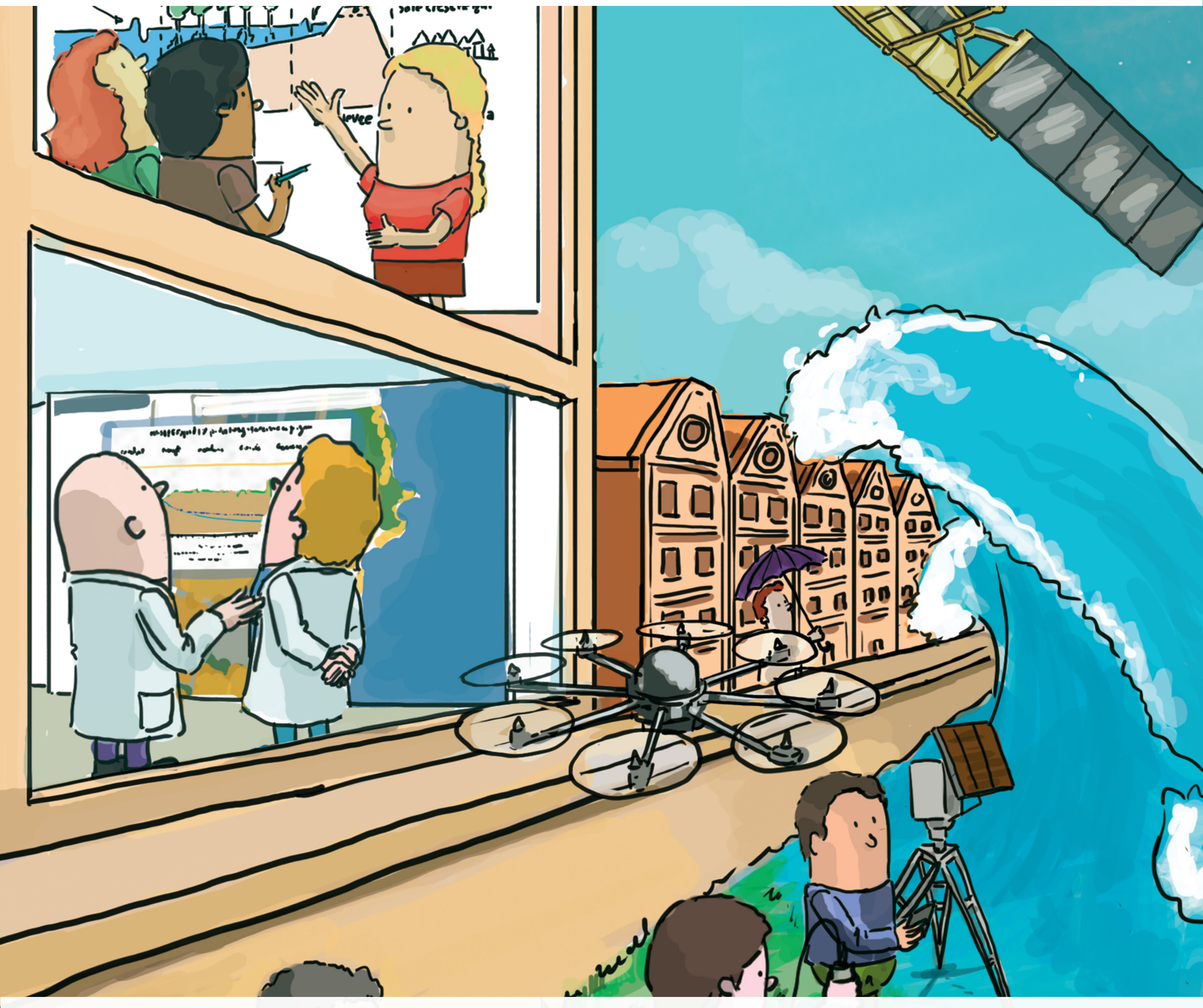

FAST

FORESHORE ASSESSMENT
USING SPACE TECHNOLOGY

Earth Observation and the Coastal Zone: from global images to local information

Project Synthesis

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Colophon

FAST – Foreshore Assessment using Space Technology

Foreshore Assessment using Space Technology (FAST, 2014 - 2018) is a project funded by the European Union's (EU) Seventh Framework Programme (FP7) for research, technological development and demonstration under grant agreement number 607131. FAST is developing down-stream services for the European Earth Observation Programme Copernicus to support cost-effective, nature-based shoreline protection against flooding and erosion.

This book aims to communicate the services generated by the FAST project to the general public as well as provide its readers with information on how to access its products after the project lifetime.

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This report and the other public outcomes of the FAST project may be downloaded from the project website www.fast-space-project.eu and the Zenodo repository (FP7FAST).

"The intricate network of channels and creeks contrasts with the regular shapes of transformed salt marsh (right of picture)," writes Edward P. Morris, who submitted the photo to the Sentinel-2 'Colour vision' photo competition.

Deltares Enabling Delta Life | University of Cambridge | GeoEcoMar® | NIOZ Royal Netherlands Institute for Sea Research | UCA Universidad de Cádiz

Copernicus The European Earth Observation Programme

Content

Executive summary

Applications and use of our outputs

The FAST project developed a web-based platform of services, the MI-SAFE package. This platform provides users with access to data and flood hazard modelling services relating to coastal wetland habitats. The main vehicle for accessing and demonstrating our services is the MI-SAFE viewer (a free online app, fast.openearth.eu). To generate the MI-SAFE package, the FAST project team measured vegetation characteristics, wave attenuation and sedimentation and erosion at 8 different coastal field sites in four different countries and in different seasons. Further, Earth Observation (EO) data from various sources was transformed into global map layers, such as global vegetation cover, vegetation change and elevation maps for the coastal zone. The MI-SAFE package, including the viewer, was developed in close consultation with our key stakeholders, individuals from a series of government, non-government, and private sector organisations.

Challenge

Flood risk is one of the most pressing challenges facing society today. Climate change and increasing population pressures on deltas and floodplains continue to raise future flood risk. Intervention to reduce such risk is urgently needed. Conservation, improved management and restoration of ecosystems and vegetated foreshores could form part of such interventions. Coastal, marine and riverine ecosystems are benefitting society in several ways by delivering what are called ‘ecosystem services’, such as carbon storage, support for sustainable fisheries and acting as a protective buffer between the sea and the land. Nature-based flood defence is thus a potentially sustainable and cost-effective strategy for flood and erosion risk reduction. Currently, however, this concept is not widely implemented. Verifiable demonstrations of the benefits have been lacking and it is clear that flood protection engineers need trusted and practical tools that provide them with quantitative information on key parameters.

Aim

The aim of the FAST project was to develop Copernicus services to determine the characteristics of vegetated foreshores and to help harness the potential of foreshores to act as part of nature-based solutions towards reducing coastal flood and erosion risk. This objective was achieved through the following sub-goals:

1. To execute a set of standardized measurements of different types of wetlands and their capacity to reduce wave energy,
2. To improve models currently used to predict wave attenuation by coastal wetland vegetation (by making sure computer models can replicate what we measure at specific locations), and
3. To find ways of measuring aspects of coastal wetlands from the air and space (using Earth Observation (EO) data) so that we can ultimately acquire such data at the global level and determine the impo tance of coastal wetlands to society at any specific location as well as globally, and finally,
4. To coalesce all the above data and make it publically available in a freely accessible online service.

MI-SAFE after FAST

The long-term sustainability of the MI-SAFE package is safeguarded as the MI-SAFE viewer is part of the Deltares software system and the FAST community part of the Deltares Open Source Community. Support and Advanced (on-request) services, remain available from the FAST team and we aim to provide ongoing support for the environmental assessment of vegetated foreshores in general and for nature-based coastal flood and erosion risk reduction solutions in particular for the foreseeable future.

The FAST team is promoting the MI-SAFE package for further development and use in other projects, using the MI-SAFE viewer as tool to support the implementation of major EU policies, such as the EU Flood Directive.

Birds eye view of coastal vegetation in front of the towns of San Fernando (right) and Puerto Real (left) in the Bay of Cádiz, SW Spain. Creator: EDEA, Universidad de Cádiz.

FAST project and team

The Foreshore Assessment using Space Technology project FAST was funded under the 7th Framework Programme of the European Commission from January 2014 to December 2017.

The funding arose from the need identified by the European Commission to develop methods for using Copernicus EO data for environmental assessments, prediction, and natural hazard risk reduction. The FAST project was funded to address this need specifically in relation to (vegetated) coastal zones and their role in reducing flood and erosion risks. The FAST team was able to develop novel ways of harnessing information derived from satellite images to assist individuals within local, national, and international organisation to better manage and reduce flood and erosion risk anywhere in the world, where vegetation forms part of the natural foreshore (the area immediately seaward of the high water line during a coastal flood). The project's products are particularly useful to engineers and managers who are considering implementing nature-based solutions as part of climate adaptation or Eco-DRR (ecologically-informed disaster risk reduction) related challenges.

The FAST team consists of scientist and Earth Observation experts of five European Institutions: Deltares, University of Cambridge (in collaboration with Specto Natura Ltd), National Institute for Marine Geology and Geo-Ecology (GeoEcoMar), Royal Netherlands Institute for Sea Research (NIOZ) and University of Cadiz.

Project Coordinator
Mindert de Vries

The FAST team during the General Assembly celebrated in Romania (2015). Left to right: Adrian Stanica[1], Daphne van der Wal[2,*], Mindert de Vries[3], Tjeerd Bouma[2], Margarida Cardoso Silva (External Reviewer), Gerrit Hendriks[3], Bregje van Wesenbeeck[3], Ben Evans[4], Edward P. Morris[5], Iris Möller[4], Myra van der Meulen[3] (top), Gloria Peralta[5] (bottom), Javier Benavente[5], Adriana Constantinescu[1], Albert Scrieciu[1], Bas Oteman[2]. Team members not present in the photograph: Maria Ionescu[1], Julia Vroom[3], Geoff Smith (SpectoNatura Ltd), Jesus Gomez[5], Jose Sanchez[5], Tom Spencer4, Pim Willemsen[2,3,**], Annette Wielemaker[2]. Institutions: 1: GeoEcoMar, 2: NIOZ, 3: Deltares, 4: University of Cambridge, 5: University of Cadiz. * University of Twente/ITC, ** University of Twente/ET.

How to contact the FAST team

There are different ways to contact the FAST team:

- Writing an email to fast@deltares.nl, or using the issue form available in the MI-SAFE viewer (section 3.2.2).
- Using social media via the FAST web site (http://www.fast-space-project.eu), the FAST and MI-SAFE twitter accounts (@FP7FAST, @MISAFE_services) or via Facebook (FastSpaceProject).
- You can also contact one of the leaders from the 5 FAST partner institutions:
  - o Deltares Mindert de Vries (mindert.devries@deltares.nl)
  - o University of Cambridge Iris Möller (iris.moeller@geog.cam.ac.uk)
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1. Introduction

Achieving fully integrated and sustainable coastal zone management is one of the greatest challenges facing European Union member states. Sea level rise, climate change, and increasing coastal pressures intensify this challenge, demanding innovative approaches towards coastal management, including flood and erosion risk reduction.

Worldwide, billions of people depend on flood defence infrastructure for their safety. Taking into account growing population in delta areas, rising sea levels, rapid subsidence, and the potential change in the frequency and magnitude of extreme events[1], our exposure to flooding is rising and, hence, our dependency upon dams, sea defences, and river levees is continuously increasing. This increased risk will necessitate rising investment in flood defence infrastructures[2]. Additionally, engineered structures often have adverse impacts on ecosystem functioning causing unexpected future costs. To reduce costs and to limit negative impacts on ecosystems, interventions that integrate natural systems within flood defence schemes are now being actively explored[3]. However, to advance such flood management approaches, a better understanding and robust scientific observations are needed, as there remain important questions hampering their applications[4]. Although empirical evidence exists for the reduction of waves, even in storm surge conditions, by shallow water, vegetated surface platforms[5], little is known of how this reduction varies with vegetation type, surface cover, or density.

To include such nature-based solutions within coastal management approaches, we need to know more about how these ecosystems work. For example, engineers may need to know the mechanisms by which vegetation reduces wave energy, how these processes 'scale up' from individual plants to large foreshores, and what the best way is to include this information in the design of flood defence schemes. Environmental managers, on the other hand, may like to know precisely where natural vegetation can be found and how those areas have changed over time.

The following sections of this book summarise the challenges, activities (‘Building the MI-SAFE package’), and achievements of the FAST project (‘Using the MI-SAFE package’). This includes a general overview of the strategy to provide the MI-SAFE services after the FAST project ends (‘Sustaining the MI-SAFE package’) and to move forward through the development of EO based services for coastal management (‘Steps toward mainstreaming EO into coastal management’). There is a wealth of additional information available via the FAST viewer (http://fast.openearth.eu) and further information and links can be found throughout this book.

[1]Lozano et al. 2004, De Sherbinin et al. 2007, Nicholls et al. 2007.
[2]Hallegatte et al. 2013.
[3]Townend and Pethick 2002, Costanza et al. 2006, Borsje et al. 2011, Temmerman et al. 2013.
[4]Bouma et al. 2014
[5]Möller et al. 2014.

2. Building the MI-SAFE package

2.1. FAST Idea

FAST was conceived as a multi-disciplinary project to provide answers to the issues raised above and any other questions raised by those with an interest in coastal management (our 'stakeholders'). The idea was to use a combination of remote sensing and field data from vegetated foreshores in four different EU countries (The Netherlands, the United Kingdom, Romania and Spain) and to map such foreshores and how their specific characteristics affect wave energy and erosion. This would result in novel ways of extracting relevant information from satellite images and thus to help predict the shoreline protection provided by those foreshores, and similar foreshores elsewhere.

The FAST approach thus makes use of scientific innovations to derive evidence and actionable information from Earth Observation (EO) resources, with a particular focus on the capabilities of the European Copernicus programme.

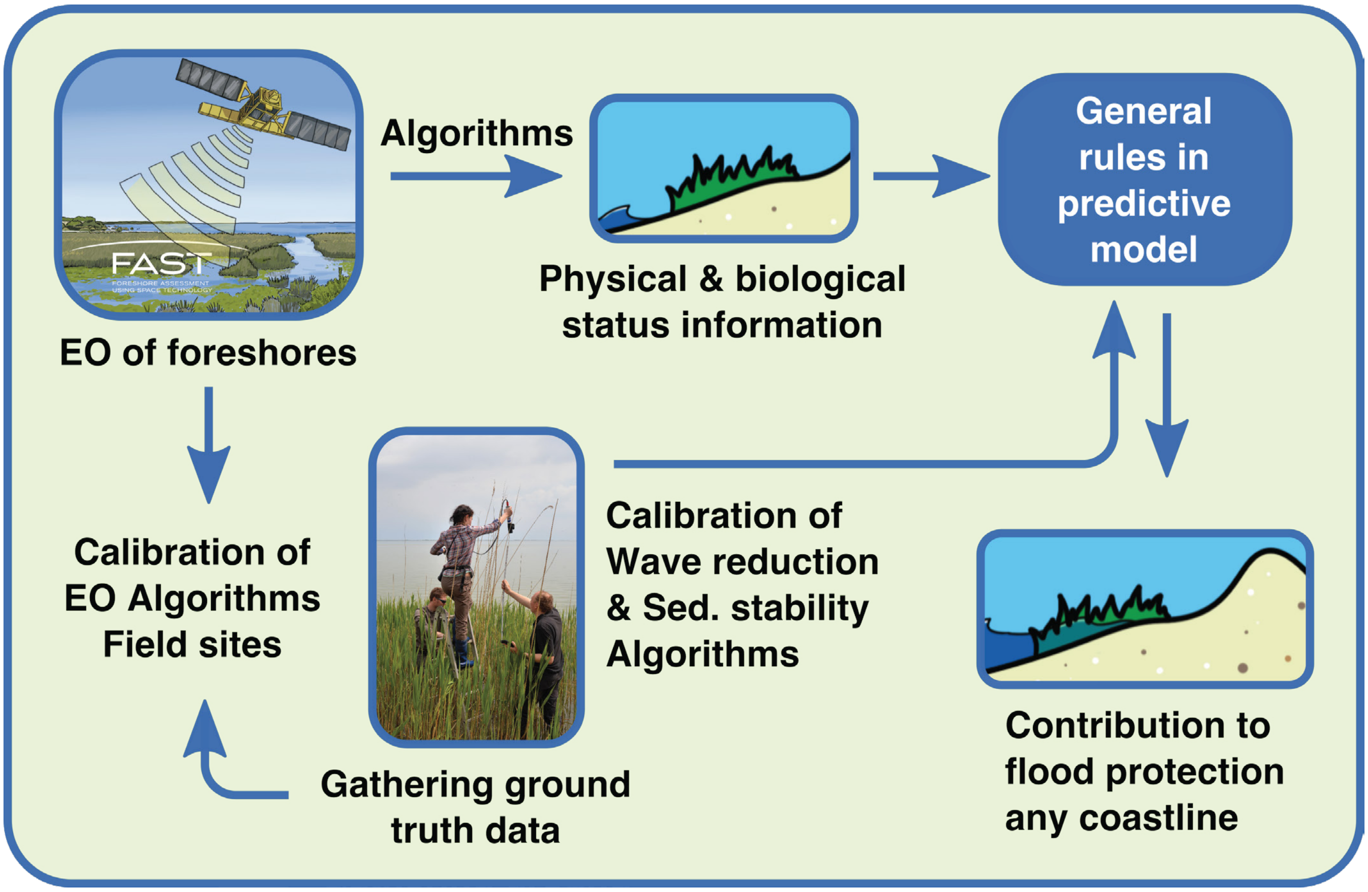


Figure 1. Scientific processes developed during the FAST project that made the generation of the MI-SAFE package feasible.

The key components of the FAST approach are thus:

1) Developing the science to underpin flood and erosion risk management strategies that include coastal wetlands, as well as a prototype user-friendly software tool (the MI-SAFE viewer) where links between the features of foreshores/floodplains and requirements for flood safety infrastructure are automated (see Figure 1);
2) Involve and engage with end-users in a user-driven approach to product design and implementation, relying on interactive consultation and regional workshops;
3) Disseminate scientific results, MI-SAFE services and outputs of the FAST project.
By bringing together know-how from a wide range of disciplines, this approach resulted in the generation of the MI-SAFE package, a platform of services that allows government agencies, industry consultants, NGOs

and the general public, to easily assess the potential of vegetated foreshores to reduce flood and erosion risks and evaluate the status of these systems. The MI-SAFE package thus makes an important contribution to European flood risk management. The MI-SAFE package is based on open source and open data and allows for development of a wider scope of applications beyond flood risk management. We used an agile development approach for interacting with any potential user of the MI-SAFE package throughout the entire project, facilitating user-input into the selection of case study sites, fieldwork, algorithm development and strategies to ensure the long-term sustainability of the MI-SAFE package.

2.1.1 The science challenge

Wetland ecosystems along fresh water and marine shorelines, such as mangrove swamps and marshes, often situated in front of flood protection structures and built-up areas, can attenuate waves, capture and retain sediment, reduce erosion, and stabilize shorelines[6]. The specific characteristics of these natural systems, such as their width and extent, elevation and the presence and type of vegetation cover, alter the degree to which they mitigate against storm surge or wave impact[7]. The same factors also influence design and long-term stability of any flood safety infrastructure[8]. By knowing more about these specific characteristics of natural systems and how they may be conserved, managed or restored, adaptable and cost-effective nature-based flood defence solutions can be achieved[9].

One of the most important properties of natural systems, and most challenging to study, is their inherent dynamic. This property allows them to, within limits, self-repair by capturing sediments and by vegetation regrowth[10]. Dynamic living systems are thus very different from static traditional, constructed, flood safety infrastructure. Understanding these dynamic features will aid the management and continuous monitoring of the ecosystem services they provide. To achieve such an understanding, ecosystem properties need to be measured (and knowledge of measurement limitations acquired) from space and in the field. Such measurements allow the derivation of algorithms for the numerical modelling of, e.g., wave dissipating potential. This will both (i) maximise and safeguard these features' contribution to flood safety, and (ii) ensure the continued provision of coastal ecosystem services.

The major scientific challenge in addressing these objectives lies in the need to establish a predictable relationship between the EO data and the numerical modelling of water flow and waves dynamics. Any application of these relationships to locations beyond the field locations for which they were calibrated and validated depends requires an understanding of the effect of such extrapolation on the quality of the inferred coastal protection function.

2.1.2 The multi-disciplinary challenge

To address such a complicated scientific challenge requires multi-disciplinary teams. Engineers, ecologists and other experts all need to jointly assess these dynamic ecosystems. Such collaboration is at the core of the FAST project. Only through working together in this way can the knowledge and the tools be developed that are needed to fully integrate ecosystems in levee, dike, or sea wall design, coastal management and monitoring. The FAST team consists of remote sensing experts, engineers, coastal geomorphologists, and ecologists that collaborated on all work packages and activities. Similar diversity of disciplines is reflected in the group of individuals with whom we consulted on what is needed by those involved in coastal management and policy. This group contains geo-engineers, civil engineers, business developers, consultants, water managers, nature conservationists and ecologists, representing governments, private enterprises, and research organisations.

[6] Möller 2006, Gedan et al. 2011, McIvor et al. 2012b, Spalding et al. 2013, Möller et al. 2014.
[7] Bouma et al. 2014, Spencer et al. 2014, Möller et al. 2014.
[8] Spalding et al. 2013.
[9] Temmerman et al. 2013.
[10] van Wesenbeeck et al. 2016.

2.2. FAST Actions

To be able to incorporate vegetated foreshores in flood defence, methods are needed for monitoring the natural dynamics that affect their wave attenuating capacity over time.

Being at the dynamic interface of land and water, foreshores and floodplains pose particular challenges for satellite observation and analysis[11]. For terrestrial environments, ways of retrieving information about the physical and biological aspects of the land surface from satellite observations are relatively well developed, particularly for use in agriculture, forestry and climate studies. Copernicus Land Core (land monitoring) Downstream Services (DS) include, for example, Leaf Area Index (LAI) and vegetation index (NDVI), provided at various spatial resolutions.

