba*	0,4	0,5	0,0	0,0	NT	
Arctic charr	*Salvelinus salvelinus*	0,2	30,6	12,9	8,0		
Trout	*Salmo trutta*	0,2	7,9	0,0	7,0		
European bullhead	*Cottus gobio*	0,2	0,4	0,0	0,0		X
Spined loach	*Cobitis taenia*	0,2	0,1	0,0	0,0		X
Grayling	*Thymallus thymallus*	0,2	0,7	0,0	0,0		
Three-spined stickleback	*Gasterosteus aculeatus*	0,1	0,7	45,5	0,0		
Crucian carp	*Carassius carassius*	0,1	0,1	0,0	0,0		
Eel	*Anguilla anguilla*	0,1	0,0	4,4	74,0	CR	
Alpine bullhead	*Cottus poecilopus*	0,0	0,1	0,0	0,0		
Salmon	*Salmo salar*	0,0	0,6	8,0	14,0		X
Nine-spined stickleback	*Pungitius pungitius*	0,0	0,5	1,1	0,0		
River lamprey	*Lampetra fluviatilis*	0,0	0,0	6,6	0,0		
TOTAL		**29**	**23**	**17**	**1127,0**	**4**	**4**

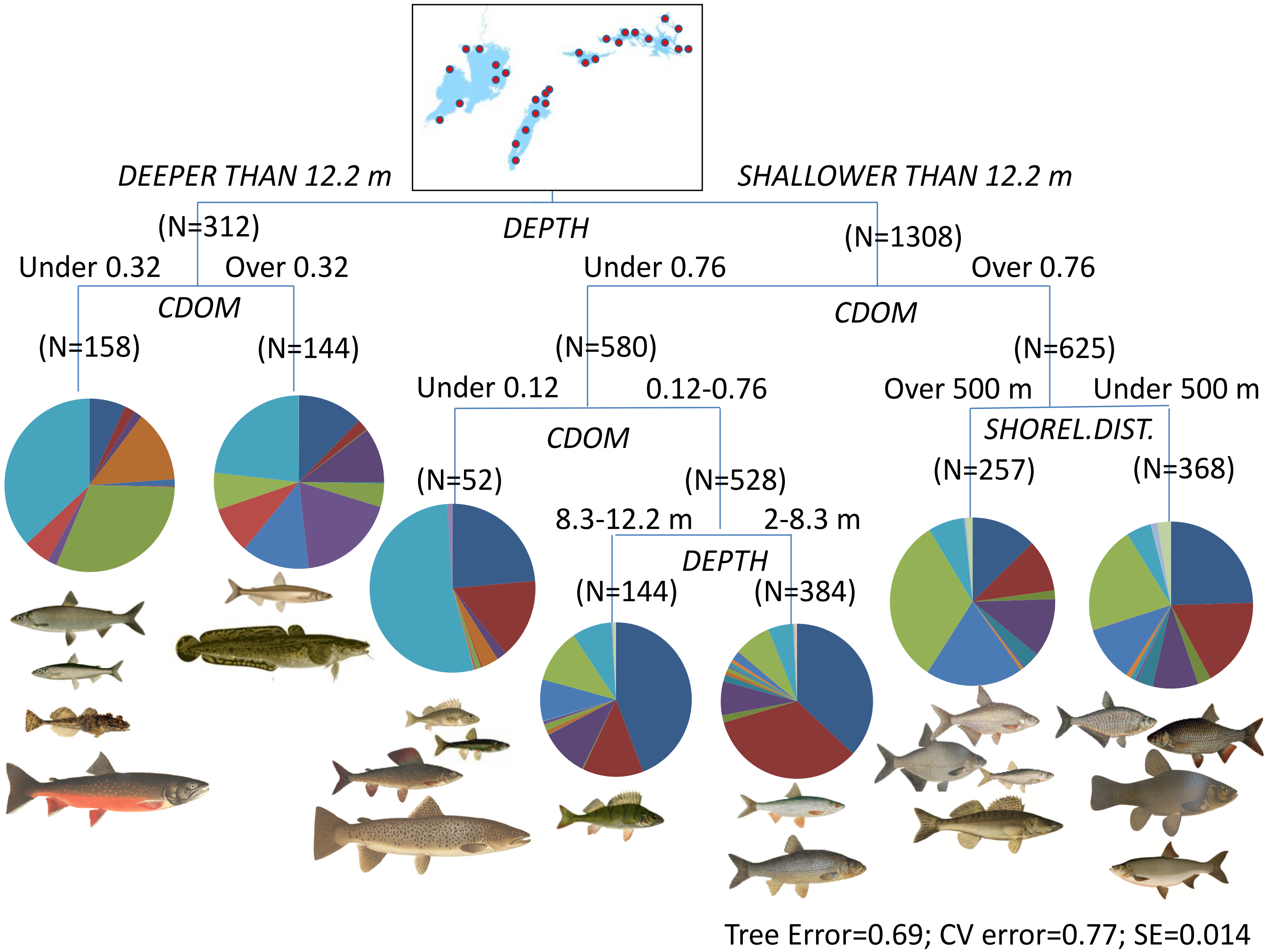


Figure 78. Multivariate results 2. The results of a multivariate tree analysis on inshore fish assemblage composition in L. Vänern, L. Vättern, L. Mälaren and L. Hjälmaren based on catches in multimesh NORDIC gillnets at 1631 different sites. The figure illustrates the splits of the communities into distinct assemblage groups. The pictures of fish species represent the characteristic species (not necessarily the most common) in each group. A summary of the overall errors of the tree is given in the lower right corner.

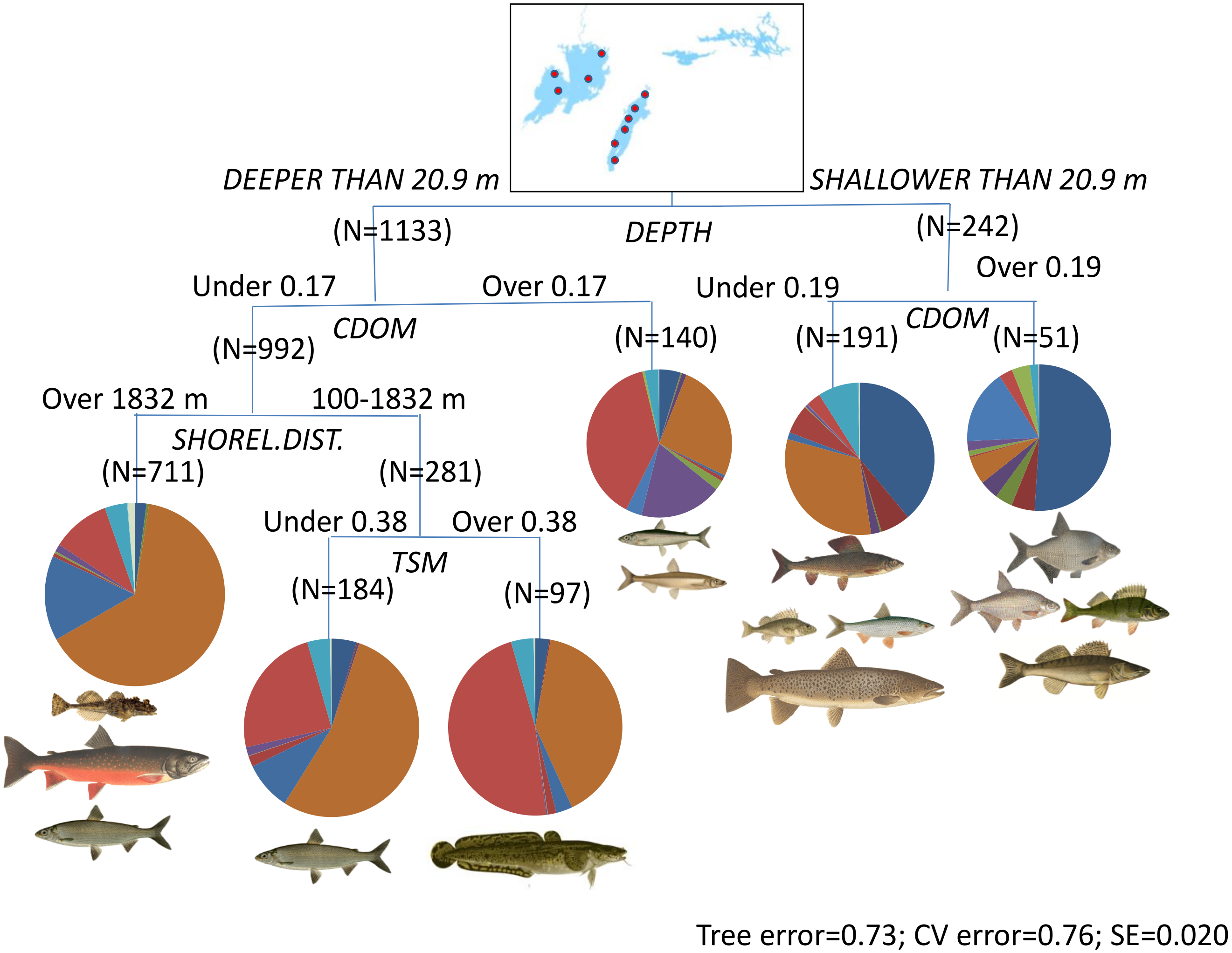


Figure 79. Multivariate results 3. The results of a multivariate tree analysis on offshore fish assemblage composition in L. Vänern and L. Vättern based on catches in multimesh DEEP gillnets at 1375 different sites. The figure illustrates the splits of the communities into distinct assemblage groups. The pictures of fish species represent the characteristic species (not necessarily the most common) in each group. A summary of the overall errors of the tree is given in the lower right corner.

