Bridging the gap between ecosystem modelling tools using geographic information systems

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Declaration of originality

This is to certify that the work is entirely my own and not of any other person, unless explicitly acknowledged (including citation of published and unpublished sources). The work has not previously been submitted in any form to the Manchester Metropolitan University or to any other institution for assessment for any other purpose.

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Date:

Abstract

The effects of climate change and human interactions on marine ecosystems are felt throughout the world, yet these effects are still poorly understood. Research efforts to attain understanding are hampered by the limitations of present-day ecosystem models to address the interrelated dynamics between climate, ocean chemistry, marine food webs, and human systems due to the discreet sciences that these models derived from.

This thesis seeks to simplify interdisciplinary model interoperability by separating its various technical and scientific challenges into a flexible and modular framework using open source GIS technology and common software development paradigms. A prototype of this framework is used to drive the food web dynamics of an existing and published marine ecosystem model with two spatial-temporal series of primary productivity. Results show that the predictive capabilities of the model enhanced by better reflecting observed species population trends, which is a promising step toward future implementations of the framework, such as in the ambitious end-to-end Nereus Model (Christensen, 2012).

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I wish to express my gratitude to a number of people for the realization of this thesis.

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I want to thank Joe Buszowksi for spending many hours involuntarily debugging the spatial framework while trying to integrate it in the Nereus model, and for his feedback when I was designing the spatial framework. I want to thank Carl Walters for still being able to make sense of the computations in Ecospace after all that it has been though, and I wish to thank Daniel Pauly for reviewing the case study.

My deep thanks go to my partner Marta Coll Montón, te quiero mucho, for reviewing this manuscript many times, for providing the Adriatic model, and for her insights in the biological dynamics expressed in the case study. I promise that I will not write another thesis. Not right now, at least.

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This study was conducted through the NF-UBC Nereus Program, a collaborative initiative conducted by the Nippon Foundation, the University of British Columbia, and five additional partners. The work is a product of Nereus' international and interdisciplinary effort towards global sustainable fisheries.

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List of acronyms

E2E (model)	End to End model
ESRI	Environmental Sciences Research Institute
EwE6	Ecopath with Ecosim version 6
FOSS	Free and Open Source Software
GFCM	General Fisheries Commission for the Mediterranean
GIS	Geographic Information System
GMIS	Global Marine Information System
GRASS	Geographic Resources Analysis Support System
JRC	Joint Research Centre
MEM	Marine ecosystem model
MIMES	Multiscale Integrated Model of Ecosystem Services
netCDF	Network Common Data Form
NOAA	National Oceanic and Atmospheric Administration
UBC	University of British Columbia

"An animal that is very abundant, before it gets extinct it becomes rare. So you don't lose abundant animals. You always lose rare animals. Therefore, they're not perceived as a big loss."

- Daniel Pauly (2010)

1 Introduction

The effects of climate change and human interactions on marine ecosystems are felt throughout the world, yet these effects are still poorly understood. Environmental changes and human interactions have profound and often irreversible impacts on marine and terrestrial ecosystems. Globally, realization is dawning that all environmental processes are interconnected, that terrestrial ecosystems cannot exist without healthy, productive oceans, and that past approaches to manage ecosystems have been insufficient to stop many aspects of our environment from steadily declining.

Marine ecosystem models (MEM) are mathematical tools that help analyze and forecast dynamics within marine ecosystems, and how these ecosystems respond to external stressors such as fishing and changes in environmental factors. MEM tools yield vital information for policy makers and scientists alike to address issues such as sustainable fishing, marine conservation, and long-term food security. However, the majority of present day MEM tools were originally built as expert tools by and for scientists to address questions of a specific scope, and thus have limited applicability. Based on largely proprietary data formats and coding platforms, existing MEM tools are often physically unfit to collaborate with other modelling approaches to address matters beyond the scientific discipline that models were written for. Yet, changing climate conditions require unprecedented analytical capabilities that address the interrelated dynamics between climate, ocean biochemistry, marine organisms, and socio-economic systems, crossing several traditional scientific disciplines in the process and covering geographical and temporal scales of several orders of magnitude. MEM tools need to become flexible enough to collaborate with other models in order to put their expert capabilities to use in such a large, analytical context.

Coupling the science of discrete MEM tools requires significant interdisciplinary effort. This challenge is exuberated by lack of communication protocols and common data standards between modelling approaches. Geographic Information Systems offer essential data formats and operations that provide the foundation for implementing the link between models, while industry-standard software design practices offer the necessary structures to enable models to collaborate. Drawing on all three disciplines this thesis proposes a flexible framework for bridging the gap between MEM tools using GIS.

1.1 Aim and objectives

The final aim of this thesis is to ascertain and improve the feasibility of MEM tools to interoperate via GIS data standards by examination of marine ecosystem modelling needs, available models and tools, interoperability criteria, data standards used in the scientific community, and scientific issues that arise from current limited model interoperability.

This thesis puts forth a technical framework that allows traditional ecosystem models to provide and consume geospatial data in a generic matter, using generic data formats and communication protocols, as a foundation for scientific collaboration to address questions beyond the scope of a single model. The aim is to fill a void in the discussion of model interoperability by providing set of technical conventions onto which environmental model interoperability can be constructed.

The thesis aim is achieved by:

- Reviewing relevant literature, focusing on prominent marine environmental models and marine ecosystem models (MEM) tools, model interoperability needs and strategies, and existing and foreseen environmental modelling interoperability standards;
- Examining the modelling capabilities, data needs, and GIS capabilities of the most widely used MEM tool, Ecopath with Ecosim version 6 (EwE6), for modelling climate change;
- Researching, testing, and analyzing the scientific challenges that derive from using GIS tools to connect EwE6 to spatial-temporal primary production data;
- Developing a prototype interoperability framework, and testing this framework with a spatio-temporal time series to drive the base of a food web in EwE6 using an existing, published ecosystem model;

- Developing a prototype data delivery framework for EwE6 to provide its model results in any GIS format suitable for interoperability with other models and spatial frameworks.

1.2 Ethical issues

Agreements to use the data for this thesis have been established through the University of British Columbia (Vancouver, Canada), and its cooperation with the Institute of Marine Sciences (Barcelona, Spain) and the Joint Research Center (Ispra, Italy) of the European Union.

Agreements to use the Ecopath models for this thesis have been established through the University of British Columbia, the Ecopath Research and Development Consortium, and the principle investigator behind the EwE6 model approach, Dr. Villy Christensen.

"I believe, then, that the cod fishery, the herring fishery, the pilchard fishery, the mackerel fishery, and probably all the great sea fisheries, are inexhaustible; that is to say, that nothing we do seriously affects the number of the fish. And any attempt to regulate these fisheries seems consequently, from the nature of the case, to be useless."

- Thomas Huxley (1883)

2 Review of relevant literature

2.1 The need for marine ecosystem modelling

The understanding of the marine environment has increased dramatically in the past few decades (Fulton, 2010), and Marine Ecosystem Models (MEM) have become indispensable tools for ecosystem-based management purposes (e.g., Leslie and McLeod, 2007; Espinosa-Romero et al., 2011). However, understanding of the cumulative impacts of a rapidly changing climate (e.g., Diaz and Markgraf, 2000; Orr et al., 2005; Hansen et al., 2006; Stock et al., 2011) and anthropogenic interactions (e.g., Hilborn and Walters, 1992; Pauly et al., 1998), and what these individual impacts mean for an ecosystem as a whole, is still in a budding stage (Ainsworth et al., 2011; Coll et al., 2012).

A growing body of research suggests that changes in the atmosphere have far reaching consequences for the oceans, such as unequal shifts of marine species distribution ranges (Stock et al., 2011) in response to changing ocean temperatures (Hansen et al., 2006), increasing anoxic water conditions due to the formation and die-off of plankton blooms (Stock et al., 2011), decreased ability of corals, crustaceans, and molluscs to build shells and exoskeletons due to ocean acidification (Orr et al., 2005;

Fabry et al., 2008), and the projected increase in frequency of major climatological events such as 'El Niño' (Diaz and Markgraf, 2000; Emanuel, 2005; Edgar et al., 2010) that have the capability to disrupt global weather patterns (Jacobs et al., 1994; Diaz and Markgraf, 2000; Webster et al., 2005), impacting the functioning of ecosystems and human ecosystems for several years.

2.1.1 End-to-end modelling

In a response to understand these far-reaching but interrelated effects a new type of ecosystem model, the end-to-end (E2E) model, has emerged. E2E models differ from traditional models by extending their scope to include the components of, and dynamics between, climate change, biochemical oceanographic processes, marine food webs models, and the human systems that interact with the marine environment (Fulton, 2010; Rose et al., 2010).

The idea of E2E modeling is receiving significant scientific interest in peer-reviewed literature (e.g., Travers et al., 2007; Erturk et al., 2008; Libralato and Solidoro, 2009; Rose et al., 2010; Steele and Ruzicka, 2011), but only two ecosystem models, Atlantis and InVitro approaches (Fulton et al., 2004; Gray et al., 2006; Fulton, 2010), truly consider the interrelated end-to-end dynamics. Other modelling approaches show significant promise by encapsulating new dynamics as they evolve such as OSMOSE (Shin and Cury, 2001; Shin et al., 2010), MIMES (Boumans and Costanza, 2007), NEMURO.FISH (Kishi et al., 2007) and EwE6 (Christensen and Walters, 2004; Christensen and Lai, 2007).

Recent inventories by Plaganí (2007), Travers et al. (2007) and Fulton (2010) describe the challenges that are faced by E2E models. For example, they need to:

- Include processes that are traditionally contained within discrete scientific disciplines, and implement bi-directional transfer of appropriate information between different sciences to reflect feedback effects between ecosystem components;

- Join processes that typically operate on spatial and temporal scales that may differ by several orders of magnitude;
- Include a potentially open-ended number of species, chemicals, socio-economic aspects, each described in a proprietary manner using different and potentially incompatible units;
- Assess the impacts and cascading effects of anthropogenic perturbations in every aspect of marine ecosystems;
- Assess and communicate the impacts of uncertainty.

Prevalent marine ecosystem modelling approaches such as Atlantis, NEMURO.FISH and Osmose address these challenges by integrating more dedicated functionality of ever increasing scope within their proprietary frameworks and code environment. Therefore, the resulting E2E models are inflexible complexes that require extensive funding and expertise to parameterize and operate. Moreover, the fixed connections within the E2E imply a fixed scientific pathway through the modelling complex, which does not allow for testing of different hypothesis within the E2E by switching model components.

More modular modelling frameworks, such as the Multiscale Integrated Model of Ecosystem Services (MIMES), offer an extensible set of modules that collaborate on a common set of data definitions and conventions focused on ecosystem value (Boumans and Costanza, 2007; Nelson and Daily, 2010). Although providing a wide range of advanced capabilities to represent the socio-economic aspects of end-to-end models, the value-focused view of this model offers limited consideration of marine ecosystems beyond exploited marine species, and is in particular unsuitable to represent ecology and the effects of climate change (Waage et al., 2008; Nelson and Daily, 2010).

Lastly, version 6 of the Ecopath with Ecosim food web model (EwE6) takes a different approach, and was designed with model interoperability in mind. EwE6 is an open source product, which enables development of linkages to other models with reasonable ease. With model interoperability in mind a plug-in system was built into the very design of the EwE6 software, which enables users to extend the capabilities of the software without having to alter the source code of the approach (Christensen and Lai, 2007). The EwE6 software will be further discussed in section 3.1 and more detail can be found in Annex A.

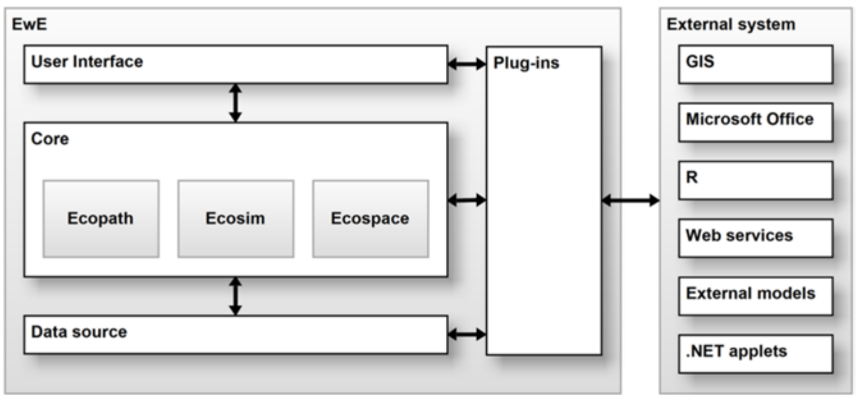

Figure 1 – Structure of the EwE6 software with plug-ins.

2.1.2 Caveats to end-to-end modelling

There is no single ideal model to address any aspect of reality because every model is based on embedded hypothesis and assumptions (e.g., Christensen and Walters, 2005; Fennel, 2008; Shin et al., 2010). Models are built for purposes and thus have unique predictive capabilities, strengths and weaknesses. Therefore, to validate predictions and quantify uncertainty, it is generally agreed that important scientific questions should be scrutinized with as many model as possible (e.g., Fulton, 2010). This paradigm has not yet been applied to E2E models, which are exceptionally sensitive to uncertainty propagation due to their complexity, many data conversions, and long computational paths (Travers et al., 2007; Rose, 2012).

Integrating MEM tools toward an end-to-end model requires unprecedented scientific and technological effort (Fulton et al., 2009; Gallagher et al., 2010; Rose et al., 2010), but other than Fulton's InVitro (Gray et al., 2006), no practical implementations of technological frameworks for model interoperability have surfaced in the literature. Theoretical paradigms abound detailing diverse approaches to connect lower and higher trophic models (e.g., Argent, 2004; Rose, 2012), but without exception these theories are posed without practical guidelines toward implementation, and without any consideration toward standardization of model interoperability or model collaboration to facilitate flexibility in end-to-end model construction.

2.2 A brief overview of GIS

2.2.1 GIS and modelling

Geographic Information Systems have been an indispensable component of environmental modelling (e.g., Goodchild et al., 1993; Wesseling et al., 1996; Jolma et al., 2008). Present-day marine environmental models are interdisciplinary efforts that depend on the spatial context provided by GIS to be successful: specialist models derive ecological, environmental, and socio-economic indicators - simple measures that represent key components of the modelled system with a meaning beyond the attributes that are directly measured – which only by means of GIS functionality are placed within a specific geographic context. Mapping the environmental variability of indicators across a geographic area enables an integrated assessment of individual, location-bound indicators within a broader geographic context (Wesseling et al., 1996).

GIS was conceived for terrestrial applications, which are characterized by largely discrete boundaries, are highly suitable for representation in a GIS, and can be geo-processed with relative simple two-dimensional GIS operations such as overlaying, buffering, reclassification and Boolean operators with high accuracy (Wesseling et al., 1996; Valavanis, 2002; Levin et al., 2009). When GIS migrated to the marine realm in the late 1980s and early 1990s the technology was faced with an entirely new set of challenges. The underwater environment is highly heterogeneous, dynamic, inter-mixed, and three-dimensional with unclear boundaries. Dynamic marine processes such as upwelling, gyres, and advection require consideration of the vertical dimension and time, at scales that differ in several orders of magnitude (e.g., Valavanis, 2002; Levin et al., 2009). Representing and analysing marine entities such as species, nutrients, oxygen, and pollutants, which disperse and interact in ways that cannot be explained using mere geographic location and proximity, requires additional knowledge of several marine disciplines such as biological and physical oceanography, marine biology, and remote sensing.

Marine environmental modelling is an interdisciplinary effort that often relies on integrated assessments of specialist model tools. Some aspects of marine modelling may be addressed using native GIS capabilities, such as habitat classification, watershed modelling, interpretation and classification of remote sensing imagery, or species distribution mapping. However, addressing the dynamics in a marine ecosystem often demands integration of GIS and dedicated models to analyze environmental, biochemical, and biological interactions in a spatial context including mechanistic approaches using modelling capabilities.

2.2.2 Challenges to integrating GIS and ecosystem modelling

The integration of the different ecosystem components into spatial analysis poses a series of challenges that are reviewed below:

Scales

In marine ecology, it is a well-established fact that individual components of an ecosystem are best modelled at relevant scales (Levin, 1992; Shin and Cury, 2001; Solimini et al., 2009). However, the adequate spatial and temporal scale to model marine phenomena of interest is a daunting task to which no standard solutions apply (Rose et al., 2010):

- Coarser scales will decrease local variability in data patterns, hence possibly eradicating crucial interactions that may drive an ecosystem;
- Too fine scales on the other hand may cause phenomena or processes to become over-represented, introducing computational instabilities and oscillations that approximate interactions at unrealistic time scales and spatial resolutions (Walters et al., 1999).

Each category of environmental models scrutinizes only directly interacting components at resolutions of space, time and modelled entities relevant to that model (Levin, 1992). Meaningful translation of data between two models is a task to which GIS environments provide only limited facilities.

Metadata standards

Lack of semantic data standards poses the greatest challenge to enable the various components of spatial data infrastructures. This problem is exacerbated when attempting to unify ecosystem models in GIS environments since the field of ecosystem modelling suffers from a similar lack of commonly adopted standards (Rose, 2012).

The need for semantic data standards for ecology has been long acknowledged for ecological interoperability in spatial and non-spatial systems (e.g., Michener et al., 1997), and several efforts aim to address this. Freely accessible taxonomic repositories such as FishBase (Froese and Pauly, 2010), the Ocean Biogeographic Information System (Grassle, 2000) and the World Register of Marine Species (WoRMS; Appeltans et al., 2011) are ongoing efforts to bring a measure of order in the surprisingly turbulent field of species classifications. Other approaches aim to centralize storage and distribution of ecological data in repositories such as Dryad (Scherle et al., 2008), an effort that requires metadata standards with ecological and GIS components (Greenberg et al., 2009). Separately, the text-based Ecological Metadata Language (EML) shows promise as a flexible structure for describing ecological data, its purpose and applicability in spatial and non-spatial contexts (e.g., Michener, 2006; Gil et al., 2008; Whitlock, 2011).

However, adaption of standards by higher-trophic ecosystem models is in its infancy. There are no binding rules and best practices how to construct higher-trophic models, which species to include, which species to aggregate, and at what spatial and temporal scales to assess species dynamics (e.g., Rose et al., 2010). Ecosystem models are inherently constructed with different motivations to address unique questions, requiring different levels of detail and different collections of variables (Fegraus et al., 2005).

Uncertainty

Uncertainty is a key threat to the liability of numerical models. Jager and King (2004) summarize the classical sources of uncertainty in ecological models as (i) uncertainty in measurements; (ii) cartographic uncertainty; (iii) uncertainty error propagation and amplification through model computations; and (iv) uncertainty between alternate input data sets. Francis et al. (2011) add a new source of uncertainty as the limited experience with predicting the behaviours of external, anthropogenic drivers: human systems are immensely complex, and future trends in urbanization, land use and economic developments will inevitably affect ecosystems in yet poorly understood ways.

Uncertainty and error propagation in GIS have received considerable attention since the early days of GIS, where the complexity of geospatial operations amplify error due to data accuracy, quality, and error (e.g., Heuvelink, 1998; Crosetto and Tarantola, 2001). Ecological models are subject to various types of uncertainty and error propagation (e.g., Hilborn and Walters, 1992; Heuvelink, 1998; Crosetto et al., 2000; Jager and King, 2004; Rose et al., 2010). The effect of error are exacerbated when environmental models and GIS are used in conjunction (Crosetto and Tarantola, 2001; Couclelis, 2003; Kacprzyk, 2010).