In the coastal region, however, where the land surface is often submerged (e.g. by tides), the downstream development of services for the monitoring of ecosystem and landform characteristics is more complex. To meet this challenge, three links can be identified in the chain towards producing a meaningful information service: (1) obtaining high spatial and temporal resolution spaceborne data, (2) translating such spaceborne data into meaningful vegetation and landform information, and (3) developing and testing model algorithms to translate the information into engineering parameters such as wave attenuation capacity. To achieve this, the following is needed:

1) **High spatial and temporal resolution spaceborne data.** Each satellite-mounted sensor detects radiation within a particular domain of the electromagnetic spectrum (e.g, optical, thermal, microwave), and is thus able to detect a particular suite of ground surface parameters. Usability of satellite imagery thus critically depends on the availability of data in sufficient spectral, spatial and temporal resolution, with the appropriate coverage and overpass frequency;
2) **Translation of spaceborne data into meaningful vegetation and landform parameters.** This requires accurate and detailed measurements on the ground. Progress is being made in terms of converting optical and microwave (SAR) data into parameters that are meaningful for assessing the bio-physical characteristics of vegetation and substrate. SAR data sets are already used to inform the management of wetlands, giving information on presence, extent and conditions of vegetation[12]. Information is needed on a range of environmental factors affecting the interaction between electromagnetic radiation received at the satellite and foreshore properties that are relevant, e.g. to wave dissipation, on the ground. At what spatial resolution information is needed, and how frequently depends very much on the structure of the foreshore and the degree to which this changes over time.
3) **Model algorithms.** To derive typical engineering parameters such as wave attenuation capacity of natural foreshores, from EO data, validated model algorithms are required, necessitating direct measurements. Firstly, EO-derived parameters such as leaf area index need to be translated into parameters that constitute relevant input into, for instance, wave-attenuation models. Secondly, 2D vertical EO pixel data on variable scales need to be converted to 1D or 2D horizontal map products at the appropriate scale for use as model input.

2.2.1 The Challenge of Direct Measurement

Field measurements are essential to gain an insight into the science of how vegetated coastal environments reduce wave energy and how these environments change over time. Measurements are also necessary to calibrate and validate satellite-derived products, such as those used within the MI-SAFE viewer for the assessment of the coastal protection provided by foreshores. Such measurements were made at eight sites, two each within each of the FAST partner countries (Figure 2), and measurements made between September 2014 and July 2016. The vegetation present on the foreshores within the FAST project ranged from Phragmites reed (Romania) to Spartina (the Netherlands), Sarcocornia (Spain) and mixed species (Aster, Puccinellia, Suaeda species) salt marsh (The United Kingdom).

[11]See reviews by Klemas 2013, Ozesmi and Bauer 2002, Henderson and Lewis 2008, Adam et al. 2010.
[12]Salvia et al. 2009, Henderson and Lewis 2008.

Figure 2. Left: Location of the study sites in Europe, including Tillingham and Donna Nook in the UK, Paulinaschoor and Zuidgors in the Westerschelde (The Netherlands), two sites in the inner Cadiz Bay (Spain), and Cape Dolosman (Razelm Lagoon) and Histria (Danube delta) in Romania. Right: The range of vegetated foreshores used for EO validation and calibration in the FAST project; Clockwise from top left: sand-rich mixed salt marsh in UK; Spartina salt marsh in The Netherlands; Romanian reed beds with seasonal growth (see decayed reed and new reed growth in the back- and foreground respectively); Sarcocornia salt marsh in Spain (photo: I Möller).

At each site, a number of square meter sized field plots (Figure 3) were marked in vegetated areas and on the unvegetated foreshore. Five plots were located in close vicinity to a line of wave measurements extending from the shore to the sea. These plots were chosen to characterise the foreshore along the wave measurement line and to link the condition of the surface (e.g. how dense, high, or diverse the vegetation cover was) to the recorded wave dissipation.

The generic field site layout is shown in Figure 4, but the exact location depended on the local situation (e.g. the diversity and density variations in the vegetation). Detailed discussions about the precise layout of sampling locations were held at each field site to ensure the capture of scientifically meaningful results (Figure 5).

Figure 3. Plant measurements carried out in one of the square meter measurement plots at Donna Nook, UK, with wave logger station in background. (photo: M. Yates)

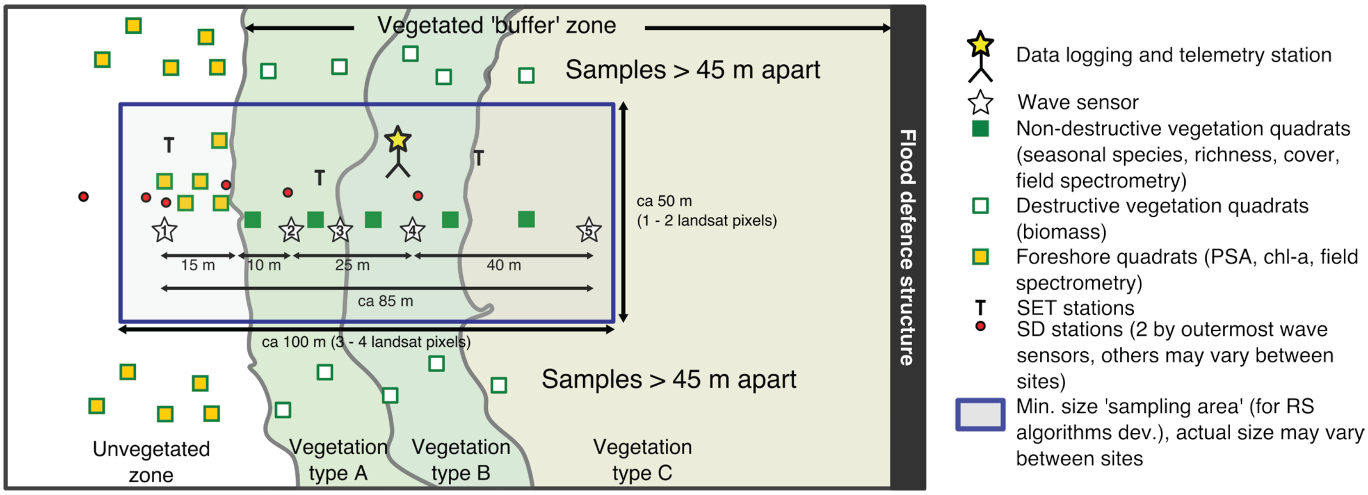


Figure 4. Schematic illustration of field sample layout used within the FAST project. Individual locations of measurements varied from this and were carefully geo-referenced.

Figure 5. Discussing detailed layout of sampling locations at Paulinaschor, The Netherlands (photo: D. van der Wal).

Two sensors for measuring surface erosion/deposition (SED sensors) were deployed next to the three most seaward located wave sensors inside the vegetation zone of each site (see Figure 6), with the exception of those in Romania and Spain, forming part of the vegetated area's wave sensor array. A third sedimentation sensor was set up next to the outermost (tidal flat) wave sensor and beyond the vegetation edge (see Figure 7). Wave sensors were mounted at fixed distances landward from the most seaward vegetation margin. The exact locations of each sensor, as for all measurement locations, were obtained using state-of-the-art differential GPS systems providing sub centimetre positional accuracy (see Figure 8). Distances between wave measurement locations varied somewhat between sites and according to variations in local topography. Details of this, alongside the measurements themselves, are available upon request.

Figure 6.
Wave monitoring stations were installed at each of the eight FAST field sites, with wires connecting up to six bottom-mounted pressure sensors (inset bottom left) (photo: I Möller).

Figure 7.
A sediment dynamics (SED) sensor on tidal flat at Paulinaschor, The Netherlands (photo: D. van der Wal).

Figure 8. Use of differential Global Positioning Systems (dGPS) for accurate coordinate and height determination of all measurement plots and instrumentation (photo: I Möller)

Measuring water level and waves: When waves travel to the shore, the rapidly changing water level causes changes in pressure at the sea bed. We measured this rapid pressure change and used it to calculate the height and energy of approaching waves. As wind and air pressure often alter the exact timing of the tides our wave measurements were triggered only when they were actually under water. We used the latest solar powered data logging technology for this (see Figure 6) and transmitted our results to our offices via remote data transmission (mobile phone telemetry) systems[13].

Measuring coastal wetland change over time: For flood risk assessment, as well as knowing the present state of the coastal foreshore, it is important to be able to assess how this may change over time. For engineered defences, the time scale over which such assessments are made is typically around fifty years. Incorporating nature into flood defence design can be beneficial for ecosystem services, but it also introduces the challenge of having to take account of natural dynamics and of the spatial variation of important attributes of the natural environment. The challenge for the FAST project was to assess these dynamics over a range of time-scales, using both our direct measurements and EO approaches.

[13]Möller et al. 1996.

Figure 9. Overview of the study site and telemetered data logging system at the Year 1 site in Cadiz Bay, ES1 (photo: G Peralta)

Measuring foreshore characteristics: Intensive field sampling allowed us to characterise the attributes of the foreshores. Sampling focused on parameters that affect either the coastal protection function of the foreshore or its stability. Alongside the detailed differential GPS surveys at each site, a large number of parameters were measured by the FAST team at least four times over the course of one year, often in challenging physical conditions, to achieve the best possible validation and calibration of the EO data.

- **Visible change over time:** Repeat photography from fixed positions was used to record any visual change of the field sites at least four times over the course of at least one year. Each individual square meter sampling plot was also photographed from the top down during each visit.

- **Spectral reflectance:** The spectral reflectance of solar radiation by the ground surface was recorded with a downward looking spectrometer at each square meter sample location (Figure 10).

- **Vegetation species:** The number of species present and the percentage of each square meter sample location covered by those species was recorded (Figure 3 above).

- **Plant metrics:** Where possible (for plant species with one central upright stem, such as Spartina or Phragmites), the height, diameter, and spacing of plant stems within each square meter sample location were noted (Figure 11).

- **Plant biomass:** The weight of the amount of plant material present aboveground was estimated by harvesting small sub-areas within certain square meter sample plots (after all other aspects had been recorded). We also used an indirect method, by recording the height at which a disc of known weight and diameter, sliding freely down a thin vertical pole came to rest on the plant layer.

- **Obstruction to water flow caused by the plant layer:** Because it is directly relevant to water flowing through the plant layer, we photographed the surface area of a 20 cm wide section of the plant layer as projected onto a red board inserted behind the layer, using a purpose-designed photographic rig (Figure 12). This allows the 'side-on' density of the plant layer to be quantified.

Figure 10. Measuring spectral reflectance of reed vegetation, Romania (photo: I Möller)

Figure 11. Working in reed beds (left) and close-up view of area within which stem diameter and density were recorded in reed vegetation (right), Romania (photo: I Möller)

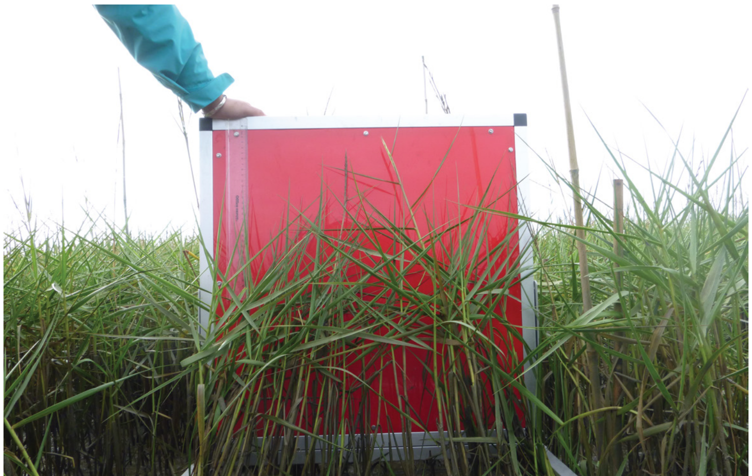


Figure 12. Photographing vegetation against red background allows the vertical structure and density variations to be quantified; these matter to water flow through and above the plants.

Figure 13. The 'shear vane' instrument for recording the rotational force that needs to be exerted on the top layer of sediment before it fails (photo: I Möller)

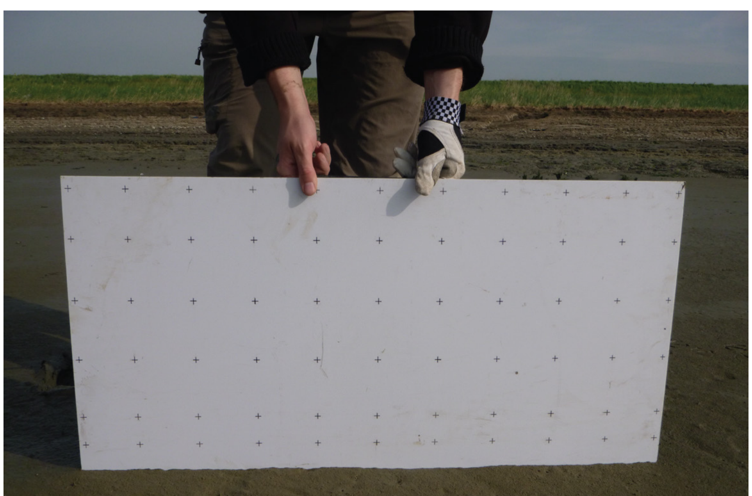


Figure 14. Surface roughness being recorded against a roughness board, Zuidgors, The Netherlands (photo L. van IJzerloo).

[14]The SED sensors were developed in house by NIOZ. These sensors detect changes in the level of sediment surface (i.e. surface lowering or deposition) by exposure or blocking of light diodes. See Hu et al. 2015 for further details.

- **Sediment Dynamics:** A series of sediment/erosion (SED) sensors[14] were vertically inserted into the ground and left to electronically record any changes in the level of the sediment surface (Figure 7 above). Alongside these measurements, we deployed erosion pins (small metal rods against which surface lowering or deposition can be measured) and a so-called 'shear vane' was used to record the force that the top few millimetres of the surface sediment layer were able to withstand, before the sediment moved (Figure 13).

- **Surface roughness:** We used a photographic method to describe in detail the roughness of the foreshore surface over a meter scale (Figure 14).

- **Surface elevation change:** Because the growth and stability of coastal vegetation is often critically dependent on the elevation of the soil surface relative to sea level, and differential GPS measurements are unable to detect millimetre accurate changes in elevation reliably, we used so-called 'Sedimentation-Erosion-Tables' (SETs) for precision measurements of changing surface elevation at fixed locations against the deep (several meters below the surface) base of the foreshore sediments (Figure 15).

- **Surface accretion:** Over several months to a year, sediment builds up on vegetated foreshores through deposition by tides, river floods, and plant growth. We recorded the thickness of this surface layer of sediment over time against a layer of white chalk (kaolinite) sprinkled onto the foreshore around the SET instruments (Figure 16). When comparing these measurements against those made with the SET above, this also allowed us to assess the degree to which the surface sediment compresses over time, as it is buried deep down within the wetland soils.

- **Water quality:** At our sites in Romania, where the foreshore was permanently inundated, we measured the chlorophyll content and the relative amount of large particles suspended within the water through direct water sampling and, more qualitatively, through recording the depth at which a white (secci) disc becomes invisible below the water surface.

Figure 15. Measuring elevation change using a Sedimentation-Erosion-Table (SET) at Tillingham, UK (photo: M Yates)

Figure 16. Accretion marker horizons sprinkled onto the marsh surface at the start of the project at Paulinaschor, The Netherlands, and buried marker horizon after two years of deposition at Donna Nook, UK (right) (photo: I. Möller)

2.2.2 The Challenge of Remote Sensing

Remote sensing allows information to be gathered over vast spatial scales at regular snapshots in time, building up a picture of the earth throughout the seasons and years, even in the most inaccessible sites. Hence, it is well suited to obtaining information on challenging, often inaccessible, foreshore environments. Remote sensing information can be collected from satellite (for example, the Copernicus Sentinels) or airborne platforms (for example, conventional aircraft or unmanned aerial vehicles (UAV's or drones)) or by taking photographs on the ground. Most optical satellites have broad-band sensors; which typically record spectral information in the visible range of the electromagnetic spectrum, e.g. those parts of the light spectrum that appear to the human eye as blue, green and red colours. Some sensors also acquire information in the near-infrared, short-wave infrared and / or thermal infrared ranges. The Multi Spectral Imager (MSI) on board the Sentinel-2 satellite acquires information in 13 spectral bands across the visible and infrared range of the spectrum. The increased number of wavebands compared to other sensors allows MSI to distinguish certain surface properties better. Likewise, the spatial resolution of the images can vary greatly. For Sentinel-2 MSI, for example, most bands are acquired with a spatial resolution of 10 or 20 m, and thus each pixel in an image would represent an area of this size on the surface (Figure 17). Sentinel-2A became operational in 2015, and Sentinel-2B in 2017, collecting an image from any surface of land or coast approximately every 5 days given favourable cloud cover conditions. In addition, Landsat data from NASA/USGS provides broad band multispectral information with a 30 m spatial resolution and has been operational over a time-span of decades. The FAST project also made use of higher spatial resolution sensors at the case study sites, such as those from RapidEye[15], which provide multispectral information with 5 m pixels. EO information is also acquired in the microwave region of the electromagnetic spectrum by RADAR sensors (such as Sentinel-1 SAR).

We used satellite imagery primarily to derive information on the elevation of the surface and on vegetation cover (in particularly on the presence and type of vegetation, the change in the area covered by vegetation, and the characteristics of the vegetation, such as its structure).

Figure 17. Copernicus Sentinel-2 MSI image of part of the Westerschelde, southwest Netherlands.

[15]RapidEye: Constellation of 5 earth observation satellites owned and operated by Planet Labs.

Measuring surface elevation from space: Water depth, alongside the roughness of the surface over which waves travel, determines the amount of wave energy lost as waves approach the shore. This makes it very important that we know the elevation of the surface in this zone (also called the topography). While the topography of land is often mapped, and sea bed depth data may only exist further off shore. Matching land-and-sea data is challenging because of different vertical datums[16]. Also, particularly, for global data sets information may be quite old; for example, SRTM global elevation was collected in the year 2000. It is possible to measure elevation directly (in the field) with high precision (~ 2 cm vertical accuracy) using laser ranging or Real Time Kinematic (RTK) satellite navigation (Figure 18), but this is difficult, slow, expensive, and time consuming, particularly in inaccessible remote areas.

Figure 18. Collecting in situ elevation data at the FAST case study sites. Creators: Edward P. Morris, Jesus Gomez Enri, Juan Carlos Gutierrez, Iris Möller, and Gloria Peralta.

So stepping up to the challenge the FAST team developed alternative methods, based on EO techniques, which allow greater spatial coverage with lower spatial resolution/precision, but provide viable (and relatively lower cost) alternatives in coastal zones. For creating Digital Elevation Models (DEMs) over larger areas (10 - 100 km scale) well established airborne Lidar or range imaging, and ship based sonar techniques are effective, however, these are still relatively costly, and not available for all coasts. To compliment these sources and fill in gaps at the km-scale, Structure from Motion (SfM) techniques with optical images collected by UAV at low tide were used to construct DEMs (see Figure 19 for some examples for the FAST case study sites).

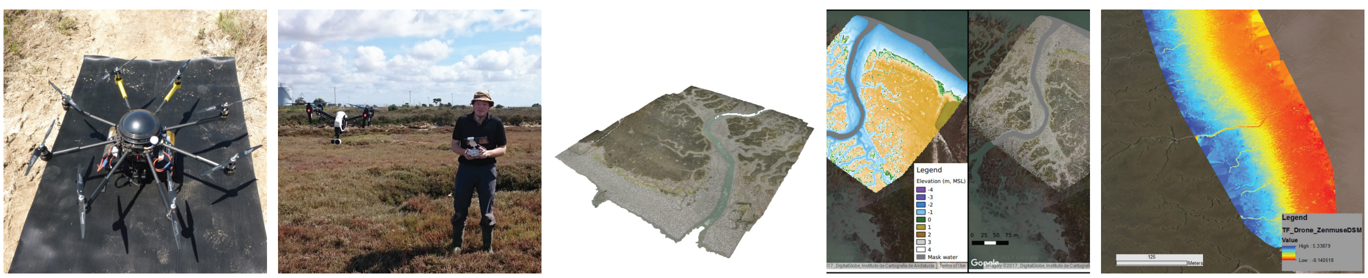


Figure 19. Collecting elevation data using Unmanned Aerial Vehicles. Creators: Edward P. Morris, and Iris Möller.

To overcome the difficulty of terrain mapping in completely inaccessible regions we used EO data to derive an estimate of coastal topography. The global coverage of publicly available NASA/USGS Landsat and Copernicus Sentinel image collections offers the possibility of applying time-series analysis to multiple images collected at different stages of the tide. By extracting the probability with which any particular point of the coastal zone is under water over time, its elevation can be inferred. While this 'waterline' technique had been pioneered prior to the FAST project[17], we made great progress in developing a fully automated procedure that generated a global 20 m pixel resolution intertidal elevation map[18].

Measuring the presence of vegetation from space: The amount and type of vegetation greatly influences how waves are attenuated as they cross the foreshore. To enable global foreshore assessments of wave attenuation by vegetation, a high spatial resolution global map of vegetation presence and absence is therefore paramount.

[16] A vertical datum is a reference point for elevations of surfaces and features on the Earth including terrain, bathymetry, water levels, and man-made structures. Vertical datums are either: tidal, based on sea levels; gravimetric, based on a geoid; or geodetic, based on the same ellipsoid models of the Earth used for computing horizontal datums. Land topography and sea bed depth maps usually are created using different datums.
[17] see Lee and Jurkevich 1990, White and Asmar 1999, Murray et al. 2012
[18] Sala Calero et al. 2017

The challenge for FAST was to create a global binary (presence/absence) vegetation map for coastal areas using thresholded Normalized Vegetation Index (NDVI) values calculated using the Google Earth Engine (GEE). For this, Sentinel-2A (10 m spatial resolution) and Landsat-8 (30 m spatial resolution) images for the coastal zone were used and filtered for clouds.

Measuring the type of vegetation from space: Vegetation type also influences waves travelling across it. The challenge for FAST was to develop a global map of key coastal vegetation types and this involved using GlobCover[19] and Corine Land Cover[20] data. For non-temperate zones on a global level, it was also necessary to use a global map of the distribution of mangroves[21].

Measuring vegetation density from space: The density of vegetation is also important in determining the effect it may have on waves travelling over it, when it is inundated. The challenge for FAST was thus to develop an index of this vegetation characteristic that could be detected from space. Currently, the most widely used spectral vegetation index is the NDVI (Normalised Difference Vegetation Index). The NDVI is based on surface reflectance in the red (R) and near-infrared (NIR) part of the electromagnetic spectrum (NDVI = (NIR-R)/(R+NIR)). NDVI has no units, and ranges from -1 to 1. While chlorophyll absorbs red light, the leaf structures of plants scatter near-infrared radiation, such that NDVI values typically increase with increasing cover, biomass or health of the vegetation. NDVI may also differ by vegetation type. Negative NDVI values typically indicate water. On the tidal flat, NDVI values relate to biomass, health and type of algae or seagrass. The FAST approach was to calculate NDVI from atmospherically corrected Sentinel-2 MSI images of different seasons, taking into account tidal variations.