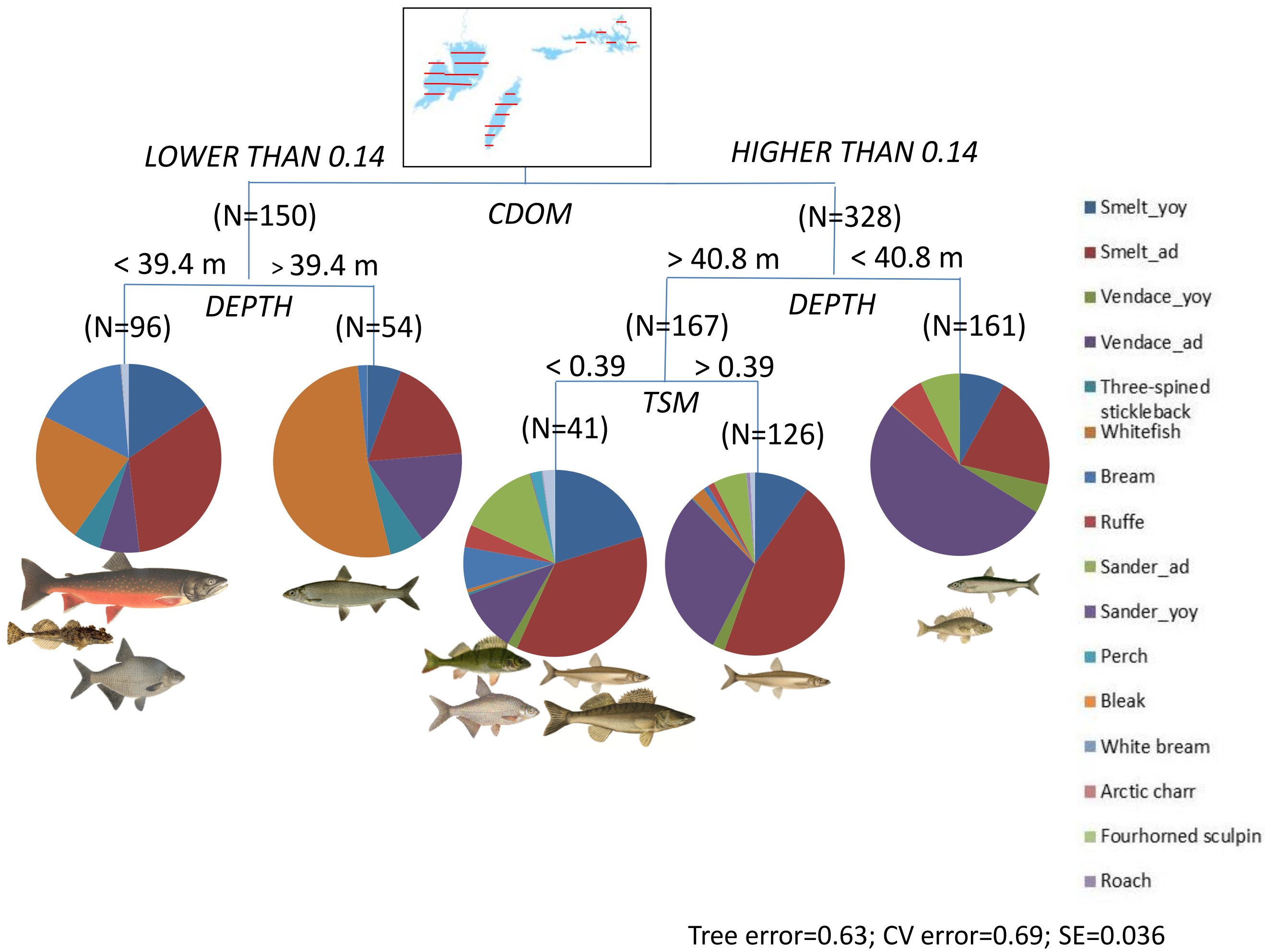
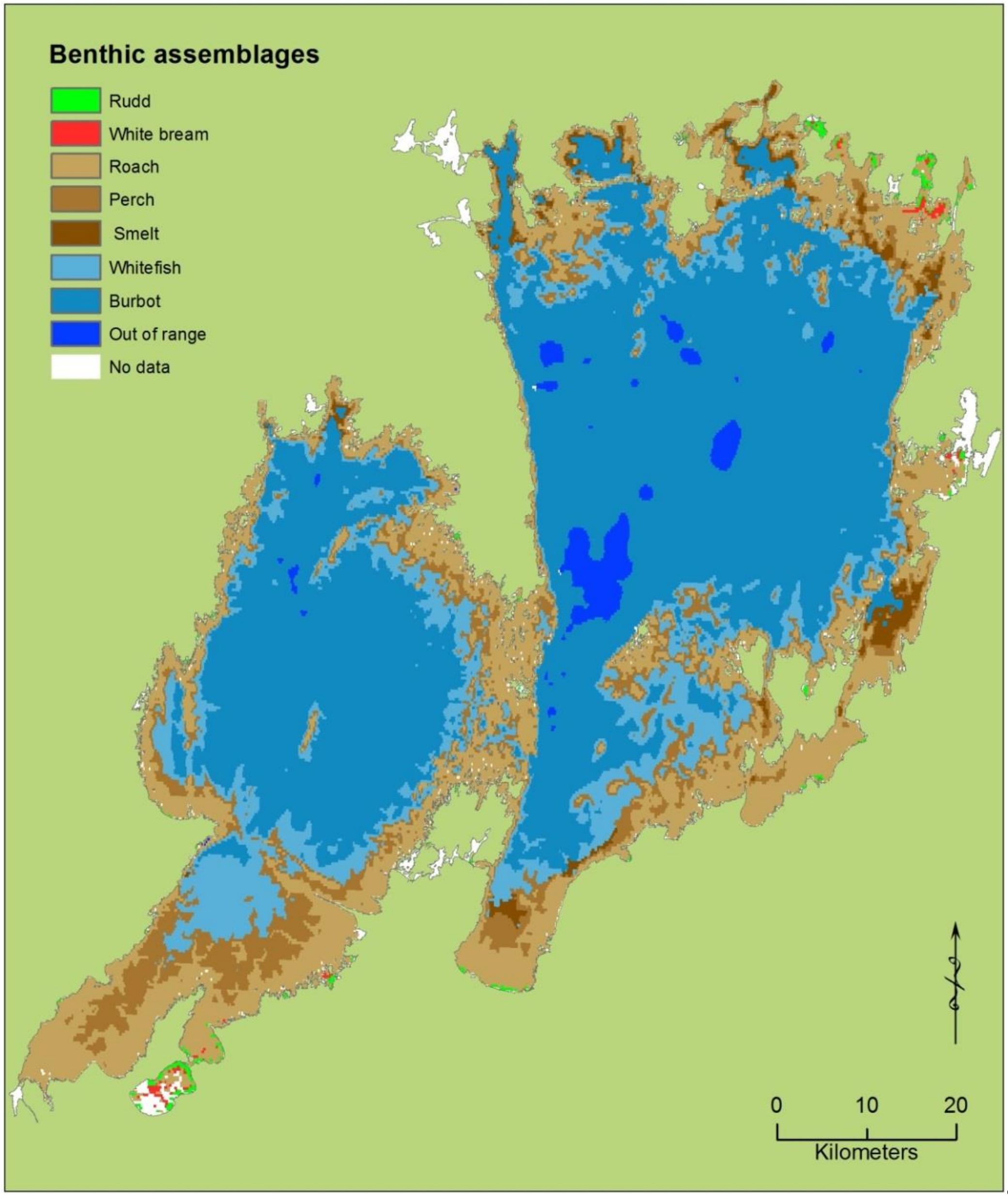


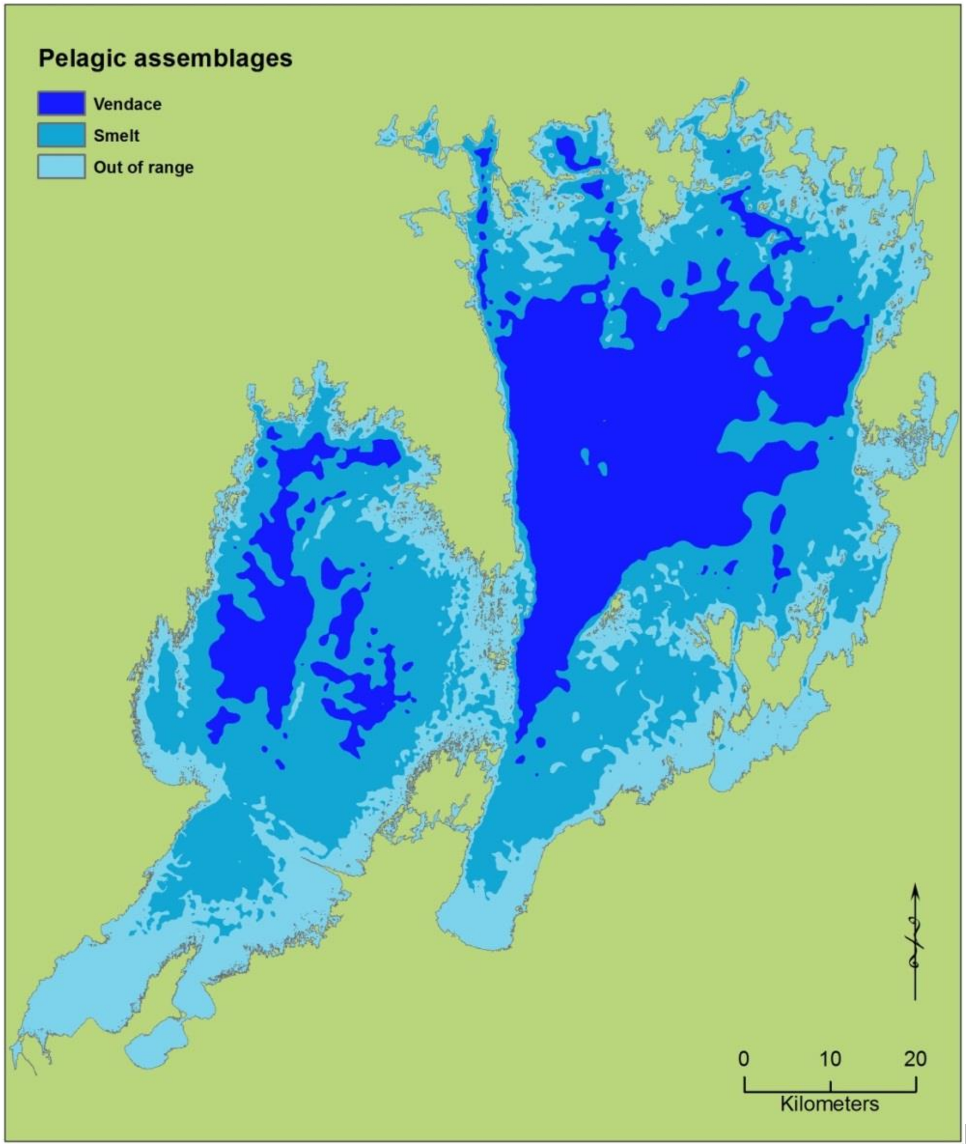
Figure 80. Multivariate results 4. The results of a multivariate tree analysis on pelagic fish assemblage composition in L. Vänern. L. Vättern. L. Mälaren and L. Hjälmaren based on results from hydroacoustic surveys with midwater trawling covering 478 segments of 1000 m length. The figure illustrates the splits of the communities into distinct assemblage groups. The pictures of fish species represent the characteristic species (not necessarily the most common) in each group. A summary of the overall errors of the tree is given in the lower right corner.

Table 17. Summary of groups identified by multivariate trees and the predictor variables and fish species that characterizes them.

Group	Other char. species	Depth	CDOM	TSM	NEAR DIST	Lakes
NORDIC GILLNETS						
Arctic charr	Four-horned sculpin, vendace, whitefish	<12.2 m	>0.32			L. Vättern
Smelt	Burbot	<12.2 m	<0.32			L. Vänern, L. Mälaren
Grayling	Trout, minnow, ruffe	>12.2 m	>0.12			L. Vättern
Perch		8.3-12.2	0.12-0.76			L. Vänern, L. Mälaren
Roach	Ide, dace	2-8.3	0.12-0.76			L. Vänern, L. Mälaren
White bream	Bream, sander, bleak	>12.2 m	<0.76		<500 m	L. Vänern, L. Mälaren, L. Hjälmaren
Rudd	asp, tench	>12.2 m	<0.76		>500 m	L. Vänern, L. Mälaren, L. Hjälmaren
DEEP GILLNETS						
Four-horned sculpin	Four-horned sculpin, Arctic charr, whitefish	<20.9 m	>0.17			L. Vättern
Whitefish		<20.9 m	>0.17		<1832 m	L. Vänern, L. Vättern
Burbot		<20.9 m	<0.17	<0.38	100-1832	L. Vänern
Vendace	Smelt	<20.9 m	>0.17	>0.38	100-1832	L. Vänern
Trout	Grayling, ruffe, roach	>20.9 m	>0.19			L. Vättern
Bream	Perch, sander, white bream	>20.9 m	<0.19			L. Vänern
HYDROACOUSTICS						
Arctic charr	Four-horned sculpin, bream	<39.4 m	>0.14			L. Vättern
Whitefish		>39.4 m	>0.14			L. Vättern
Sander	Perch, white bream, smelt	>40.8 m	<0.14	<0.39		L. Mälaren
Smelt		>40.8 m	<0.14	>0.39		L. Vänern, L. Mälaren
Vendace	ruffe	<40.8 m	<0.14			L. Vänern, L. Mälaren


Benthic assemblages
Rudd
White bream
Roach
Perch
Smelt
Whitefish
Burbot
Out of range
No data
0
10
20
Kilometers

a.



b.

Figure 81 a and b. Multivariate results 5. Map predictions illustrating the results from multivariate trees applied on L. Vänern using CDOM, depth and nearest distance to shoreline as predictors. A) inshore and offshore benthic assemblages combined. B) pelagic assemblages. The species name indicates the most characteristic and/or dominating species in a certain group.

Predicting the distribution and response of individual fish species to remote sensing variables

To predict the availability of essential habitats we tried to relate remote sensing parameters and other relevant environmental predictors such as depth to fish monitoring data on individual species. These, so called distribution models were fitted against field measured water depth, TSM in August, CDOM in August and the nearest distance to the shoreline. All these predictors are available as continuous raster maps. To obtain predictions and to test the importance of various explanatory variables we first explored the data using co-plots and scatter plots. We also tried to identify outliers and test whether response variables were normally distributed and then if they needed to be log (+1) transformed prior to analysis. The majority of the tested response variables from monitoring with gillnets was not normally distributed and the numbers of zeros in some cases were relatively high. The data on certain species also violated homogeneity requirements. The hydroacoustic data on density and biomass of the focal investigated species on the other hand was normally distributed after log-transformation. This resulted in two different types of approaches for the existing species. A minor number of species was analyzed using linear regression modelling (pelagic smelt, vendace, sander and total pelagic fish density). For species with other distributions and with non-linear relations to explanatory variables we instead used GAMs (Generalized Additive Models). Both model types relate the distribution of certain fish species and/or life-stages to environmental descriptors. GAMs display how the individual main effects influence the response by using smoothing splines. Generalized additive models can be described as semi-parametric extensions of generalized linear models, useful for fitting non-linear relationships without prior assumptions on the shape of the response (57). For GAMs we used presence/absence data with binomial error distributions and with a logistic link function. To avoid overfitting models we set a limit of df=3 of final models. The models were run using the "mgcv" package for R (3.1.1) connected to Brodgars interface version 3.7.4 (53). To assess linear regression models and GAM performance and to select the best available models we used Aikake's Information Criterion (AIC) in a stepwise procedure.

Results - Species-specific patterns

The vast majority of the best models (both GAMs and linear regression models) contained remote sensing parameters. Particularly CDOM in August was often the best predictor for many species (Tab. 18). The best GAM-models (white bream and whitefish) explained 66 and 63% of the deviance (Fig. 82). The level of CDOM and depth was the two most important predictors for the majority of species and the final models were in all cases made up of a combination of depth and CDOM (Tab. 18; Fig 82-85). The species that seemed to respond most strongly to CDOM were bleak, whitefish, sander and white bream (Tab. 18; Fig 82-84). The relationships were often non-linear, indicating that these species are influenced positively or negatively once a threshold in CDOM is reached. Bleak, sander and white bream all responded positively to increased CDOM levels. Whitefish instead responded negatively. Perch and roach are the dominating benthic species in many of the studied water bodies. For both these species there was a hump-shaped relationship between prevalence and CDOM levels when CDOM was used together with depth as smoothers in GAM-models (Fig 82 & 83). For the third dominating species, ruffe, on the other hand there was no clear trend in the response to any of the remote sensing variables.