In inter-model scenarios, feedback effects amplify error further, and thus subtle parameter variations due to uncertainty may lead to significant changes in long-term predictions (Kearney et al., 2012). In a complex modelling approach, error needs to be measurable. It is necessary to assess how uncertainty in input data, model parameters, etc. propagates through individual model components, but also through the individual linkages between the models in an integrated assembly. Furthermore, measures of fit of intermediate model results to observed data may provide further diagnostics on model uncertainty.

2.3 Summary

The effects of climate change have underpinned the already known fact that all ecosystems are related, and that ecosystem modelling tools to date are insufficient to perform an integrated assessment of dynamics in the entire ecosystem at long term, large spatial scales. In order to assess global impacts of climate change and to make predictions about the future of our oceans, integrated analysis will have to be performed at global scales. For managing global issues involving climate and sustainable utilization of the marine environment we will first require global understanding of these issues, for which the modelling capacity is slowly emerging.

A major challenge for ecosystem modellers that is still waiting is to build modelling capacity on an integrated, global scale. Currently a wide array of modelling approaches exist that support in-depth exploration of specific aspects of the environment, but models are rarely linked, operate on different scales in time and space and under not necessarily related assumptions. These models were not engineered to interoperate, lacking features to exchange data with other models in a standardized manner. Integrated modelling frameworks on the other hand are built to address overarching questions, but are in turn criticized for not being able to cover phenomena at proper level of detail.

GIS technology forms an essential part of environmental modelling, but GIS capabilities are underutilized due to a lack of semantic data standards within the realm of GIS itself, and lack of ecological data standards in marine ecology. The lack of generic abilities to communicate hampers efforts to leverage the full capabilities of GIS and ecological models for inter-model assessments, and yields hybrid approaches that are characterized by either a partial implementation of GIS functionality into ecosystem models, or by a partial implementation of ecological assessments within a GIS (e.g., Valavanis, 2002; Manso and Wachowicz, 2009). As a result, such end-to-end models are developed as narrow paths, based on inflexible chains of interwoven models, lacking transparency to validate embedded hypothesis.

To advance on our understanding of ecosystem dynamics and our capability to forecast, science and technology cannot be viewed separately and should be scrutinized in equal measure as we push forward, while we take in the important lessons from past research. This applies well to the context of E2E modelling. There is large potential that the 1990s struggles of merging MEM tools into more capable marine modelling approaches will be repeated all over again when constructing state-of-the-art E2E models. End-to-end models are staggering efforts that aim to address atmospheric, physical, biological, and socio-economic factors across wide spatial and temporal scales, crossing many traditional scientific, technical, and political boundaries. Such endeavours cannot be accomplished by scientific experts alone, but should draw benefit in equal measure from lessons learned in technical and social sciences.

It would, for instance, be very exciting if we could reuse the existing, published higher trophic level models in Figure 2 for addressing larger ecosystem questions by simply re-engineering those tools to better collaborate for this larger scope without having to rebuild new models. This thesis hopes to set first steps toward this standardization.

This thesis puts forth a technical framework that allows traditional ecosystem models to provide and consume Geospatial data in a generic matter, using generic data formats and communication protocols. This provides a foundation for scientific collaboration to address questions beyond the scope of a single model. The thesis may advance in filling a void in this discussion by providing the theorists and scientists with a set of technical conventions onto which MEM model interoperability can be constructed.

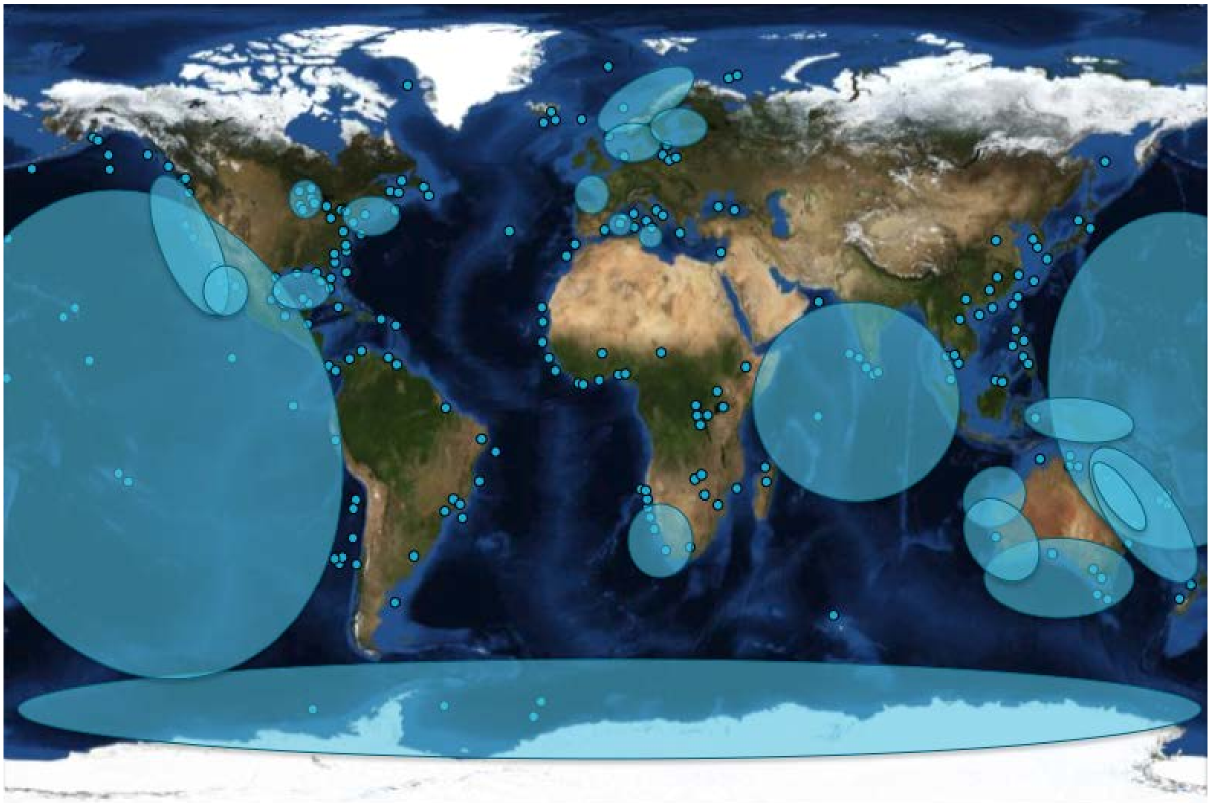

Figure 2 - An overview of published Atlantis, EwE, and OSMOSE models (Adapted from Fulton, 2010).

"Make things as simple as possible, but not simpler"

- Albert Einstein

3 Material and methods

3.1 Ecological model

For this thesis the ecological modelling approach Ecopath with Ecosim version 6 or EwE6 has been selected to serve as a test case for spatial-temporal model interoperability. EwE is the most widely used model for assessing aquatic food web dynamics and the impact of human exploitation (Figure 2), with an estimated 6000 users in more than 150 countries, and with more than 600 academic publications to date (ProQuest, 2012). EwE is increasingly used in ecosystem based management assessments (e.g., Christensen and Walters, 2005, 2011; Cisneros-Montemayor et al., 2012), despite criticism for its perceived simplicity (Plaganyí, 2007).

The software is developed using the Microsoft .NET platform (Christensen and Lai, 2007), which offers a range of technical benefits such as compatibility with a suite of programming languages and the theoretical ability to run on any operation system (ECMA International, 2012).

The EwE6 approach is deemed as prime candidate for model interoperability. The software has seen a wide range of applications and is increasingly used in ecosystem based management assessments (e.g., Christensen and Walters, 2005, 2011; Cisneros-Montemayor et al., 2012). The need for integrated ecosystem assessments have led to recent additions to the approach, such as for example a management strategy evaluation module, an integrated species distribution envelope model, and facilities to integrate with digital taxonomic libraries. Migration to the .NET environment facilitated the additions of a plug-in system that allows users to complement the EwE6 approach with new functionality without making physical changes to the EwE source code. As part of this thesis, the software is being extended via plug-ins to interoperate with external spatial-temporal models.

Annex A provides a cursory overview of EwE version 6.2.0 (released 20 June 2011) to illustrate its potential in a model interoperability environment. The core model of the EwE approach is the Ecopath model (Christensen and Pauly, 1993; Pauly et al., 2000; Christensen and Walters, 2004), a static model of marine ecosystems. NOAA, the National Oceanic and Atmospheric Administration, celebrated the approach as one of the ten biggest scientific breakthroughs in its 200 year existence (NOAA, 2007). Most relevant to this thesis, though, is that the static mass-balance snapshot model Ecopath became the precursor to the time-dynamic model Ecosim (Walters et al., 1997; Walters, 2000) and the time-space dynamic model Ecospace (Walters et al., 1999, 2010).

In 1995 the Ecosim module was added to the desktop software for exploring past and future impacts of fishing and environmental disturbances over time. Ecosim re-expresses the linear Ecopath equations as a set of differential equations and solves these for regular time intervals for any given time period, under the assumption that biomasses and the ability of any group to produce and consume are variable.

The third core module of EwE is the spatial/temporal model Ecospace, a spatially explicit multi-species ecosystem model (Walters et al., 1999, 2010; Christensen et al., 2003; Christensen and Maclean, 2011). Ecospace has been widely applied to quantify the spatial impacts on marine species due to fishing, and to analyse the outcomes of management options such as the establishment of marine protected areas and its impact in terms of spatial distribution of marine species and fishing effort (e.g., Walters, 2000; Martell et al., 2005; Walters et al., 2010; Fouzai et al., 2012). It can also be used to develop spatial optimization routines (Christensen et al., 2009) and assess the impact of climate change by linking the

Ecospace model with low trophic level models (Fulton, 2011).

The Ecospace model was built to model biomass interactions within an ecosystem across a two-dimensional grid over time. Ecospace distributes Ecopath biomass values of functional groups across a grid of equally sized cells, and uses the Ecosim equations to model how biomasses vary within each cell in the grid over time by taking trophic interactions, fishing and species movement into account. Spatial variations in driver variables such as the primary productivity map have significant impacts on the Ecospace dynamics (Martell et al., 2002).

However, up to version 6.2.0 of the EwE software, a continued and major shortcoming of the Ecospace routines has been its lack of facilities to read and produce true geo-spatial data into driver layers. Map data to Ecospace needs to be sketched onto the map user interface (Figure 3) by hand using a mouse, or can at most be read carefully crafted comma-separated text files without explicit spatial reference. Facilities that tried to mitigate this lack of functionality, existent in the precursor to EwE6, were not

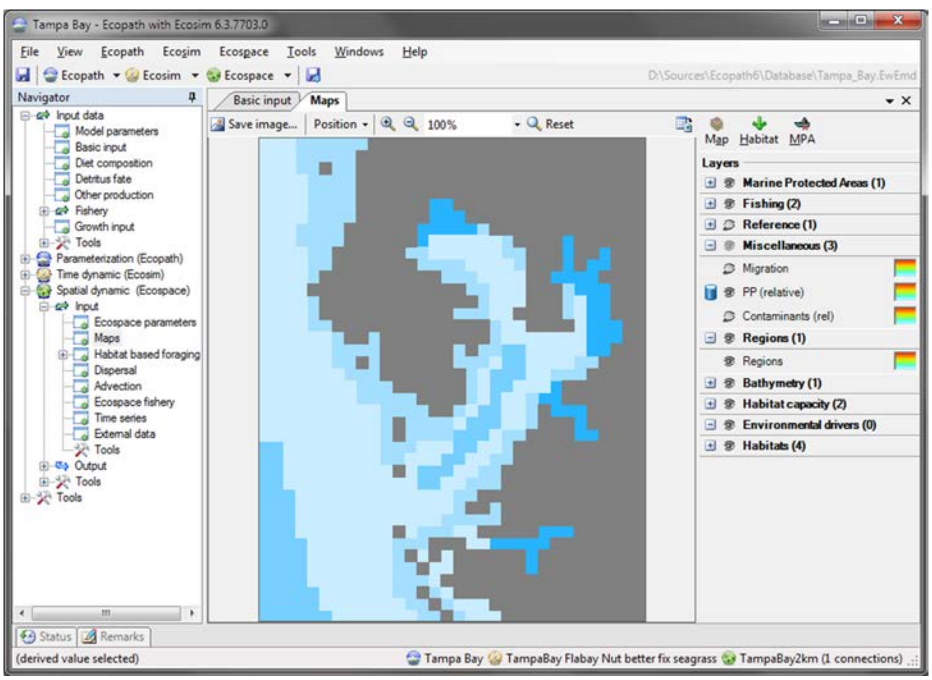

Figure 3 – The main Ecospace user interface in the EwE6 desktop software.6.3.

implemented in the EwE version 6 because of limited applicability (Christensen and Lai, 2007).

This thesis addresses the inability of Ecospace to handle GIS data and interact with other spatially enabled ecosystem models by defining a spatial temporal data framework that encapsulates the Ecospace model (Figure 4) to interact with a wide range of spatial data sources.

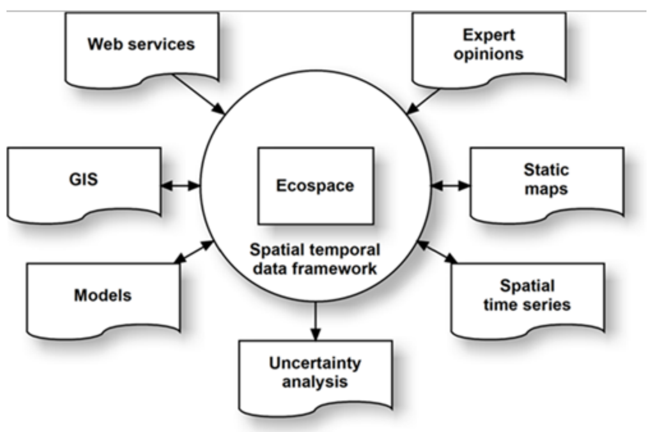

Figure 4 - A spatial temporal data framework that encapsulates the Ecospace model, and provides access to a wide range of spatially enabled data sources.

3.2 Framework

The Ecopath and Ecosim models have been successfully linked to other models, but the spatial model Ecospace has seen little use in this regard due to lack of facilities to exchange data. Since its initial development in 1999 the ability for Ecospace to exchange spatial-temporal data has been desired. Continued popularity of the EwE approach, increasing demand for the ability to use the Ecospace model in conjunction with spatial analytical tools, specialist models, and planning tools such as Marxan (e.g., Loos, 2011), and facilities offered by the mature .NET programming environment, gave rise to the idea of a flexible spatial-temporal data framework to solve the data connectivity shortcomings of Ecospace.

In this chapter such a framework is conceptualized, designed and implemented. First, a theoretical framework is designed. Requirements for the framework are identified, and a theoretical design for the framework is discussed. This theoretical framework is then converted to a functional design. Then, candidate GIS programming toolkits are evaluated and a GIS programming toolkit is selected to implement a prototype of the framework. Lastly, this prototype is presented.

The terms spatial temporal data framework, spatial framework, or framework may be used interchangeably for the same principle.

3.2.1 Methodological design

Requirements

From an Ecospace operational perspective, the framework needs to fulfill the following technical requirements:

1. Provide access to static spatial files of relevant data to generate an Ecospace basemap;

2. Deliver spatial time series of relevant data into Ecospace during execution time to drive the model;

3. Enable Ecospace to deliver its results as spatial time series for consumption by tools and models outside of the Ecospace model;

4. Enable read and write access to geospatial data formats and data delivery media common to the environmental sciences;

5. Enable Ecospace data interoperability for any spatial extent and Ecospace raster cell size.

To serve in an end-to-end model interoperability environment the framework needs to facilitate Ecospace to:

6. Support bi-directional exchange of spatial-temporal data with an open-ended range of collaborating models in an end-to-end approach;

7. Support scientifically sound translation of data between external models and Ecospace;

8. Support flexible access to sub-models in the Ecospace model to test different hypothesis;

9. Support the use and exchange of ecological metadata;

10. Store intermediate results to allow assessments of error;

11. Enable outside control to when Ecospace executes a time step.

To serve in a GIS interoperability environment a framework needs to enable Ecospace to:

12. Support for the use and exchange of spatial metadata;

13. Support a suite of geospatial operations needed to interpolate geospatial data into Ecospace;

14. Support a detailed overview of performed data conversions;

15. Provide access to all intermediate data produced to facilitate uncertainty analysis.

Functionally, the framework will be operated by users that may have limited GIS experience. From a usability point of view, the following additional requirements were identified:

16. Minimize the need for users to interact with the framework without violating framework capabilities and functionality;

17. Minimize complexity in user interfaces;

Lastly, the framework should not pose any limitations to future unforeseen uses, thus it should:

18. Permit inclusion of access to new file formats, new data delivery media, and new spatial operations in the future.

Conceptual design

The conceptual integration of the spatial framework into EwE6 is summarized in Figure 5. Spatial data is either used to define an Ecospace base map at model initialization, or is used to drive Ecospace maps during every time step. Ecospace results are presented as GIS data through the spatial framework. The requirements listed in the previous section can be conceptually grouped into layers of functionality within the spatial temporal data framework, as displayed in Figures 6 and 7.

Figure 6 reflects the flows of data through interacting layers of functionality when external data is brought into the Ecospace model. Data, derived from external GIS or models, is scientifically adjusted to fit the parameterization of the Ecospace model (layer 1). The resulting data, or data directly derived from readily available GIS data sources, is converted to the spatial dimensions of an Ecospace basemap (layer 2). This data is then inserted in the running instance of the Ecospace model (layer 3). All layers produce intermediate results, which then, in conjunction with produced Ecospace results, can be used in statistically analysis for uncertainty.

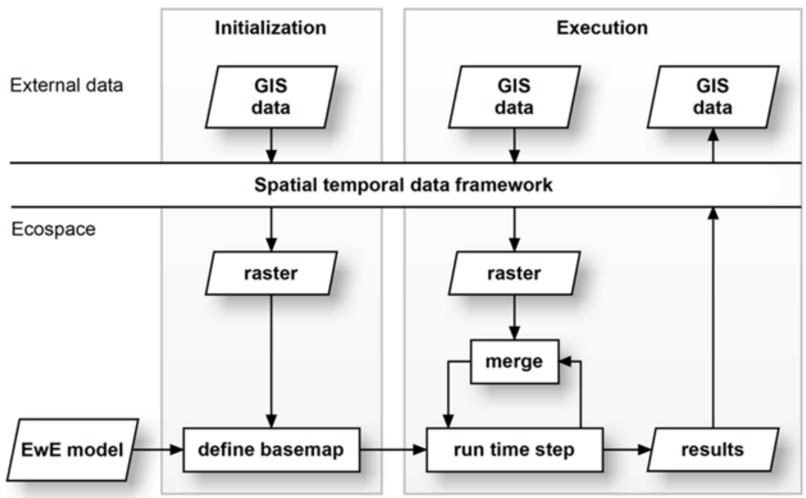

Figure 5 - Conceptual overview of the framework, which provides external GIS data to Ecospace model initialization and at runtime, and provides Ecospace results in spatial data formats when the model execute.