Measuring vegetation structure from space: The structure of the plants over which waves travel is also important in determining the degree to which the waves' energy is dissipated. One measure of the plants' structure is the 'Leaf Area Index', a measure of the green leaf area of the plants per unit of ground area. The challenge for FAST was to derive this measure from Sentinel-2 MSI in tidal environments. The algorithm for Leaf Area Index implemented in such products is based on a neural network approach, trained on a database of vegetation characteristics and associated Sentinel-2 reflectances.

2.2.3 The Challenge of Modelling Waves

To assess the effects coastal and fluvial habitats have on flood risk, the degree to which they cause wave attenuation must be accurately determined[22] (Figure 20). Direct measurement of waves is often not possible, particularly where foreshores are inaccessible, and certainly not under extreme conditions. Numerical modelling of waves is thus necessary to allow wave dissipation over any given foreshore and under a series of flood scenarios to be assessed. Numerical models of wave attenuation over vegetation require the frontal surface area of vegetation (based on measures of vegetation height, stem diameter and density) as well as the 'bulk drag' (dependant also on the flexibility of vegetation) to be taken into account in the form of a 'drag coefficient'. The challenge for the FAST project was thus to develop a generic (EO-based) approach for determining this coefficient for any vegetated foreshore.

Some evidence points at the fact that biomass is a governing parameter determining wave attenuation by vegetation. Some experiments show that in small flumes different species, with differing densities, diameters and flexibilities show similar wave attenuation with the same biomass[23]. This may imply that biomass is a more generic trait that can be used to estimate capacity for wave reduction of different vegetation types. If biomass can be translated to frontal surface area a link between the key parameter in numerical models and a parameter that is easily derived on large-scales through for example satellite images can be made (Figure 21). On satellite images, biomass can be assessed through infrared reflectance by using the NDVI (Normalized Vegetation Index), and leaf surface area in the horizontal plane can be estimated through LAI (Leaf area Index) (Figure 21). Both are very standard measures for vegetation assessments and were ground referenced for the FAST field sites.

[19]Global coverage, 2009.
[20]CLC, European coverage, 2000-2006.
[21]Giri et al. 2011.
[22]Koch et al. 2009; McIvor et al. 2012a; Narayan et al. 2016.
[23]Bouma et al. 2005.

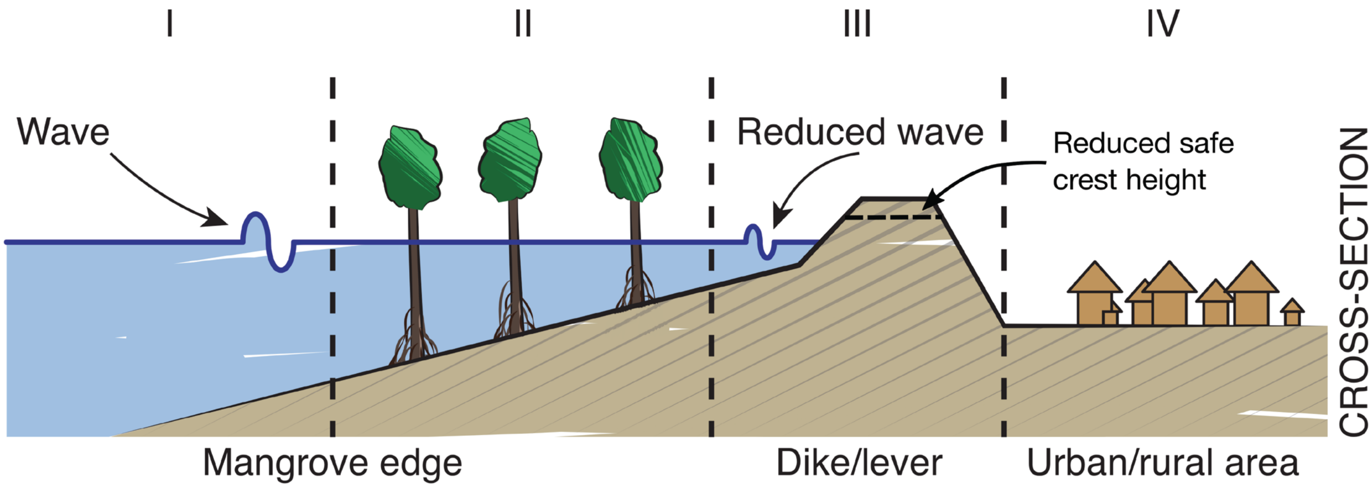


Figure 20. Vegetation and wave attenuation translated to reduction in risk. Schematization of wave attenuation over a mangrove foreshore and relation to hazard: The large incoming wave (I) is attenuated by the mangrove belt (II). As a result, a reduced wave reaches the levee (III), and the protected area (IV) is safe behind a relatively low levee.

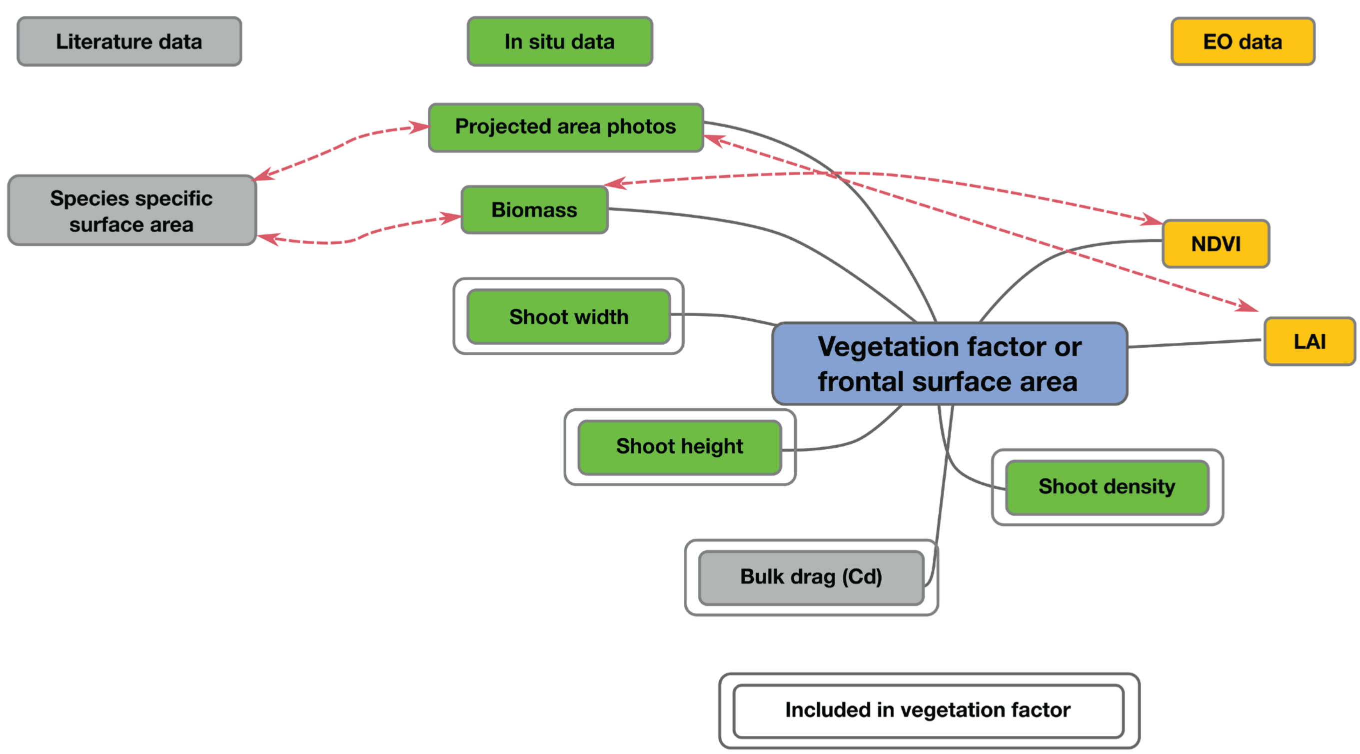


Figure 21. Relationships between field, literature and Earth Observation data explored in FAST.

The effects of both the vegetation and the topography of the foreshore on wave attenuation were quantified using the open source wave model XBeach[24]. Numerical models were validated using the FAST field measurements on wave attenuation. However, quantification of parameters that summarize vegetation characteristics in these models was not only achieved by exploring FAST field measurements on vegetation, but also by looking at data from literature. Variance in data for stem height, diameter and density was used to inform model sensitivity runs (Figure 22). The MI-SAFE viewer applies a standard hypothetical levee between the foreshore and the land (Figure 20) and the numerical model calculates wave height reduction due to the vegetated foreshore by using an empirical formulation that transforms this energy reduction into required levee crest height for a standard levee[25]. Knowledge of a required coastal protection height with and without an existing foreshore, can then be easily related to construction costs saved due to protection provided by a foreshore.

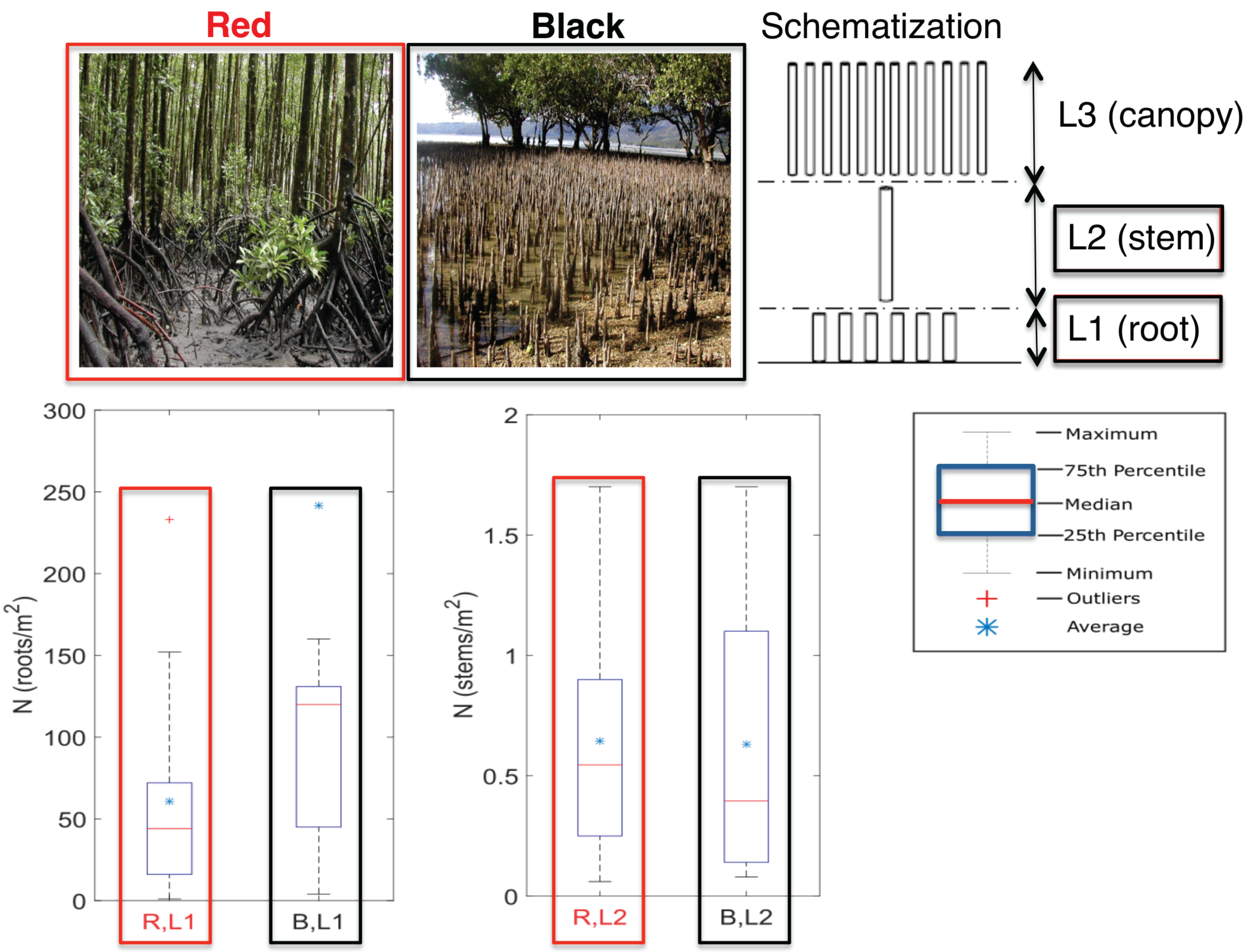


Figure 22. Number of mangroves stems and roots per m2 from literature data (From Janssen 2016). The information was used to estimate the vegetation factor for mangrove as used in the MI-SAFE viewer.

[24]van Rooijen et al. 2016.
[25]Pullen et al. 2007.

3. Using the MI-SAFE package

3.1. FAST progress in science and flood risk management

The FAST project has achieved both, progress in terms of providing new scientific insights into the wave dissipation by European coastal wetlands in relation to vegetation type and bed morphology, as well as a way of predicting such wave dissipation from satellite remote sensing. A great step has been made in filling the gap in availability of high resolution intertidal elevation data through using open access Earth Observation imagery. Modelling of wave attenuation by vegetation has been progressed by obtaining general relationships for predicting relevant vegetation properties from EO imagery. These building blocks of progress have allowed the FAST team to use spaceborne sensors to assess the flood protection service provided by vegetated foreshores and make this knowledge available to the scientific community as well as individuals involved in coastal planning and management.

3.1.1 Progress in Science

3.1.1.1 New insights into wave dissipation over coastal vegetation

Through comparison of wave statistics between and within sites, we were able to derive and compare energy attenuation and coastal protection characteristics of the diverse topographic and botanical compositions represented across the study locations (Figure 23 - Figure 25).

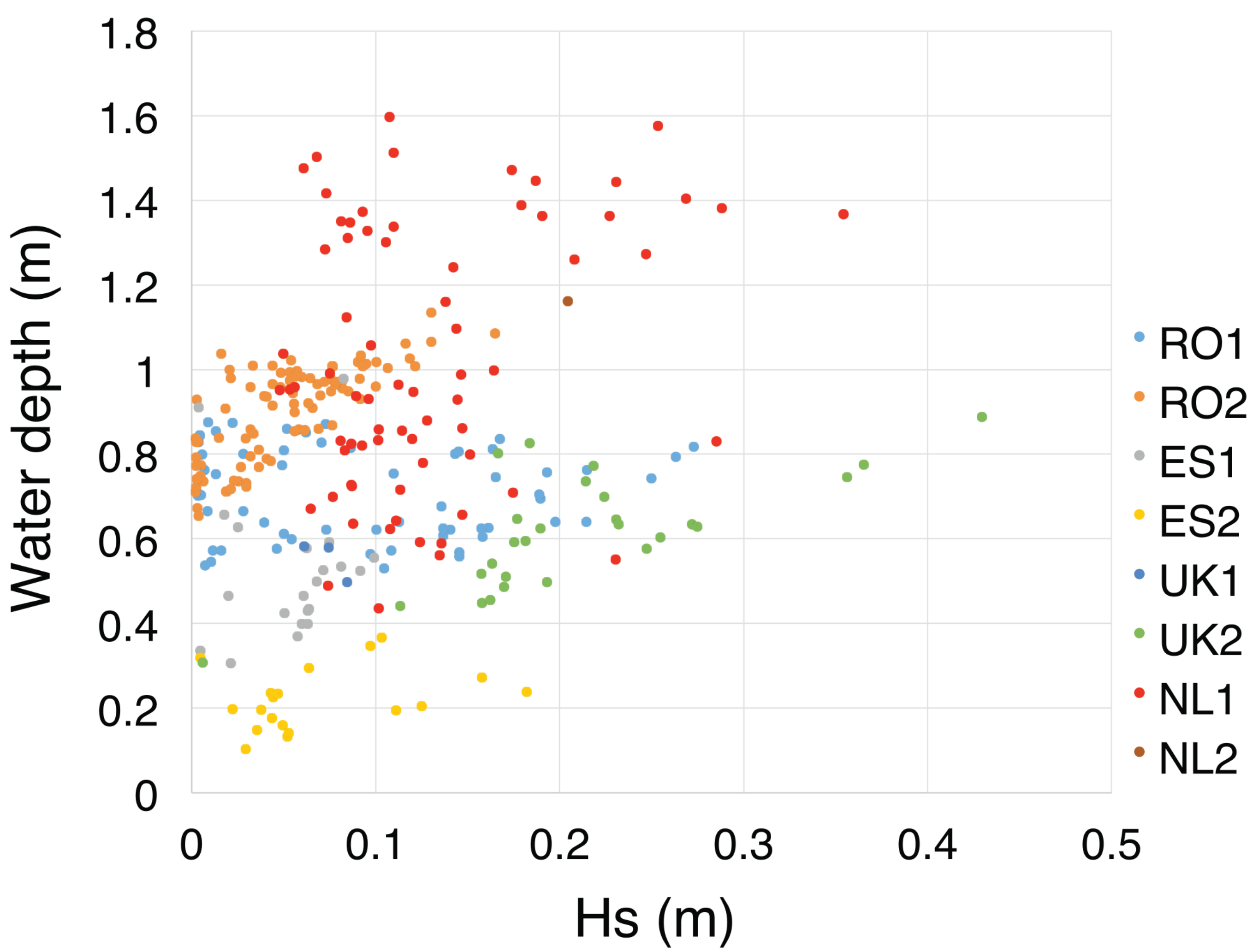


Figure 23. Water depth and wave height as measured at the seaward margin of vegetation during inundation of the foreshore. Different colours represent the eight different foreshores monitored as part of the FAST project.

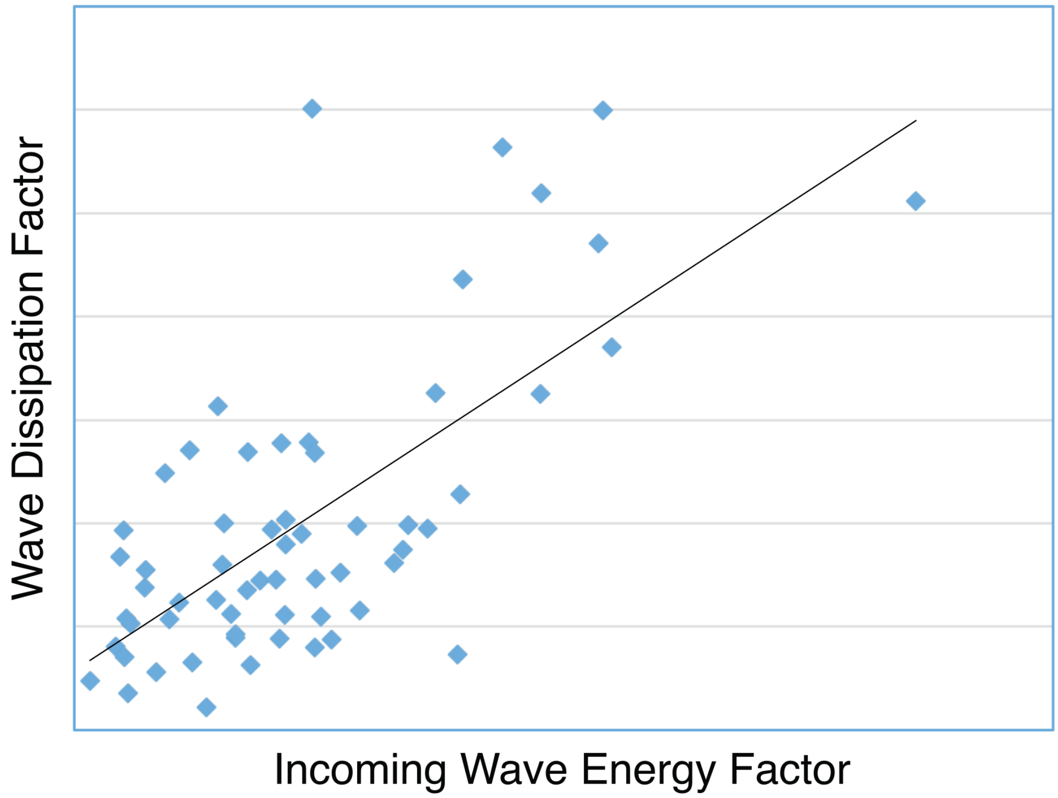


Figure 24. Example of how wave dissipation (Y-axis) varies with incoming wave energy (X-axis), Paulinaschoor, The Netherlands.

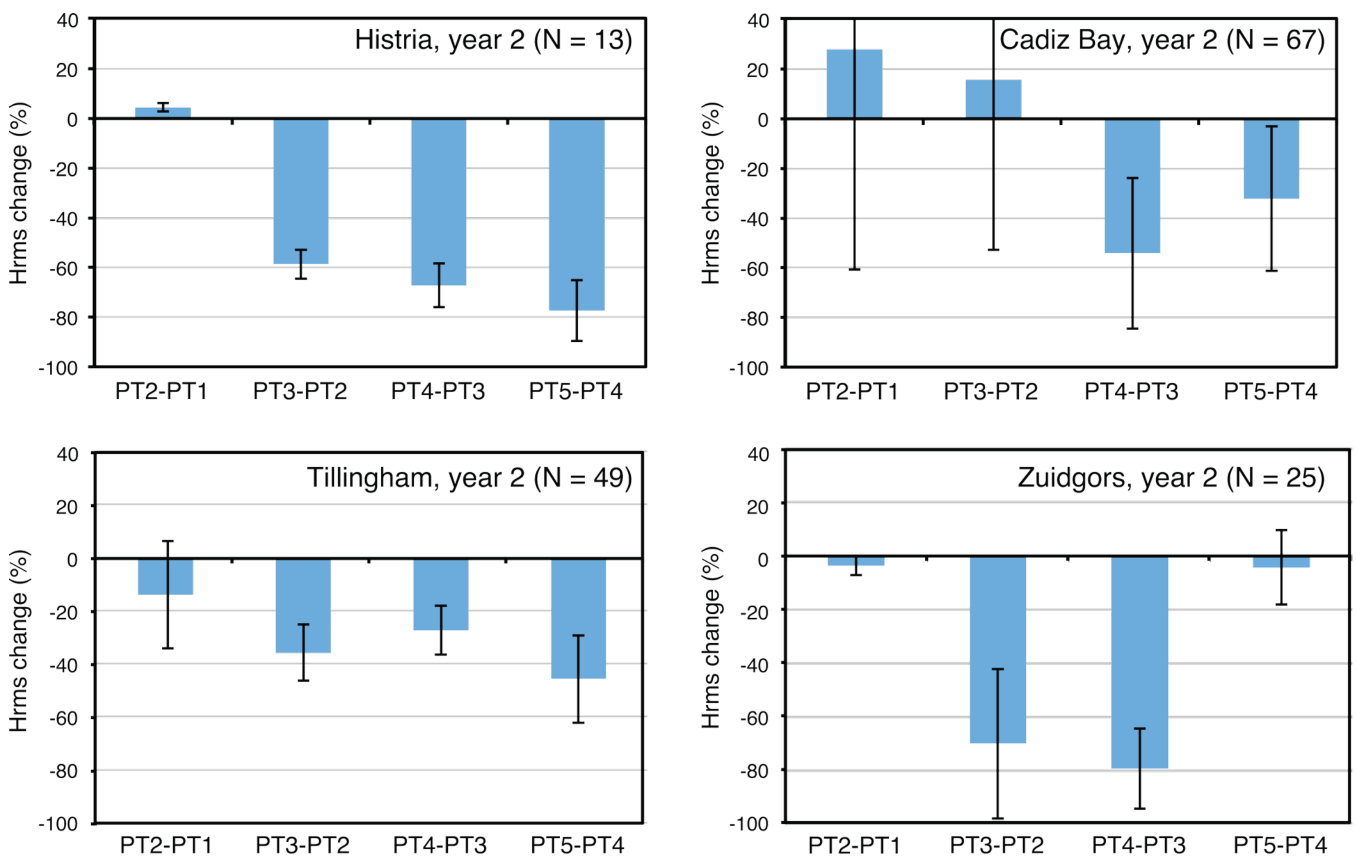


Figure 25. Average wave height change (in %) at four of the eight FAST field sites. Results are comparisons between pairs of wave sensors from the seaward location (PT2-PT1: unvegetated) to the landward (PT3-PT4: vegetated) locations along the cross-shore measurement line.