*Table 18. AIC values, degrees of freedom and deviance explained for the first step in a GAM-model selection procedure for a selected number of fish species. Degrees of freedom in the final models were set to be maximally df=3. The model was binomial using a logistic link function and based on data from multimesh gillnets with gear type as a nominal factor. The model predictors contained in the final and best models (when assessed using AIC) are given in shaded color. *CDOM and TSM are August means.*

	CDOM*	DEPTH	TSM*	NEAR DIST**	FINAL MODEL
White bream					
AIC	1430,0	1838,5	2493,0	2686,3	1290,7
edf	6,1	1,0	6,4	4,8	
Deviance explained (%)	62,7	53,9	34,7	33,1	66,1
Whitefish					
AIC	1806,7	1856,7	3311,9	2667,0	1472,9
edf	4,6	6,5	7,7	8,0	3,0
Deviance explained (%)	55,2	55,5	31,9	36,3	63,3
Roach					
AIC	1976,1	1678,0	3328,6	2595,2	1609,9
edf	9,5	4,5	9,3	7,3	
Deviance explained (%)	49,7	56,9	14,9	33,6	58,6
Bleak					
AIC	1495,9	1566,2	1921,0	2255,1	1211,0
edf	6,8	3,0	7,9	1,0	3,0
Deviance explained (%)	45,6	46,4	30,1	23,2	56,3
Sander					
AIC	1794,0	2479,7	2205,2	2928,9	1723,8
edf	8,8	6,6	7,7	8,3	
Deviance explained (%)	45,3	26,8	32,5	13,8	47,3
Perch					
AIC	3206,9	2444,2	3680,0	3276,1	2186,1
edf	7,4	2,2	8,0	7,0	
Deviance explained (%)	20,0	40,8	8,2	21,1	45,2
Bream					
AIC	2033,84	2171,35	2807,33	2595,22	1991,87
edf	6,6	2	8,8	4,73	
Deviance explained (%)	40,5	36,2	17,8	23	41,9
Smelt					
AIC	965.23	988.99	1070.32	1063.4	953.76
edf	5.63	2.81	4.46	3.6	
Deviance explained (%)	39,0	33,0	22.3	23,1	38,6
Burbot					
AIC	2506,72	2267,9	2900,59	2816,59	2204,55
edf	7,61	8,75	1,84	8,76	
Deviance explained (%)	22,3	31	0,0963	14,4	31,4
Sander YOY					
AIC	1001,5	1007,7	1113,3	1187,1	970,3
edf	4,8	3,6	9,9	3,0	
Deviance explained (%)	28,9	28,1	21,5	15,2	31,3
Asp					
AIC	366,7	379,2	436,6	481,4	367,1
edf	4,2	1,0	9,9	1,0	
Deviance explained (%)	26,1	22,2	7,7	18,9	25,6
Vendace					
AIC	2038,3	2171,48	2305,42	2371,61	2146,42
edf	8,56	6,43	2	6,51	
Deviance explained (%)	17,9	12,3	6,5	4,18	23,9

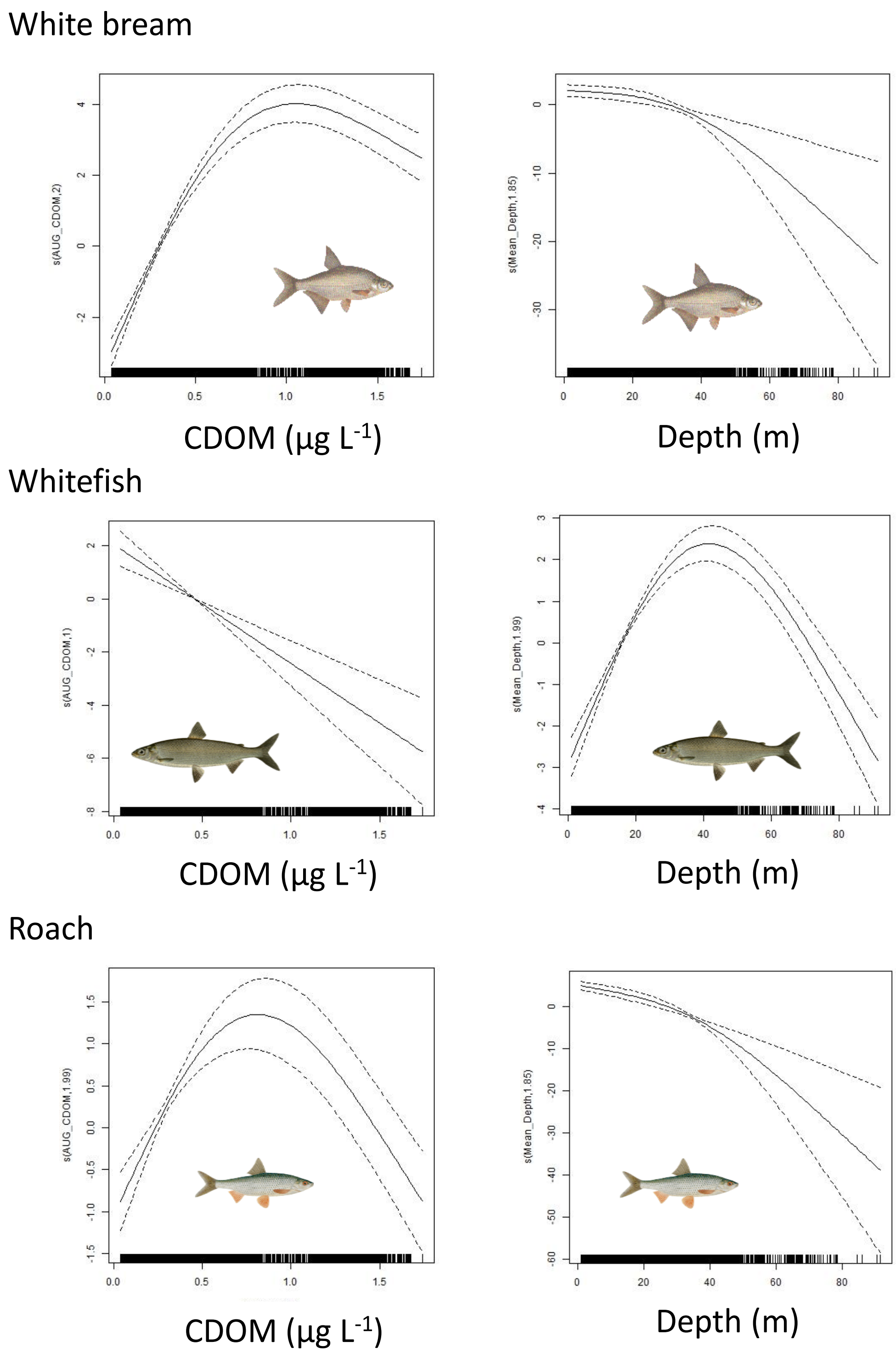


Figure 82. Smoothing functions for GAM models applied to various fish species caught in multimesh NORDIC gillnets. All models were fitted to two predictor variables: CDOM in August and the mean depth of the sampling sites. The models were of the form: Y1 ~ 1 + s(Mean_Depth) + s(AUG_CDOM) + AUG_CDOM:Mean_Depth+ε.

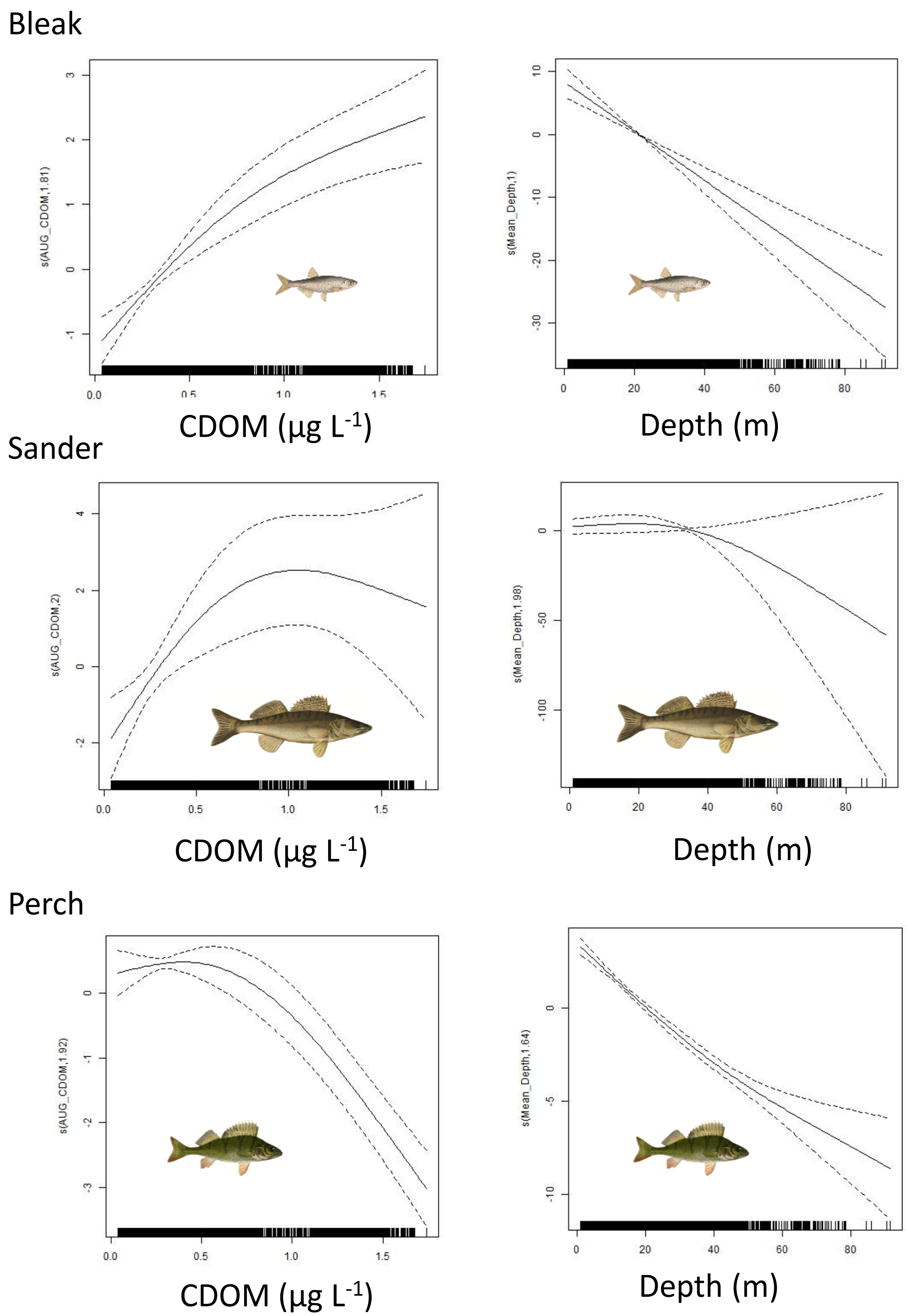


Figure 83. Smoothing functions for GAM models applied to various fish species caught in multimesh NORDIC gillnets. All models were fitted to two predictor variables: CDOM in August and the mean depth of the sampling sites. The models were of the form: Y1 ~ 1 + s(Mean_Depth) + s(AUG_CDOM) + AUG_CDOM:Mean_Depth+ε.