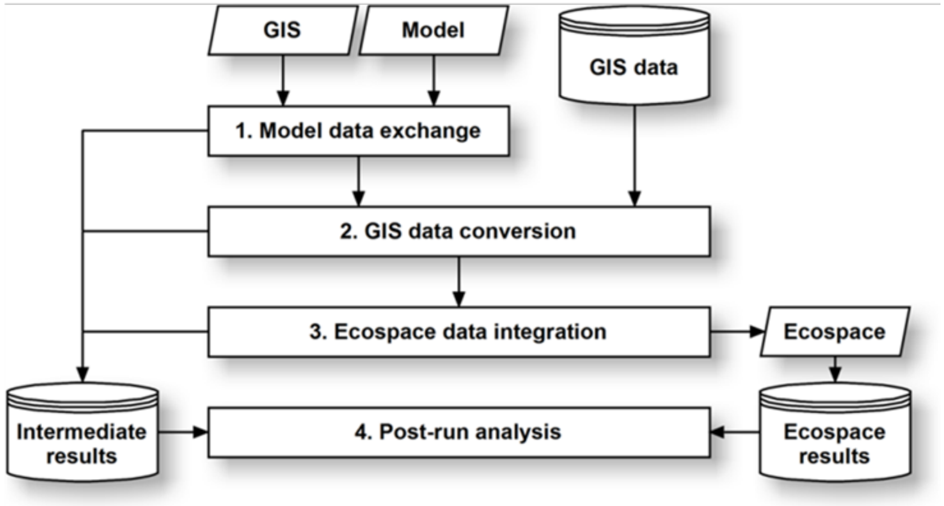

Figure 6 - Conceptual layers of functionality within the framework when integrating external data into Ecospace: (1) inter-model data exchange to match Ecospace parameterizations, (2) GIS data conversion to match Ecospace resolution, (3) Ecospace data integration, and (4) post-run analysis.

Figure 7 is somewhat simpler, and reflects the flows of data through the same interacting layers when Ecospace has computed results. For consistency layer numbering is kept identical to Figure 6. In (Figure 7), Ecospace result maps are converted to georeferenced GIS data (layer 2), which may be stored in a GIS repository or may be scientifically adjusted to feed into external models (layer 1). Intermediate results and Ecospace results serve to perform statistical analysis after the model has run (layer 4).

The conceptual organization of functionality into layers of similar functionality is a first organizational step toward building a comprehensive, modular and extensible model interoperability framework. The layered design facilitates interaction with Ecospace at different levels of complexity, depending of data exchange needs:

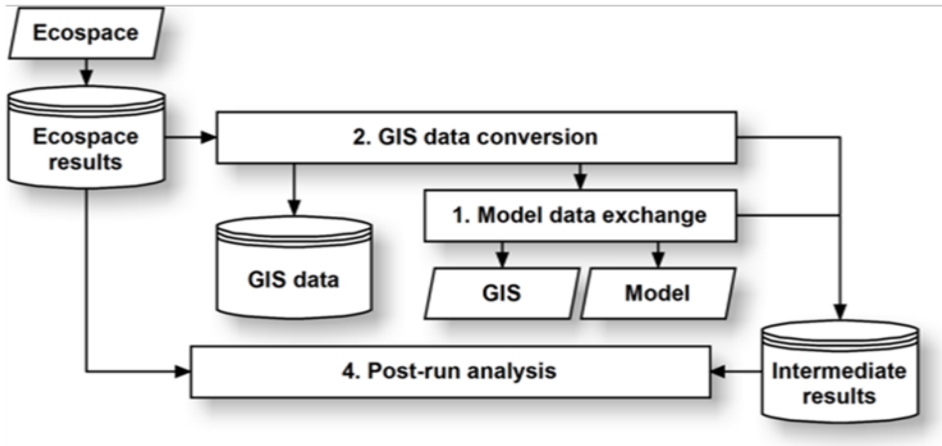

Figure 7 - Conceptual layers of functionality when the framework dispenses Ecospace data: 2. conversion of Ecospace results to spatial formats, and (1) inter-model data exchange, and (4) post-run analysis.

- Data that is readily available for integration into Ecospace, such as produced by plug-ins that perform secondary analysis on Ecospace data, can be directly integrated into the running Ecospace model via layer 3 in Figure 6. GIS processing and model exchange steps can be bypassed;

- Spatial data that reside outside the EwE6 application but that are scientifically compatible with spatial driver variables in Ecospace require conversion from external spatial formats to grids that are compatible with Ecospace. These data enter the framework in layer 2 (see Figure 6), are loaded and processed by the conversion layer, and then passed on to the integration layer (layer 3 in Figure 6) for further processing;

- Spatial data that cannot be accepted or accessed by Ecospace in their current form will require scientific translation in layer 1 (see Figure 6), before undergoing conversion to an Ecospace format in layer 2 and integration in layer 3. Such data may be delivered by external models in a model interoperability environment, or may reside in a GIS that is able to communicate with the spatial framework.

Modular organization

Within each layer, facilities must to be available to fulfill the framework requirements earlier identified in this section. Most of these requirements are deliberately open-ended to offer the ability to cater to future, unpredictable needs of the framework. Hence, capabilities of the spatial framework should be allowed to grow when needed. This calls for a modular design of the framework.

Modularity, in software technical terms, is a technique that breaks down functionality in separate, interchangeable components called modules. A modular program consists of chains of modules that work together to implement the purpose of a program. Modules can be grouped in similar functionality, where each module of the same type implements similar functionality in a different way, and modules of the same type can be freely exchanged to switch functionality without disrupting the flow of a

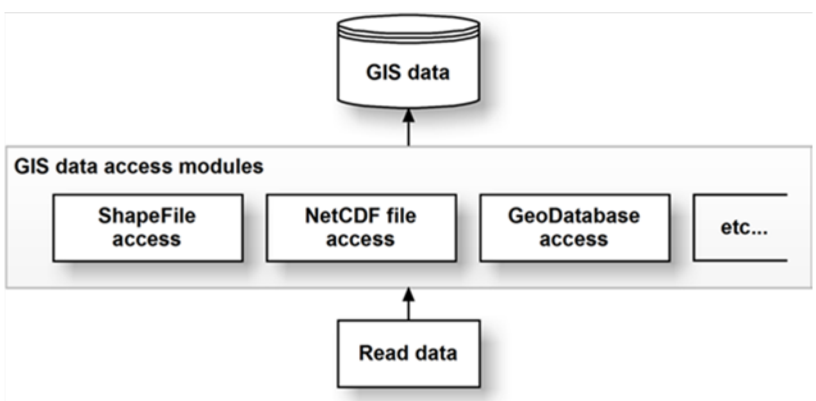

Figure 8 – A modular approach to reading GIS data. Different GIS data access modules offer the framework access to unique GIS data formats and storage media, and modules can be added without disrupting existing modules.

program. Additionally, modules can be added to a program without compromising the workings of the system (e.g., Cook, 1991; Gamma et al., 1994).

A modular approach to the framework would yield benefits of flexibility and extendibility. Figure 8 provides an example of multiple and exchangeable data access modules.

The principle of modularity, even though a common software design principle since the introduction of object oriented programming in the early 1970s (Gamma et al., 1994), is not being applied in the field of E2E modelling. GIS systems have been leveraging the power of modular design at least since the first release of GRASS (the Geographic Resources Analysis Support System) in 1982. Yet, designers of most marine ecosystem models have not adopted modularity as a strategy to simplify ecosystem model interoperability.

The spatial framework posed here is based on the assumption that model interoperability becomes feasible if the tasks in a model interoperability scenario are intuitive separated and grouped by functionality, and are then executed via chains of relatively small, configurable and dedicated modules. The layered structure of the framework conceptually separates the different tasks that need performing into logical steps, while modules provide targeted, specialist solutions to address these logical steps.

Design for open-ended use

The framework designed here may see many different uses, and most challenging will be to apply the framework in an end-to-end ecosystem model environment. The model interoperability layer is designed to implement one-on-one translation modules reminiscent of ‘brokers’ in the InVitro approach (Gray et al., 2006). InVitro is an agent-based model interoperability system that manages the collaborative executing of a cluster of ecosystem models. Here, a central time step controller synchronizes the timed execution of the individual models, and orchestrates the exchange of data by

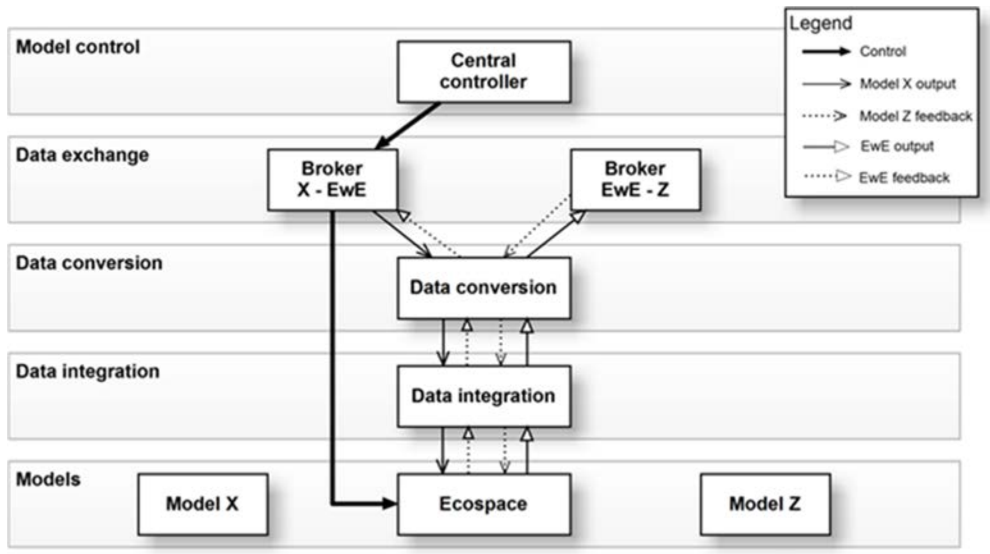

Figure 9 - Conceptual overview of EwE in a model interoperability framework, featuring a central time step controller, and brokers between dedicated models that propagate results and feedback effects.

connecting two models via dedicated data translation sub-models referred to as brokers. A conceptual layout of integration of EwE in such an environment is given in Figure 9.

If Figure 9 is considered for the purpose of metadata processing and delivery, it becomes instantly clear that brokers will perform this task. At the broker level, external GIS data is interpreted and translated between sciences. Due to their knowledge of both scientific models, brokers are key candidates to interpret geospatial and ecological metadata to drive their conversion process. Upon conversion, brokers will describe data alterations in new metadata to accompany the data that they just converted.

If Figure 9 is considered for uncertainty analysis, it becomes clear that every step in the framework may attribute to uncertainty, and that intermediate results between the different layers in the framework should be accessible for performing spatial analysis. Note that uncertainty analysis is not incorporated in this figure; the types of analyses and when analysis is wanted depends on the type of the data and its contextual use. What is clear is that the spatial data framework must guarantee that statistical meta-analysis can be performed to assess any stage of the model interoperability chain.

3.2.2 Functional design

The functional design of the spatial framework formalizes the conceptual framework outlined in the previous section.

The division of functionality into the layers 'data access', 'data conversion', and 'data integration', as identified in section 3.2.1 (see Figures 6 and 7), are translated into modular code components of similar name (see Figure 10).

The fourth layer of functionality, 'post-run analysis' (see section 3.2.1 Figure 6), is split in two parts.

- The first part comprises generation and storage of intermediate results produced by the data access, data conversion, and data integration components of the framework;
- The second part, the actual analysis, must be executed outside the flow of the framework to facilitate analysis whenever needed. This analysis should be done using independent spatial statistical analytical tools that do not rely on the technology within the framework to avoid bias.

Figure 10 reflects the pathway of how incoming data is processed through the framework:

- First, external spatial temporal data is located and loaded into the framework for a particular time step or at model initialization. The components in the data access layer that perform this task are a category of modules called datasets, represented by the code component *ISpatialDataSet* in Figure 10. Datasets are interchangeable modules that provide read and write access to spatial data, and each dataset implements access to a specific data storage format, such as files, a specific type of geo-database, a spatially enabled web service, a specific external model, or an interoperability broker (see Figure 9).

To facilitate post-run analysis, the Datasets will enter performed activity and decisions in the spatial operations log, represented by the code component *ISpatialOperationsLog* in Figure 10;

- Loaded spatial data is passed on to the data conversion layer to a family of modules called converters, represented by the code component *ISpatialDataConverter* in Figure 10. Converters perform all GIS operations required to transform incoming spatial data into a raster compatible with a particular driver map layer in the Ecospace model. This raster is represented by the code component *ISpatialRaster* in Figure 10. Converters are interchangeable modules that are

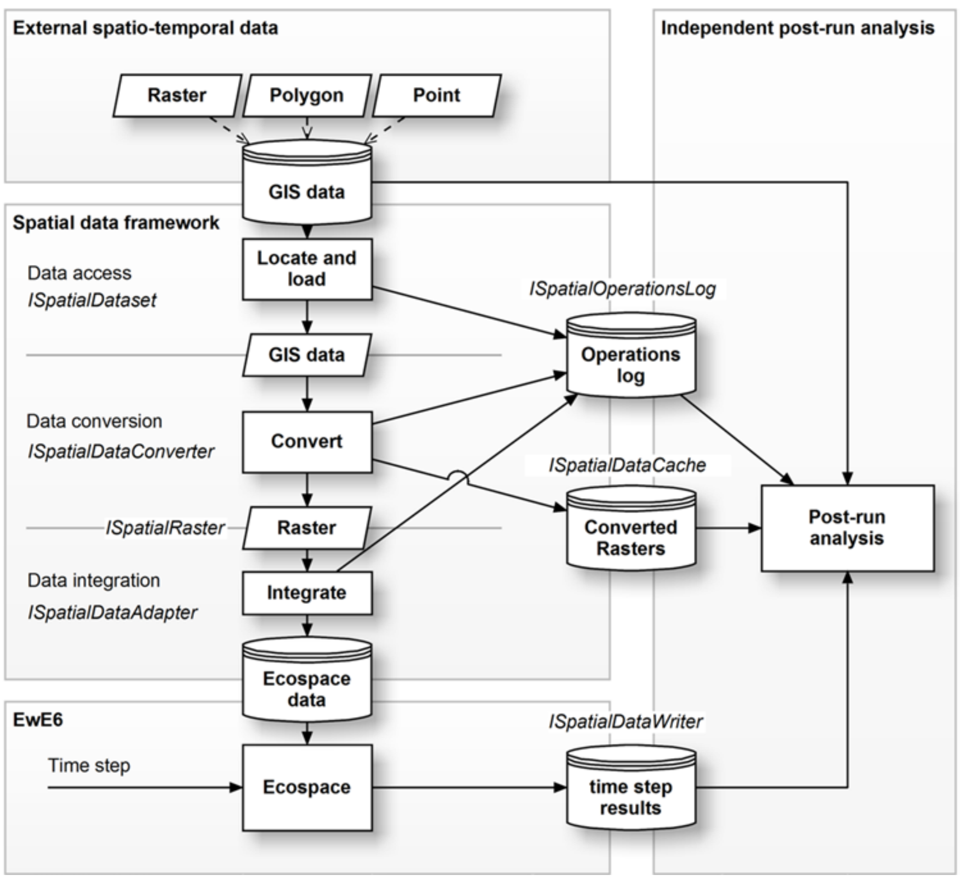

Figure 10 - A schematic functional design of the framework, displaying how external data is brought into Ecospace.

capable of performing one type of conversion each, such as different type of raster conversions and vector to raster conversions.

Converters will log performed spatial operations into the spatial operations log. Additionally, the rasters that are produced by the converters are stored in a cache that serves to (i) provide the outcome of conversion steps available for post-run statistical analysis, and (ii) to facilitate reusing the intermediate data for a next model run which will enhance the performance of the spatial temporal data framework (not depicted in Figure 10);

- Converted raster data is passed on to the data integration layer to a family of components called adapters, represented by the code component *ISpatialDataAdapter* in Figure 10. Adapters perform the task of placing the loaded and converted raster data into the correct maps of the Ecospace model, and may trigger Ecospace to perform dedicated tasks to ensure that integrated data is conrrectly included in the running computations. The Ecospace model will offer an adapter for every type of map that can be provided with external data.

  Adapters will enter their activity in the spatial operations log for post-analysis purposes;

- During Ecospace execution, results are written to a spatial map files via the code component *ISpatialResultWriter*. These files can be included in any desired post-run statistical analysis.

The reverse pathway, when Ecospace results are passed through the framework for delivery as GIS data, is given in Figure 11. This pathway is similar:

- Result maps produced by Ecospace are passed to an adapter for the type of result data. The adapter encapsulates the map data into a generic *ISpatialRaster* grid for processing by the spatial data framework;

- The result grid is received by *ISpatialDataConverter* converter. Any conversion that needs to be

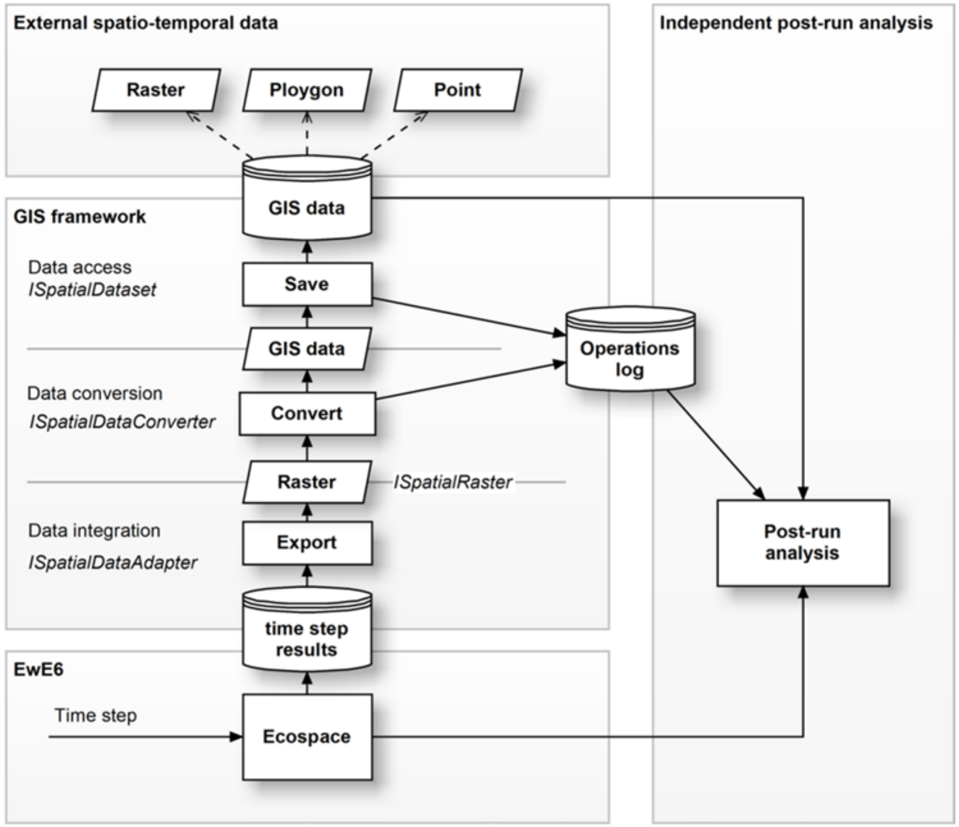

Figure 11 - Data exchange framework – producing data.

performed, such as raster-to-vector conversions, will be handled here;

- The converted data is passed to *ISpatialDataSet* which then makes the data available for external use by for instance saving the data to a file, to a geodatabase, or by passing the data on to a model interoperability broker.