3.1.1.2 A New Global Elevation Map

Using the modified ‘waterline’ technique mentioned earlier[26], we developed a prototype 20 m pixel resolution intertidal elevation map covering most of the global coast (Figure 26) using 20 years of earth observation data. This was compared against our measurements on the ground, and high resolution DEMs (from Lidar, Sonar, and UAV measurements) at the FAST case study sites, as well as two independent sites in the USA. Mean Absolute Error (MAE), an indication of accuracy, between observed and predicted elevation (m, MSL) at each of the validation sites ranged between 0.2 m and 0.8 m. This represents a vertical accuracy of between 10% to 20% of the tidal range, suggesting that this prototype product can help to improve on the present publicly available coastal elevation products i.e., SRTM and GEBCO.

Figure 26. Global intertidal elevation map, zooming in on the east coast of the United Kingdom. The colour scale ranges from yellow (high elevation) to dark blue (low elevation).

3.1.1.3 A global map of vegetation

FAST successfully developed a global coastal vegetation layer that allows broad vegetation types, i.e., intertidal vegetation (salt marshes), inland marsh (reed beds), broad-leaved forest (riparian willow forests and mangroves), to be distinguished (Figure 27).

[26]see Sala Calero et al. 2017 and the Science behind MI-SAFE, available at the MI-SAFE viewer (fast.openearth.eu)

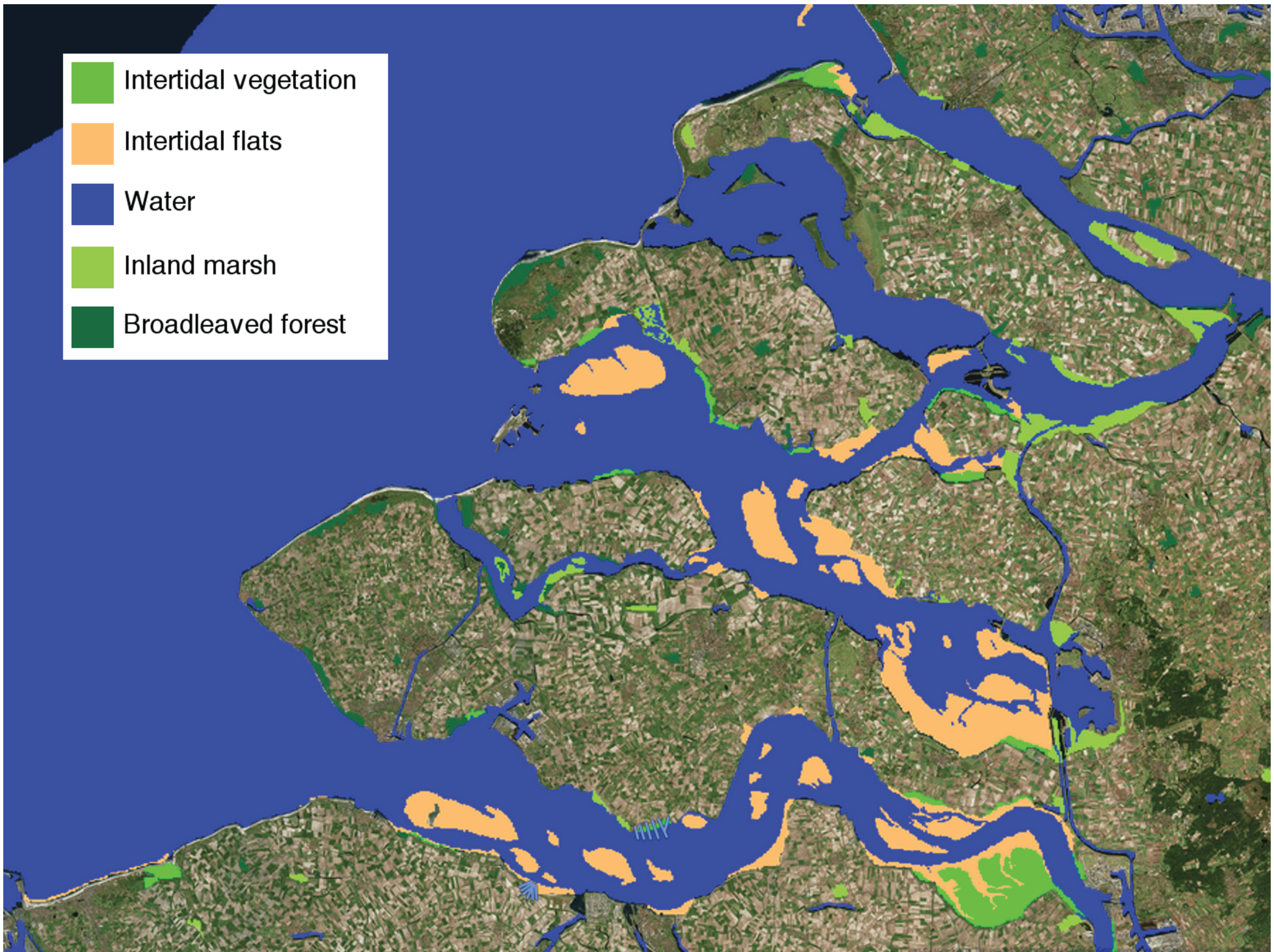
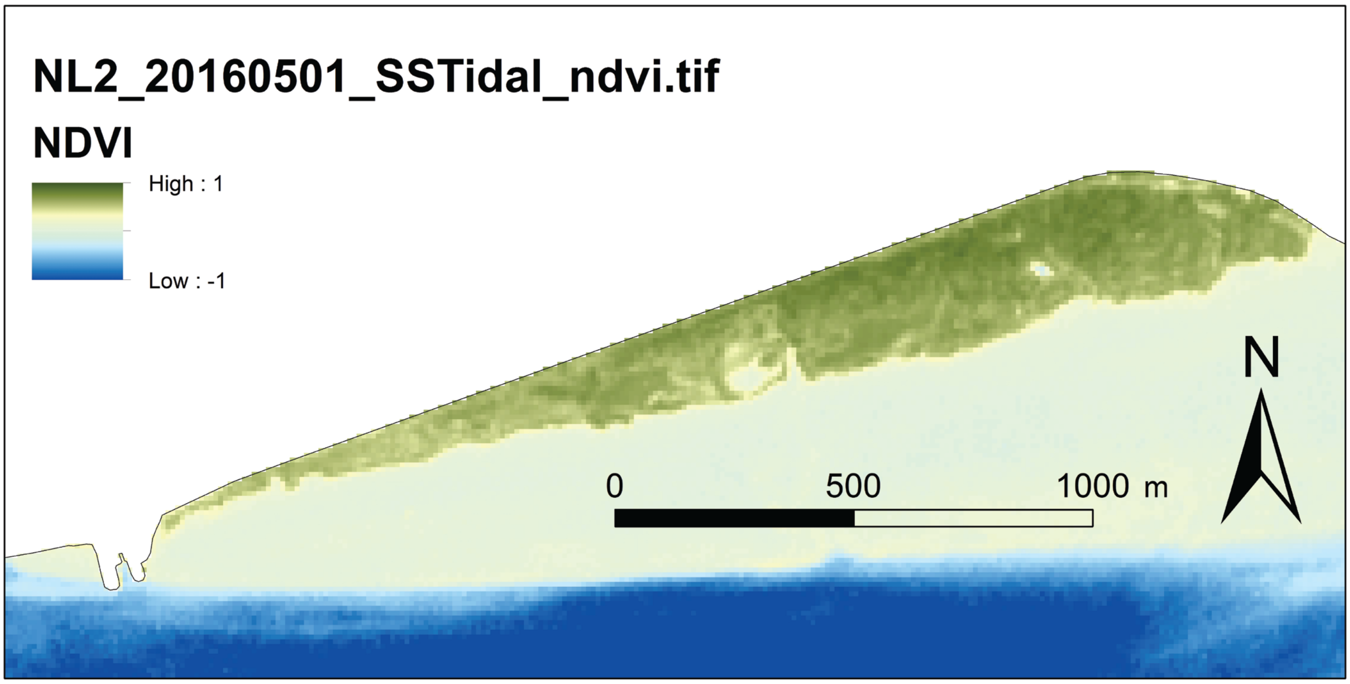


Figure 27. CORINE reclassification (2011-2012) for Europe, with example of the southwest of the Netherlands (Specto Natura Ltd. and University of Cambridge). Original file for reclassification CLC2012 from http://land.copernicus.eu/pan-european/corine-land-cover/clc-2012.

3.1.1.4 A new map of vegetation properties

The FAST project successfully produced a map layer showing the NDVI of vegetated coastal surfaces from atmospherically corrected Sentinel-2 MSI images of different seasons (top panel in Figure 28). FAST developed another map layer with information on the Leaf Area Index (LAI) of emerged salt marsh vegetation (areas for which the NDVI exceeded 0.3; bottom panel in Figure 28). The maps can be produced for any vegetated foreshore, but within FAST, layers were produced for the case study sites as proof of concept.



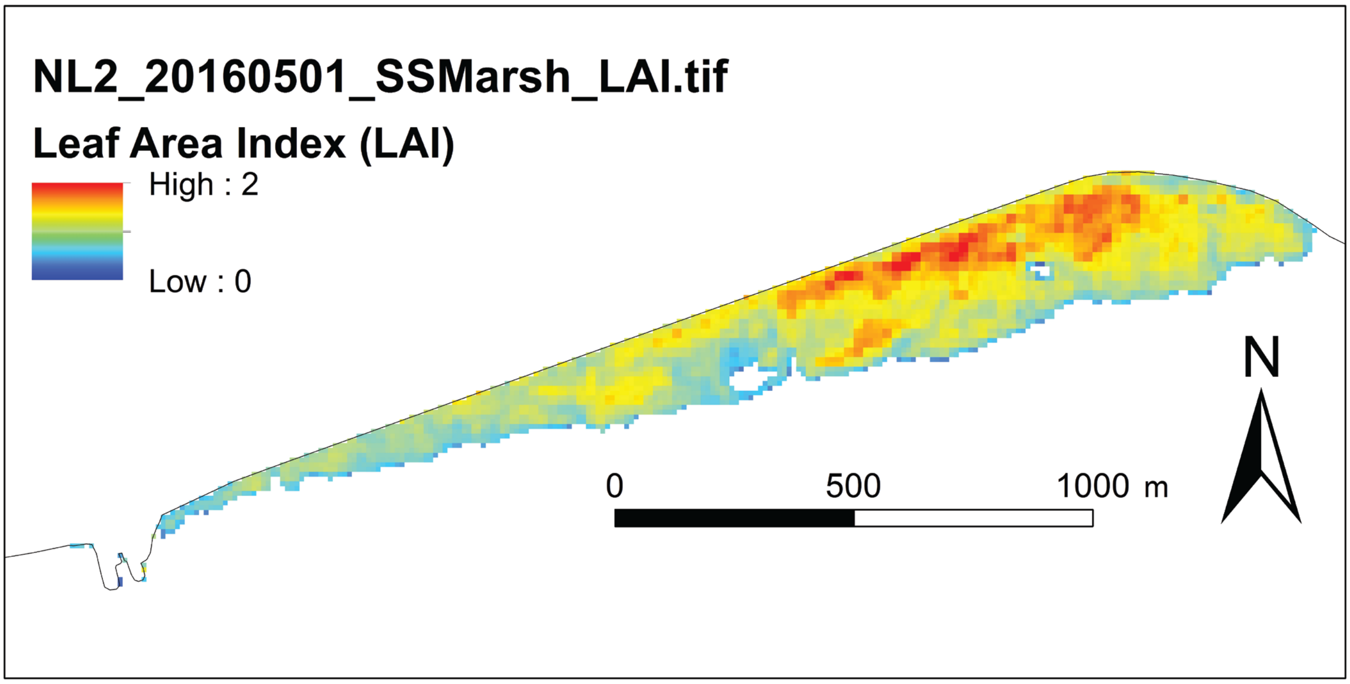


Figure 28. (Top) Normalised Differential Vegetation Index (NDVI) and (bottom) Leaf Area Index (LAI) of the marsh at Zuidgors (Westerschelde, Netherlands). Maps based on Sentinel-2 Copernicus image data from 1 May 2016 (NIOZ).

3.1.1.5 An assessment of salt marsh (edge) and mudflat stability and its drivers

By combining recent Sentinel 2 imagery with the historic Landsat archive we were able to map changes in vegetation extent along coastlines between the 1980s and present. This analysis has been conducted at a global scale, with 30 m pixels, and serves to identify the coastal regions that are most dynamic.

At regional scales marsh edge stability over two decades has been assessed at high spatial resolution from aerial photographs. This technique, demonstrated over approximately 300 km of the East Anglian coast, is capable of resolving marsh edge position changes of the order of 0.1 m/year. A new classification of marsh edge configurations has also been developed, based on airborne laser altimetry data, that has allowed for regional-scale inventories of the 3-dimensional structure of marsh margins[27]. The characteristics of the marsh margin have been shown to be associated with the amount of dynamism observed at that location, giving practitioners a quantitative basis for rapid assessment of likely change based on visual assessments of landforms in the field.

Rates of retreat of the marsh edge were also quantified in the Westerschelde estuary, Netherlands, using aerial images. Prior research has quantified the erodibility of sediment cores collected from the marsh edge using wave tanks. Results[28] reveal that wind exposure and presence of pioneer vegetation in front of the cliff can be key factors governing cliff retreat rates at the large scale, while foreshore morphology may be partially related to cliff retreat at the intermediate scale, and erodibility of the sediment can be important at the local scale. Thus, both extrinsic and intrinsic factors determine the fate of the salt marsh but at different scales.

Through detailed field measurements, we developed methods[29] to gain an insight into the stability of coastal wetland sediments over time[30],[31]. Figure 29 provides an example of the seasonal bed level dynamics we recorded at the site at Zuidgors, the Netherlands.

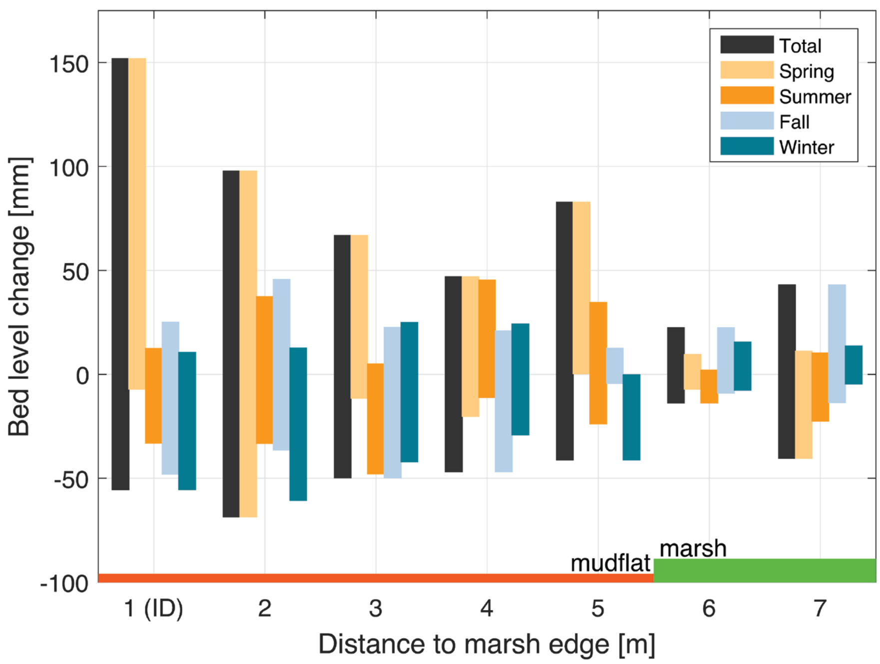


Figure 29. Seasonal sediment dynamics at Zuidgors (Westerschelde, Netherlands), 2015-2016. The maximum and minimum bed level change measured with the SED sensors was calculated for every season. In general, at this location, largest positive bed level variation (sedimentation) occurred in spring, while largest negative bed level variation (erosion) was estimated in autumn and winter; the bed level dynamics were larger on the mudflat than within the marsh (after Willemsen et al., 2017).

[27]Evans, submitted
[28]Wang et al. 2017.
[29]Hu et al. 2015.
[30]Hu et al. 2017.
[31]Willemsen et al. 2017

3.1.1.6 A globally applicable prediction of wave dissipation across foreshores

Through our collection of both ground measurements and EO data, we were able to discover relationships between in situ vegetation measurements at our field sites and leaf area index (LAI) as derived from EO. We were then able to incorporate LAI as a representation of vegetation effects in our wave modelling using XBeach, and quantify the effect of spatial and seasonal variations in vegetation cover on wave attenuation. We found that seasonal variation in vegetation cover has large effects on the amount of wave attenuation by vegetation, and hence also has significant effects on the required crest height of any landward protection structure (see Figure 30). Consequently, a good estimate of vegetation cover and taking into account seasonal dynamics is crucial when designing nature-based flood defence systems. Similarly, accurate bed level measurements are important as these may considerably influence the amount of wave attenuation provided by the foreshore. Recommended coastal protection structure crest heights can vary by around 20% depending on which methods are used to record bed levels. Coarse resolution foreshore topography data give less accurate predictions of wave attenuation. Finally, vegetated foreshores seem marginally more effective in reducing water levels and waves under 'mild' conditions (small water levels and waves) than under extreme conditions.

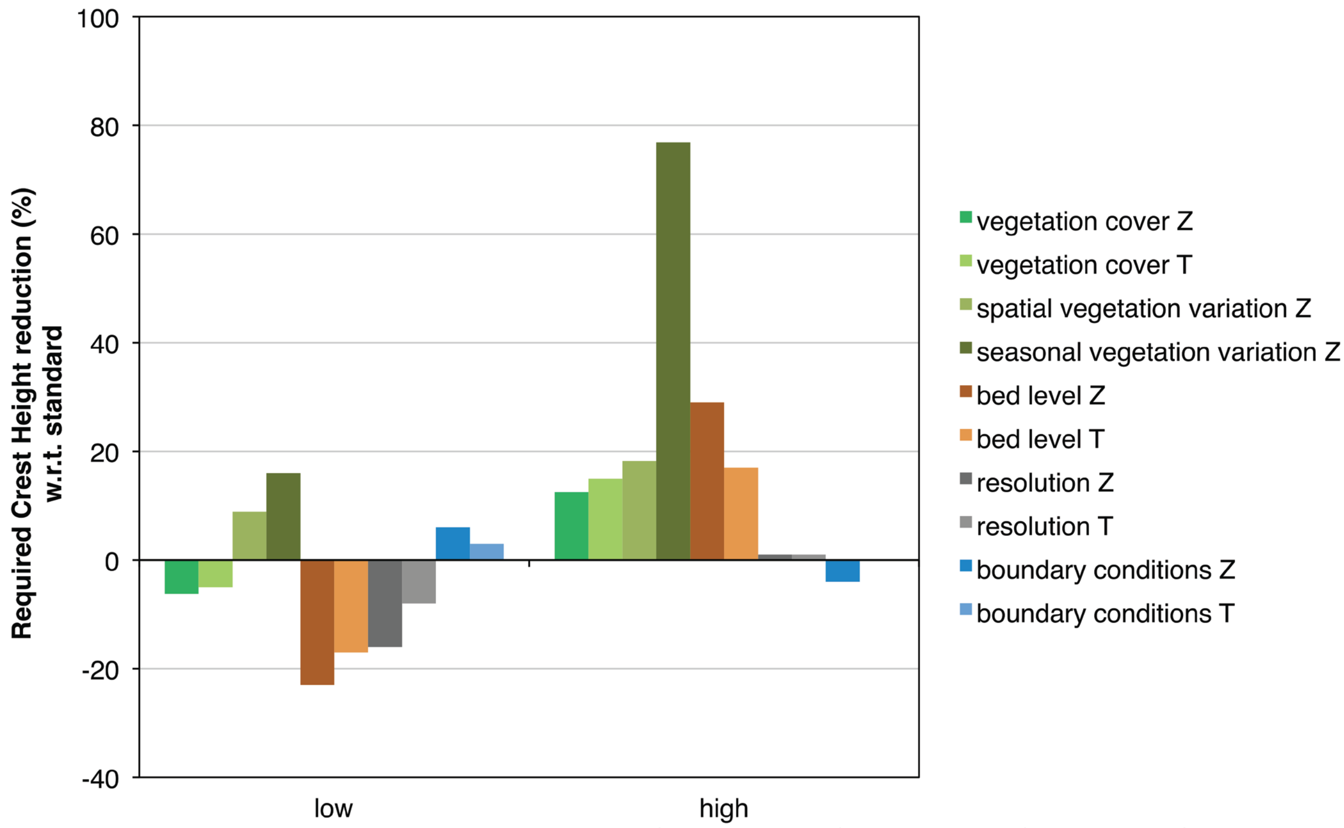


Figure 30. The effects of foreshore vegetation cover type (light green bars) and condition (darker greens), bed elevation (browns), EO data resolution (greys), and water level / wave conditions (blues) on wave dissipation and thus the reduction in the required crest height of a coastal defence structure for 'High' and 'low' parameter settings within the model ('Z' and 'T' refer to Zuidgors and Tillingham case study sites).