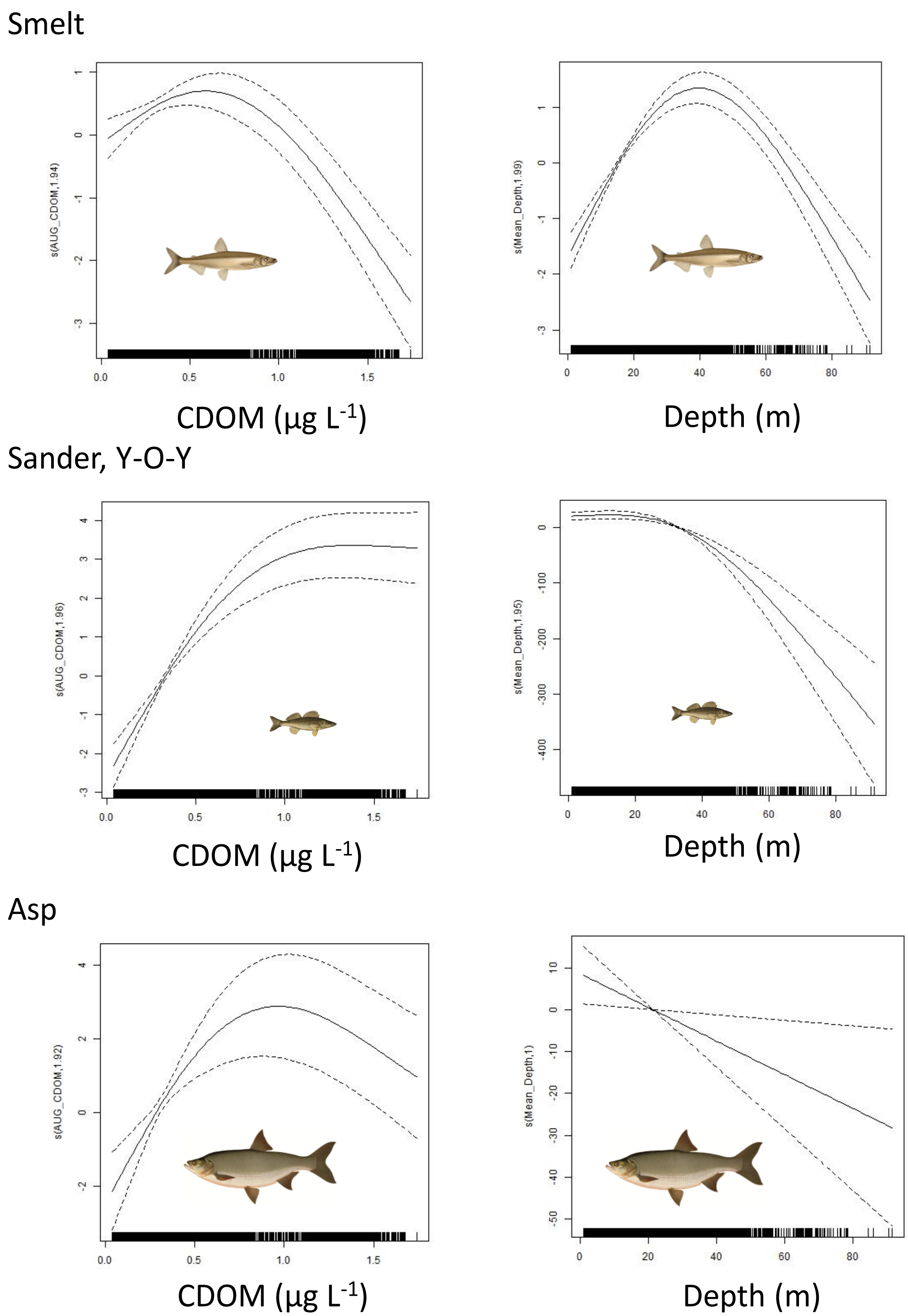


Figure 84. Smoothing functions for GAM models applied to various fish species caught in multimesh NORDIC gillnets. All models were fitted to two predictor variables: CDOM in August and the mean depth of the sampling sites. The models were of the form: Y1 ~ 1 + s(Mean_Depth) + s(AUG_CDOM) + AUG_CDOM:Mean_Depth+ε.

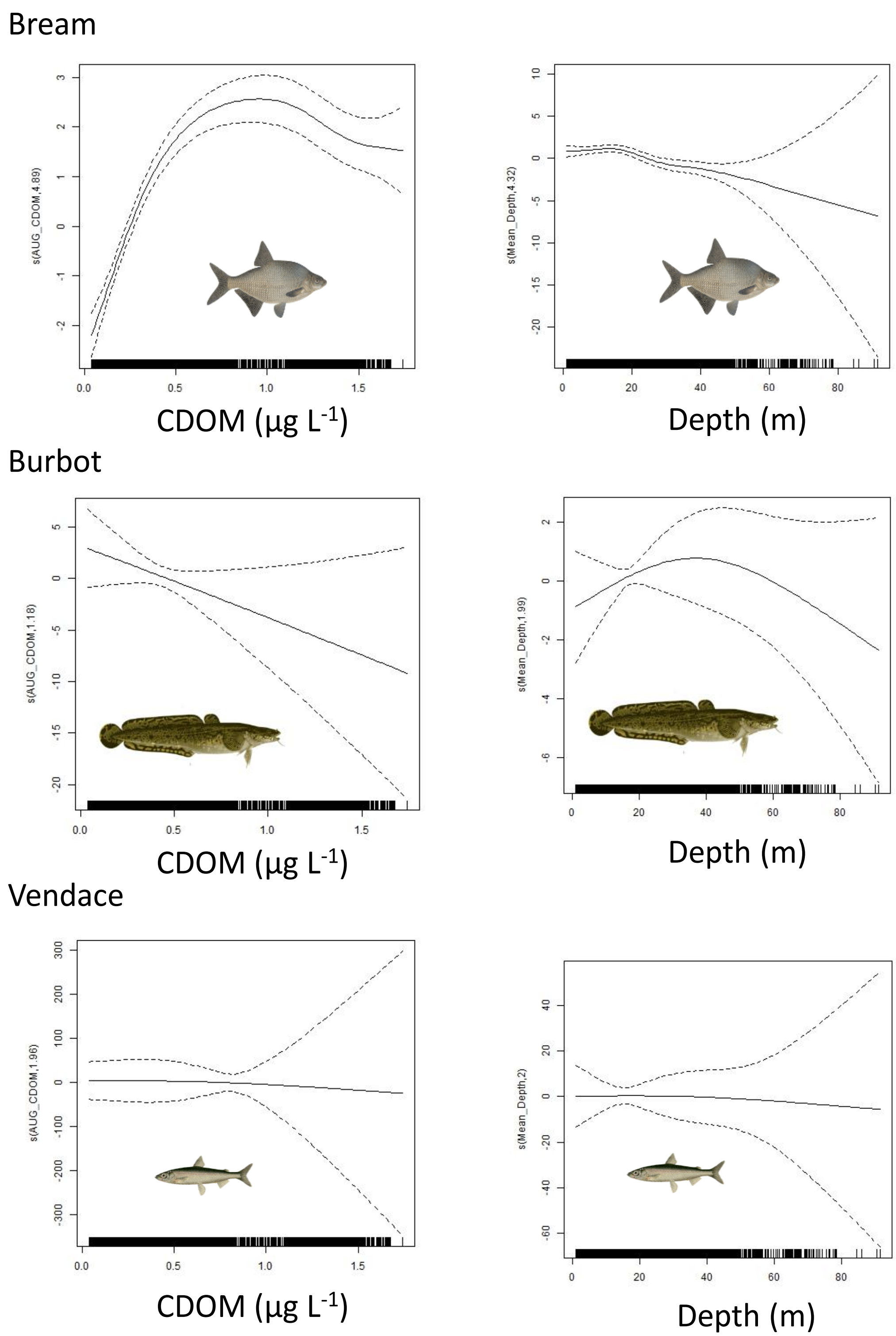


Figure 85. Smoothing functions for GAM models applied to various fish species caught in multimesh NORDIC gillnets. All models were fitted to two predictor variables: CDOM in August and the mean depth of the sampling sites. The models were of the form: Y1 ~ 1 + s(Mean_Depth) + s(AUG_CDOM) + AUG_CDOM:Mean_Depth +ε.

The trends for pelagic species estimated with acoustics were highly influenced by the comparatively high abundance of certain species in some of the basins in Lake Mälaren (Fig. 86 & 87). The total density of fish was positively correlated to CDOM (Linear regression model, df=473, r^2=0.59, p<0.001). The density of the dominating pelagic species, smelt, was significantly and positively correlated to CDOM (Lin. regression model, df=473, r^2=0.36, p>0.001). Both density and biomass of sander was positively correlated to CDOM (Lin. regression model, biomass: df=473, r^2=0.28, p>0.001, density: df=473, r^2=0.35, p>0.001) (Fig. .88). Sander young-of-the-year was also estimated with acoustics. The density of juvenile sander was positively correlated to CDOM (linear regression, df=473, r^2=0.60, p>0.001). This pattern was highly depending on the fact that they only occurred in three of the investigated basins. These were all situated in Lake Mälaren: Blacken, Granfjärden and Ekoln. The highest densities were observed in Blacken and Ekoln. In contrast, adult sander occurred in seven of the studied water bodies, indicating that the recruitment of sander is restricted to certain water bodies and that adult feeding areas are more wide-spread.

Both the biomass and density of vendace was only weakly correlated to remote sensing parameters. Recruitment of vendace was markedly higher in the two major basins of L. Vänern (Dalbosjön and Värmlandssjön) (Fig. 89). Both biomass and density of adult vendace on the other hand was the highest in the two deepest basins of L. Mälaren (Lambarfjärden and Prästfjärden) (Fig. 90). Adult vendace has a strong preference for cold water and aggregate in the deep, cold-water parts of these basins in the summer. They also grow comparatively large (mean adult length is around 24 cm) in L. Mälaren. They thus make up a considerable part of the biomass in the deeper parts of the water column in these areas. Spatial models containing biomass, abundance, presence/absence and other metrics can be constructed based on the relationships with remote sensing derived variables and applied to map layers in GIS. We have chosen to exemplify the potential outcomes of using this approach by showing the results from one of the more simple models on total abundance of pelagic fishes in Lake Vänern (Fig. 91).

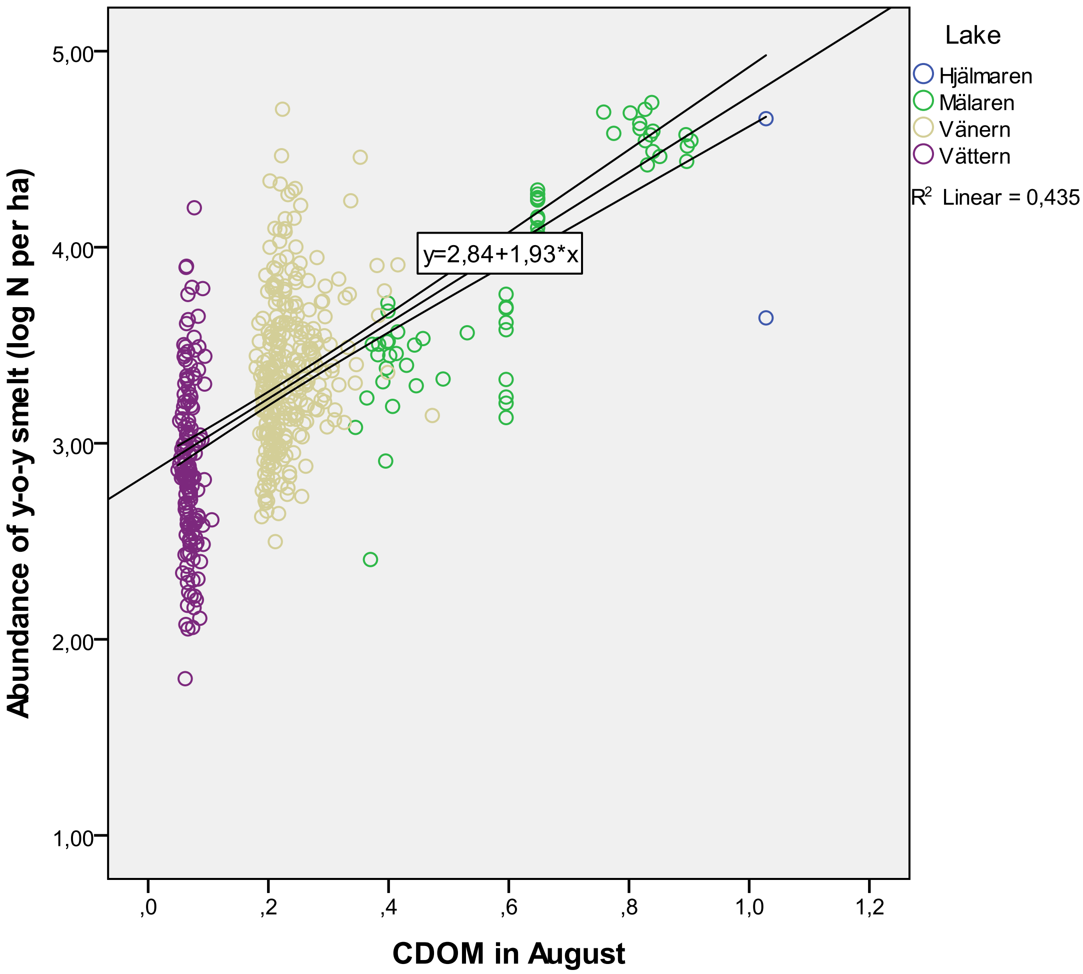


Figure 86. Smelt young-of-the-year density estimated with hydroacoustics plotted against the level of CDOM (µg L^{-1}) in August. A linear regression has been fitted to the data. The outer lines represent 95% confidence intervals.