Implementation

The implementation of the spatial framework needs to be open to future changes. The system may require access to new data formats, storage media, and different models which demands flexibility in adding new ISpatialDataset modules to the framework. New conversion modules may be required if the internal structure of GIS data is incompatible with existing converters, or if different GIS operations are needed. Additionally, new adapters, operation logs, and result writers may be needed to extend the capabilities Ecospace itself. Here, the existing EwE6 plug-in structure provides the flexibility that is needed.

The EwE6 plug-in manager, one of the core components of the EwE6 software, investigates code libraries in the EwE6 application directory when EwE6 is launched. All libraries that match a plug-in

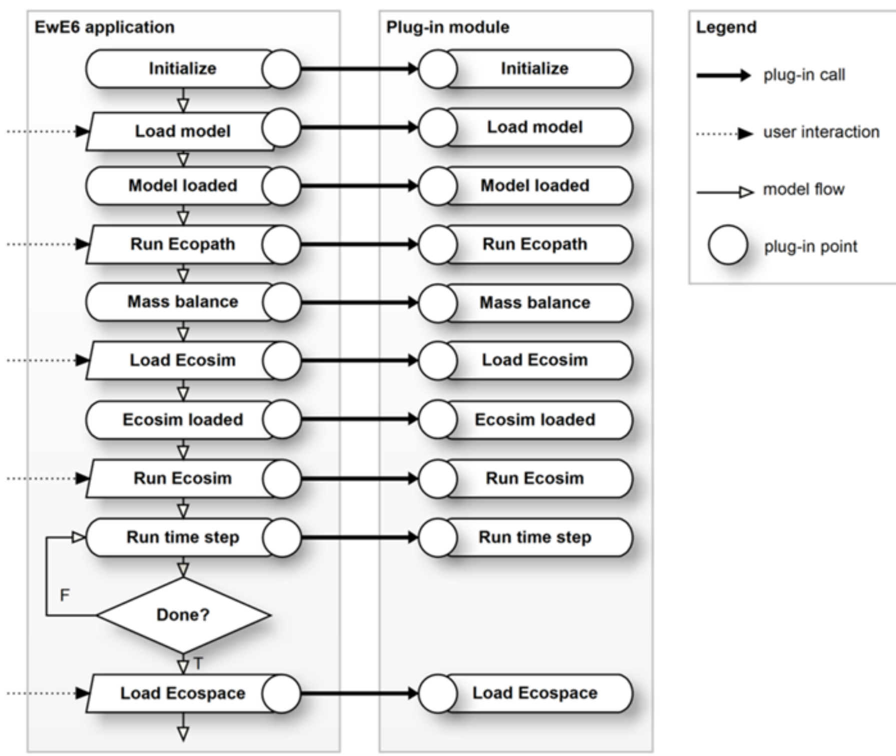

Figure 12 - An illustration of how plug-in points are integrated into the flow of the EwE6 application.

signature are loaded into the EwE6 application. Each plug-in library can decide to implement one or more plug-in points, which are invoked dynamically in the flow of the EwE6 application (see Figure 12).

All data framework components that may require future extensions are thus included as plug-ins points.

This gives the spatial data framework the flexibility to incorporate new GIS functionality without modifications to the EwE6 source code. Even better: the plug-in structure allows addition of spatial data framework modules by any developer with access to the EwE6 source code.

Example sequence diagram

The interaction diagram in Figure 13 provides an example of how the Ecospace, adapter, dataset, converter and GIS toolkit collaborate, and how data flows through these objects, in order to bring external data into the Ecospace model. The dataset here is a hypothetical GIS file reader, and the data converter in this example performs a hypothetical set of GIS operations to convert a GIS raster into a format compatible with the Ecospace model. This schematic diagram illustrates the conceptual interactions only, and is not intended to present a complete overview. For instance, interactions with the spatial data log and the spatial data cache, as mentioned earlier in this section, are not included.

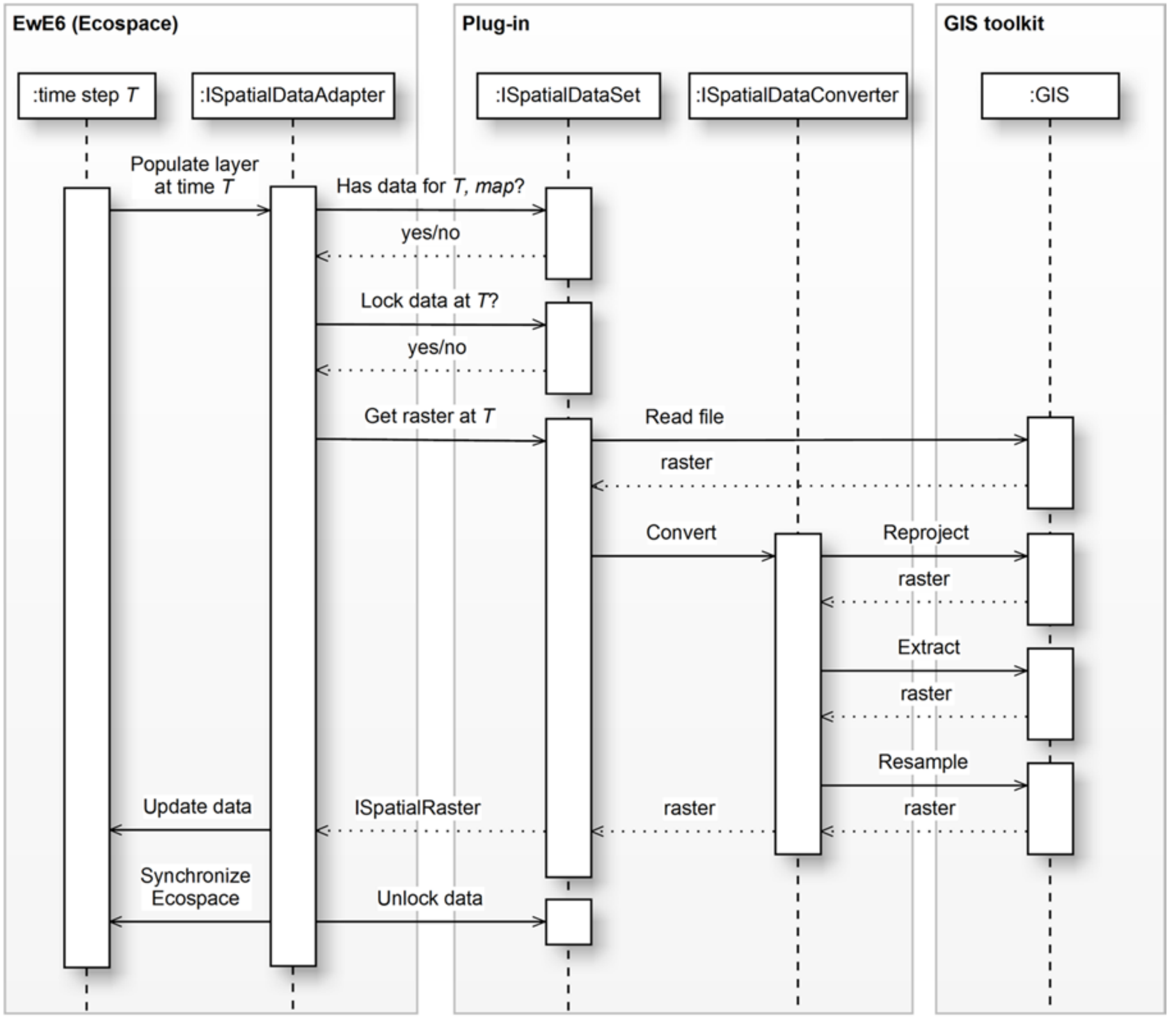

Figure 13 - Interaction diagram, showing how Ecospace, an adapter, a dataset, a converter and a GIS toolkit communicate to perform the core framework task to read external data.

Figure 13 illustrates the deliberations that will be made by the framework when trying to access external data. Note that the interaction diagram in Figure 13 shows that Ecospace, the spatial temporal data framework and the GIS toolkit are physically separate .NET modules. Adapters are embedded within the EwE6 application because of their deep integration with the Ecospace model. Datasets and converters are implemented as separate plug-in modules, and different plug-in libraries can utilize different GIS toolkits if needed. This extra modularity ensures that the EwE approach does not become reliant on third-party developed software.

The challenge is now to present this modular framework in a cohesive manner to EwE users in the prototype. First, a GIS toolkit will be selected in the next section to implement the prototype of the spatial temporal data framework.

3.2.3 GIS Toolkit

To implement the prototype of the spatial framework a GIS programming toolkit needs to be selected. In this section, candidate GIS toolkits are reviewed for collaborating with EwE and a toolkit is selected.

Requirements

Several considerations apply when selecting suitable GIS programming toolkits for implementing a spatial-temporal framework for EwE:

1. **Capabilities**

   A GIS toolkit for Ecospace should support a range of GIS raster, vector and grid data formats and data connectivity methods common to the environmental sciences. Based on repeated requests for Ecospace data connectivity, a candidate toolkit must support at least read and write access to grid file formats netCDF/HDF, ESRI ASCII and binary grid (bdg) files, and GeoTIFF files. Supported vector file formats should include ESRI ShapeFile, Geography Markup Language (GML), and elevation data formats such as DEM. At the moment of writing no immediate need has been expressed to exchange data with common geodatabase formats or geospatial web services. It would be prudent to assume that future uses of the spatial framework require facilities to interact with web services and spatial enabled databases such as PostGIS and Microsoft SQL Server.

A GIS programming toolkit should provide a library of basic spatial operations for vector and raster datasets. The Ecospace model operates exclusively on gridded data and the GIS toolkit must support the basic geospatial operations to convert raster and vector data into a format compatible with EwE.

To process raster datasets for consumption in Ecospace, the candidate toolkit must provide at least the means to explore the cell values in a raster, and must be able to report the dimensions, cell size and data type of the raster. Fundamental spatial operations such as merging, extracting and splitting raster data are needed. In order to convert raster to Ecospace the toolkit must support means to resample and interpolate raster content using algorithms such as linear interpolation, kriging, and inverse distance weighting.

In order to process vector data, the toolkit must be able to report the type of vector data in a spatial set, must be able to loop over features in the vector data, and query and modify feature attribute data. Fundamental spatial operations such as merging, clipping, and overlaying vector data are needed. The toolkit should be able to convert vector data to raster by specific attribute values. Furthermore, the toolkit should be able to perform polygon area calculations.

Last but not least the toolkit should be able to convert spatial data between geographic projections.

Visualization capabilities are not required for the current version of EwE6 since the application is shipped with a simple but sufficient map rendering engine (see Figure 3). However, GIS toolkit visualization capabilities are considered for possible future use;

2. **Intellectual property**

   A GIS programming toolkit should permit distribution with the EwE6 software. The EwE6 desktop software and its source code have been freely available since their inception. Over the years, several user-developed modifications have been contributed to the approach (e.g., Kavanagh et al., 2004; Beecham et al., 2009; Gascuel et al., 2009). With the 2011 foundation of the Ecopath International Research and Development Consortium a need arose to formalize a license model for the Ecopath approach. In 2012, the software approach was officially licensed under the GNU Public License version 2 as true Free and Open Source Software (FOSS). This license grants any EwE user the freedom to: (i) run the program, regardless of purpose; (ii) study and adapt the program; (iii) redistribute the software; and (iv) improve the software and to release these improvements to the public, provided improvements inherit this same license model. This license model poses restrictions to the GIS programming toolkits for implementation of the spatial-temporal data framework.

As such, the EwE approach can only incorporate and publicly release FOSS components that are compatible with the EwE license, thus excluding commercial, paid-for toolkits;

3. **Technical environment**

A candidate GIS programming toolkit must be compatible with the Microsoft .NET environment, the platform that used for the EwE6 source code (see section 3.1).

Free open source GIS toolkits implemented in.NET languages such as C# and VB.NET can be directly integrated in the software development environment of EwE6, which facilitates development and trouble shooting. For this reason, technical preference is given to .NET-based GIS toolkits.

The interaction between C and C++ software and .NET applications is limited to the Windows platform. Efforts are under way to port EwE6 to other operating systems, and a GIS toolkit written in C or C++ cannot be used outside the Windows environment. C and C++ toolkits may be useful to construct the framework prototype, and are therefore included in the evaluation.

.NET applications can interact with programs written in Python and Java via wrapper libraries or via Mono, an open source cross-platform for the .NET framework. Mono, for instance, is the current platform of choice to enable EwE6 to run on operating systems other than Windows. At the time of writing the EwE6 user interface is not fully Mono compliant, and implementation of the spatial framework could not wait for this compliance to be realized. Java and Python GIS toolkits are evaluated for potential future use;

4. **Extensibility**

   Due to the intended open-ended applicability of the framework, it must be possible to add new functionality to a candidate GIS toolkit at any moment. Open source software can be extended, per definition, via modifications to its source code. However, this is rarely a desired option because this will make source code deviate from publicly and centrally maintained versions, which could lead to complications when code needs to be synchronized with this central repository. Therefore, native extensibility features within the toolkit are preferred for toolkits that offer relatively small sets of core functionality;

5. **Support**

   Active support of a development team, number of individuals participating in software development, frequency of public releases and updates to source code, and level of engagement of software developers and users in discussion forms may be indicative of how well open source software is maintained and how long it may be around (e.g., Ramsey, 2007). Frequent, continued, and recent activity in these areas is therefore valued in the evaluation. When reviewing open source GIS software, Ramsey (2007) also takes the width of the developer community – the number of participating organizations and available funding, among other factors - into account. However, a number of high profile and broadly supported open GIS initiatives such as Feature Data Objects and OpenEV seem to have stopped.

Additionally, the completeness and actuality of reference documentation, availability of discussion groups, and volume of available code examples on the Internet are highly relevant.

Lastly, this review focuses on open source GIS toolkit libraries only. Desktop GIS such as GRASS, Quantum GIS, SAGA, and uDig, and web-based mapping and analysis GIS solutions such as OpenLayers, MapServer, and MapBuilder are not consider at this stage. Interoperability to these tools is technically feasible, but will require complex programming constructs to synchronize and validate the communication between the framework and the remote GIS. This added complexity will make the prototype framework difficult to test and comprehend. Hence for the prototype, which aims to showcase the feasibility of the framework, only GIS toolkits that facilitate direct interaction with .NET are evaluated.

Reviewed candidate GIS programming toolkits for the spatial temporal data framework are presented in Annex B. There, for each toolkit the main purpose is listed, along with its license and utilized programming language. Then, capabilities and support levels are rated to suitability for the EwE spatial temporal data framework as follows: – (not supported or unsuitable), + (basic support, usable for EwE), ++ (supports all features needed by EwE), +++ (support exceeds needs of EwE), and ? (insufficient information available for assessment).

Selected toolkit

After careful evaluation (see the comparison chart in Annex B), the open source GIS toolkit DotSpatial (http://dotspatial.codeplex.com/) was selected. The license of this library is identical to that of EwE6 and hence poses no obstructions to releases with EwE. DotSpatial is developed in C#, a language of the .NET family, and can thus be directly integrated in the EwE6 code base.

DotSpatial provides bi-directional access to required raster and vector GIS file formats, and provides foundation support for connecting to spatial databases and geo web services. Additionally, DotSpatial has strong map visualization capabilities that may benefit future developments in EwE.

DotSpatial supports modular extension of its capabilities via a plug-in structure similar to that of EwE6, where plug-in components are automatically recognized and activated when needed.

There is substantial support information for programming DotSpatial available on the Internet. In particular, discussion forums dedicated to the DotSpatial GIS toolkit refer to a wide range of freely available code examples. The DotSpatial programming manual is technical but complete. The DotSpatial source code, which can be obtained for free, includes an extensive set of code projects that demonstrate how to operate basic and advanced functionalities of DotSpatial.

Lastly, the DotSpatial user community is actively engaged with the developers in discussion forms, and development activity occurs almost daily. There is a substantial amount of user-contributed C# code involving DotSpatial programming. The development process is transparent, offering clear milestones and insight in the evolution of the DotSpatial code base. Lastly, updates to the DotSpatial toolkit are issued twice per year, which can be considered frequent among open source toolkits. The newest version of DotSpatial was released a month before this thesis was submitted (http://dotspatial.codeplex.com/releases/view/87867).

The only downside to DotSpatial is its reliance on the GDAL (Geospatial Data Abstraction Library) for accessing a range of raster and vector GIS file formats. At time of writing, these GDAL libraries are included in DotSpatial as traditional Windows code libraries. These libraries are not part of the .NET family of languages and are only accessible to .NET code via the Windows operating system. These libraries will not be usable by other operating systems in their current form, and DotSpatial will not be able to leverage their functionality when EwE is ported to another operating system.

This shortcoming was not deemed prohibitive to using the DotSpatial toolkit for the framework prototype. An operating system independent version of the EwE6 should not be expected before the summer of 2013, and present efforts by the DotSpatial developer team indicate that this hiatus may be solved before then.

"All models are wrong, but some are useful"

- George E. P. Box (1987)

4 Prototype

The prototype of the spatial temporal data framework was implemented using the DotSpatial GIS toolkit and was designed in accordance with the designs discussed earlier in this section. The main purpose of the prototype is to demonstrate the feasibility of extending the Ecospace model with a framework of modular, abstract components that simplify GIS spatial data connectivity. If successful, this framework will be used for a series of ambitious model interoperability projects waiting to integrate the Ecospace model in GIS environments such as the Nereus Model (Christensen, 2012). Perhaps the approach utilized in this framework can be a used as a foundation for simplifying and compartmentalizing complexity in order to further model interoperability. But let's introduce the framework first.

The prototype of the spatial temporal framework integrates with the EwE6 user interface in several locations, such as shown in Figure 14.