3.1.2 Progress in Flood and Erosion Risk Management

A sustainable interaction between human society and the dynamic natural system provides a great number of hydraulic and environmental engineering challenges. Approaching these challenges one-project-at-a-time, while attractive from a budget management perspective, results in grave inefficiencies in the development and maintenance of the basic elements that are invariably involved: data, models and tools.

Hardly any project is by itself of sufficient scale to comprehensively develop easy, accessible, high quality data archives, state-of-the-art model systems and well-tested practical analysis tools under version control. As a result, research and consultancy projects commonly spend a significant part of their budget setting up basic infrastructure, most of which dissipates again once the project is finished.

We have gathered, reclassified or produced open format layers of information on elevation (topography and bathymetry), vegetation, water level and wave statistics; using EO resources (e.g. Sentinel satellite images), but also data collected in situ. These layers, together with the intensive scientific fieldwork that underpins FAST, have been used to establish relationships between elevation and vegetation properties and water level and wave dynamics. Those relationships have been used to calibrate the open software wave model XBeach and thus to estimate the effects of foreshore vegetation on wave attenuation and dike (sea wall) overtopping. Finally, all this information has been made available via OpenEarth, an open source initiative to archive, host and disseminate Data, Models and Tools for marine & coastal scientist and engineers. It aims to remedy the above-described inefficiencies by providing a project-superseding approach.

Through this project-superseding approach, marine & coastal engineers and scientists can learn from experiences in previous projects and each other. This can lead to considerable efficiency gains, both in terms of budget and time. Products are shared freely via various web based tools such as the website http://www.openearth.nl/ (see 'work'-tab) and its associated wiki page[32]. As a result research and consultancy projects no longer need to waste valuable resources by repeatedly starting from scratch. Rather they can build on the preserved efforts from countless projects before them.

3.2. The MI-SAFE package: Products and Services

The MI-SAFE package refers to the full range of scientific and other advisory services available to users via the MI-SAFE viewer and offered as Advanced level services by the FAST team. These services range from help with the use of the MI-SAFE viewer to additional advice on nature-based coastal protection in the form of discussions with members of the FAST team to more formal contracts ('service level agreements') set up between users and the FAST team. The MI-SAFE services are thus motivated by the desire to help users of the MI-SAFE viewer to implement nature-based solutions for coastal flood and erosion risk reduction (Figure 31). To generate the MI-SAFE services, FAST has gathered, reclassified or produced open format layers of information on elevation (topography and bathymetry), vegetation, water level and wave statistics; using EO resources (e.g. Sentinel satellite images), but also data collected in situ. These layers, together with the intensive scientific fieldwork that underpins FAST, have been used to establish relationships between elevation and vegetation properties and water level and wave dynamics. Those relationships have been used to calibrate the open software wave model XBeach and thus to estimate the effects of foreshore vegetation on wave attenuation and dike (sea wall) overtopping[33].

The MI-SAFE services are unique because they are:

- A combination of worldwide coastal coverage and high-resolution local analysis;
- A unique resource providing flood hazard related parameters in many areas of the world that no other source can deliver;
- Based on transparent and verifiable scientific insights;
- Using automated coupling of EO, water level, wave and vegetation modelling;
- Based on Open Geospatial Consortium (OGC) data streams – to be used with your own system, with free access and in standard formats;
- Built with Open Source tools - adaptable to your own tool chain; Supported by the OpenEarth open source and free software community;
- Versatile, with advanced functionalities that cater to specific needs of users.

[32]Ehttps://publicwiki.deltares.nl/display/OET/OpenEarth
[33]For further details see https://publicwiki.deltares.nl/display/OET/The+Science+behind+the+MI-SAFE+tool.

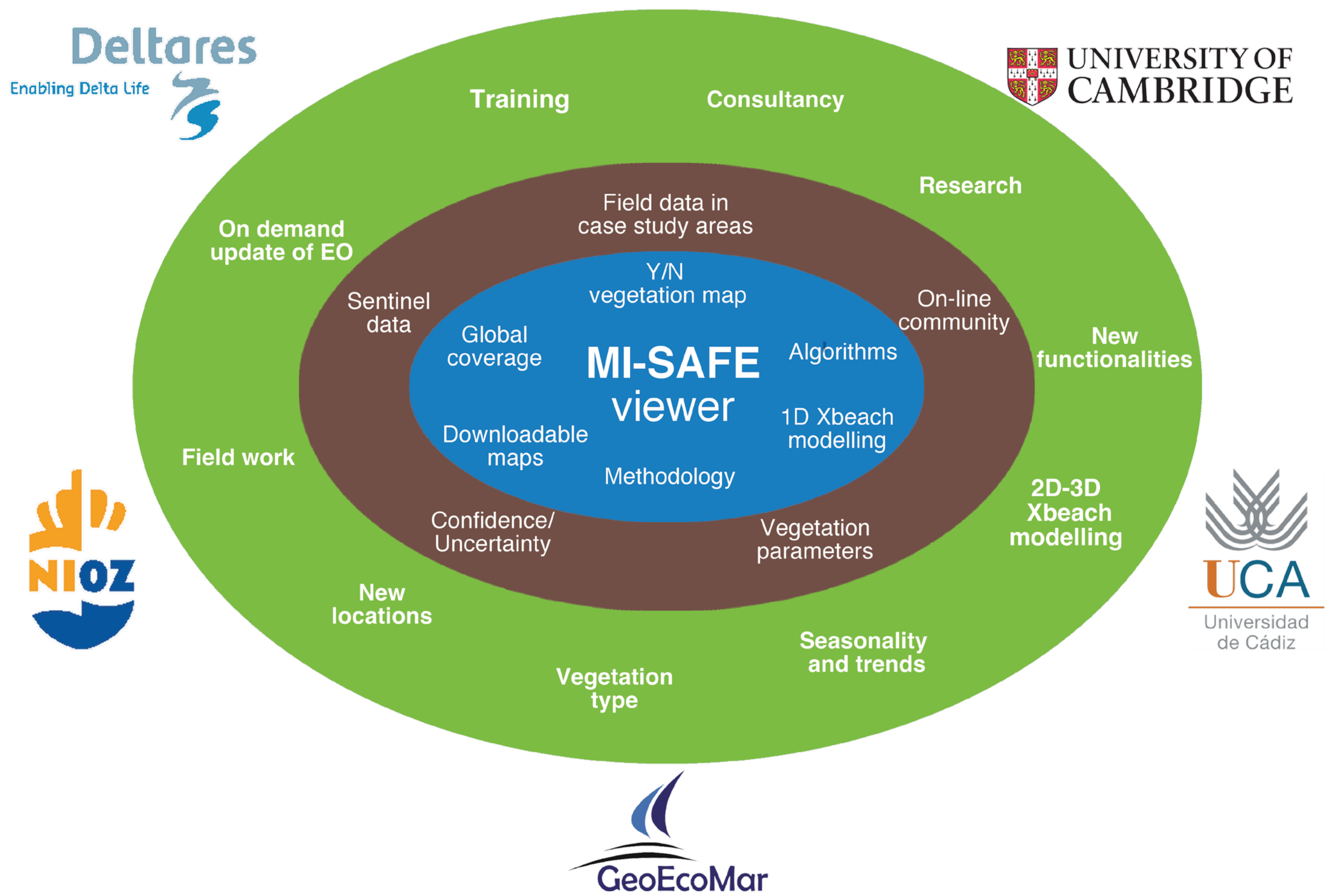


Figure 31. Summary of the MI-SAFE package, specifying services offered at the different levels. The MI-SAFE viewer gives free access to the Educational (blue) and Expert (brown) levels of services. Advanced level services (green) are available only on request by contacting with the FAST team (see logos).

3.2.1 The structure of the MI-SAFE package

The MI-SAFE package provides two types of services, data and modelling, at three levels (i.e. Educational, Expert and Advanced levels) (Table 1), using the MI-SAFE viewer (http://fast.openearth.eu/) as the main vehicle for service distribution and demonstration:

1) **Open Geospatial Consortium (OGC) data stream Service.** Accessible via the MI-SAFE viewer and available via MI-SAFE GeoNetwork CSW catalogue[34] (Educational and Expert level services) with additional products available on request from the FAST team (Advanced level services). This service provides OGC data on:
   - Elevation (bathymetry and topography).
   - Vegetation (presence, leaf-area-index, types).
   - Wave and water level statistics (significant wave height, tidal range).
2) **Open Source Modelling Service.** Accessible via the MI-SAFE viewer (at Global scale for the Educational level and at high resolution in the FAST study sites for the Expert level). On request from the FAST team, this service also includes calibration/validation for new sites and the modelling of new processes (Advanced level services). This service offers:
   - XBeach model with vegetation for coastal, delta and riparian regions. Calibrated and validated for the FAST case study locations.
   - Flexible integration of data, using OGC data streams (inputs and outputs) and link to Delft Dashboard - easy connection to Delft3D, LISFLOOD, and many other open software models also built into Delft Dashboard.
   - Open data and open source products based on OpenEarth conventions.

[34]http://fast.openearth.eu/geonetwork/srv/eng/catalog.search#/home

3.2.2 The MI-SAFE viewer: Educational and Expert levels of services

The MI-SAFE viewer[35] is a web-based platform that allows the user to interrogate information on any particular vegetated foreshore in the world to help inform their knowledge and decision regarding the attributes of that foreshore and its role in providing natural flood protection. This user-friendly on-line tool gives free access to the Educational and Expert[36] levels of services (and their corresponding documentation) conditional upon acceptance of the non-commercial service level agreement, the MI-SAFE Viewer User Agreement (Figure 32). This agreement includes information allowing the appropriate attribution of the various sources of information and an understanding of the specific applicability and quality associated with the outputs, cautioning against any unintended or inappropriate use of the information.

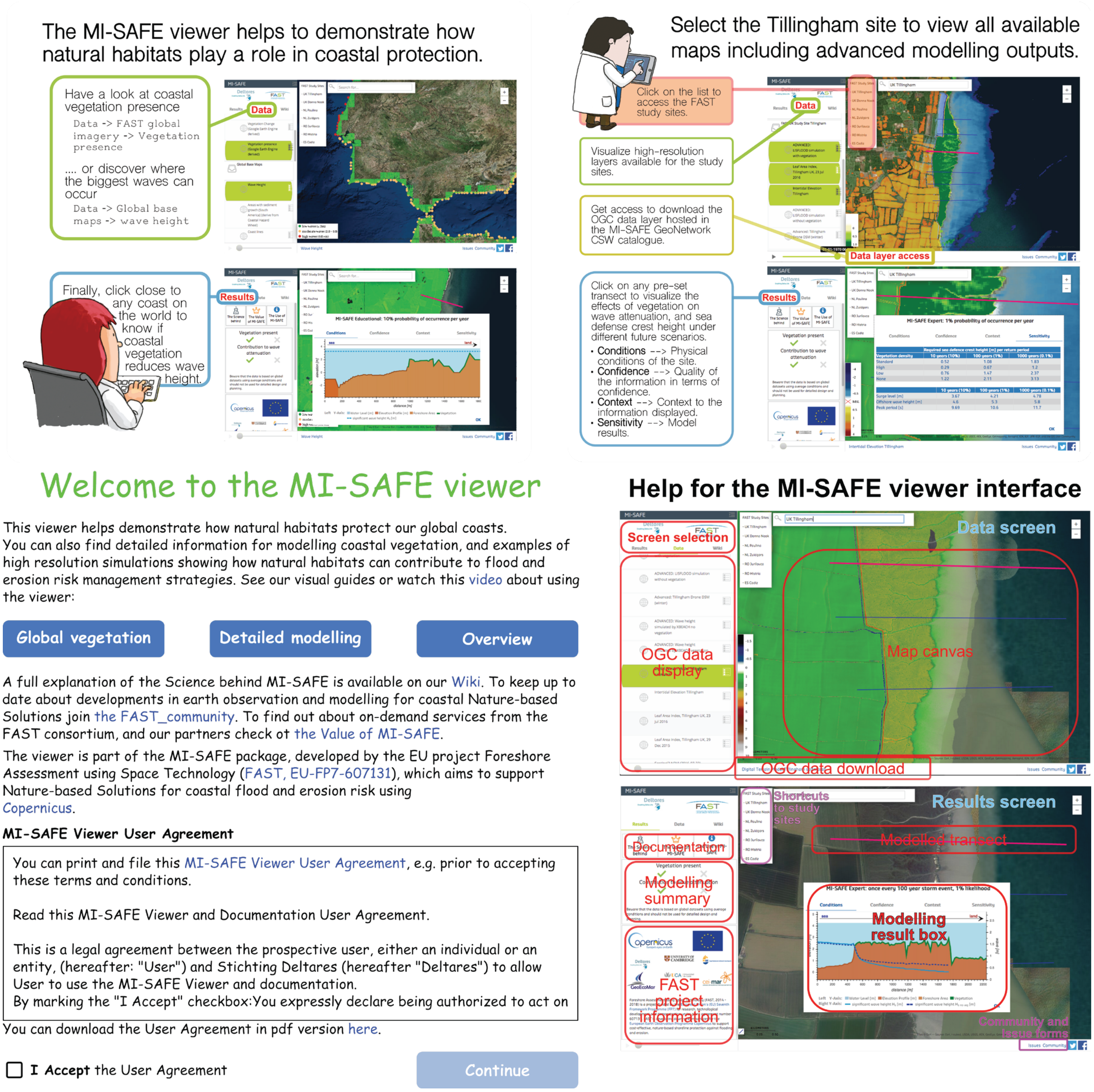


Figure 32. Pop-up screen when starting a new MI-SAFE viewer session (fast.openearth.eu) and small view of corresponding help windows. Clock-wise from top-left to right: Global vegetation, Detailed modelling and Overview.

[35]http://fast.openearth.eu/

[36]Educational and Expert levels of MI-SAFE deliver different availability and completeness of information.

The MI-SAFE viewer has two screen modes, Results and Data[37] (Figure 33). The ‘Data’ screen displays and gives open access to environmental information map layers (metadata and link to the map layer available in the MI-SAFE GeoNetwork CSW catalogue and accessible via the MI-SAFE viewer), whereas the ‘Results’ screen provides the MI-SAFE modelling outputs.

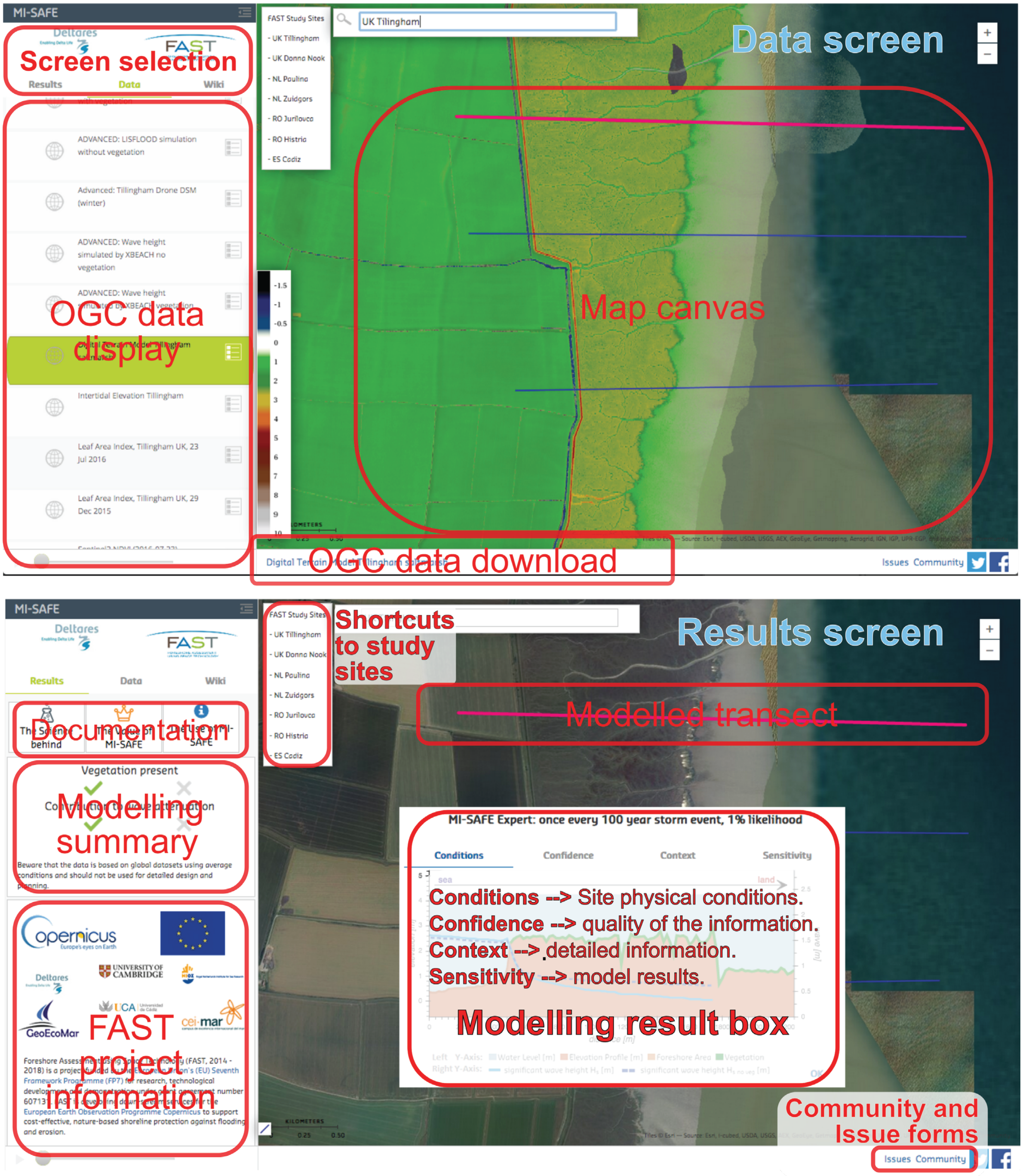


Figure 33. Screen shots of the MI-SAFE viewer interface. Top) 'Data' screen. Bottom) 'Results' screen. (1) Shortcuts to FAST study sites; (2) Community and issue forms. http://fast.openearth.eu.

[37]Technical and scientific details on MI-SAFE products and services are available via the MI-SAFE viewer at fast.openearth.eu.

1) Find closest shoreline (within search radius of 1 degree, approximately 110 km; open street map (OSM) shoreline dataset).
2) Define a cross section of 2 km landwards and 2 km seawards.
3) Query various datasets: elevation data (bathymetry, intertidal elevation, srtm), vegetation (vegetation type, vegetation occurrence), wave height and period and storm surge level.
   Define the calculation transect (from seaside toward high water line) and extract data required for XBeach model.
4) Query the XBeach model results table for the most similar combination of elevation (slope), vegetation type and wave patterns.
5) Get XBeach results for water level / wave conditions with a return period of 10 years (10% probability) in
6) order to determine the contribution vegetation makes to wave attenuation (shown in the Impact tab). The result derived from step 2 – 5 is presented in a graph (see Figure 34).

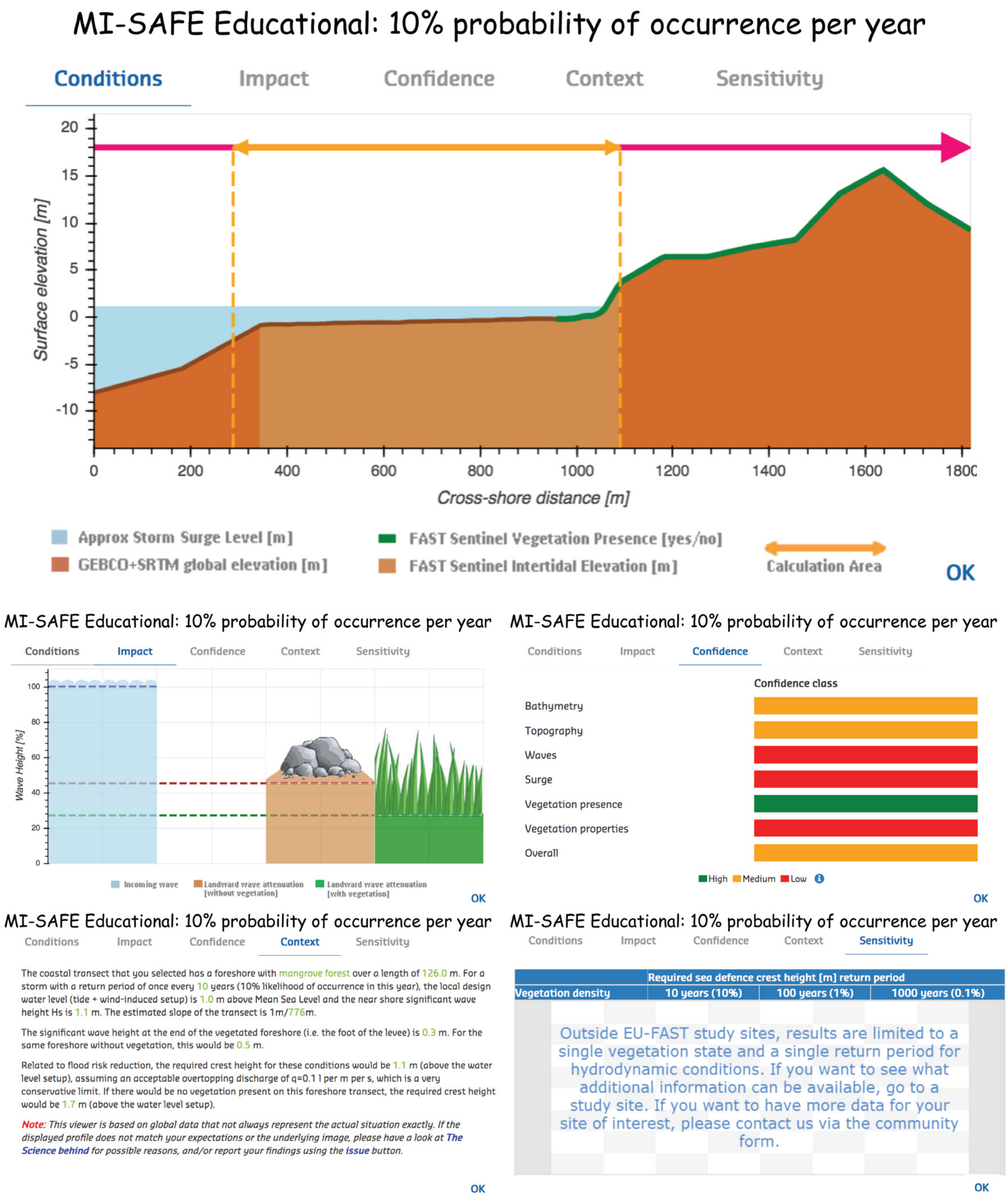


Figure 34. Screen shots of the five results tabs generated via the Educational level MI-SAFE viewer (near Côte d'Ivoire, i.e. outside the FAST study sites).