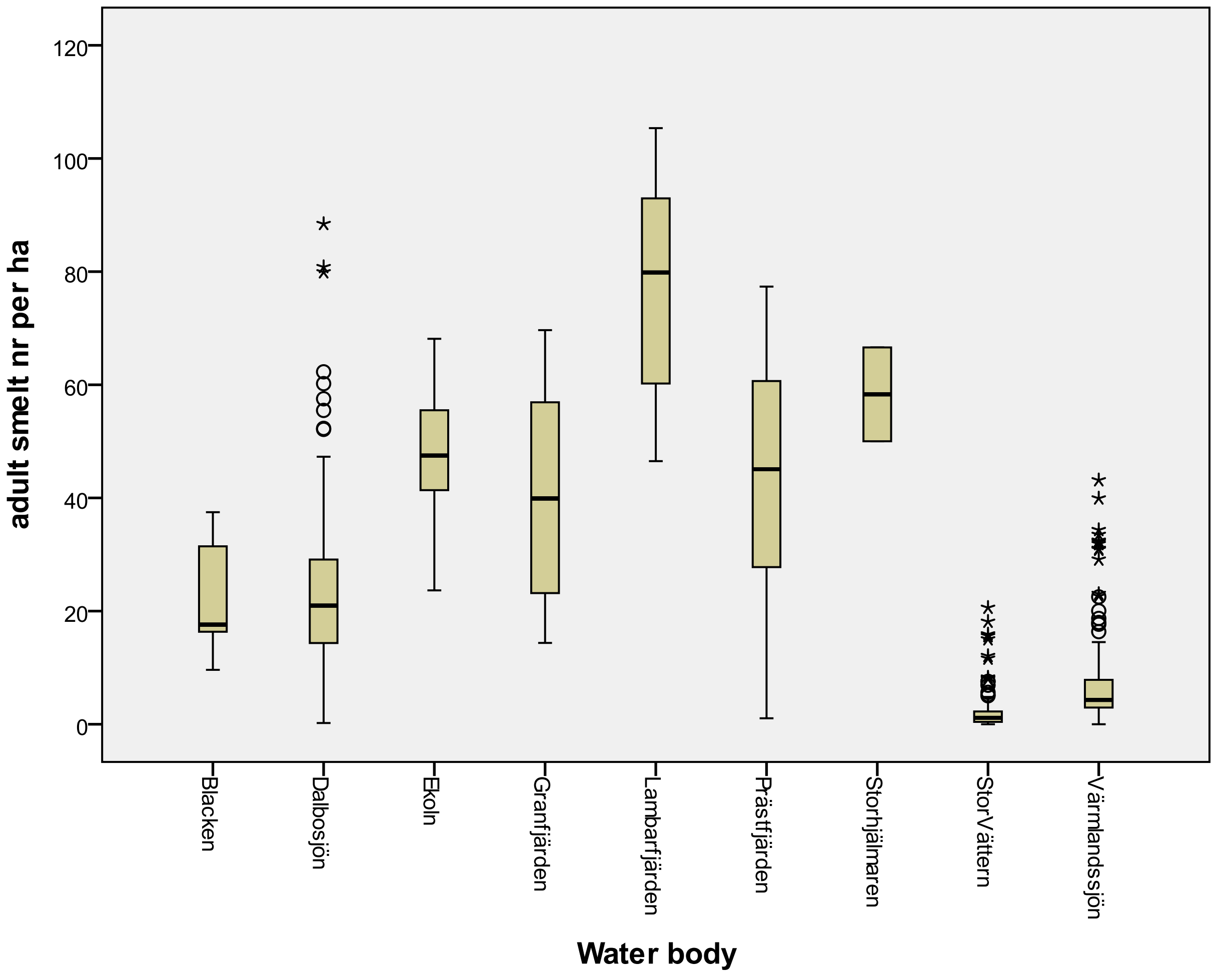


Figure 87. Adult smelt abundance in the various water bodies that has been studied with hydroacoustic surveys. All data are from 2011-2012 except Stor-Hjälmaren that was investigated only in 2009 and Lambarfjärden that was investigated only in 2013.

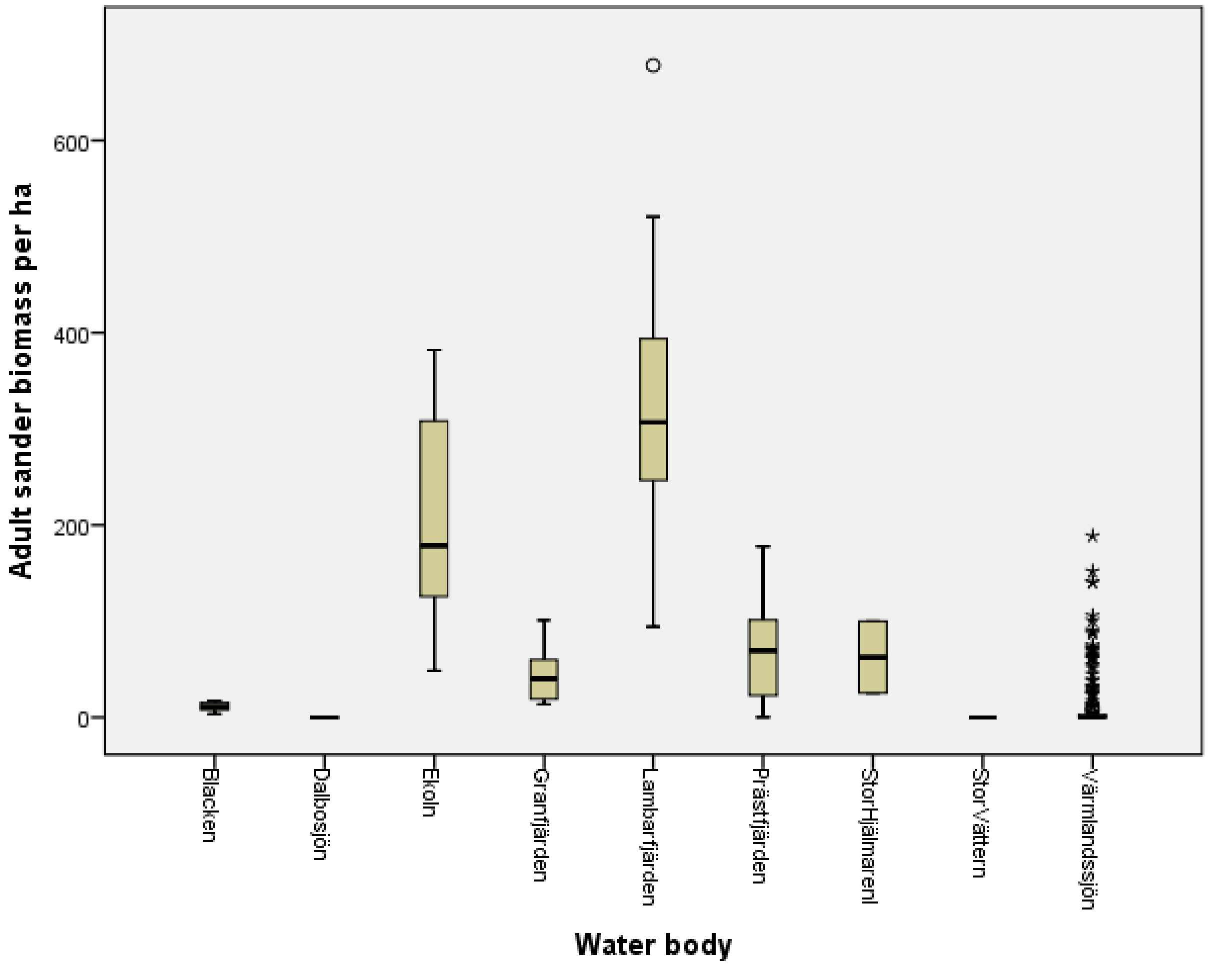


Figure 88. Adult sander biomass in the various water bodies that has been studied with hydroacoustic surveys. All data are from 2011-2012 except Stor-Hjälmaren that was investigated only in 2009 and Lambarfjärden that was investigated only in 2013.

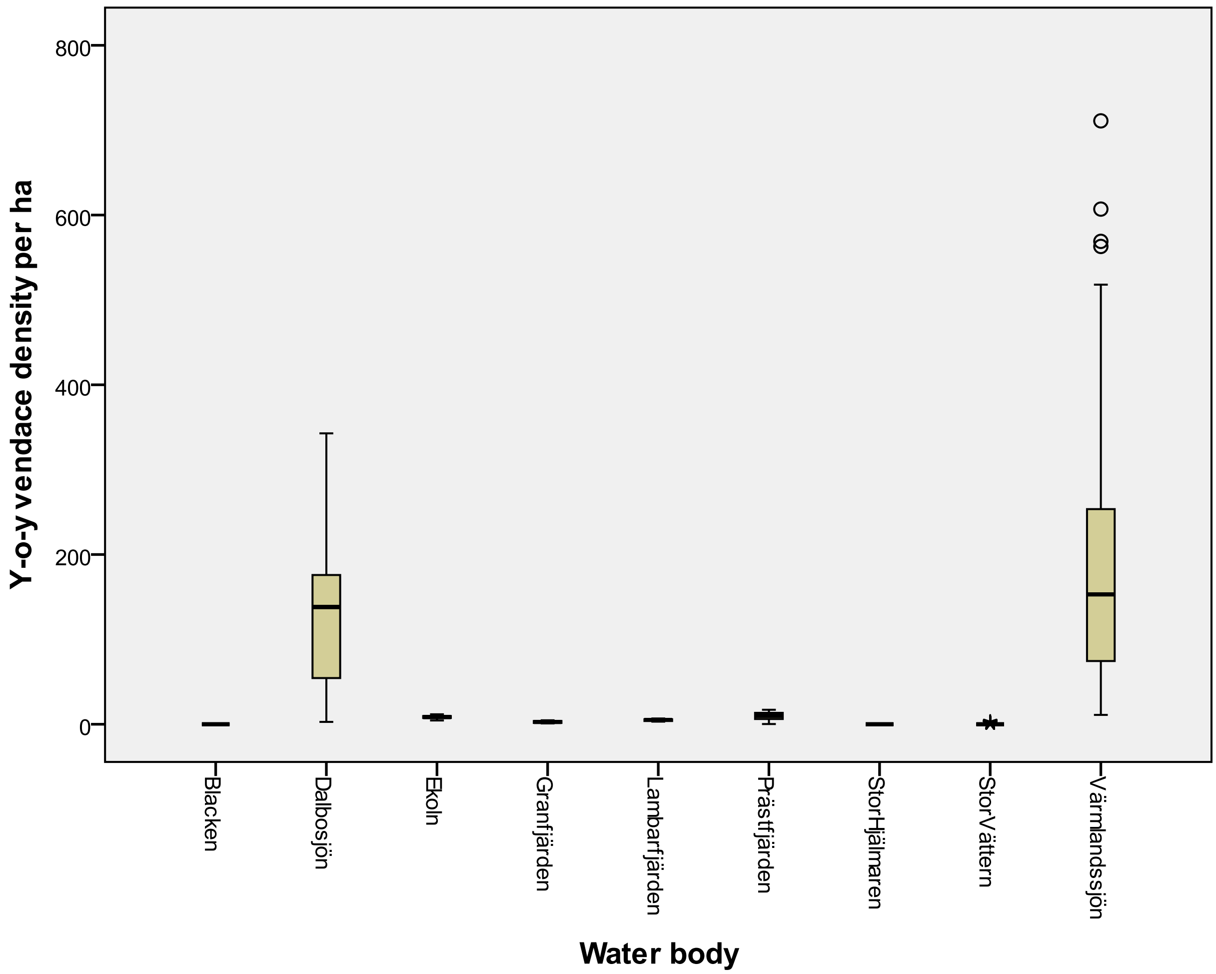


Figure 89. Number of young-of-the-year vendace estimated in hydroacoustic surveys in nine water bodies in Swedish large lakes. All data are from 2011-2012 except Stor-Hjälmaren that was investigated only in 2009.

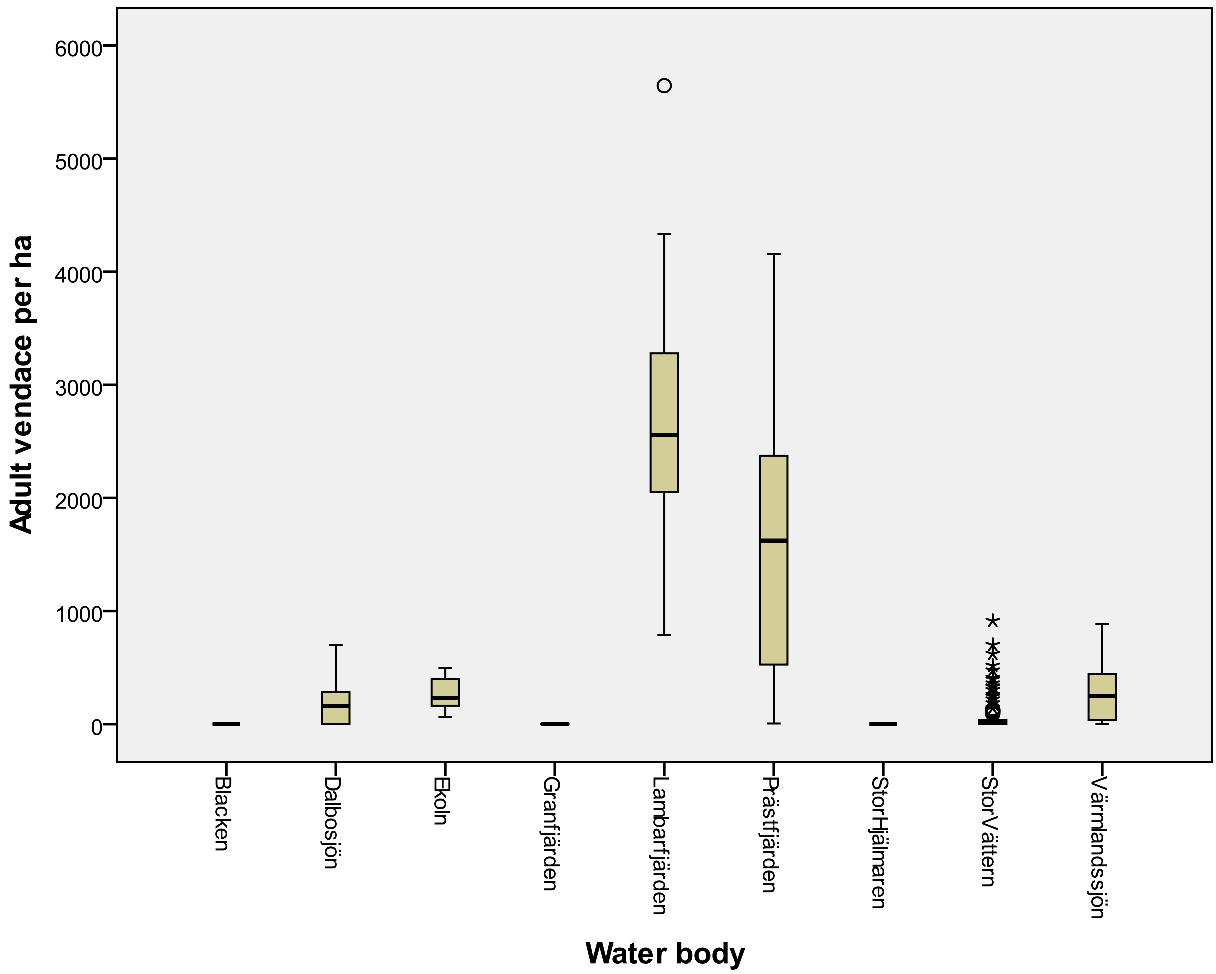


Figure 90. Number of adult vendace estimated in hydroacoustic surveys in nine water bodies in Swedish large lakes. All data are from 2011-2012 except Stor-Hjälmaren that was investigated only in 2009.