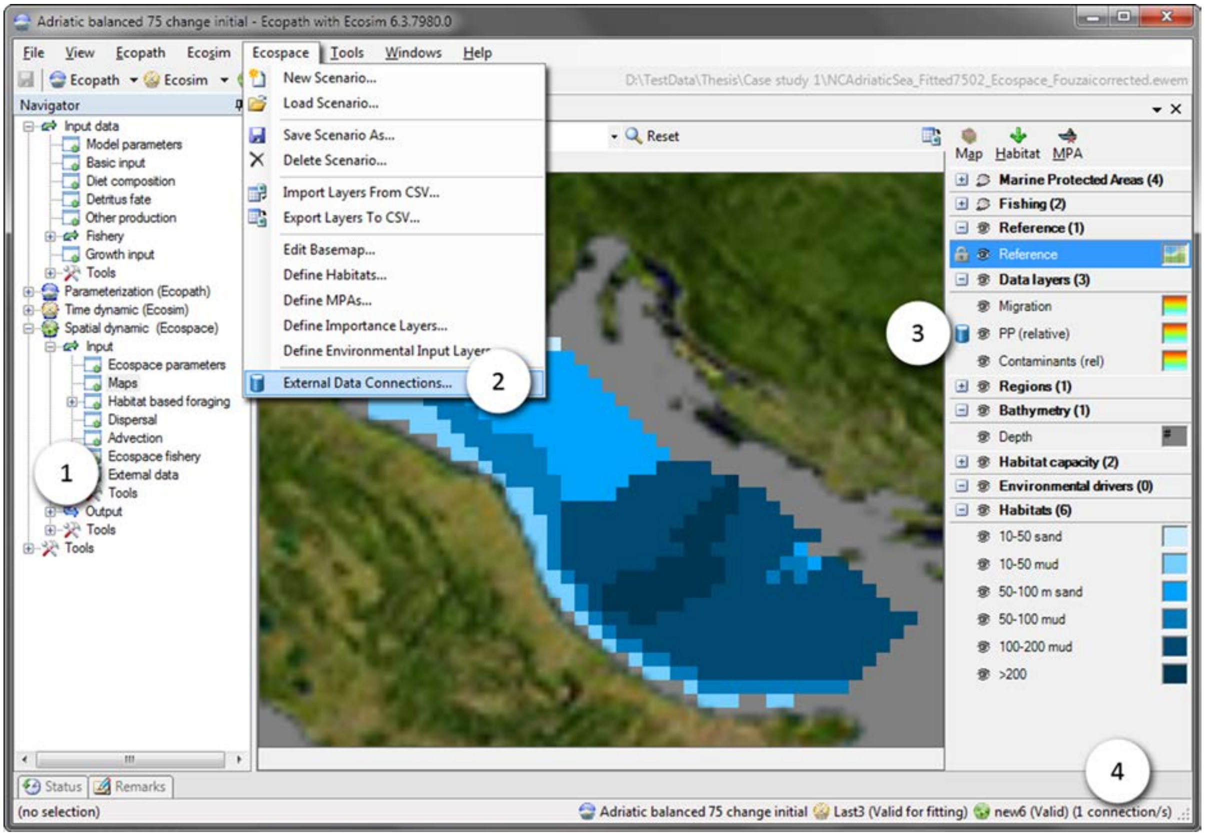

Figure 14 - The EwE6 user interface, with indications to the presence of the external spatial data facilities: (1) an item in the EwE navigation tree, (2) a configuration option in the Ecospace menu, (3) an indicator beside a layer in the Ecospace map interface to indicate each layer connected to external data, and (4) an indicator to notify the user of the number of active external data connections.

Connections

The chain of connected components throughout the spatial data framework can be complicated to understand, especially for busy academics that just want to “get the biology done”. As such, the chain of components that connect a spatial map layer to external data is simply referred to as an ‘external data connection’.

Users can manage external data connections from a central user interface displayed in Figure 15. From this interface users can perform the tasks needed to configure the spatial temporal data framework:

- Select an Ecospace layer for which to configure an external data connection (area 1). Layers connected to external spatial data connections are indicated with a blue database image;
- Create, configure, and delete datasets, and assign created datasets (area 2) to the Ecospace map currently selected in (1). Note that the form refers to data sets as connections, which was, after much deliberation, chosen as a more intuitive term to present to EwE users;
- Assign a converter to the currently selected Ecospace map and connection, and configure the selected converter (area 3);

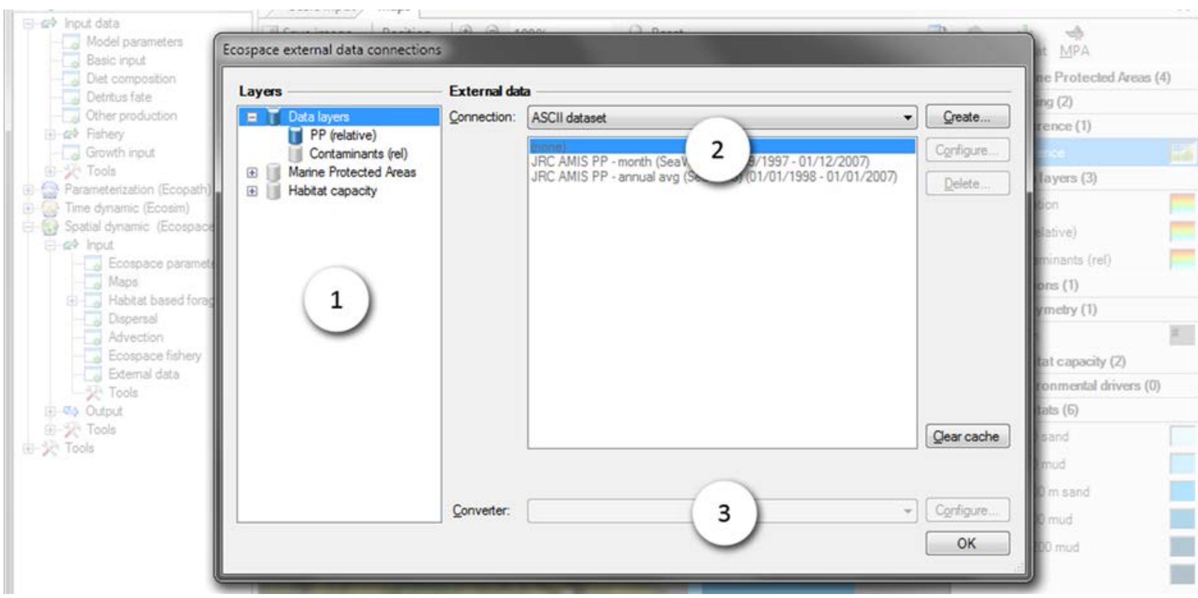

Figure 15 - The central interface to manage external data connections to the Ecospace map, showing (1) Ecospace layers that accept external data connections, (2) elements to manage data sets, and (3) elements to select and configure converters.

- Additionally, this form provides an option where users can clear any intermediate spatial result files that have been created and cached by the spatial temporal framework.

Three experimental types of data sets have been built for testing the spatial framework prototype. A single file dataset facilitate connections to a single geo-spatial file without explicit temporal dimension. A multi-file dataset allows connections to a time-indexed collection of GIS files. Last, a simulated model interoperability dataset was created for testing model interoperability capabilities of the framework. The model interoperability dataset will be used in future research; the multi-file dataset will be briefly explained to illustrate the workings of the framework. This dataset will also be used extensively in the case study (see Chapter 5).

The multi-file dataset maintains a time-stamped index to a list of geo-spatial files. Time steps must correspond to the monthly, first day of the month time steps of Ecospace, for which this type of data set may provide access.

The modularity of the framework allows datasets to provide configuration user interfaces when needed. The configuration interface for the multi-file dataset is displayed in Figure 16. Here, users can enter desriptive data about a dataset, and build a temporal index to spatial files found on a local computer or a network. Each file is tagged to the first day of a month. Via this date, the dataset will be able to locate required files when the spatial temporal data framework executes. The multi-file dataset, developed for this thesis, exclusively utilizes the DotSpatial GIS toolkit to interact with geospatial data files.

Once defined, datasets can be reused for different Ecospace models. Datasets can even be shared between users in an organization via a local network.

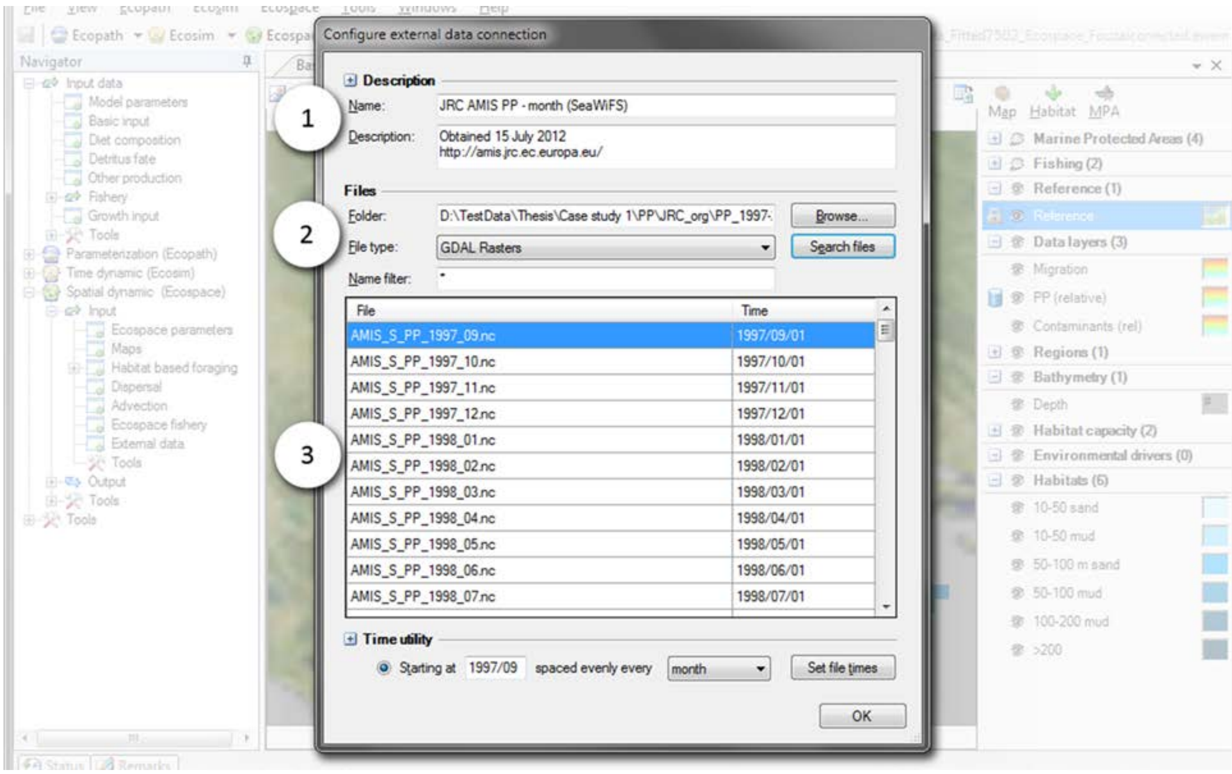

Figure 16 - User interface, developed for this thesis, for configuring a data set to a series of spatial-temporal files. A dataset needs a description (1). Files can be added from folders (2). Every file is tagged by date (3), which allows the spatial-temporal framework to locate external data when Ecospace executes. The dataset in this figure is connected to a directory of netCDF files.

The first converter that was included in the spatial data framework prototype is a direct raster converter. This type of converter can only operate on incoming raster data, and transforms this raster via three fundamental GIS raster operations to an Ecospace-compatible grid of cells. First, the converter performs a projection transformation to conform the data set to the standard Ecospace projection, WGS 84. Secondly, the raster is clipped to the spatial extent of the Ecospace basemap. Lastly, the clipped raster is converted to a grid of equal number of rows, number of columns, and cell size as defined in the Ecospace basemap.

The prototype framework requires means for users to assess the spatial and temporal compatibility of external data with the location and time span of an Ecospace model. This interface is depicted in Figure 17. Here, all active external data connections are presented along the Ecospace run time to show the temporal overlap between model and external data (area 3 in Figure 17). In the map area (area 1) the spatial overlap of the model (area 2) with datasets are shown, and users will be alerted if spatial data

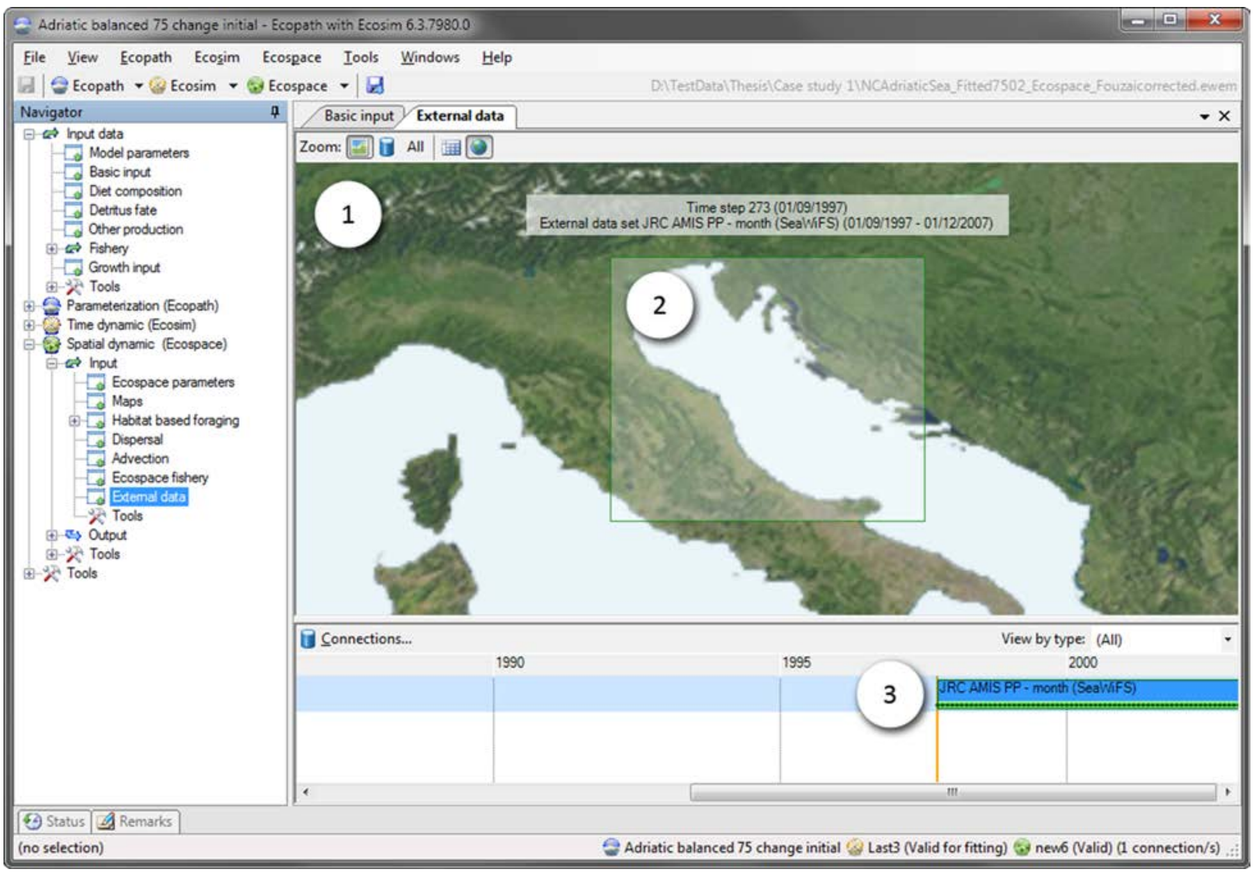

Figure 17 – The EwE6 user interface that provides a cursory overview of the spatial and temporal compatibility of external data with an Ecospace model. The map section (1) of the interface shows the area of the Ecospace map (2), and provides details for selected data connection and time step (3).

does not overlap or partially overlaps with the model area. The connection selected in Figure 17 utilizes the global dataset of primary productivity that will be used in the case study (see Chapter 5).

Last, Figure 18 shows the EwE6 interface where the Ecospace model executes. Here, new entries in the spatial operations can be viewed in the status panel. The spatial operations log is also written to the hard disk to enable post-run analysis.

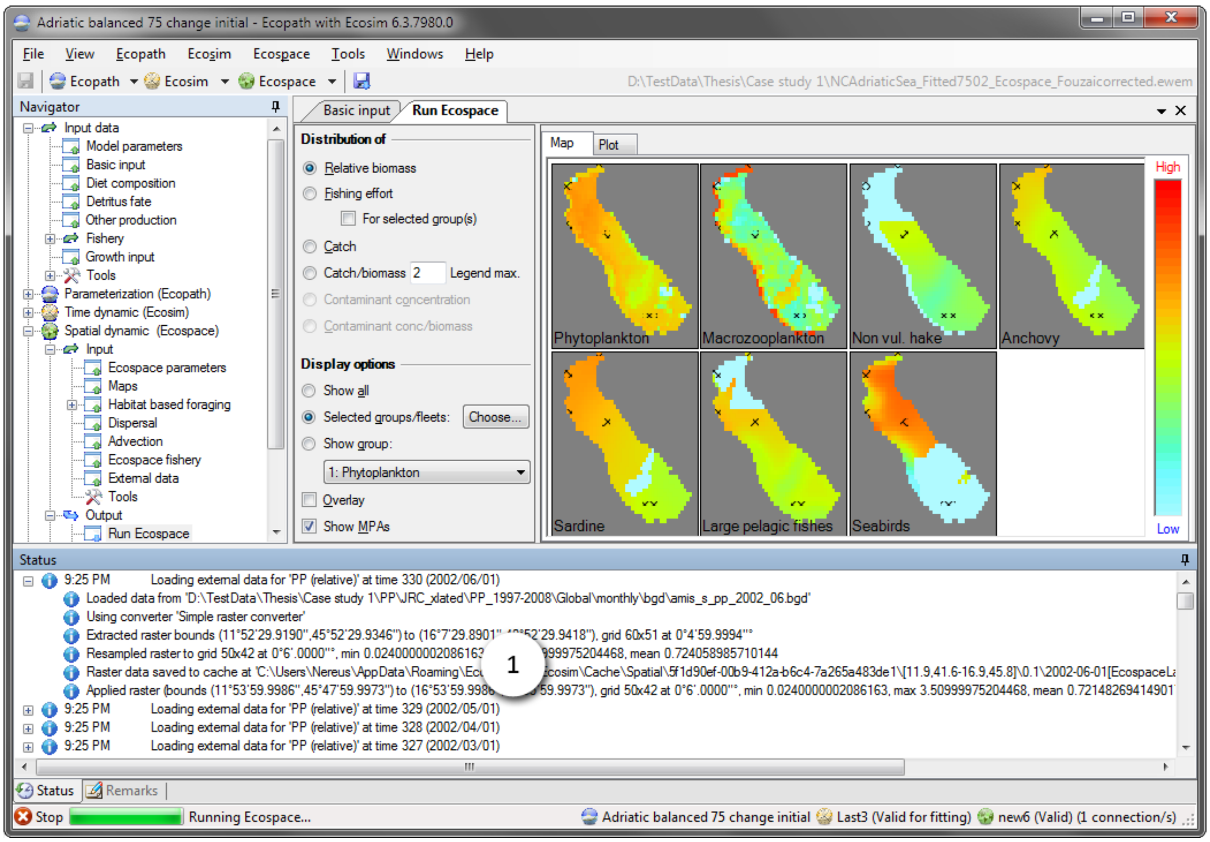

Figure 18 – EwE6 interface from where the Ecospace model is executed. The status panel (1) shows an excerpt from the spatial operations log as produced by the spatial temporal data framework.

“We, the generation that faces the next century, can add the solemn injunction ‘If we don't do the impossible, we shall be faced with the unthinkable.’”
- Petra Kelly *(Hertsgaard, 1993)*

5 Case study

5.1 Introduction

The Northern-Central Adriatic Sea is one of the most productive areas of the Mediterranean Sea and one of the major fishing grounds in southern Europe. It plays an important role in the economies of European countries such as Italy, Croatia and Slovenia. However, a dramatic expansion of fisheries has taken place since early 1970s (Coll et al., 2009, 2010; Fortibuoni et al., 2010; Lotze et al., 2011).