3.2.2.2 MI-SAFE Expert level

The Expert level shows what is possible if there is high-resolution data available, as gathered for the FAST study sites. The procedure to generate the corresponding outputs is a bit different. For FAST study sites, XBeach simulations and calibration procedures have been carried out specifically for the displayed transects. These calculations as well as the transect characteristics are readily stored in the database and directly available for plotting (Figure 35).

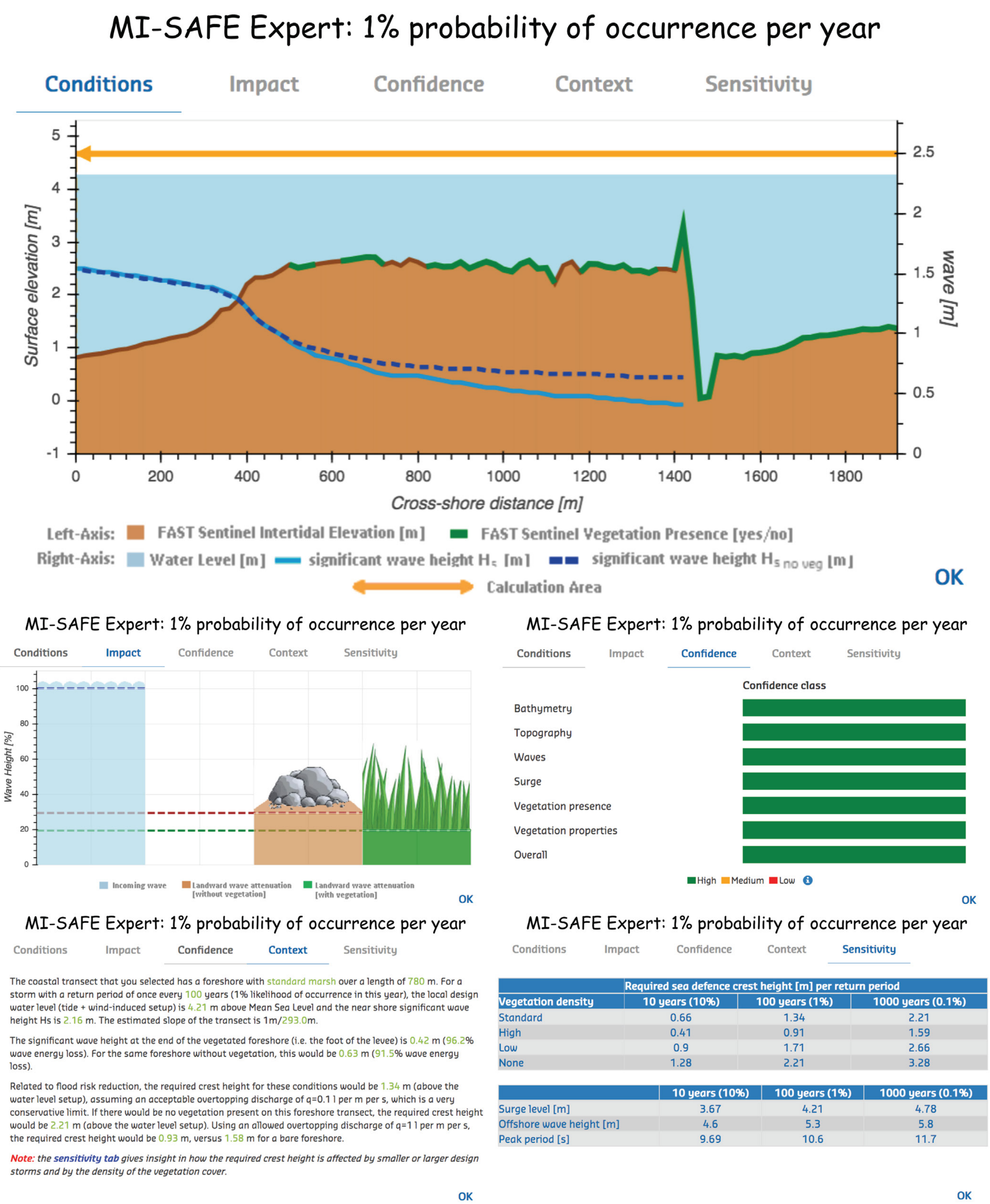


Figure 35. Screen shots of the five output tabs of the MI-SAFE viewer at Expert level for the Tillingham case study site.

Besides the much improved representation of the bathymetry/elevation data, the Expert level gives more information on the XBeach inputs and results (such as incoming significant wave heights and periods and required crest heights) for 3 return periods (Figure 35).

3.2.3 MI-SAFE Advanced level

The Advanced level of the MI-SAFE package aims to provide tailor-made solutions for end-users with specific needs relating to foreshore habitats or nature-based solutions for this zone.
This level offers the most versatile services of the MI-SAFE package available on request, services that can range from validation/calibration of new sites to development of new functionalities (Table 1). To access the Advanced level of services users are encouraged to contact the FAST team. The FAST team is a team of renowned international experts with knowledge of foreshore vegetation and coastal nature-based solutions (NBS). The Advanced level services may include[38] (Figure 36, Figure 37):

- OGC data services: Spatial products with increased spatial resolution for regional and local studies and increased information on storm surge impacts following FAST protocols and map-outputs. The generation of these products may include in situ and/or remote (Earth Observation) data collection, processing and reporting, or uploading of increased resolution maps in geoservers (e.g. MI-SAFE GeoNetwork CSW catalogue), such as elevation maps for new sites to improve outputs. The MI-SAFE package can deliver OGC data (maplayers) services on:
    - o Elevation data: acquired by dGPS, UAVs, air/ground Lidar, or EO.
    - o Vegetation data: field surveys, UAVs, EO and trend analysis.
    - o Wave attenuation data: field measurements, long-term deployments.
    - o Sediment dynamics data: field measurements and long term EO.
- OS modelling services: Development of new model functionalities, calibration and validation.
    - o Implementation of 1D, 2D or 3D model schematizations using full XBeach functionality[39].
    - o Generation of new algorithms and data fusion, calibration and validation of model outputs for a specific or for different regions.
  - o Linking of EO data and wave modelling to other modelling toolboxes.
    Flexible integration with users' GIS databases using OGC data streams (inputs and outputs) and link into Delft Dashboard - easy connection to Delft3D, LISFLOOD, and many others open software models also built into Delft Dashboard.

To provide these services, the MI-SAFE package offers a quick assessment of user needs with the FAST team. Additionally, for end-users with interest in learning how to get the maximum benefit from our services, there is also an offer of beginner and advanced training packages.
Depending on the specific end-user requirements, our Advanced services can be provided as consultancy, training[40] and/or support. These services offer opportunities tailored to individual users including data collection, setting up EO workflows, tuning models, exploiting OGC data streams or large-scale deployments.

[38]Some examples of Advanced level services are available in the MI-SAFE viewer for the Tillingham study site
[39]Modelling support is available from the active XBeach community https://oss.deltares.nl/web/xbeach; Sala Calero et al, 2017.
[40]Workshop available during the International Delft Software Days, or offered as tailored courses on request

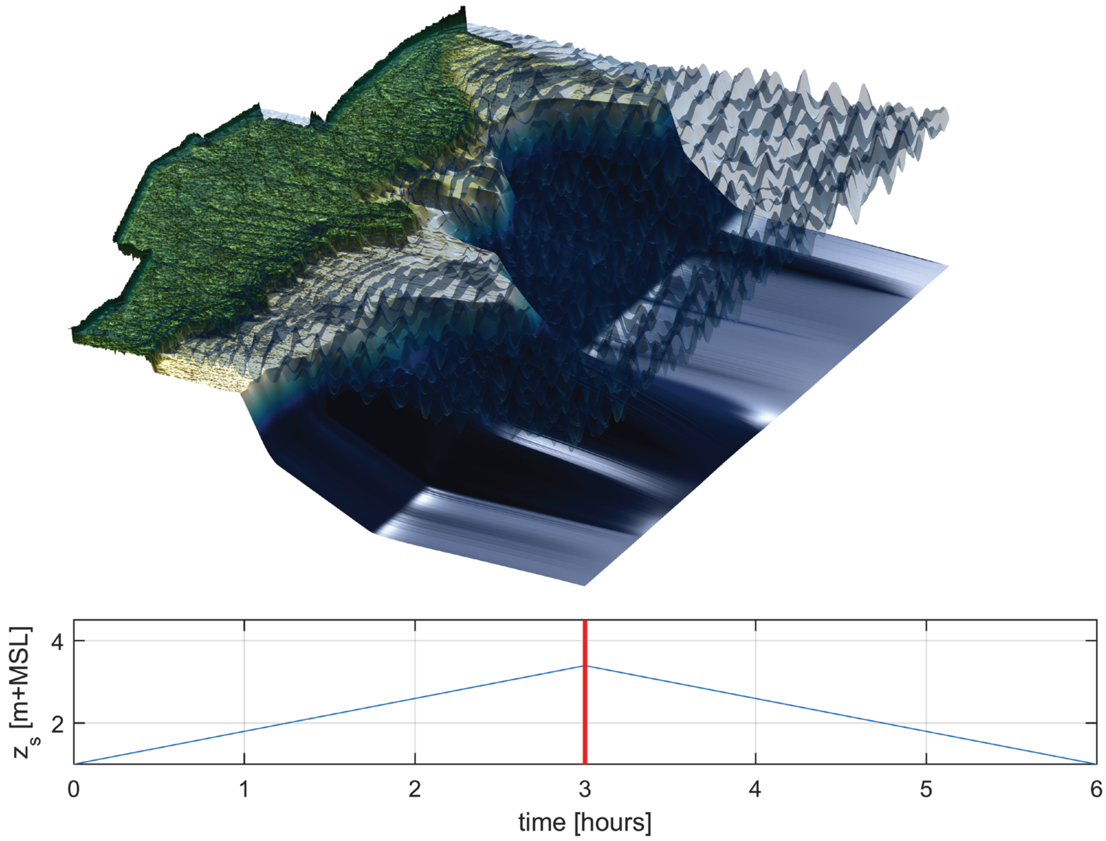


Figure 36. Advanced output of XBEACH model (near Tillingham, in cooperation with RISC-KIT project)

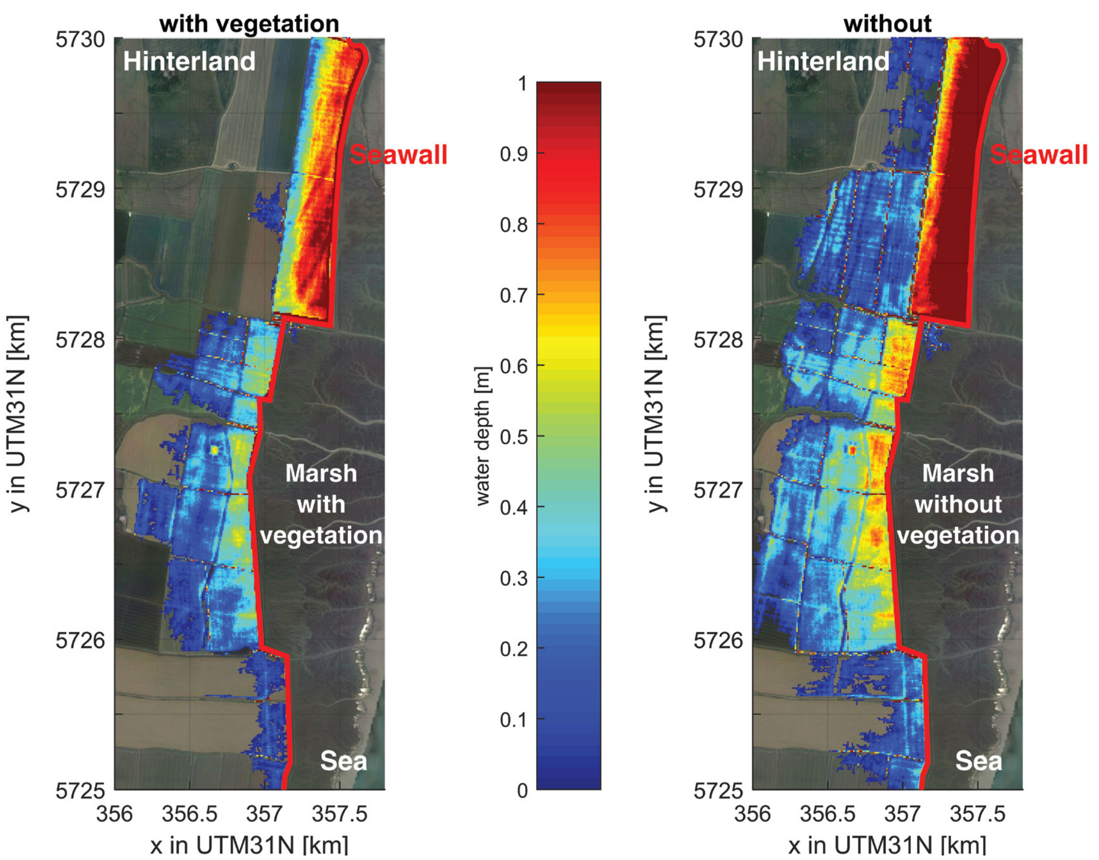


Figure 37. Advanced output of LISFLOOD inundation model (near Tillingham, in cooperation with RISC-KIT project)

Table 1. Summary of the MI-SAFE package services, including a short description and corresponding access information. The MI-SAFE viewer includes Educational and Expert level services. MI-SAFE Advanced refers to services only offered on request, although several examples of Advanced level services are already available in the MI-SAFE viewer for our Tillingham study site (UK).

MI-SAFE service component	Product/Service description	Accessibility
Bathymetry/topography OGC data		
Global	Global topography and bathymetry (SRTM15+, SRTM30+)	MI-SAFE viewer
Global intertidal elevations	Global intertidal elevation layer	
Regional/Local topography	EMODNet	MI-SAFE Advanced
Regional/Local topography: Land (10 - 1 km^2)	Lidar, UAV**, Ground-lidar, dGPS	
Vegetation OGC data		
Global	Globcover 2009 [Reclassed]	MI-SAFE viewer
Europe	EU Corine landcover (2011-2012)	
Global/coast	Global Yes/No Vegetation Maps, Global Vegetation change	
Local (10 - 1 km^2)	EO processing (NDVI, LAI)*, UAV, Ground-Spectrometry, Ground-Sampling	MI-SAFE Advanced
Water level and wave data		
Global/Coast water statistics	ERA-interim	MI-SAFE viewer
Regional/Local near-shore water modelled statistics	FAST-SWAN, FAST-XBEACH-VEG (1D, 2D and 3D)	MI-SAFE Advanced
Local shallow water measured statistics	Ground-Measurements	
OS modelling		
Open Source Modelling	XBeach with vegetation**, Flexible integration using OGC data streams**	OpenEarth / MI-SAFE Advanced

MI-SAFE Advanced level services may include: Development (EO processing and new functionality modelling), data collection, review and quality check. These services can be provided as consultancy, training or support.
*Available products for study sites at the MI-SAFE viewer (Data folders).
**Examples of these services available at the MI-SAFE viewer, under the data folder of FAST UK Study Site Tillingham.

4. Sustaining the MI-SAFE package

The MI-SAFE package will be sustained beyond the FAST project's lifetime, as it is part of the open source community administered by Deltares. The FAST team continues to provide supporting services through tailored service level agreements with individual users of the MI-SAFE package, growing the community of experts and users who work together, both nationally and internationally, towards more sustainable flood and erosion risk management.

The non-commercial services of MI-SAFE follow the Open Science philosophy of providing free services on open platforms and in standard formats to maximize their usability. Following this philosophy, even when free and open, when using this information, users must acknowledge the sources of any data and information used, and use the information provided via MI-SAFE only for the purposes indicated and compatible with the stated data uncertainties and resolution (i.e. quality).

In the case of the MI-SAFE package, these requirements above are incorporated into a single legal non-commercial service level agreement, the MI-SAFE Viewer User Agreement, and any end-user must accept these conditions before using the MI-SAFE viewer (Figure 32).

4.1. Exploitation plan of the MI-SAFE package

The three levels (Educational, Expert and Advanced) of the MI-SAFE package (including the MI-SAFE viewer) and their services, data and modelling, have been developed under an agile system of end-user consultations to provide answers to their needs. Therefore, the MI-SAFE package has been designed to cover a wide range of potential target markets and segments of users, including the engineering community, government organisations, international research institutes, international governmental branches, non-governmental organisations and the general public.

Keeping end-user needs as the main focus, the FAST project has generated the basis for further development of nature-based solutions (NBS) based on Copernicus and Earth Observation resources. Outputs from the FAST project, such as the MI-SAFE services, are applicable to diverse fields such as coastal risk management, ecosystem based coastal management, climate change adaptation, or environmental education. However, the development of any NBS that are based on the use of these services requires financial support beyond the end of the FAST project.

Considering that vegetated coastal areas and nature-based solutions are fields in continuous change and development, and taking into account the valuable diversity of FAST partners' expertise, our business model is organized according to a Platform Model (Figure 38). Platform business models facilitate exchanges among interdependent groups, usually users and producers. These exchanges allow users to create and consume values (products and services), facilitating the framework for the co-creation of services and, therefore, for the long-term sustainability of the product, in this case the MI-SAFE package.

[27]The Climate Change Committee UK, Adaptation Sub-committee (2013). Managing the land in a changing climate, Progress Report 2013, 137pp.

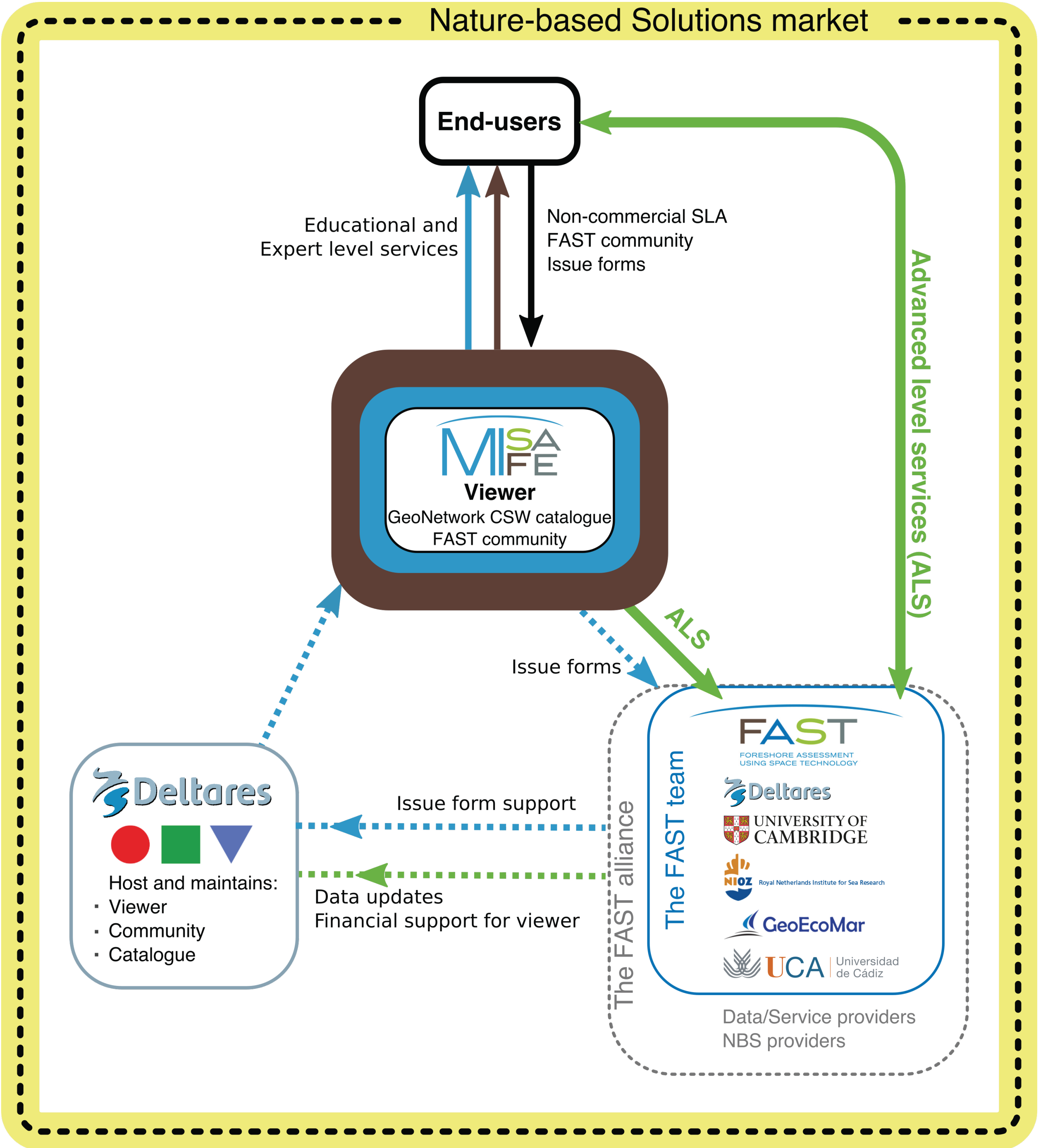


Figure 38. Schematic representation of the exploitation plan for provision of MI-SAFE package beyond the FAST project funding period. Blue, dark brown and green lines represent Educational, Expert and Advanced level services respectively. Solid lines represent interactions with end-users, dashed lines represent internal interactions within the FAST team / alliance. Educational and Expert level services are offered via the MI-SAFE viewer, Advanced level services are provided via direct interactions with end-users. Advanced level services require the establishment of Commercial Service Level Agreements.

A platform business structure provides enough flexibility for every partner to provide their specific expertise, while the MI-SAFE package includes the expertise of the entire FAST team.
After the FAST project end, the FAST team may pursue the option of a more formal ‘alliance’, adding higher value multi-services (taking example from other Open Source projects and the Open Source Platform as a Service), with more specific guidelines of how to deal with division of work. This structure will facilitate bringing in new partners, and partners leaving from the FAST alliance (Figure 39).