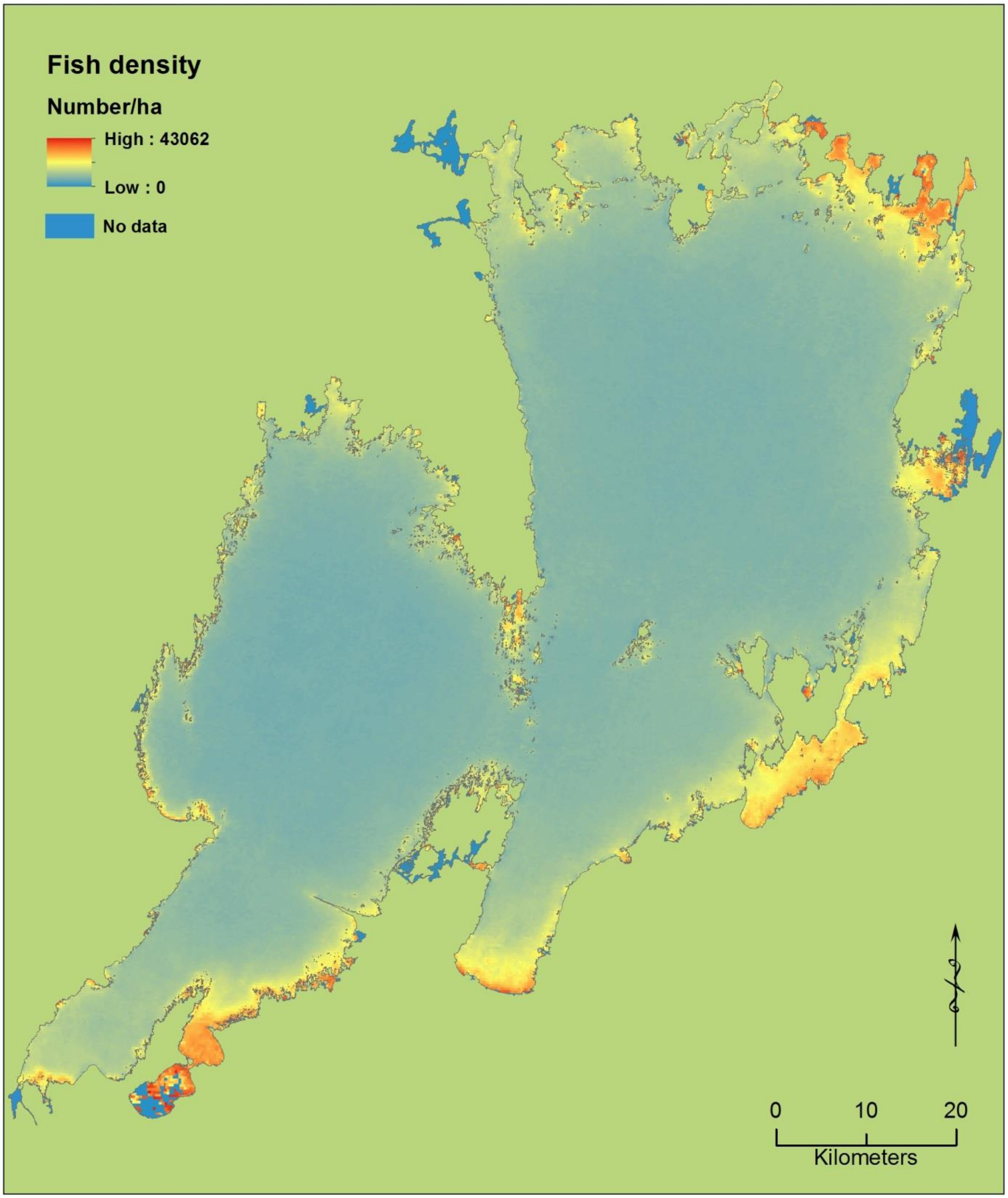


Figure 91. Map prediction of the total density of pelagic fishes applied to L. Vänern. The prediction was based on a linear regression model with CDOM in August as the main predictor variable. Note that this prediction is an illustration of how remote sensing layers can be used but that it has not been properly validated against field data.

Rare species

Certain species only occurred in very low numbers and it is thus hard to analyze if their distribution and abundance is related to remote sensing variables. Some of these species (asp, eel and vimba) are also red-listed. Particularly asp appeared to be favored by increasing CDOM levels (see tab 18). Eels were extremely rare in the catch in multi-mesh gillnets, only one individual occurred in the catch (in Ekoln, Lake Mälaren). They were also very rare in the catches in midwater trawling. Over the twenty-five year period during which this survey has been conducted only 34 eels have been caught. The mean length of eel was 53 cm, thus a majority of the catch consisted of yellow eels. Of these, 31 were caught in Lake Mälaren and three in Lake Vänern. No eels were caught in the other lakes. The majority of eels were caught between 15-20 m depth. Among the different basins in Lake Mälaren, the highest catches were obtained in Blacken and Granfjärden. These basins also have the highest commercial catch of eels in all water-bodies. The data on eels is not sufficient for modelling their distribution but considering that they mainly occurred in the more productive and shallow basins, a combination of depth and Chl a could be two promising factors that could be used for stratification of future monitoring and modelling efforts on eel. Besides the environmental preferences of the species, the distribution of eels could be hypothesized to also be influenced by stocking. In these four lakes the stocking intensity has been highest in Lake Mälaren and Lake Vänern. In Lake Vänern stocking has increased considerably in the last 3-4 years as a part of the Swedish eel management plan (41). Since the catch of eels is made up mainly of larger individuals, the recently stocked eels have not yet reached the size where they are caught in monitoring with mid-water trawling.

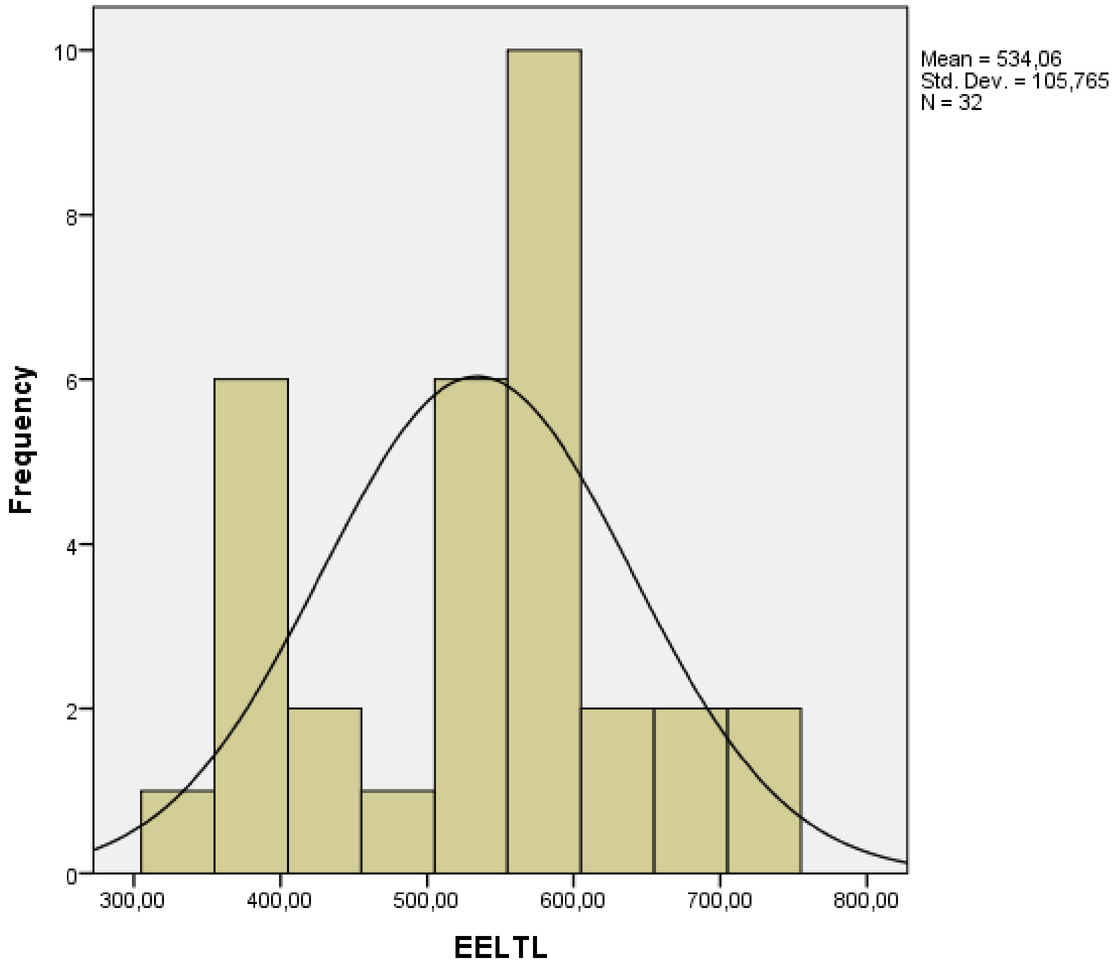


Figure 92. A histogram showing the total length of eels caught in midwater trawling.

Test of candidate metrics and remote sensing derived pressure variables as a tool to assess the status of water bodies in large lakes.

Fishes are one of the organism groups that are used as an ecological quality element within the water framework directive to assess the ecological quality of a water body. A first attempt to construct a European level assessment index using three selected metrics was described by Argillier et al., (2013) (2). In Sweden, ecological quality has so far been assessed using the EQR8 index (2). This multi-metric index was built to analyze the impact of several different pressures, one of them eutrophication. However the index has not been developed for larger water-bodies and performs rather poorly in such systems mainly due to the lack of reference waters and because of the markedly higher species diversity in larger systems is not accounted for (58). A similar multi-metric index, but that uses fewer metrics, EQR4, has been used to assess also larger water bodies in Finland (40; 39; 30). In contrast to the Swedish EQR8, these metrics have been chosen with care to mainly capture the influence of eutrophication on fish communities. Both these indices are constructed to compare a certain site with reference conditions from a large set of water bodies within the same climate region/lake type. Since there are currently (to our best knowledge) no relevant reference water bodies that can be used as a comparison to the very large water bodies in our study we cannot apply neither EQR4 nor EQR8 directly to our results. Instead we chose to test a selected number of metrics that are known to describe how fish communities react to eutrophication. Besides some of the metrics that are used to calculate EQR4 and EQR8 we also studied the metrics suggested as candidates to assess ecological quality of coastal areas in the Baltic Sea (60 and 61). Even though certain of these metrics are more focused on measuring the effect of fishing, they may still be of interest and of use in freshwaters. We concentrate on eutrophication as our main pressure variable since predictors assessed through remote sensing most probably describes eutrophication better than other pressures. We hypothesize that eutrophication primarily enhances the production of phytoplankton and thus leads to increased levels of Chl a and CDOM but also secondarily by negatively affecting the depth penetration of macrophytes and leading to a more pronounced re-suspension of sediments by wave action, thus also leading to increased levels of TSM. We tried to avoid metrics that are built on classification of species into tolerant / not tolerant species and natural / introduced species mainly since such classifications require knowledge on fish introductions and tolerance biology that are not available for these water bodies. In total, we tested thirteen different metrics:

1. WPUE, weight per unit of effort expressed as g fish / 100 m^2 of multi-mesh gillnet/
2. NPUE, number per unit of effort expressed as number of individual fish / 100 m^2 of multi-mesh gillnet
3. MEAN SIZE, mean size of all the fishes in the catch
4. N SPECIES, the number of species in the catch
5. SHANNON'S D, a diversity index calculated using biomass
6. SIMPSON'S D, a diversity index calculated using biomass
7. PROP CYPR1, the proportion of cyprinids (by biomass)
8. PROP CYPR2, the proportion of cyprinids (roach not included, using biomass)
9. PROP SALM, the proportion of salmonid fishes (using biomass)
10. PERCH/CYPR, the quota of perch vs. cyprinids (when roach is excluded)

11. SMELT YOY, the density of young-of-the-year smelt in the pelagic zone (individuals per hectare)
12. PDENSITY, density of fishes in the pelagic zone (individuals per hectare)
13. PBIOMASS, biomass of fishes in the pelagic zone (kg per hectare)

All metrics were calculated using all available data from the investigated period, thus aggregating data from several years. We believe this may give more robust and precise estimates of the different metrics. Particularly since the maximum duration of the time series in this case equals one WFD assessment cycle (six years). These different metrics were calculated for the thirty water bodies with available fish data using the same approach as in Argillier et al. (2013) (2). The first two metrics (NPUE and WPUE) were only calculated using gillnet data. The last three metrics were only calculated using hydroacoustic data. Since data from DEEP multimesh gillnets only exist from a limited number of water bodies we only use data from NORDIC multimesh gillnets. For NORDIC gillnets we tested the metrics for each of the two gears (coastal and lake types) separately. Some metrics (NPUE, WPUE, PDENSITY and PBIOMASS) were log (+1) transformed prior to analysis. Each metric was then tested against remote sensing parameters using stepwise multiple linear regression. The best metrics are presumed to have a low variation (CV) within water-bodies and high between water bodies and should react strongly to the pressure variables in a straight-forward and easily predicted and interpretable fashion.