This case study builds on an EwE ecological model representing the Northern-Central Adriatic Sea ecosystem (Coll et al., 2007), previously fitted to available time series of data from 1975 to 2002 (Coll et al., 2009, 2010) (see the overview of the fitting procedure in Annex A - Fit to time series procedure), and from which an Ecospace model had been developed (Fouzai et al., 2012). This model was used to evaluate the new spatial-temporal framework for Ecospace developed for this thesis. This case study represents the first application of the new spatial framework applied to Ecospace at a small geographic scale. While applying the new spatial-temporal framework, the result (both considering data in monthly time steps and annual time steps) were compared with the original fitted model (Coll et al., 2009) that had been made spatially explicit using the original version of Ecospace (Fouzai et al., 2012). The aim was to analyse if results from the ecological model would be modified and would be improved by applying the new spatial capabilities.

5.2 Methodology

5.2.1 Study area

The study area is located in the Northern-Central Adriatic Sea, geographical sub-area (GSA) 17 of the General Fisheries Commission for the Mediterranean (GFCM, 2001). The Northern-Central Adriatic Sea is a semi-enclosed basin located in the northernmost part of the central Mediterranean. The primary production varies from a productive (potentially eutrophic) shallow northern basin to an oligotrophic deeper central basin (Zavatarelli et al., 2000). This production is influenced by a large number of rivers discharging into the basin, particularly the Po River (Artegiani et al., 1997; Zavatarelli et al., 1998; Pinardi et al., 2006). This area presents clear spatial dynamics of the marine productivity, with higher productivity in the shallower northern waters and western areas near the coast, and low productivity in the eastern and southern areas which are deeper.

This area was chosen because of its productivity, ecological and fisheries characteristics (Bombace, 1992) and the availability of previously developed and published ecological models (Coll et al., 2007, 2009; Fouzai et al., 2012). The total area is approximately 55,500 km^2, with an average depth of 75 m, and a maximum depth (in the Pomo Pit) of about 273 m (Figure 19). This area includes all international waters 12 miles (nm) off the coast of Italy, Slovenia and Croatia. In addition, Italian territorial waters beyond 3 nautical miles of the western coast (or less than 10 m depth) were included. The area within 3 nm of the Italian coast was excluded because this area is dominated by artisanal fleets and trawling is banned. The area covered by Slovenian and Croatian territorial waters was excluded from the eastern part of the study due to lack of data availability.

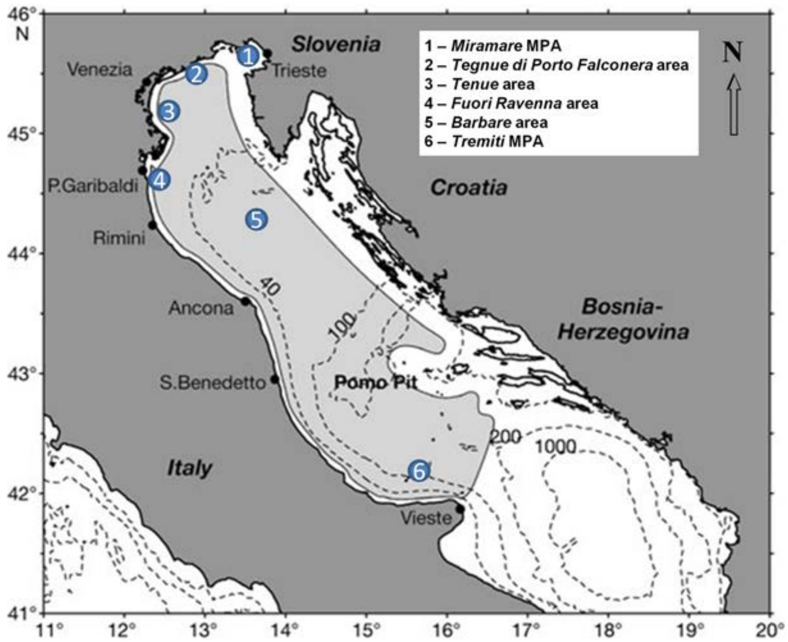

Figure 19 - The Northern-Central (NC) Adriatic Sea study area. The light-grey area represents the spatial coverage of the ecological model available. Current protected areas and biological conservation zones are also indicated.

5.2.2 The ecological model of the Northern-Central Adriatic Sea

The EwE6 software (EwE, Christensen and Walters, 2004) was previously used to develop a trophic mass-balance model of the Northern-Central Adriatic Sea and to quantify the ecosystem impacts of fishing (Coll et al., 2007). This model represented the area in the 1990s, and was fitted to data from 1975 to 2002 (Coll et al., 2009, 2010). More recently, a spatial model was developed (Fouzai et al., 2012) using the spatial module of the EwE6 software, Ecospace, to examine various fishing management options.

For this case study, the spatial Northern-Central Adriatic model was driven by two spatial-temporal series of primary production through the framework. Results were compared to the original fitted spatial-temporal model to assess the impacts of applying external spatial data to a food web model, and to assess the workings and impact of the spatial temporal framework.

5.2.3 External primary production data

A global, monthly spatial-temporal time series of primary productivity data, derived from the SeaWiFS sensor with a spatial resolution of 9 x 9 km and covering the period from October 1997 to December 2008, was provided by the Joint Research Centre of the European Commission (JRC) in Ispra, Italy.

The primary production calculation (Mélin and Hoepffner, 2010) is based on a depth-resolved and wavelength-resolved model following the original formalism described in Platt and Sathyendranath (1993) and implemented at global scale by Longhurst et al. (1995). At any given location and time, the model takes into account the total irradiance available for photosynthesis between 400 and 750 nm, the phytoplankton biomass indexed by the concentration of chlorophyll, as well as the physiological capacity of phytoplankton organisms to perform photosynthesis. The spatial and temporal changes in phytoplankton metabolism and its vertical distribution are considered in the model through the partition of the global ocean into biomes and provinces within each of which some parameters related to photosynthesis and depth profile of chlorophyll are assigned according to knowledge from field observations. The primary production estimates obtained at global scale with this approach are broadly consistent with those from other models (Carr et al., 2006), and its outputs compare favourably with independent field measurements collected in various parts of the oceans (Friedrichs et al., 2009; Saba et al., 2011).

The assignment of the photosynthetic parameters PB_{max} and E_k is achieved by the combined use of a temperature dependent relationship for the maximum growth rate (Eppley, 1972) and a variable formulation to retrieve the Carbon-Chlorophyll ratio following the empirical relation of Cloern et al.

(1995). The dataset consists of monthly mean primary production values from October 1997 to December 2007, and was expressed in grams of carbon per m^2 per day. The data in the time series was stored as a NetCDF file for each monthly, global map, and was reported by NetCDF metadata to be scaled to log_{10}. Pascal Derycke confirmed this scale, which was applied for ease of display in the GMIS website (Derycke, 2012), considering that primary production is often considered as following a log-normal distribution.

This data is available for download through the JRC GMIS (Global Marine Information System) web portal (http://gmis.jrc.ec.europa.eu).

5.2.4 Configuration of the spatial-temporal data framework

The new spatial framework was applied in a series of steps. First, the Northern-Central Adriatic Ecospace model , with 42 rows and 50 columns at 0.1° cell size, and fitted to data, was geo-referenced to spatial extent 11.9° W, 41.6°S, 16.9°E, 45.8°N (Figure 20). The excluded areas, motivated in section 5.2.1 Study area, are clearly visible as gray cells in this figure.

Secondly, two sets of time series were derived from the JRC primary production data. The original base 10 logarithmic scale of the data did not match the linear scale of primary production in Ecospace and needed to be scaled. Additionally, an annual average series was needed to assess whether the ecosystem model - which was not created with explicit seasonal dynamics - would respond differently to monthly varying and annual averaged external data.

Thus, the following datasets were created:

1. A monthly dataset with linear-scaled primary productivity data, containing a geospatial file for each month of data, and,
2. An annual average dataset calculated from the monthly rescaled data set, with a geospatial file for each annual average.

The monthly dataset covers average primary production patterns from October 1997 to December 2007. The annual dataset covers average primary production patterns from 1998 to 2007. Figures 21 and 22 present these datasets for the study area.

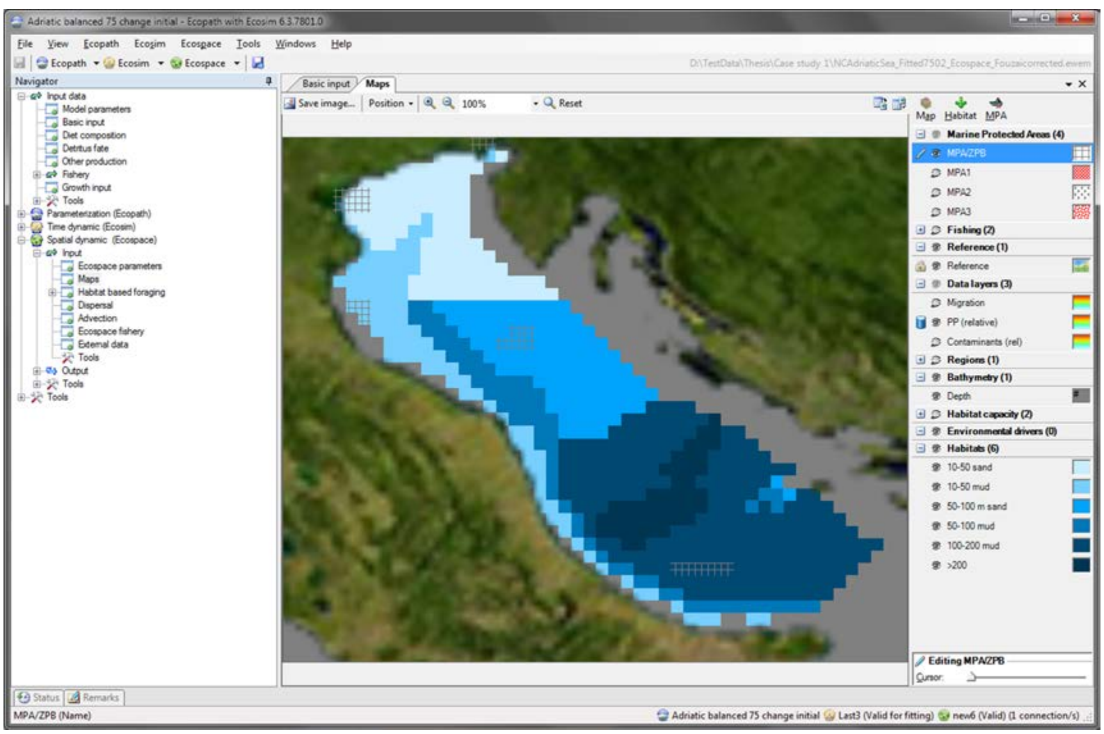

Figure 20 - Ecospace study map of the Northern-Central Adriatic Sea. This map with a reference image illustrates the spatial fit in the Ecospace maps interface.

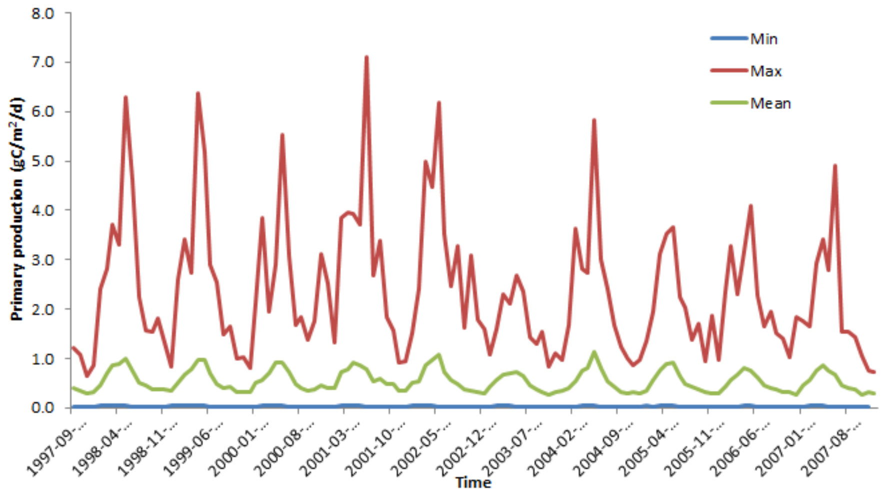

Figure 21 –Minimum, maximum, and mean primary production rates for the North-Central Adriatic in the monthly dataset.

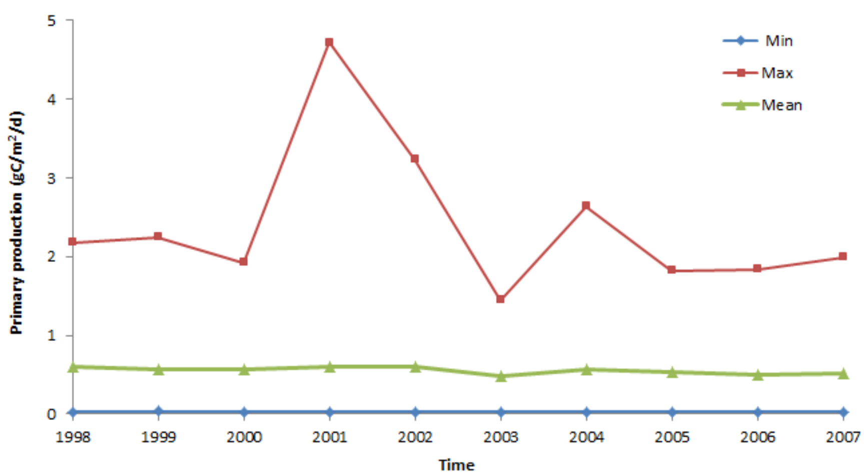

Figure 22 - Minimum, maximum, and mean primary production rates for the North-Central Adriatic in the annual dataset.

Then, the new spatial-temporal data framework, developed for this thesis, was used to connect the derived datasets to Ecospace. As mentioned in the discussion of the spatial framework in section 3.2 and reflected in Figure 23, loading external data through the spatial-temporal framework requires configuration of three components: a connection, a converter and an adapter (see section 3.2.2).

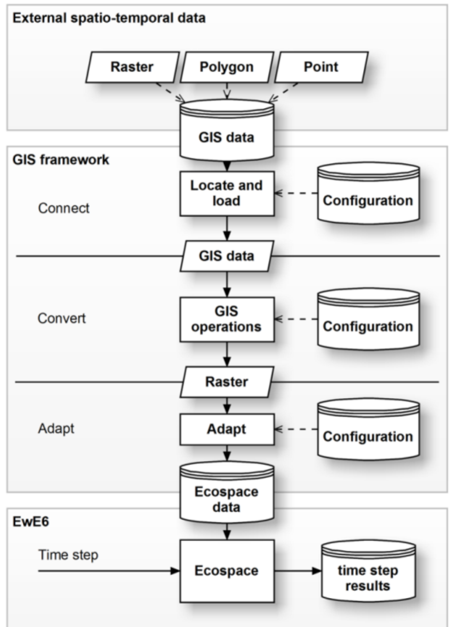

Figure 23 – A conceptual overview of how the spatial-temporal data framework loads, adjusts, and integrates spatial data into Ecospace.

Connect

The connection component provides access to the storage medium of the external data. The initial implementation of the spatial data framework contains only connection components that provide access to GIS data stored in a wide range of file formats. However, the abstract design of the spatial framework enables that, in theory, data connections can be programmed to access any external source of GIS data, such as GIS web services, GIS desktop analytical environments, ecological models that provide GIS data, etc. For this case study, the file based connection component was used to provide access to both datasets (Figure 24).

Convert

The converter component performs the set of spatial operations needed to prepare GIS data, acquired by the connection component, for integration in Ecospace. The initial implementation of the spatial-temporal framework contains a converter component that only performs a series of simple raster operations, but the design of the spatial-temporal data framework allows for inclusion of other types of converters with limited programming effort. For this case study, the simple raster converter was selected (Figure 24), which first extracts all raster cells that overlap with the spatial area of the Ecospace model, and then resamples these cells to the Ecospace grid cell size (see Figure 25).

Adapter

Lastly, converted raster data is integrated into a running Ecospace model. Ecospace represents primary production as a rate relative to the absolute primary production rate defined in the Ecopath model. For this case study, the JRC data, which stipulated maps of absolute primary production rates, needed scaling to base Ecopath primary production rates for proper integration into Ecospace.

The primary production data adapter of the spatial data framework requires this scaling factor to be entered, and provides a means to calculate this option for an external data set. Given that the Ecopath model represented one year (Coll et al., 2007), this scaling factor was calculated by dividing the annual averages for the first complete year of data in both datasets by the Ecopath primary production rate (Figure 24).

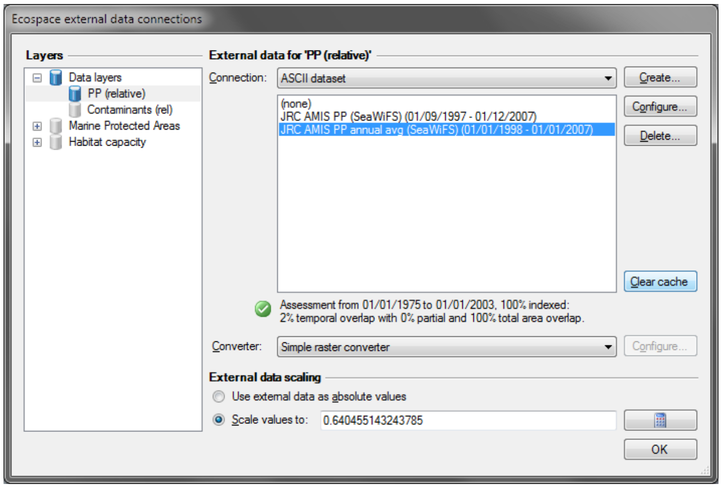

Figure 24 – The new user interface, developed for this MSc thesis, to connect sets of external spatial-temporal data to Ecospace layers.

Based on this configuration, Figure 25 shows how the JRC GMIS primary production data flows through the spatial-temporal data framework for this case study.

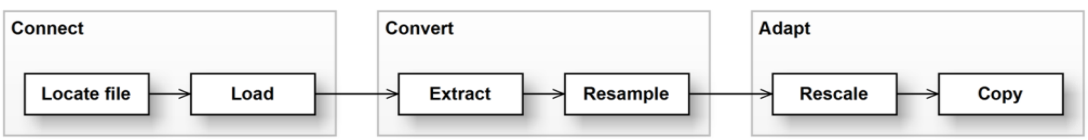

Figure 25 – Flow of GIS data through the spatial-temporal data framework for this case study. GIS data files are located and loaded, converted to suitable raster data consumption by Ecospace, and then rescaled and copied into the internal Ecospace data layers.

5.2.5 Zero-impact analysis of the spatial-temporal framework

Prior to running the external primary production datasets through the spatial-temporal data framework, a zero-impact analysis was performed to ascertain that the framework was capable of correctly incorporating external data. The primary production map used by Fouzai et al. (2012) was exported to an ESRI-compatible ASCII raster for the model area. Figure 26 shows this extracted map.