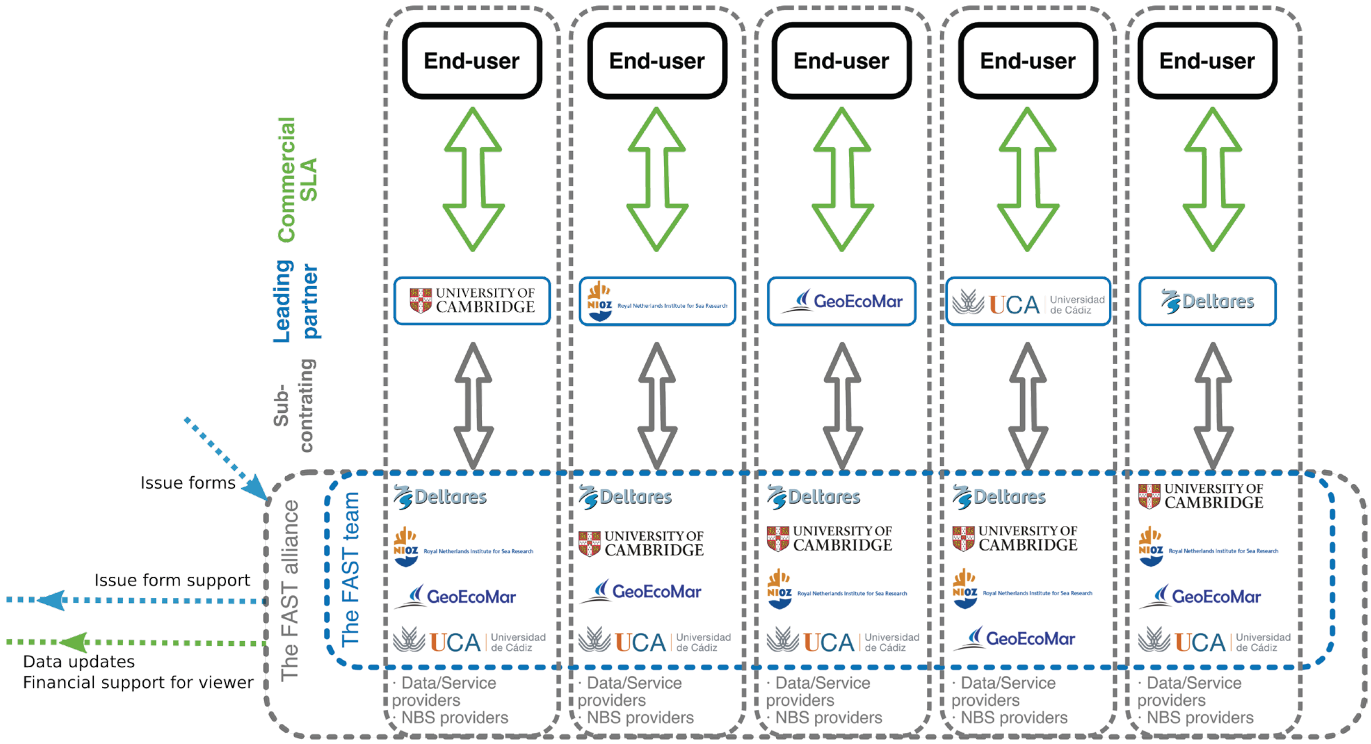


Figure 39. Summary of the FAST team internal agreement to provide Advanced level services. End-users may contact the FAST team via the MI-SAFE viewer or via personal contact with a single partner. The provision of Advanced level services requires the establishment of a Commercial Service Level Agreement (SLA), led by a single partner of the FAST team who will subcontract to other partners, as necessary. Every commercial SLA will include a budget for update and maintenance of the MI-SAFE viewer and every leading partner will include in the commercial SLA the possibility of sharing information with the MI-SAFE viewer, when feasible. See also Figure 38.

4.2. Building of a Community

A sustainable interaction between human society and the dynamic natural system provides a great number of hydraulic and environmental engineering challenges. Hardly any project is by itself of sufficient scale to comprehensively develop easy, accessible, high quality data archives, state-of-the-art model systems and well tested practical analysis tools. As a result, research and consultancy projects commonly spend a significant part of their budget setting up basic infrastructure, most of which dissipates again once the project is finished.

Open source initiatives aim to remedy the above-described inefficiencies by providing a project-superseding approach. OpenEarth (OE) is an open source initiative that provides a platform to archive, host and disseminate high quality data, state-of-the-art model systems and well-tested tools for practical analysis. Through OE, marine & coastal engineers and scientists can learn from experiences in previous projects and each other, gaining in terms of budget and time. Products are shared freely via web-based tools. As a result, research and consultancy projects no longer need to waste valuable resources by repeatedly starting from scratch, allowing improving the use of the resources.

The FAST project has been developed following the OpenEarth philosophy and using OpenEarth tools. The FAST data management was setup properly and in a standardized way according to the OpenEarth philosophy. Adopting this approach has resulted in the MI-SAFE viewer being fully embedded in Deltares System (Deltares brand for all Deltares software services and ready-to-use software products; https://www.deltares.nl/en/software-solutions/).

After the FAST project ends, the services of the MI-SAFE package will remain active. The MI-SAFE viewer will be operative and hosted at Deltares system (https://www.deltares.nl/en/software-solutions), whereas the FAST team will stay active for support and provision of Advanced services (on-request, see section 4.1), which also will provide economical support for the maintenance and update of the MI-SAFE viewer.

A key for Deltares System success is the role of the community (Open source and free software community; http://oss.deltares.nl). Through this community, any user of MI-SAFE has access to scientists, engineers and software developers, including both service providers and customers, committed with the open source philosophy.

Through the community, users will remain informed about updates to the MI-SAFE package (including MI-SAFE viewer) and can exchange information on nature-based solutions for coastal environments in general. Demonstration and dissemination of the MI-SAFE package during the FAST project created numerous occasions to interact with our end-users, both face-to-face during events and conferences and during online webinars[41]. The interaction with our end-users revealed that most end-users interested in the MI-SAFE package are aligned with the open source data and modelling philosophy and sustainable solutions (Figure 40).

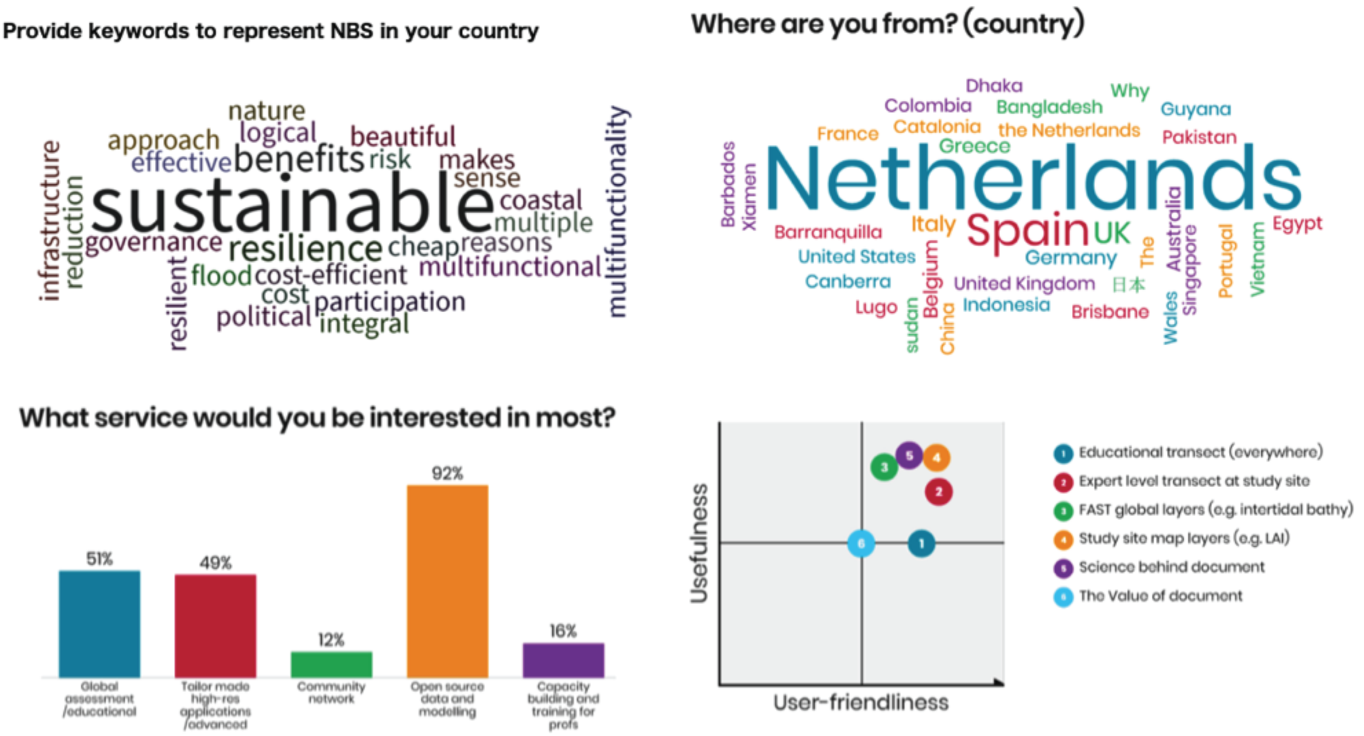


Figure 40. Characteristics of MI-SAFE viewer end-users. Source: End-user interactions during the second FAST webinar, celebrated on 31st October 2017. See https://doi.org/10.5281/zenodo.1064754 for presentation and link to recorded webinar.

4.3. The Advanced applications of the MI-SAFE package

The FAST team has already achieved a number of advanced applications of the MI-SAFE package for various clients for a wide scope of issues. The case studies below illustrate the role that users of MI-SAFE play within the future development of the MI-SAFE package.

[41] You can access to the FAST project dissemination products via the ZENODO repository, using FP7FAST as keyword.

4.3.1 Coastal flood and erosion risk management in the UK

Within the UK context, the UK's Climate Change Committee (The CCC) identified 'managed realignment', the breaching of existing sea defences to allow agriculturally used land to be converted back to intertidal wetlands, as one of the key coastal climate-related flood and erosion risk adaptation responses (see Figure 41). Within this context, the Climate Change Committee[42], advised the government that sea level rise is likely to increase the spending requirement for coastal defence to £200 million annually by 2030. Such an increase would constitute a 60% rise on 2013 levels. Meanwhile, coastal natural habitats have been identified as significant in their role as natural coastal protection and local authorities have been advised to realign approximately 10% of their sea defences by 2030 to 15% by 2050. This would reduce the rising cost of coastal defence and recreate valuable ecosystem services that have been lost over the past decades.

Figure 41. An aerial view of the Royal Society for the Protection of Birds (RSPB)'s Wallasea Island Wild Coast Project, taken in April 2015 (BAM Nuttall).

In this context, local authorities, such as those of the UKs low-lying east coast regions, are under particular pressure. The MI-SAFE viewer may be critical in the implementation of a more holistic approach towards flood and coastal erosion risk management in this region. Three key ways forward have been identified through stakeholder consultations in the UK:

- **Better communication around nature-based coastal management options.** In stakeholder communications during the FAST project, the MI-SAFE viewer has been identified as offering a potential mechanism through which better communication between stakeholders around possible managed realignment projects or coastal wetland restoration schemes may take place. The ease with which the MI-SAFE viewer offers quick access to geospatial information on specific coastal locations and the independent scientific approach adopted within the FAST project allows discussions around coastal management options to be more focussed and evidence based.
- **Access to, and awareness of, a multitude of coastal databases.** The UK Environment Agency and other UK government and non-government organisations hold important valuable geospatial data products that

[42]The Climate Change Committee UK, Adaptation Sub-committee (2013). Managing the land in a changing climate, Progress Report 2013, 137pp.

could be supplemented and combined with globally available datasets as well as field sampled data, such as those acquired during the FAST project and offered via the MI-SAFE viewer. Discussions during stakeholder consultations within the UK have highlighted the future potential for such 'data collaborations'.

- **Better science-policy linkages.** Discussions with UK stakeholders in the government and charity sector have highlighted the need for closer collaboration between those who may be able to offer independent scientific advice and those with responsibilities of safeguarding the future of coastal communities and coastal national assets. These discussions have thus highlighted the value of the Advanced level MI-SAFE services which can be accessed through the MI-SAFE viewer: the FAST team offers easy and quick access to a team of internationally renowned scientists who are able and willing to respond to urgent requests for information and provide up-to-date scientific advice on the value of natural coastal habitats as important components of coastal flood and erosion risk management.

The FAST team is looking forward to continued work with UK stakeholders in these three key areas.

4.3.2 Marsh Recession and Erosion in Canada

At the western edge of the Fraser Delta in Canada, situated in the Metro Vancouver area, are Sturgeon and Roberts bank Wildlife Management Areas (Figure 42 A and B). These vast inter-tidal areas are an important wetland ecosystem; the marshes provide food and shelter for fish, as well as vast numbers of migratory birds flying between annual breeding grounds in the north and wintering grounds in the south. Because of these functions, the area is of high international ecological significance. Human activity is widespread within the Delta, and inevitably has had a profound impact on hydrological functioning. Since 1905, dikes have been constructed along the Fraser river and sea, and there is strong evidence that the fringing salt marsh has receded. Dredging and redirection of the outflow from the Fraser River are also thought to have limited the sediment supply to the marsh, potentially escalating coastal erosion issues. Although there are plenty of studies suggesting that changes have taken place in the foreshore marshes of Fraser Delta, a large scale, long-term perspective is missing. Tools like Aquamonitor[43] can help to detect regions where changes in coastlines have occurred in the past 30 years. These are complimented by the techniques developed in FAST (made available as the MI-SAFE package) that enable time-series of inter-tidal elevation, and vegetation cover to be derived at sites of interest[44], allowing detailed modelling of hydrodynamics, and evaluation of any potential changes in risk. Applying these latest techniques, using 30+ years of earth observation information, to the Fraser Delta revealed that indeed substantial marsh recession (~ 500 m) had occurred on Sturgeon bank, and was associated with changes in elevation (~ 0.5 m), and slope of the foreshore previously occupied by marsh (Figure 42 C, D, and E). A detailed look at the evolution of these changes revealed that the recession in marsh extent mainly occurred between the 1980s and 1990s, whereas changes in elevation lagged by 10-20 years[45]. Hence, using satellite imagery, and advanced MI-SAFE services in collaboration with high quality data providers, we were able to shed new light on the mechanisms affecting the Fraser Delta, allowing the regional managers to consider new angles to tackle their local challenges.

This work was executed by Delft University of Technology (Prof. Dr. Ir. S.A. Aarninkhoff and PhD candidate Richard Marijnissen), in collaboration with various Canadian agencies (see report for details), with technical assistance from the FAST team (Dr Edward P. Morris, UCA).

[43]Donchyts et al. 2016.
[44]Sala Calero et al. 2017.
[45]Marijnissen and Aarninkhof 2017.

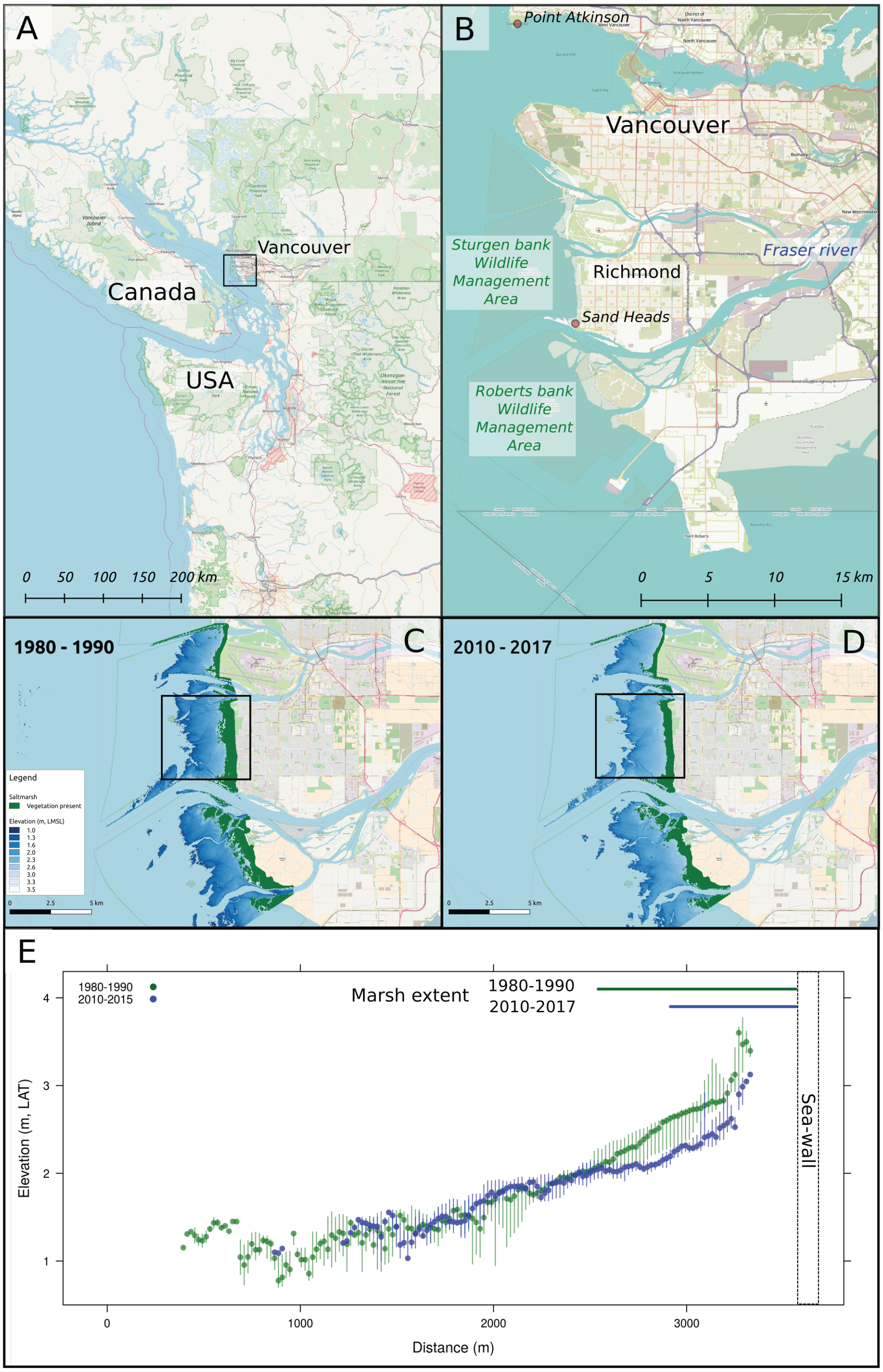


Figure 42. Marsh recession and associated changes in foreshore elevation at Sturgeon bank, Richmond, British Colombia, Canada. Map showing region (A). Map showing the location of the Sturgeon bank Wildlife Management Area, situated on the foreshore directly adjacent to Richmond, part of the Metro Vancouver area (B). Marsh extent (presence) and intertidal elevation (m, LAT Sand Heads) derived from the NASA/USGS Landsat between 1980-1990 (C), and 2010-2017 (D). Polygon's represents area shown in panel E. Median ± interquartile ranges (0.25, 0.75) of elevation (m, LAT Sand Heads) for 10 across-shore transects on Sturgeon bank in the periods 1980-1990 (green), and 2010-2017 (blue). Maximum marsh extent in each period is shown at the top of the panel as thick horizontal lines extending from the landward sea-wall (dashed polygon; note height of the wall is not indicated).

4.3.3 Predicting Storm Impacts on Louisiana Coastal and Deltaic Systems

The hurricane-prone Louisiana coast experiences wetland loss at a long-term average rate equivalent to more than a football field per hour, which totalled 1,883 square miles (mi2) over 1932–2010. The reasons for the tremendous wetland loss are both natural and anthropogenic in origin. Natural causes include subsidence from sediment compaction and dewatering, eustatic sea-level rise, growth faults, isostatic adjustments, and erosion due to waves and surges. Anthropogenic causes include channelization of the Mississippi River, canal dredging through wetlands, and fluid withdrawal. The decline will greatly accelerate when the barrier islands, which now protect large parts of the coastline, drown and the marshes become exposed to higher wave energy.

To combat the devastating wetland loss, the Louisiana Coastal Master Plan has prioritized barrier island restoration, sediment diversions, shoreline protection, and marsh creation projects. Marsh creation projects constitute the nation's largest investment, over 20 billion USD, in the 2012 Coastal Master Plan. Furthermore, hard-engineered hurricane protection projects, such as the Greater New Orleans Hurricane and Storm Damage Risk Reduction System designed by the U.S. Army Corps of Engineers, rely on the natural landscape (barrier islands, ridges and coastal wetlands) in front of the levees and structures to attenuate the surge and wave forcing. In this way, the wetlands are an integral part of the flood defence system. However, the effectiveness of the wetlands in their flood defence function has thus far been difficult to quantify. While the physical process of wave attenuation is fairly well understood, an outstanding issue is that these formulations need input parameters such as vegetation type, density, stem height and stem diameter that are not easily obtained in situ for large areas. Moreover, these parameters vary greatly in space and time. The project will make use of recent advances in a number of European Union-funded projects that couple the remote sensing of wetland properties to high-resolution hydrodynamic and eco-morphodynamic prediction models, and adapt and apply these techniques to the Louisiana Mississippi Delta (Figure 43).

The numerical models XBeach and Delft3D compute hydrodynamics, sediment transport and morphological change, and are proven tools in studies of barrier island and wetland environments. These models need input of biophysical characteristics. Using existing open-source software, these inputs will be derived from Sentinel satellites following the FAST project. We propose to use local ground referencing (e.g. Coastwide Reference Monitoring System data) to calibrate the algorithms to coastal Louisiana vegetation communities using protocols that have been established and make this database available to the government and the research community. The knowledge and products developed will be disseminated through outreach to local implementers of the Louisiana Coastal Master Plan and training of students and research fellows.