Results - Assessing ecological quality of water-bodies

We tested a number of metrics, among which many have been previously used to assess ecological quality of water bodies. There was no significant influence of the gears used in any of the metrics analyzed (ONE-WAY ANOVA, interval for all tested metrics, df=36, F=0.03-2.6, p=0.12-0.96). The main difference between the two gear types is that the larger Nordic multimesh gillnets for coastal areas had a lower variation in all the tested metrics. Both when measured within and between water bodies. This is mainly believed to be an effect of the larger surface area of the coastal gillnets. There was also a tendency, albeit not significant, that the number of species was higher in coastal gillnets (ONE-WAY ANOVA on N SPECIES, df=36, F=2.6, p=0.12).

Indicators that were related to the number or biomass of fish in the catch (NPUE, WPUE) correlated poorly with pressure variables measured using remote sensing (Tab. 19-20). Some of the commonly used indicators (Shannon D and Simpsons D as well as mean number of species) were only weakly correlated to remote sensing parameters. The most promising indicators instead captured the species-shifts that take place as a consequence of eutrophication. Of these, the most promising ones were PROPCYPR2 and PERCCYPR. Both these metrics describe how the percentage of cyprinids in the catch (when roach is excluded) increases with increased eutrophication pressure. As described earlier roach does not respond positively to eutrophication pressures in these large lakes as it is believed to do in smaller systems. For pelagic areas, the density of fishes was by far the best metric. Some other indicators were also significantly correlated to the pressure variables, of which the proportion of salmonids and the proportion of smelt y-o-y was the most promising. Given the strong results for some of the metrics we recommend that the proportion of cyprinids (when roach is excluded) in coastal multimesh NORDIC gillnets and the density of pelagic fishes in hydroacoustic surveys is further explored as the primary candidate metrics to assess ecological quality in water bodies that are part of large Scandinavian lakes (Fig. 93).

Table 19. Results from a multiple regression analysis to test candidate metrics to assess ecological quality in large lakes. Data from sixteen water bodies obtained through surveys using coastal-type NORDIC multimesh gillnets. n v e= no variables entered to model. na=metric not available.

Nr	Metric	Best variable	Mean	SD	r^2	sig.	Partial correlation	alfa
1	logNPUE	AugCDOM	2,19	0,15	0,31	0,03	0,54	0,19
2	logWPUE	MayCDOM	3,60	0,14	0,27	0,05	0,52	0,17
3	MEAN SIZE	n v e	34,30	7,26	n v e	n v e	n v e	n v e
4	N SPECIES	MayCDOM	12,09	2,44	0,35	0,02	0,59	3,49
5	SHANNON	n v e	1,15	0,22	n v e	n v e	n v e	n v e
6	SIMPSON	n v e	0,59	0,08	n v e	n v e	n v e	n v e
7	PERC CYPR 2	AugCDOM	0,50	0,20	0,88	<0,001	0,90	0,94
8	PERC CYPR 1	AugCDOM	0,32	0,20	0,55	<0,001	0,74	0,34
9	PERC SALM	MayCDOM	0,02	0,05	0,56	<0,001	-0,75	0,12
10	PERCH/CYPR	AugCDOM	0,57	0,47	0,78	<0,001	-0,89	-0,95
11	SMELT YOY	na	na	na	na	na	na	na
12	logPDENSITY	na	na	na	na	na	na	na
13	logPBIOMASS	na	na	na	na	na	na	na

Table 20. Results from a multiple regression analysis to test candidate metrics to assess ecological quality in large lakes. Data from twenty-one water bodies obtained through surveys using lake-type NORDIC multimesh gillnets. n v e= no variables entered to model. na=metric not available.

Nr	Metric	Best variable	Mean	SD	r2	sig.	partial correlation	alfa
1	NPUE	MayCDOM	2,16	0,27	0,31	0,01	0,56	0,32
2	WPUE	n v e	3,64	0,19	n v e	n v e	n v e	n v e
3	MEAN SIZE	AugCDOM	36,81	16,54	0,41	0,00	-0,64	-21,78
4	N SPECIES	MayCDOM	10,72	2,67	0,48	0,00	0,69	4,01
5	SHANNON	MayCDOM	1,09	0,27	0,49	<0,001	0,70	0,41
6	SIMPSON	AugCDOM	0,58	0,11	0,47	0,00	0,69	0,15
7	PERC CYPR 2	MayCDOM	0,51	0,15	0,36	0,00	0,60	0,25
8	PERC CYPR 1	MayCDOM	0,33	0,19	0,37	0,00	0,60	0,20
9	PERC SALM	AugCDOM	0,01	0,03	0,20	0,04	-0,45	-0,02
10	PERCH/CYPR	MayCDOM	0,48	0,41	0,43	0,03	-0,65	-0,58
11	SMELT YOY	na	na	na	na	na	na	na
12	logPDENSITY	na	na	na	na	na	na	na
13	logPBIOMASS	na	na	na	na	na	na	na

Table 21. Results from a multiple regression analysis to test candidate metrics to assess ecological quality in large lakes. Data from nine water bodies attained with hydroacoustics combined with midwater trawling. n v e= no variables entered to model. na=metric not available.

Nr	Metric	Best variable	Mean	SD	r2	sig.	partial correlation	alfa
1	NPUE	na	na	na	na	na	na	na
2	WPUE	na	na	na	na	na	na	na
3	MEAN SIZE	n v e	11,42	11,55	n v e	n v e	n v e	n v e
4	N SPECIES	AugTSM	6,11	1,60	0,47	0,04	0,68	0,28
5	SHANNON	n v e	0,90	0,20	n v e	n v e	n v e	n v e
6	SIMPSON	n v e	0,50	0,12	n v e	n v e	n v e	n v e
7	PERC CYPR 2	n v e	0,14	0,15	n v e	n v e	n v e	n v e
8	PERC CYPR 1	n v e	0,14	0,15	n v e	n v e	n v e	n v e
9	PERC SALM	AugCDOM	0,22	0,22	0,74	0,00	-0,86	-0,58
10	PERCH/CYPR	n v e	0,03	0,07	n v e	n v e	n v e	n v e
11	SMELT YOY	MeanTSM	0,18	0,14	0,61	0,01	0,78	0,03
12	logPDENSITY	AugCDOM	4,22	0,43	0,87	<0,001	0,94	1,22
13	logPBIOMASS	MayCDOM	2,11	0,50	0,51	0,03	0,71	0,85

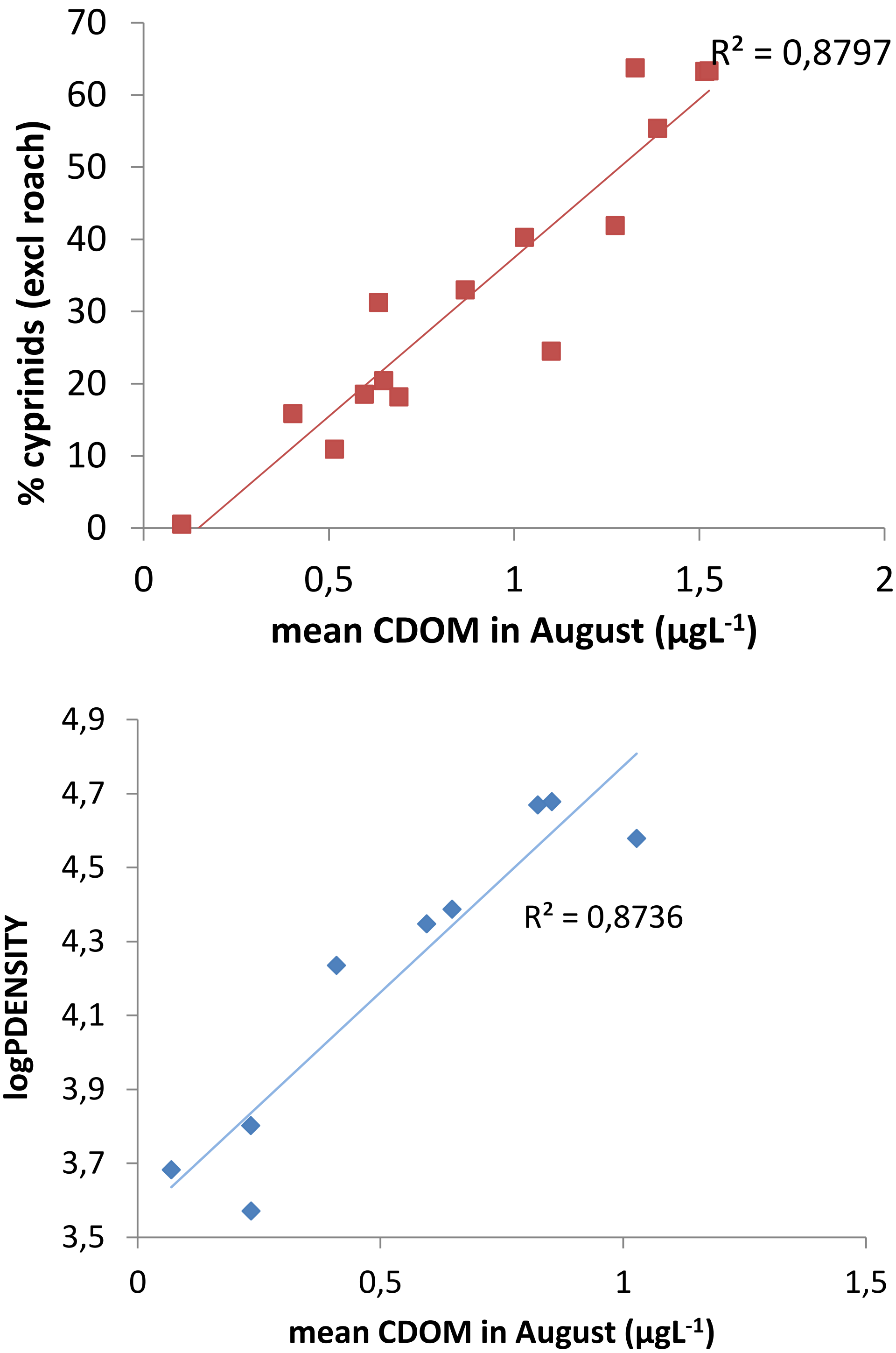


Figure 93 a and b. The two best metrics were a) PROPCYPR2, proportion of cyprinids in NORDIC multimesh gillnets of the coastal type when roach was excluded and b) logPDENSITY, the density (log individuals per hectare) of pelagic fishes in hydroacoustic surveys.

Each member state is obliged to assess the ecological status of their water bodies. To assess ecological status, reference fish communities should be defined and the status of a certain water body analyzed by examining its deviation from the condition of the reference community. This approach is problematic in the very largest lakes of EU since they have unique features compared to smaller systems and it is very hard to find adequate reference water bodies. Another complicating aspect is that many of the largest lakes are divided into many water bodies based on hydromorphometrical conditions. Some of the largest lakes in the EU are situated in Sweden and were part of this study. Even though it is difficult to find pristine reference systems of this size there are gradients between and within these water bodies that can be used to test the potential of different metrics that can be used to assess ecological quality. One other solution to this problem could be to hindcast reference conditions by modelling it (Baker et al., 2005).