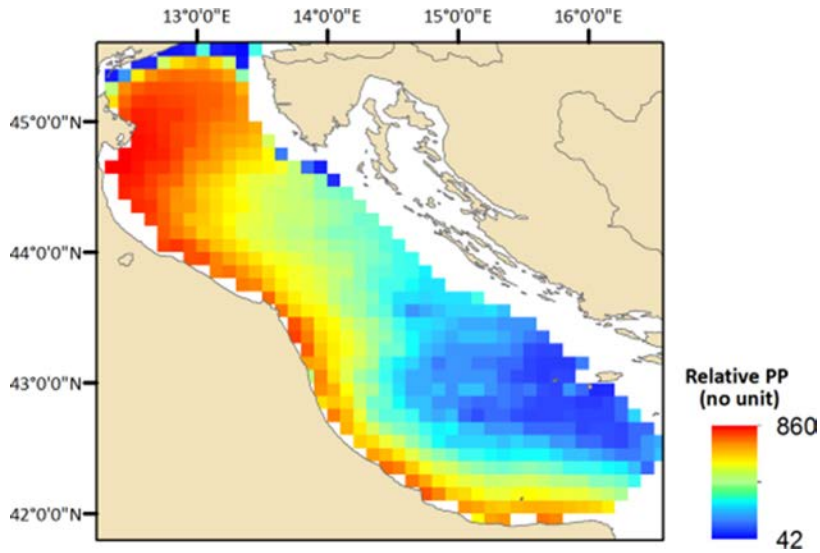

Figure 26 - Original relative primary production map in the Ecospace model.

An external data connection to this raster file was created, and was temporally aligned to the model start date, and the Ecopath-to-Ecospace scaling factor for this file was calculated (Figure 27). This configuration ensured exact spatial and temporal alignment of an external copy of the primary

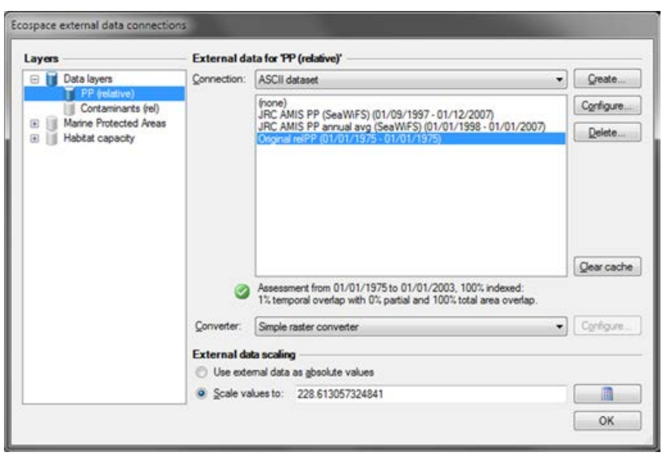

Figure 27 - External data connection to the original primary production distribution map of Figure 26.

production map originally embedded in the model used by Fouzai et al. (2012). Executing this classic Ecospace model using this external data map should produce identical - or near-identical results due to possible numeric precision conversion artifacts - to running the model without this external map data. If the results are identical, the spatial-temporal data framework correctly performs a zero-impact analysis.

The zero-impact hypothesis was validated by numerically comparing the primary production maps that Ecospace produces at the end of the first time step. These maps represent the primary production distribution after one month of food web effects. The classic, fitted to time series model was executed with and without the zero-impact primary production map, and the resulting primary production maps at the end of January 1975 were numerically identical (results not shown here). This analysis confirmed that the framework was able to incorporate original driving data without producing deviating results. The framework was thus deemed suitable for incorporating the JRC-derived PP datasets.

5.2.6 Spatial scenarios

The Northern-Central Adriatic Ecospace model was then run under three scenarios:

1) A scenario with the classic fitting to time series data, without any forced primary productivity data (Coll et al., 2009) (original scenario);
2) A scenario with the fitted model to time series data, including the external data connection to the monthly rescaled PP data set (Figure 21); and
3) A scenario with the fitted model to time series data, including the external data connection to the annual rescaled PP dataset (Figure 22).

The procedure to read external time series of data into Ecospace (scenarios 2 and 3) was validated by extracting minimum, maximum and mean primary productivity values for the annual and monthly datasets for relevant cells in the Ecospace model (see Figure 28). These trends match the patterns reported by Mozetič et al. (2010) and Cabrini et al. (In press) of decrease in primary productivity in the last decades in the Northern-Central Adriatic.

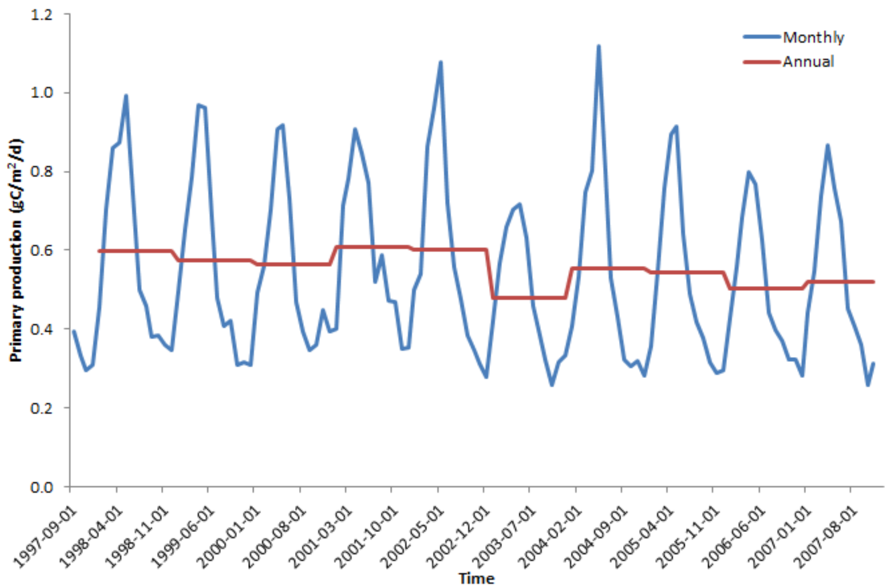

Figure 28 – Minimum, maximum, and mean values for the monthly and annual primary production datasets, extracted by the spatial framework for relevant Ecospace cells.

The scenarios were run from 1975 to 2008 using Ecosim fitted to the original time series data, followed by the Ecospace module afterwards. These results were then analysed looking at the temporal and spatial dynamics of phytoplankton and other specific components of the food web (Annex C). The groups were chosen by taking into account the ecology of different functional groups of the model and their direct or indirect relationships with phytoplankton (Coll et al., 2007, 2009).

5.3 Results and discussion

Results are presented for the three scenarios: (i) without external spatial-temporal data, (ii) with monthly spatial-temporal PP data, and (iii) with annual averaged spatial-temporal PP data.

Results are only presented for the phytoplankton group. Analysis of impacts on the entire food web, and on functional groups others than the phytoplankton group, are supplied in Annex C.

5.3.1 Phytoplankton dynamics

Temporal patterns of phytoplankton biomass

Ecospace produced the following phytoplankton biomass time series, relative to the Ecopath start value, for each of the three scenarios (Figure 29):

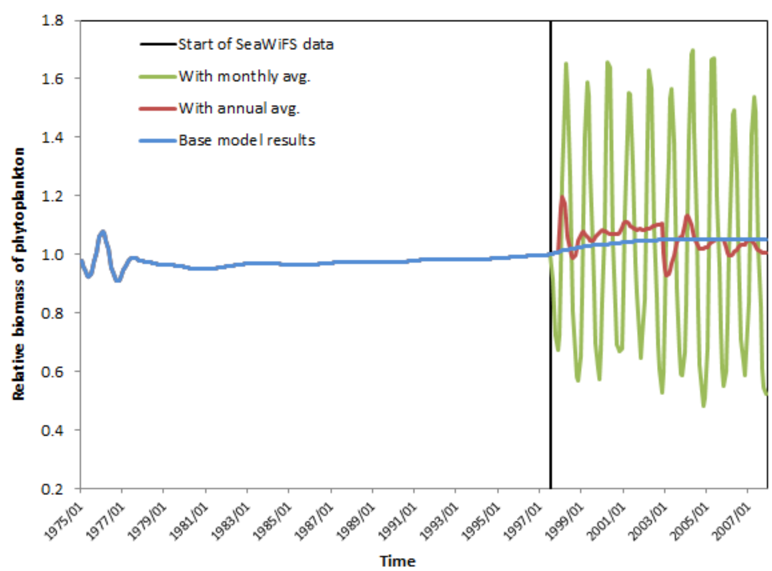

Figure 29 – Predicted relative (final / initial value) biomass of phytoplankton for each of the scenario runs. The start of SeaWIFS data being read by the modelling framework is indicated by a black vertical line.

The original run of the model, starting in 1975, predicted a steady biomass of phytoplankton from late 1970s to the late 1990s and in the last part of the time series the model showed a slight increase of phytoplankton that levelled out toward the end of the time series (Figure 29, blue line). On the contrary, the second scenario, with monthly spatial-temporal PP data, showed high variation of relative biomass of phytoplankton over time starting from the beginning of the new dataset in 1997 (Figure 29, green line), in agreement with the monthly PP dataset (Figure 21). The third scenario, with annual averaged spatial-temporal PP data, showed smaller fluctuations than the second scenario, a slight increase of phytoplankton biomass from late 1990s to early 2000s and then a slight decline with time (Figure 29, red line). These declines, predicted using the new framework, are in line with results from the study area (Cabrini et al., In press; Mozetič et al., 2010) and are quite different from the original model. This highlights the importance to drive the spatial Ecospace model with external primary production data to improve the capability of models to better predict realistic ecological patterns and incorporate the present and future impact of climate change.

Spatial distribution of phytoplankton biomass

The original GMIS PP dataset, as provided by the Joint Research Centre, shows the following spatial distributions of primary production for 2007 (Figure 30):

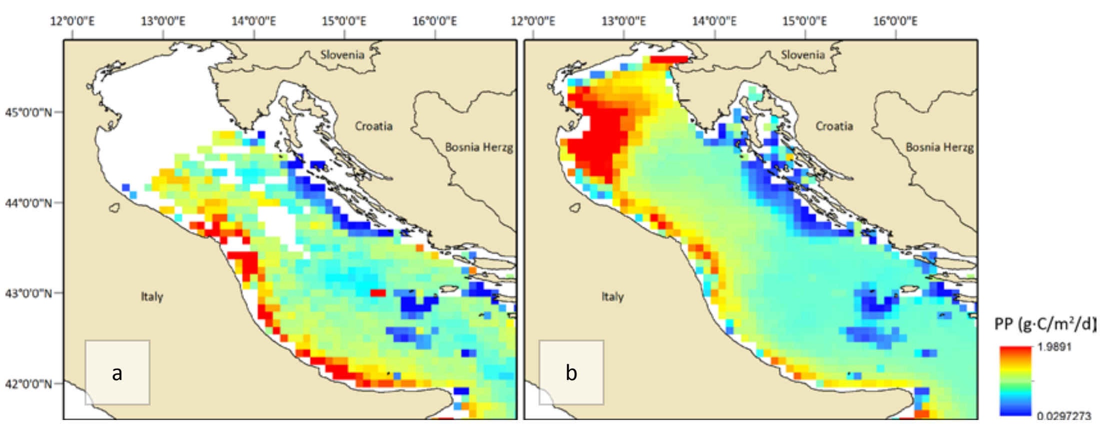

Figure 30 - Original dataset distributions of primary production for 2007: (a) December 2007, (b) annual average for 2007.

The distribution of primary productivity shown in Figure 30 highlights the highly productive northern areas, and the influence that this production has on the western coast of the northern and central

Adriatic Sea, while the eastern and central areas show less productivity. This is linked with the oceanography and water circulation of the area (Artegiani et al., 1997; Zavatarelli et al., 1998, 2000).

The spatial results of the original run of the model did not capture the distribution of phytoplankton biomass particularly well (higher in northern and western areas and lower in southern and eastern areas (Figure 31a). This is due to a more homogeneous distribution of primary production data from the model (Figure 26) than the observations in the area (Figure 30). On the contrary, the second scenario, with monthly spatial-temporal primary productivity data, and the third scenario, with annual averaged spatial-temporal primary productivity data, better reproduced the expected spatial patterns of phytoplankton biomass that occur in the area, with less productive regions in the southern and eastern part of the maps (Figures 31b and 31c).

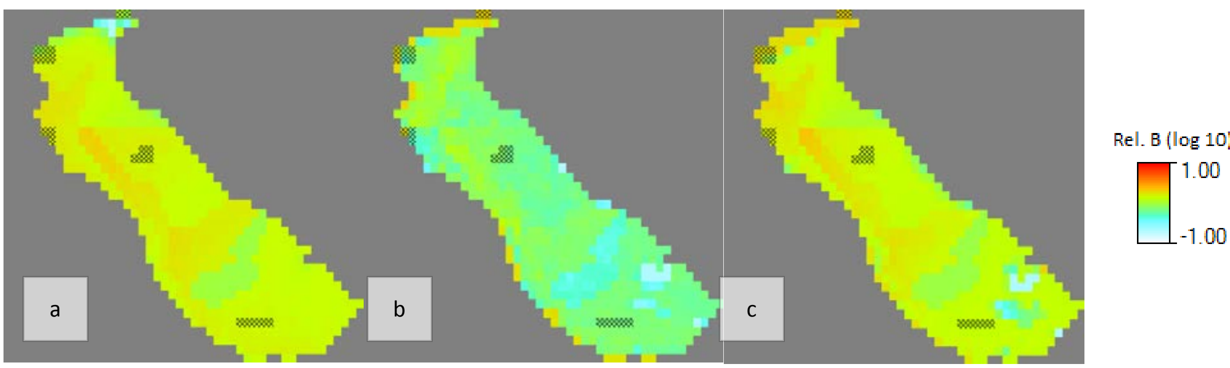

Figure 31 - Ecospace map showing the distribution of relative biomass of phytoplankton for the last year of the simulation, 2007. Results are related with the model (a) without external PP data, (b) with monthly PP data, and (c) with annual PP data.

5.4 Conclusions of the case study

This case study is the first of its kind to drive the spatial and temporal dynamics of the Ecopath trophic level food web model with spatial-temporal time series, and shows great promise for incorporating GIS analysis into food-web models. The zero-impact analysis showed that the spatial-data framework is able to deliver reliable data into Ecospace. The flexible organization of the framework facilitated calibration and execution of the Ecospace model with a minimal set of required steps while demonstrating transparent access to GIS data. Spatial operations such as raster data interpolation and resampling that were selected in the spatial data framework configuring functioned as expected, seamlessly converting the JRC data to the spatial extent of the selected Ecospace posing any further demands on the user. A longitudinal log of spatial operations was produced by the framework, and converted spatial files were made available for post-analysis enabling for further validation and analysis.

Overall, results of this first implementation of the new spatial framework are satisfactory and by implementing the new framework biological results of the model improved. The original run of the model did not predict well the correct temporal and spatial dynamics of primary production for the period from 1998 to 2007. However, using the new spatial-temporal data framework, the dynamics of primary producers were in line with their declining trend observed in the recent past (Cabrini et al., In press; Mozetič et al., 2010). These results highlights the importance to drive the spatial Ecospace model with external data to improve the capability of models to better predict observed temporal and spatial patterns of primary producers. Simulations including the external data reproduced more realistic spatial distribution of phytoplankton and thus yielded more accurate spatial distributions of zooplankton and other analysed organisms. In addition, changes in the temporal dynamics of phytoplankton biomasses cascaded up the food web and influenced the dynamics of zooplankton and other organisms of the food web (see Annex C).

"Chaos is found in greatest abundance wherever order is being sought. It always defeats order, because it is better organized."
- Terry Pratchett, Interesting Times *(1994)*

6 General discussion

The framework designed, implemented and tested for this thesis was intended as a structural design for connecting marine ecosystem models to other tools delivering and using geo-spatial data. The objective of this thesis was not to deliver in-depth GIS-driven ecological assessments, nor was this thesis intended as an in-depth discussion of geo-spatial analytical capabilities. The principal aim of this thesis was to lay the foundation of an extensible and dynamic framework for connecting separate marine ecosystem models through GIS functionality in order to address ecological issues at scales beyond the capabilities of a single model. The author concludes that this aim has been achieved with the prototype that was developed during the work.

The developed framework can be further integrated into Ecospace to drive other dynamics of the model, such as species distributions, fishing dynamics, or habitat degradation scenarios. The framework can be further extended to connect to other environmental models or specialist GIS environments. The habitat capacity model (Figure 32), a new development of Ecospace model described in section Annex A, is an example of a modular model, that, when driven by external temporal and spatial data, will provide the EwE6 approach with a range of new analytical possibilities.

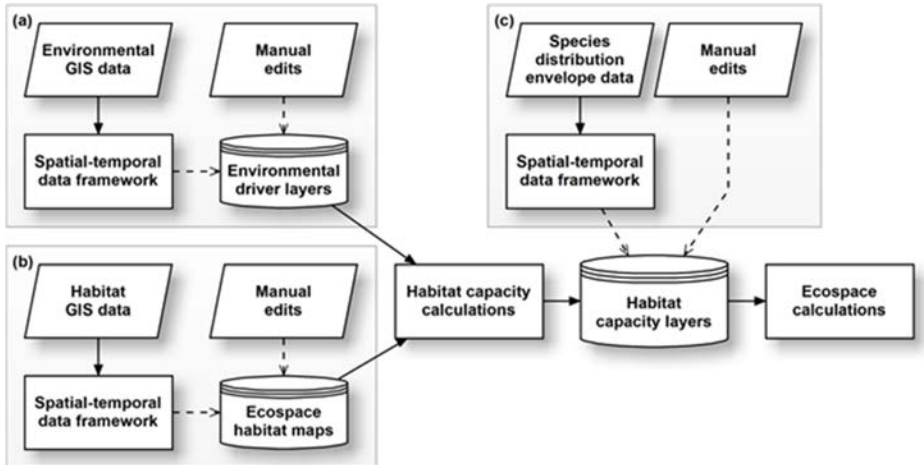

Figure 32 - The habitat capacity model as a modular model. Users can opt to (a) compute capacity from environmental driver layers, (b) compute capacity from habitats, or (c) bypass options (a) and (b), and directly derive habitat capacity from external species envelope models. Options (a) and (b) can be employed in conjunction. Data for (a), (b) and (c) can be either manually entered, or can be driven by the framework.

The prototype implementation of the framework developed here utilizes a limited set of simple GIS capabilities that served to demonstrate the potential that GIS functionality offers in the framework. However, the placeholder capabilities are real: data conversions, projection conversions, raster operations and transparent data delivery methods have shown that the core functionalities of the framework function as required. The zero-impact analysis, performed in the case study, revealed that native model data, once externalized and processed through the framework, produces model results that are identical to the initial model results. This validation indicates that the prototype operations in the framework function as intended. The framework actually improves the capability of the Ecospace model to better approximate observed ecosystem dynamics, as was demonstrated with the case study. The framework has shown to be robust and reliable.

The structure of the framework is extensible and flexible in applicability due to its modular design and separation of model interoperability concepts. Utilizing the plug-in structure of the EwE6 software, the framework can be extended with new capabilities by any programmer familiar with .NET. Datasets can be written and added to the system to interact with different storage media. New GIS operations can be included if new conversions are needed, and potentially every Ecospace input map layer can be driven by external data. The framework presents its modular components in a flexible user interface intended to provide GIS functionality to non-expert GIS users. The framework is transparent by providing an overview of intermediate results, which enables validation of intermediate results and statistical analysis. Additionally, the framework promotes separation of sub-models in an interoperability environment, which facilitates switching hypothesis in an end-to-end modelling approach.

The author hopes that this conceptually simple and elegant framework may further the discussion between model developers how to forward end-to-end modelling.