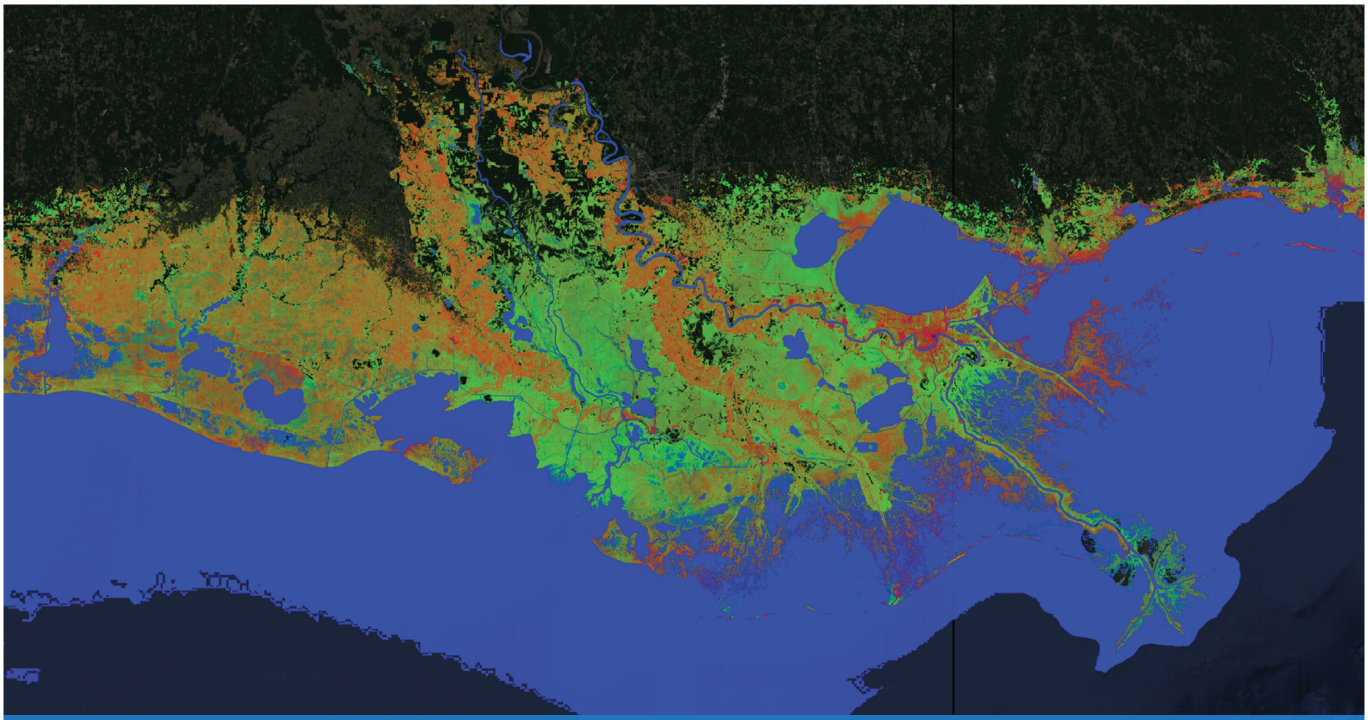


Figure 43. Red-Green-Blue image showing example of linear spectral unmixing to derive proportions of pixels classified as bare (red), vegetation (green), and water (blue) in the low elevation coastal zone of Lousiana, USA. Bare or unvegetated regions may be artificial surfaces, such as the city of New Orleans, or natural surfaces, such as beaches and mudflats. Background image Google Satellite. Creator: Edward P. Morris (UCA).

4.3.4 Rijkswaterstaat River Flood Risk program

Within the Netherlands, the MI-SAFE products are now considered by the Ministry of Infrastructure and Water for predicting the impact of vegetation cover change on river discharge, with the objective of providing efficient management information for large river sections. In addition, the possibility of producing ecotope maps of the Wadden Sea from the available map layers in relation to requirements of the Water Framework Directive implementation is being considered. In cooperation with partners from the Ecoshape foundation, especially consultancy firm Witteveen en Bos, the FAST team is exploring the application of MI-SAFE products to a quick assessment of NBS potential of coastal areas as basis of a project proposal for a specific area.

Within Deltares links have been established with EU RISC-KIT, EU BASE, EU EMODNET, global AQUEDUCT Flood Analyzer, global AQUAMONITOR and global Coastal Hazard Wheel projects. This is focusing on re-using and further developing the maplayers and EO-model integration available in the MI-SAFE package for other case study applications.

4.3.5 Aqueduct Global Flood Analyzer

The Aqueduct Global Flood Analyzer[46] by the World Resources Institute is a web-based interactive platform which measures river flood impacts by urban damage, affected GDP, and affected population at the country, state, and river basin scale across the globe. It aims to raise the awareness about flood risks and climate change impacts by providing open access to global flood risk data free of charge. The Analyzer enables users to estimate current flood risk for a specific geographic unit, taking into account existing local flood protection levels. It also allows users to project future flood risk with three climate and socio-economic change scenarios. These estimates can help decision makers quantify and monetize flood damage in cost-benefit analyses when evaluating and financing risk mitigation and climate adaptation projects.

Presently, the Global Flood Analyzer is being extended to include possible coastal flood risk reduction by nature based coastal defences. This extension uses various maps based on EO data made by the FAST consortium (high-resolution coastal vegetation presence and intertidal elevation), as well as algorithms for assessing wave attenuation over vegetated foreshores developed for the MI-SAFE viewer.

[46]http://www.wri.org/our-work/project/aqueduct

5. Steps toward mainstreaming EO into coastal management

5.1. Towards Scientifically-Informed use of EO for Coastal Management

The MI-SAFE package has been developed to perform at various scales. At the global scale, the FAST project produced brand new and unique EO-based information. To obtain this information, the Google Earth Engine online services were used to digest enormously large datasets that are open for public use. The development of open data structures allowed efficient combination with existing global maps of various parameters, available at various online open sources. Although the global datasets have relatively low spatial resolution and are un-validated for many coastlines, the result represents a step forward in spatial resolution beyond what is now available and is providing a complete information set required for assessing nature's contribution to flood risk reduction worldwide. The global application points a way forward in the utilization of the increasing flood of high resolution data for producing information relevant for assessing the status of the coastal zone. The combination of EO derived information with a pre-run dataset of model results makes this assessment quantitative and quick.

At the locations of the specific study sites, the project has utilized the latest generation of sensors from the Sentinel-2 platform in combination with extensive ground reference data. In addition, local elevation maps (LIDAR and Drone derived) were added. This allowed quantification of flood risk reduction potential of this foreshore at the highest possible resolution and with the greatest confidence, using the full potential of state-of-the-art modelling techniques.

The MI-SAFE viewer allows access to world wide databases as well as local databases crucial for assessing flood risk reduction potential. It is unique in its combination of modelling and EO capability. We believe that we have created a perfect platform that can further evolve and adapt to accommodate new developments in data-availability and requests from users to provide adapted functionalities in advanced modalities through training and cooperation with the FAST team.

The MI-SAFE approach clearly provides a major step forward in quantifying the contribution of natural foreshores to flood risk reduction. Crucial building blocks of progress have been added. The FAST team is convinced that the state-of-the-art application to study sites is of high quality. However, MI SAFE is not a design tool.

Spatial resolution limits the minimal amount of areal change that can be confidently observed through EO platforms. At present, longer term changes need input from older LANDSAT imagery. The vegetation change map produced by the FAST team, therefore needed a temporal resolution of twenty+ years. This allows establishing minimum areal changes of 30 meters. However, smaller spatial changes, e.g. of mudflats elevation or of salt marsh and mangrove cover need higher resolution data, such as that provided since 2016 by the Sentinel satellites (5 to 10 year scale 10 meter resolution) and airborne platforms (e.g. Lidar).

Further, evidence from true-to-scale wave flume experiments suggests that while significant wave attenuation by vegetation occurs under actual storm conditions, the effect of such storms on vegetation (e.g. uprooting or breakage of stems) is less well known[47]. The effect of vegetation on infragravity waves, which is important for smaller variations in runup and overtopping, also requires future study.

Likewise, the empirical overtopping formulae are not based on data from vegetated foreshores that differ significantly from the tested conditions. Therefore, the MI SAFE viewer should be considered as a quick assessment tool of the potential of the effect of foreshores to flood risk reduction. The Advanced level of services offer more detailed assessments on request.

The Educational level of the MI-SAFE package offers services at a global scale. Therefore, and considering the uncertainties associated with this scale, the MI-SAFE viewer has to be used strictly as a demonstration tool. Hurricanes/typhoons, for example, are underrepresented in the Educational level, as their occurrence is highly locally and temporally variable. The automated offshore wave transformation (from the DIVA database) to nearshore waves is very basic and does not take sheltering by islands into account. Nevertheless, these limitations can be overcome by running localized wave models, at larger computational cost (Advanced level service that is offered on request).

[47]Möller et al, 2014

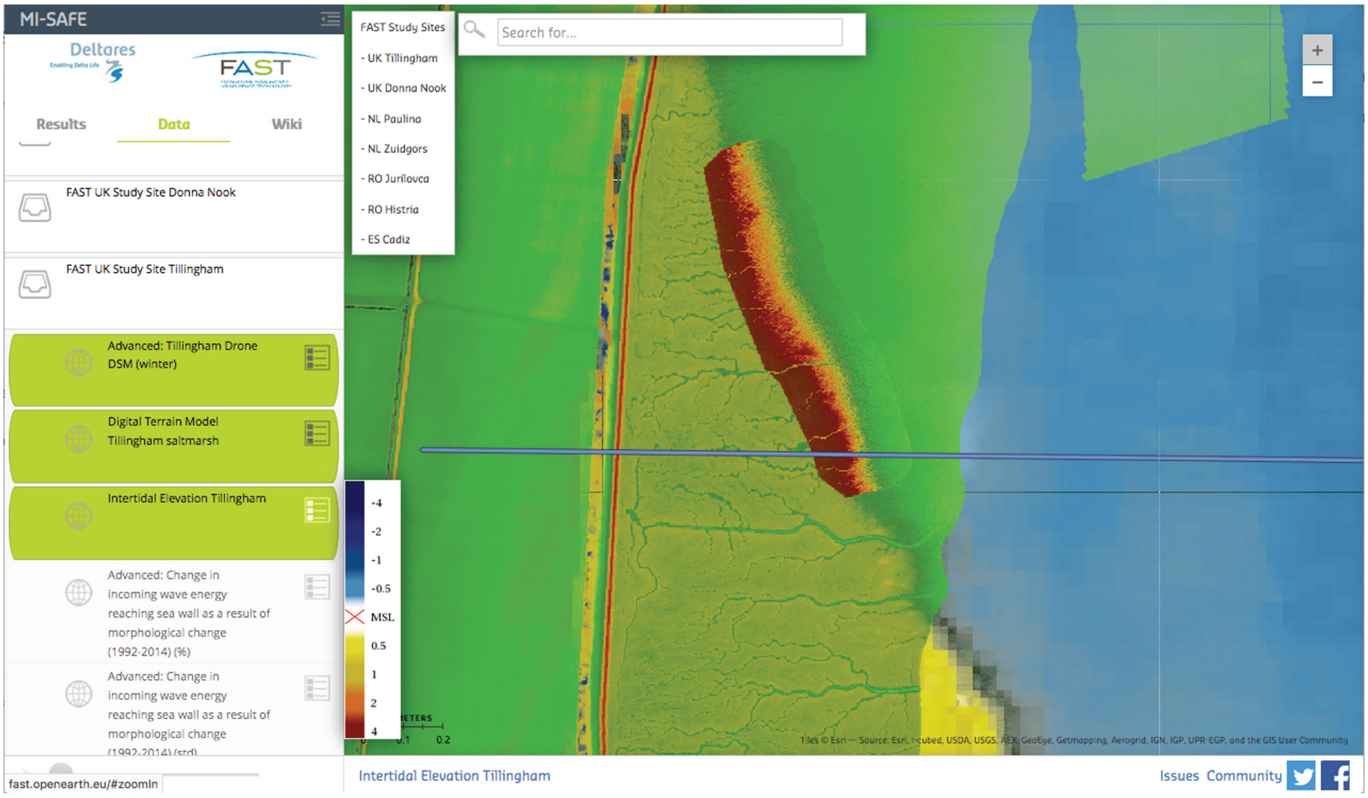


Figure 44. Various resolutions of Tillingham Intertidal Elevation (FAST global map, yellow hues), DTM (LIDAR, green hues) and Drone derived DSM (red hues) from various sensor sources are available in the MI-SAFE viewer.

5.2. Future Solutions

Since the start of the FAST project, the field of nature-based flood defences has been expanding rapidly. Similarly, the use of Earth Observation data for several downstream services has taken off through the launch of the Google Earth Engine platform that provides access to global satellite data and a rapid online calculation platform. Both developments will ensure continuation of knowledge, services and products developed under the MI-SAFE package. The MI-SAFE services will be extended into the Aqueduct flood analyser, which is an online tool currently focussed on river flooding, but that will be extended to coastal flooding, effects of vegetation on mitigation of flooding and possibly in the future also with to evaluation of possible solutions.

FAST field data and measurements will be used together with other quantitative studies for setting design criteria and evaluation metrics for nature-based flood defences. Last year design guidance focussing on risk assessment was brought out by over 25 parties of which some of the FAST team partners were leading[48]. Currently, more detailed guidelines are developed by an even wider group of stakeholders and the FAST team is well represented in this. Several other proposals with PhD's that built on and extend FAST knowledge have already been granted or are under development.

There is a strong need for more data from field settings during extreme hydrodynamic conditions to validate models but also to identify failure mechanisms of vegetated foreshores. FAST has begun to address the long-term stability of ecosystems, but a more probabilistic approach could quantify uncertainty in ecosystem persistence over longer time-scales.

5.3. Advise to future EO focus

The benefits and exploitation of the current increase in EO observing capacity are still yet to be fully realised as the infrastructure and analysis paradigms catch up with the rate at which imagery is now becoming available. The status of the observing capacity with suitable spatial resolution is now such that SAR data can be acquired every few days and most cloud free situations are imaged by an optical system of some form. Not all of these data are free and open, but commercial data providers are now offering access under terms which are becoming

[48]World Bank. 2017. Implementing nature-based flood protection: Principles and implementation guidance. Washington, DC: World Bank.

viable with respect to supporting monitoring applications. Also, applications are tending to become more data agnostic so that they can be driven by a range of data sources and these sources can be accessed online rather than requiring the physical delivery of information.

In the future, data availability will continue to improve and will no longer be a restriction on most application areas. However, end users of geospatial data require actionable information in a specific spatio-temporal context, rather than what could potentially be 100s of Terabytes. worth of imagery. A paradigm shift away from raw imagery has been occurring with the development of the analysis-ready data and intermediate product concepts to deliver information in support of broad range user needs. Pre-processed analysis-ready data is now available for automated analysis in time (radiometry), and space (geometry) with per pixel metadata that allows users to filter to their requirements at the time of analysis. Intermediate products take the processing one step further by converting the reflectance or backscatter of the images to a physical property of the surface (e.g. roughness) or an indicator (e.g. NDVI) and delivering them as near-complete coverages for a particular time window. These concepts will support the development of services such as the MI-SAFE package.

A range of platforms similar to Google Earth Engine, used in this project, are also emerging. These platforms support the production of EO-based information at local to global scales by providing virtually infinite amounts of storage and high performance processing capabilities. Many of these platforms off direct links to the image data, such as SentinelHub from Synergise or LandMonitoring.Earth from GeoVille. The European Commission is developing a Copernicus Data and Information Access Services (DIAS) that will facilitate access to Sentinel data and information from the Copernicus services. It will provide data and information access alongside processing resources, tools and other relevant data, to boost user uptake, stimulate innovation and the creation of new business models. All the above initiatives could deliver information to, or even host, services such the MI-SAFE viewer.

The Copernicus programme is now an excellent example of European cooperation and the most comprehensive EO programme of global value, contributing to tackling challenges of global nature and reconfirms the current objectives of Copernicus. It can thus be assured that services built on Copernicus data will have a long and sustainable future, as well as, opportunities to expand and evolve.

Within the Copernicus Land Monitoring Service (CLMS), there are a number of developments which have a direct link to coastal zones and the work of FAST. Most obvious is the development of a local component service specifically aimed at coastal zones which could potentially deliver regular habitat / land cover and biophysical property maps. This component is still in the early stages of development with opportunities for the FAST team to influence the structure and specification during the implementation phase. In a more general sense, the CLMS offers a range of products which could be exploited by the MI-SAFE package, such as the Riparian Zones local component and the High Resolution Layer (HRL) Water and Wetness. There are plans for additional HRLs, such as a phenology indicator which could potentially give useful results in the coastal zone for algal mats and emergence of pioneer coastal wetland habitats.

As well as the increasing availability of EO, the capabilities of the sensors will also increase. The commercial operators will address the VHR (Very High Resolution) domain, with sub 5 m spatial resolutions, but with increasing spectral information for detailed surface / habitat mapping. The EC plans to continue with the current Sentinel imaging activities at least into the 2030s and also expand the Sentinel fleet to imaging spectrometer and surface temperature measures of a quality and spatial resolution for the intertidal area.

The MI-SAFE viewer, with its role in integrating remote sensing and in situ data, is a tool that can support the development of the Observation Node for the future DANUBIUS-RI ESFRI Research Infrastructure. Newly accepted on the ESFRI (European Strategy Forum for Research Infrastructures) Roadmap in 2016, the future Pan-European distributed Research Infrastructure for Advanced Science on River-Sea Systems integrates in situ with remote observations dealing with the water, sediments and biota fluxes in a source-to-sink pathway (mountains to the seas, with a focus on transitional zones: deltas, estuaries and lagoons). The fluxes are then analysed, modelled and used for the development of sustainable management scenarios at river-sea system scale.

MI-SAFE could serve as one of the models regarding data integration - and could be analysed by the DANUBIUS Preparatory Phase consortium to check its development potential.

Besides its role in supporting a better integration of Copernicus with ESFRI RIs, another important role is the further development for use in evaluation of efficiency of nature-based solutions on vegetated coasts and deltas (see UK examples given in section 4.3.1 above). With further development, MI-SAFE also has a strong potential of use in estimating the role of vegetation in slowing down flooding during high water periods in rivers. It thus plays an important role in supporting the successful implementation of the European Floods Directive.

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Glossary

Algorithm	Procedure or formula solving a problem. For example, a computer program is an elaborate algorithm.
Biomass	The mass of living biological organisms in a given area or ecosystem at a given time.
Coastal management	The organisation, planning and executing of activities and ecosystems in the coastal zone.
Copernicus	European Programme for the establishment of a European capacity for Earth Observation.
CORINE	Coordination of information on the environment. A program initiated in the European Union in 1985 to create a database with land cover maps.
DEM	Digital elevation map.
dGPS	Differential Global Positioning Systems for accurate coordinate and height determination.
DSM	Digital surface map.
DTM	Digital terrain map.
Eco-DRR	Ecologically-informed Disaster Risk Reduction.
End-users	A person or legal entity that is ultimately using a product or service.
EO	Earth Observation. EO is the gathering of information about planet Earth's physical, chemical and biological systems via remote sensing technologies supplemented by earth surveying techniques, encompassing the collection, analysis and presentation of data.
FAST	Foreshore Assessment using Space Technology (FAST, 2014 - 2018). Project funded by the European Union's (EU) Seventh Framework Programme (FP7), grant agreement n°. 607131.
FAST team	Group of scientist and Earth Observation experts of five European Institutions: Deltares, University of Cambridge (in collaboration with Specto Natura Ltd), National Institute for Marine Geology and Geo-Ecology (GeoEcoMar), Royal Netherlands Institute for Sea Research (NIOZ) and University of Cadiz.
Flood risk assessment	Identifying the risk of flooding, often including mitigating measures to prevent floods or actions to be taken during the flood.
Foreshore	The part of the shore between the low water mark and the high wáter mark or the toe of any constructed flood protection barrier.
GPS	Global Positioning System.
LAI	Leaf area index.
(Levee) crest height	The heighest point of the flood protection structure (e.g. levee, dike or sea wall).
LIDAR	Light Detection and Ranging (LIDAR) is a remote sensing method that uses light in the form of a pulsed laser to measure ranges (variable distances) to the Earth. Generally used to produce digital elevation maps.
LISFLOOD	2-D hydrodynamic model specifically designed to simulate floodplain inundation in a computationally efficient manner over complex topography.
Map layer	GIS database containing groups of point, line, or area (polygon) features representing a particular class or type of real-world entities.

MI-SAFE GeoNetwork CSW catalogue	A GeoNetwork CSW catalogue is an open source catalog that publishes metadata using the OGC CSW (Catalog Services for the Web) protocol supporting HTTP binding to invoke the operations. The MI-SAFE GeoNetwork CSW catalogue provides the metadata of the products developed and used to develop the MI-SAFE viewer. http://fast.openearth.eu/geonetwork/
MI-SAFE package	The services and products from MI-SAFE at all levels of services (Educational, Expert and Advanced), amongst which the MI-SAFE Viewer.
MI-SAFE viewer	The website http://fast.openearth.eu/ and the documentation available in association with it.
Model	A combination of data and inferences mathematically describing and/or visualising a certain phenomenon.
Mudflat	(Also known as tidal flat) Coastal wetlands that form when mud is deposited by tides or rivers.
Multi-disciplinary project	A project based on knowledge and experience from different academic disciplines to create a new understanding of complex situations
NBS	Nature-based Solutions: Solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience. (definition used by European Commission)
NDVI	Normalised Difference Vegetation Index, which is based on surface reflectance.
OE	OpenEarth. Free and open source initiative to deal with Data, Models and Tools in earth science & engineering projects, currently mainly marine & coastal. see more information at https://publicwiki.deltares.nl/display/OET/OpenEarth.
OGC	Open Geospatial Consortium.
Open Science philosophy	Efforts to make results from scientific research more accessible to the scientific community, businesses and society in general.
OS	Open Source. Denoting software for which the original source code is made freely available and may be redistributed and modified. In a similar way, open data refers to data freely available, redistributed and modify.
Parameters	A set of physical properties whose values determine the characteristics and/or behaviour of something.
RISC-KIT	Resilience Increasing Strategies for Coastal-Tool kit.
SED sensor	Sensors for measuring surface erosion/deposition, detecting changes in the level of sediment surface (i.e. surface lowering or deposition) by exposure or blocking of light diodes. These sensors were developed in house by NIOZ.
Spatial resolution	A measure of how fine an image is, usually expressed in dots per inch (dpi).
Stakeholders	A person, group or organisation that has a stake in a certain phenomenon.
UAV	Unmanned Aerial Vehicle.
Vegetation factor	Parameter used for modelling the effects of the vegetation on wave attenuation. This parameter can be calculated using different data sources. See Figure 21 for details on data sources explored in the FAST project.
Wave attenuation/dissipation	The loss of wave energy with a resulting decrease in wave height
XBeach	Open source two-dimensional model for wave propagation, long waves and mean flow, sediment transport and morphological changes of the nearshore area, beaches, dunes and backbarrier during storms.
Zenodo	Zenodo is a research data repository created by OpenAIRE and CERN. Use FP7FAST as keyword to find products from the FAST project in Zenodo. https://zenodo.org/.

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