Our results indicate that at least two of the tested metrics have a large potential when assessing ecological status: percentage of cyprinids when roach is excluded and the density of pelagic fishes. The reason for roach not reacting as predicted in other environments could be that roach may benefit from eutrophicated areas by enhanced recruitment but that the adults can migrate to feed far from the eutrophic basins (52). Another plausible explanation is that roach is not a specialized plankton-feeder, particularly older and larger roach feed more on benthic resources and thus cannot compete with more specialized species such as white bream and bleak that can benefit more from eutrophic conditions. The exclusion of roach when calculating the percentage of cyprinids was discussed as an option in Olin et al. (2013) (30). One problem with this approach is when calculating this metric in large lakes situated further north. Certain of the cyprinid species that dominated eutrophic water bodies in our study (white bream, zope and asp) occur less frequently in northern lakes where often roach are the only existing cyprinid. Pelagic fish density on the other hand should be a potential metric with more universal qualities and hopefully useful in other areas.

Abundance, composition of the community and age/size composition of focal species needs to be included for assessing ecological status based on fish data from lakes (8). We have used several metrics based on abundance and community composition but only one metric that is related to age and size (MEAN SIZE) and this metric does not capture reproduction failure or abnormal size structure of focal fish species in a very precise manner. Using more developed size or age distribution metrics could be a potential tool to combine with our two candidate metrics to further assess ecological status of fish assemblages in large lakes. However, one important feature of these systems is that they are often heavily influenced by fishing which is known to affect size and age distribution of certain species. Thus, age/size based metrics for large lakes should be selected with care.

Both fishing intensity and stocking have the potential to influence the status of fish (directly) and other parts of the food-web (indirectly) through trophic cascades. Such top-down processes could even alter the state of our main pressure variable (CDOM/Chl a). This is a phenomenon that is a requirement for bio-manipulation. Small plankton-eating fish is removed (either through fishing or stocking of predators) and zooplankton that are released from predation increase their grazing on phytoplankton leading to a higher water clarity. Even though such mechanisms are important, the majority of the water bodies with high CDOM/Chl a were situated in sheltered areas that are markedly influenced by phosphorous run-off indicating that bottom-up processes are more important in our studied systems.

Another aspect that sets large lakes apart from smaller ones is that they are divided into several water bodies. Fishes can thus migrate from one water body to another. This means that the ecological status of one water body could be affected by the conditions in another water body. Certain species also exist in several genetically unique stocks that sometimes overlap in distribution (10, 32).

One important advantage of using remote sensing variables is that the pressure variables have a higher resolution both in time and space making it possible to link the conditions of a certain sampling occasion to the actual environment in that spot. This is particularly important in large lakes with pronounced gradients in productivity and large habitat heterogeneity.

We have used fish data from several types of gears and from two different methods covering many of the existing habitats in large lakes although we have not used data from the shallowest parts of the littoral. The potential of this approach, merging data from several habitats and methods has been discussed by Diekmann et al. (2005) (62) and further elaborated in Rask et al. (2011) (39). To our best knowledge, very few studies have combined hydroacoustics and multi-mesh gillnets when assessing ecological status of fish communities. The inclusion of acoustics is in our point of view particularly important in these large systems dominated by pelagic species. Given the rapid technical development of hydroacoustics we also believe that it would be important to further explore the possibility to use hydroacoustics also in the smaller and shallower water bodies. One example is the development of wide-beam echosounders, mounted on tow-bodies located very close to the water surface which will make it possible to use acoustics even in shallow areas.

Provfiske ger svar om miljön

I Nossans mynning i utloppet i Vänerfjorden Dettern bedrivs sedan början av april och över hela sommaren 1995 provfiske som ingår i ett projekt för kommande regional miljöövervakning.

I direktiven till "provfiskaren" biologen Anders Kinnebäck, Skövde skriver länsstyrelsen i Skaraborgs län: Projektet skall se på fiskens roll som indikator på miljöförändringar. Fisken har varit och kommer också i framtiden att vara av stor betydelse beträffande miljöförändringar. Detta är ett av huvudskälen till varför fisk bör ingå som en naturlig del i den framtida miljöövervakningen. Anders Kinnebäck bedriver liknande provfisken i Lidans och Tidans utlopp i Vänern.

Började i april

Provfisket har pågått sedan början av april med utsatta nät ett dygn i veckan, för Nossans del på måndag och vitjning på tisdag. Från juni och fram över sommaren blir det ett provfiske i månaden. I september skall Anders Kinnebäck ha sin rapport klar till länsstyrelsens mark- och miljöenhet. Rapporten skall innehålla uppgifter om bland annat artsammansättning av fiskbeståndet i Nossan, Lidan och Tidan och ter upp till 74 millimeter. Man tar också vattentemperaturen som för Nossans del var 16 grader C i vecka 22 men den hade i tisdags fallit till 14,9 grader C. I början på april var det plus 2,8 grader C. Tidans vattentemperatur i vecka 22 var 18 grader C. Vid tisdagens provfiske fick man också upp en så kallad Tagelmask som skall vara ett tecken på näringsrikt vatten.

Biolog

Anders Kinnebäck som är biolog med specialité på sötvattensförhållanden (limnologi, inlandsvattnens växt- och djurliv) började att studera på Komvux som 27-åring, efter att ha arbetat på Volvo Pentaverken i Skövde, haft handelsanställning, varit fritidsledare och sophämtare. Härefter följde fem år på Uppsala universitet på biologilinjen med den specialinriktning som tidigare nämnts. Anders Kinnebäck är född i Skövde och är nu 33 år.

Medhjälpare vid provfisket i Nossans utlopp är yrkesfiskare Ivar Blomberg, Ås och han tycker att det varit trevliga och intressanta fisketurer med Anders Kinnebäck. Fiskelyckan har växlat från 35 kg i vecka 22 till en mindre fångst i tisdags. Så kallad vitfisk till exempel brax har varit övervägande men det har även blivit gädda och gös i nät samt slom (nors).

Länsstyrelsens provfiskare biolog Anders Kinnebäck och yrkesfiskare Ivar Blomberg efter återkomsten till Ivars hemmahamn från senaste provfisketuren. Fisken i näten mäts, vägs och artbetstäms och skrivs in i protokoll för att bilda underlag i framtida regional miljöövervakning.

One of the authors seen in an early newspaper article about gillnet monitoring in Dättern, L. Vänern. This is one of the most heavily eutrophicated water bodies in our study as indicated by the abundant catch of various cyprinid species.

Conclusions

The applicability of remote sensing methods has been evaluated and demonstrated and we can conclude that MERIS based products could support the assessment of the WFD quality factors phytoplankton, transparency and fish in the investigated lakes. Good correspondence between time series based on in situ and satellite data was presented, and a significant improvement in the sampling frequency could be obtained by adding complementary satellite based products of water quality to the monitoring program. In addition, MERIS based products add information about spatial patterns and trends for the entire lake. This indicates that the process of dividing lakes into homogeneous water bodies also could be supported. Furthermore, the analysis show that remote sensing data can be used to enhance the interpretation of data collected in fish monitoring surveys.

In low-moderate humic waters, chlorophyll concentrations up to approximately 30 mg m^{-3} and biovolumes up to approximately 2 mm^3/l, could be accurately detected. Regarding higher biovolumes (2-11 mm^3/l), there were very few match ups available for validation. However, realistic time series for stations "Södra Björkfjärden" and "Granfjärden" (0.5-6 mm^3/l) have been produced, which indicates that the upper limit is above 2 mm^3/l. The established calibration algorithm for AbsF generates realistic results between 0-0.15, but saturates at higher humic levels. Time series of Secchi depth between 1-16 meters that are in line with field observations has been produced, which means that the established calibration algorithm should be valid for most of the investigated water bodies. Regarding turbidity, the evaluations indicate that the calibration algorithm should be able to produce accurate estimates between, at least, 0-20 FNU. Finally, with respect to detection of cyanobacterial blooms, the conclusion is that the results are promising and that on-going research will show the applicability of the algorithm, with respect to lower limits for Chl a concentration.

Our analyses show that remote sensing data can be used to enhance the interpretation of data collected in fish monitoring surveys. The influence of other pressure variables could be further resolved through studying how data deviate from the predicted response of species and assemblages to the pressure of eutrophication. We identify at least two potential candidate metrics that should be further evaluated as tools to assess the impact of eutrophication in large lakes. Our results also have implications for the design of fish monitoring programs. Since CDOM/Chl a in many cases could be used as the main predictors for fish distribution and assemblage composition it is possible to use these parameters to assure that all the existing habitats/assemblages are covered in the programs. It is important to cover the entire gradient of the most important pressure variables elsewise it can be laborious to predict or model the dynamics of a species or assemblage when going outside the interval covered in the survey program (48; 19). In most of the studied lakes the gillnet survey programs cover the entire gradient from heavily eutrophic to oligotrophic conditions. The very deepest areas, on the other hand are not covered to the same extent mainly due to practical and economic constraints. To cover the off-shore areas in L. Vänern for example would require very long travelling distances by smaller boats. The hydroacoustic surveys instead covered a much more limited interval of the eutrophication gradient, which is mainly a result of this survey focussing on the largest and deepest basins. With the current hydroacoustic equipment being used, the near-range is a bit over 5 meters which limits its potential use in shallow areas. There is also a practical problem conducting midwater trawling in more shallow or small and sheltered areas. One potential future application area of remote sensing data is the apportionment of midwater trawl catches to adjacent acoustical density estimates. This geostatistical process uses environmental information to improve the assignment precision (54). Since CDOM was the most powerful predictor variable of hydroacoustic data it is very likely that inclusion of this parameter in the apportionment approach might increase the precision of the resulting estimates.

There are several possible application areas of remote sensing data in fisheries management. The phytoplankton production in a water body is known to limit the yield of most fisheries. If the production prerequisites can be described using remote sensing it can be used as a rough measure of potential long-term yield of a fishery. Deviations from predicted catches can be used to interpret the exploitation level in a water body. We attempted to analyse if the catches in the Swedish large lakes depended on the level of Chl a. Fishermen report their catches in certain subareas. Unfortunately, these areas were not available as GIS-layers which made it hard to exactly calculate the catch per unit of area. Nevertheless, when making a rough interpolation there seemed to be a trend of larger catches in some of the most productive areas with higher Chl a levels (Stor-Hjälmaren and Galten in L. Mälaren are two obvious examples). These relationships deserve to be more precisely evaluated in the future.

In mid-2015 a new satellite, called Sentinel-3a, will be launched by ESA. This is the first of a series of satellites that have instruments to continue the mission after ENVISAT – MERIS. ENVISAT was an experimental satellite and Sentinels-3 is one of the new series of operational satellites. The new "MERIS" is called OLCI (Ocean and Land Colour Instrument) and is very similar to MERIS but with improved radiometric and spectral properties. One year after the launch of Sentinel-3a, Sentinel-3b is planned for launch. With two satellites in orbit, there will be a daily coverage of MERIS like satellite data over Sweden. Before the estimated lifetime of the initial two satellites has expired, Sentinel-3 c and 3d will be launched, to assure a continuity of data. Successful results from these developments can thus be implemented and used on operational basis after the launch of Sentinel-3.

Business plan

If the method and products prove successful and applicable, we believe the chance for operational implementation with respect to many of the directives and management plans is good. There is a strong interest from the end user organisations to identify and introduce alternative and/or complementary methods for assessment of the ecological status of habitats and the mapping of the distribution of species and habitats in Swedish freshwaters. The Swedish Agency for Marine and Water Management (SwAM) and/or the Swedish Water Authorities have been responsible for monitoring in the past; further discussions with end-users will be required to identify the agencies responsible for monitoring in future.

In addition to the application of our results directly in the field, we envisage that our novel approach using satellite data in freshwater monitoring can be extended to cover larger areas and smaller water bodies, in Sweden and abroad. That is: we foresee ample opportunity for follow-up projects that will enable wide-spread application of our innovations, meeting the international requirements on ecosystem monitoring throughout Europe and improving the cost-effectiveness of environmental monitoring.

Project group

Contact	Organisation	Title / Expert area
Petra Philipson	Brockmann Geomatics	Remote sensing specialist and consultant / Aquatic remote sensing
Per Wramner	Brockmann Geomatics	Scientist and consultant / Senior fisheries and environmental specialist
Alfred Sandström	SLU	Scientist / Aquatic ecology and spatial modelling
Anders Asp	SLU	Research assistant / GIS-analyses, fish biology
Thomas Axenrot	SLU	Scientist / Hydroacoustics, fish ecology
Anders Kinnerbäck	SLU	Research assistant / data bases, fish biology
Henrik Ragnarsson-Stabo	SLU	Scientist / community dynamics, fish ecology
Willem Dekker	SLU	Fisheries scientist/ Fisheries biology and statistical analyses
Åsa Andersson	HaV	Investigator / Aquatic ecology
Sara Peilot/Mats Rydgård	VnVVF	Water expert / Limnology. Coordination of environmental monitoring.
Ingrid Hägermark	MnVVF	Biologist /Coordination of environmental monitoring.
Måns Lindell	VtVVF	Water/Fisheries expert / Limnology. fisheries and coordination of environmental monitoring
Lotta Carlström	HjVVF	Water expert / Limnology. coordination of environmental monitoring
Susanne Kratzer	Stockholm University	Scientist / Biological oceanography and remote sensing
Niklas Strömbeck	Strömbeck Consulting	Scientist and consultant /Limnology, oceanography, remote sensing and aquatic optics.

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