The prototype as presented in this thesis certainly has shortcomings. The current version of the Ecospace model offers no facilities to read or produce metadata, and self-directed model linkages could not be explored. This shortcoming of the EwE6 approach will need to be addressed in the future.

There are also potential pitfalls to the modular structure of the framework. Too many modules can lead to disorder, which may make the framework difficult to use. If this becomes a problem new structures may have to be added to ensure the framework remains conceptually organized and workable.

Additionally, the modular division of responsibilities, and the consecutive step-wise processing of data through the framework by different components, may be a larger source of error than if all GIS interactions and processing steps were executed within a single module. This should be researched in once the framework is fully utilized. The post-run analysis data that the framework currently provides will be an essential aid to this end.

“The one who says it cannot be done should never interrupt the one doing it”

- George Bernard Shaw (attributed)

7 Conclusions and future developments

The combined effect of a changing climate and human exploitation is affecting global marine ecosystems in ways that we are only beginning to understand. Traditional ecosystem models and Geographic Information Systems (GIS), indispensable tools to the effort of attaining understanding and exploring ecosystem dynamics and management options, are not designed to collaborate, which is needed to address the cascading effects of change through marine ecosystems. Efforts to build such models – often referred to as end-to-end models - by combining existing ecological models tend to yield rigid complexes of hypothesis with limited applicability. A flexible system is needed to the construction of modelling complexes with a focus on model interchangeability, where different hypotheses can be employed to assess an ecosystem from different points of view. The primary goal of this thesis was to define that system via GIS technology.

To this end, a literature search was conducted to assess the state of end-to-end ecosystem modelling approaches, and to explore the capabilities of Geographic Environmental Systems for integrated model approaches. This provided an overview of successes, shortcomings and needs to integrated ecosystem modelling efforts.

Next, a flexible spatial-temporal data exchange framework was conceptualized, defined and implemented in a prototype to allow Ecospace, the spatial model of the EwE ecosystem modelling approach, to dynamically integrate geospatial-temporal data from any external source into its computations, and to dynamically provide its results in common spatial data formats for further model interoperability. For the implementation of the framework a range of GIS programming toolkits were evaluated. The selected DotSpatial geospatial toolkit successfully provided the essential geo-spatial data connectivity and geospatial operations to the framework.

The workings of the framework were successfully tested in a case study, where primary production time series derived from SeaWiFS satellite imagery were chosen to drive the dynamics of the Ecospace food web. The external data enhanced the predictive capabilities of the Ecospace model, while it allowed thorough validation of the correct internal workings of the framework.

There are already several promising projects pending to integrate and extend the capabilities of this newly developed framework. The most recent addition to the Ecospace model, the habitat capacity model, added combined food web and species distribution envelope assessments to Ecospace, which will allow for a wide range of new predictive ecosystem dynamics assessments once the habitat capacity model is connected to external spatial temporal data delivered by the framework.

The framework is currently being integrated in the Nereus Model (Christensen, 2012), an ambitious inter-academic research project to perform global ocean assessments with an end-to-end model scope. This project is likely to challenge every capability promised by the new developed framework, requiring the Ecospace marine food web model to interact with climatological, biochemical and socio-economic models.

Another project that recently started will focus on generation new Ecospace base maps from external data sources. This work is performed with partial funding from the National Oceanographic and Atmospheric Administration (NOAA).

A project currently under consideration involves development of a quantitative methodology for users to assess the suitability of alternate external GIS data sets to drive a given Ecospace model. Just as models need to be exchangeable in an end-to-end approach, models should show robustness when driven by data of similar content but from different sources. Traditionally, Monte Carlo-type uncertainty analysis are used to test model output sensitivity to inputs, but this is not feasible in model interoperability scenarios due to computation times of days to months. Future research may be dedicated to find an indicative measure of fit between two alternate datasets. If this measure can be found, a relatively quick pre-assessment could save significant effort and lengthy computation times to discover that datasets are not compatible.

Lastly, Ecopath, Ecosim and Ecospace should acquire the ability to deliver and interpret metadata to further model interoperability. Research efforts are planned to integrate Ecological Metadata Language (EML) support into the EwE approach, and include this support into the spatial temporal data framework developed for this thesis.

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Annex A Principles of the Ecopath with Ecosim approach

This annex provides supplementary information to the introduction of EwE6 in section 3.1.

The Ecopath with Ecosim (EwE) approach was first proposed and realized as a case study of the French Frigate Shoals (Polovina, 1984). This publication introduced path analysis to the field of ecology, where primary producers such as aquatic plants and phytoplankton convert radiant energy into organic substances which form the nutritional foundation for marine life. Via chains of predation this energy travels along identifiable path ways through a food web. The mass-balance constraint that Polovina included in this model stated that the total amount of energy that transfers through a food-web – but that also passes through individual organisms during their life cycles or gets exported as catches - must balance, since energy is neither created nor destroyed. The combination of path analysis and mass-balance yielded a model that, based on a relatively small number of input parameters, was scalable enough to capture the characteristics of individual ecosystems, and proved to be surprisingly accurate despite its perceived simplicity (Christensen and Walters, 2004).

The simple principles and relative light data input requirements were instrumental to the wide adaptation of the approach, which arrived timely to the need for a common yet flexible model to marine ecosystem assessment.

A.1 Ecopath

The core model of the EwE6 approach and previous versions is the Ecopath model (Christensen and Pauly, 1993; Pauly et al., 2000; Christensen and Walters, 2004). In Ecopath, organisms of similar population dynamics and ecological function are numerically combined into functional groups (also referred to as *groups* or *pools*), with the exception of species that are deemed of significant importance to the modelled ecosystem which are either represented as individual groups or as a group for each significant life stage. The Ecopath model is based on the presumption that every ecosystem is in a state where the total amount of incoming and outgoing energy balances. By considering a relatively small set of input parameters that represent the dynamics of, and interactions between, functional groups in an ecosystem, Ecopath validates this assumption in a mass-balance assessment.

The Ecopath model describes average energy flows over a given time period which is typically one year (Christensen and Walters, 2004).

In its foundation, the linear equations that constitute to the Ecopath mass-balance assessment are quite simple. Since the system is assumed to be in a steady state, groups must also be in a steady state, thus the total energy input of a group must equal its output. This is expressed in Ecopath as:

$$Q = P + R + U \qquad \text{(eq. 1)}$$

Q is consumption of a group, P its production, R the amount of energy that it respires, and U the amount of unassimilated food. The production P of a group is defined as:

$$P = M2 \cdot B + E + BA + Y + M0 \cdot B \qquad \text{(eq. 2)}$$

Here, *B* is the biomass of a group for the Ecopath time period, *E* is the net migration of this group in the system, *BA* is the biomass accumulation in the ecosystem, Y is the catch, *M2* is the rate of predation mortality exerted onto the group and *M0* is its other mortality rate. Predation mortality *M2* is the total amount of group *(i)* that is eaten by other groups *(j)*, and is expressed relative to the biomass of the group as:

$$M2_i = \sum_{j=1}^{n} \frac{Q_j \cdot DC_{ji}}{B_i} \quad \text{(eq. 3)}$$

The term Q indicates the consumption rate of predator *(j)* and DC_{ji} is the fraction of the diet of predator *(j)* contributed by group *(i)*.

The other mortality *M0* term in equation 1 aggregates all mortality not related to predation such as mortality due to parasites or diseases and is computed as:

$$M0_i = P_i \cdot (1 - EE_i)/B_i \quad \text{(eq. 4)}$$

Here, the ecotrophic efficiency coefficient *EE* represents the production of group (i) that is used within, or removed from the system – i.e. the mortality that is “explained” by the model. By combining the equations above, the mass balance constraints now determine that every group *(i)* can be represented by the following equation:

$$B_i \left(\frac{P}{B}\right)_i \cdot EE_i - Y_i - E_i - BA_i - \sum_{j=1}^{n} Q_j \cdot DC_{ji} = 0 \quad \text{(eq. 5)}$$

This, in essence, is the heart of the Ecopath model.

Equation (5) shows that only three of the four core parameters - biomass (*B*), production rate *(P/B)*, consumption rate *(Q/B)*, and ecotrophic efficiency *(EE)* -need to be entered; the mass balance constraint allows for estimation of the missing term. Not coincidentally, the terms *P/B*, *Q/B* and *Y* are derived from traditional ecological analysis and population dynamics, ensuring that parameter data is widely available, which has contributed to the wide adaptation of the approach.

Ecopath also supports inclusion of fishing efforts and fishing discards into the mass balance assessment (see term M0 in equation 4), and contains delay-difference age/size structures for key populations. In-depth explanations can be found in Pauly et al. (2000), Christensen and Walters (2004), Christensen et al. (2009), and Walters et al. (2010).

The Ecopath model facilitated its use for analyses such as ecological networks (Christensen and Pauly, 1992; Heymans and Baird, 2000), primary production required (Pauly et al., 1995), and mass-balance assessments of ecosystems world-wide. NOAA, the National Oceanic and Atmospheric Administration, celebrated the approach one of the ten biggest scientific breakthroughs in its 200 year existence (NOAA, 2007). Most relevant to this thesis, though, is that the static mass-balance snapshot model Ecopath became the precursor to the time-dynamic model Ecosim (Walters et al., 1997; Walters, 2000) and the time-space dynamic model Ecospace (Walters et al., 1999, 2010).

A.2 Ecosim

In 1995 the Ecosim module was added to the desktop software for exploring past and future impacts of fishing and environmental disturbances over time. Ecosim re-expresses the linear Ecopath equations as a set of differential equations and solves these for regular time intervals for any given time period, under the assumption that biomasses and the ability of any group to produce and consume are variable.

The core equation of Ecosim is based on Ecopath model parameters and applies the mass-balance over time:

$$\frac{dB_i}{dt} = \frac{P}{Q} \cdot \sum Q_{ji} - \sum Q_{ij} + I_i - (M0_i + F_i + e_i) \cdot B_i \qquad \text{(eq. 6)}$$

where dB_i/dt represents the growth rate of group (i) over the time interval *dt* in terms of its biomass B_i.

The consumption rate terms *Qji* and *Qij* are computed based on the foraging arena concept.

A.2.1 Foraging arena

Central in the Ecosim model are dynamic effects of predation (Walters et al., 1997). Traditional predation interactions, based on biomasses of predator, prey and diet rates (known as 'mass action' or Lotka-Volterra assumptions) assume predation to be a function of abundance in predator and prey. Such models could be made to work for small population numbers, but tended to be highly unstable for more complex populations. These models assumed near-linear increases of predators and extinctions of prey, an effect long known not to happen in reality (e.g., Pielou, 1981), even with high predator abundances (Pauly et al., 2000).

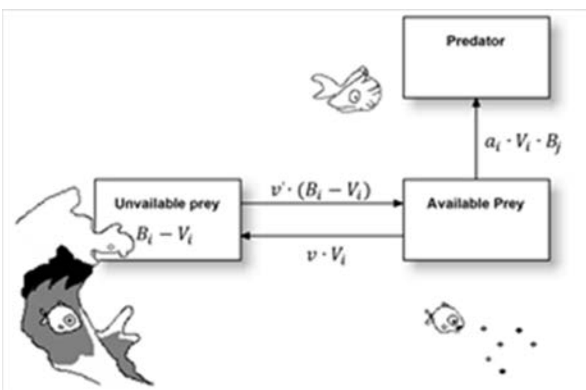

Figure A-1 - The foraging arena theory: only a portion of prey biomass is available to predation at any given moment.

The foraging arena theory was proposed in Ecosim to better approximate reality, and avoid the instabilities of Lotka-Volterra based models. The foraging theory, which could be best thought of as a "risk management behaviour model" (Walters et al., 1999), numerically represents the fact that at a given moment only a fraction of prey biomass in a given aquatic ecosystem is available to a certain predator because of behaviours and physical mechanisms (Walters et al., 1997): fish spend significant amounts of time hiding from predators, and are mainly vulnerable to predation when foraging for food themselves (Figure A-1). Numerically, Ecosim divides biomass *B* of prey group *(i)* into a portion that is available *(V_i)*, and a portion that is unavailable *($B_i - V_i$)* to predation. Prey species transfer between these states at a rate v that corresponds to the fraction of time that prey species can be observed to spend in a 'vulnerable' state. The Lotka-Volterra predation calculations thus only apply to the vulnerable portion of prey *(i)* $V_{i,}$ which is subject to predation as a direct function of predatory biomass B_j at a rate the predators searching rate a_i.

The vulnerable biomass V_{ij} of prey *(i)* to predation by predator *(j)* at a given time t can thus be expressed as the amount that is gained at rate v_{ij} from the pool of unavailable biomass *($B_i - V_i$)* minus the amount that transfers to an invulnerable state $v`_{ij}\ V_{ij}$, minus the amount of biomass of *(i)* that is eaten by *(j)* as $a_{ij}V_{ij}B_{ij}$:

$$\frac{dV_{ij}}{dt} = v_{ij}(B_i - V_{ij}) - v`_{ij}V_{ij} - a_{ij} \cdot V_{ij} \cdot B_{ij} \qquad \text{(eq. 7)}$$

Introduction of the foraging arena equations achieved dynamic stability in complex food webs when constrained to limited space and time, which was facilitated other uses of the EwE approach such as exploration of trade-offs in harvesting strategies (Ahrens et al., 2012). Additionally, this essential stability enabled the development of the spatial module of EwE, Ecospace. However, before moving on to Ecospace, I wish to indicate two functionalities in Ecosim pertaining uncertainty: fit temporal models to time series of data, and the Monte Carlo and Pedigree statistical routines to address data uncertainty in the model.

A.2.2 Fit to time series procedure

The Ecosim model can be calibrated to reference time series of available data (such as relative or absolute species biomass and catch data), along with estimates of temporal fishing impacts dynamics (most notably fishing mortality and fishing effort), into a statistical measure of goodness-of-fit (sum of squared deviations, *SS*) that is frequently used as a metric for assessing the fit of the model to real data. This measure of fit compares model predictions to observed data when available, and is expressed as a weighted sum of squared deviations of log observed catches and biomasses from log predicted catches and biomasses (Christensen and Walters, 2004; Shannon et al., 2004; Coll et al., 2008).

During the fitting, Ecosim calculates the values for vulnerabilities *(*from *equation 7)* to minimize SS deviations between predicted and observed parameters. The model can also calculate an environmental anomaly obtained from the calibration process (which represents a multiplier of the initial Ecopath value of primary producer groups' growth P/B), and that also is used to minimize SS deviations. This anomaly can be then correlated with the environmental data available.

A.2.3 Parameter uncertainty

To address the issue of parameter uncertainty, the Ecosim approach features a Monte Carlo statistical test that draws random input variables to Ecopath from user-provided frequency distributions. When ran for a user-defined number of trials, outcomes are evaluated using the mass-balance constraint and physiological constraints as computed by Ecosim against reference time series (such as used to fit the time series, for example). Expressed in sum of squared deviations (SS) values, the best fitting trial is retained and can be applied to the Ecopath model as new input values for its core variables P/B, Q/B, B, and EE.

This methodology can be used to estimate confident intervals in output parameters of the model.

Users of the approach can also express input parameter confidence by using the pedigree system integrated in Ecopath. Serving a dual purpose, this system can be used to (i) describe the origin of data and (ii) provide a measure of data confidence based on their origin. The confidence intervals provided as part of the pedigree information can be directly connected to determine the frequency distributions used by the Monte Carlo approach (Pauly et al., 2000; Christensen and Walters, 2004).

The pedigree index is used by model users to compare the quality of their model to the overall distribution of pedigree indices of available models, such as published in Morisette (2007).

A.3 Ecospace

The third core module of EwE is the spatial/temporal model Ecospace, a spatially explicit multi-species ecosystem model (Walters et al., 1999, 2010; Christensen et al., 2003; Christensen and Maclean, 2011). Ecospace has been widely applied to quantify the spatial impacts on marine species due to fishing, and to analyse the outcomes of management options such as the establishment of marine protected areas and its impact in terms of spatial distribution of marine species and fishing effort (e.g., Walters, 2000; Martell et al., 2005; Walters et al., 2010; Fouzai et al., 2012). It can also be used to develop spatial optimization routines (Christensen et al., 2009) and assess the impact of climate change by linking the Ecospace model with low trophic level models (Fulton, 2011).

Ecospace is primarily designed to assess the spatial cascade effects of policy screening approaches, rather than to be used for detailed quantitative descriptions (Walters et al., 1999).

The Ecospace model was built to model biomass interactions within an ecosystem across a two-dimensional grid over time. Ecospace distributes Ecopath biomass values of functional groups across a grid of equally sized cells, and uses the Ecosim equations to model how biomasses vary within each cell in the grid over time by taking trophic interactions, fishing and species movement into account.

Beside a mass-balanced Ecopath model and an Ecosim configuration, the Ecospace model requires the following minimal set of inputs:

- Definition of a so-called basemap, which identifies the spatial bounds, number of rows, and number of columns of an Ecospace model grid. The temporal resolution of an Ecospace model is dictated by an underlying Ecosim model (Walters et al., 1999).

- A depth map, identifying water cells (expressed as positive, non-zero depths) and land cells (all other values). Note that the terms depth, land, and water are used in a metaphorical sense. Water cells merely serve to identify in which cells relevant biological interactions occur. Usable terrestrial-based Ecospace applications have successfully switched the land/water concepts without noticeable side effects (e.g., Krebs et al., 2009). Depth is expressed in meters (Walters et al., 1999).

- A relative primary productivity map that identifies primary productivity variations across the basemap. The default map in an Ecospace map assumes a homogenous distribution of primary productivity that can be changed to account for localized variations in productivity (Walters et al., 1999).

  When the Ecospace model initiates, a scaling factor is calculated by dividing the sum of P/B values in the Ecospace map by the number of water cells and the Ecopath P/B ratio. This scaling factor is then used to distribute Ecopath primary productivity values across the Ecospace map. Throughout an Ecospace model run this productivity pattern is kept constant, and is used to spatially distribute fluctuations in primary productivity.

Additionally, Ecospace supports inclusion of:

- Habitat information, such as maps, group-habitat usage preferences, and habitat-fishing preferences that are used to limit species occurrences and fishing effort;

- Marine protected area maps and fishing limitations direct the allocation of fishing effort in the Ecospace model;
- Additional fishing cost maps influence dispersal of fishing effort;
- Migration patterns, dispersal rates, and occurrence envelopes for individual groups to drive movements;
- Arbitrary regions for aggregating spatial results.

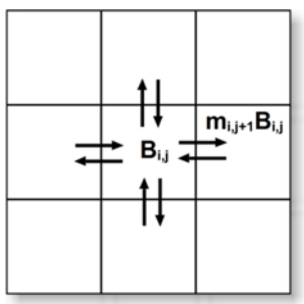

Figure A-2 - Functional group movement in Ecospace.

Species movement in Ecospace is constrained to vertices of adjacent cells, and is dictated by differences in cell suitability for individual groups (Figure A-2). Movement cannot occur diagonally, and cannot occur across cells land cells. Biomass within a cell is assumed to be homogenous, e.g. rapidly mixing. For boundary cells – cells at the outer edges of the grid – it is assumed that biomass conditions in the non-modelled cells are equal to the conditions in the cell.

A.3.1 Habitat foraging capacity model

Up to and including Ecospace version 6.2, biomasses of functional groups were distributed according to presence/absence habitat preferences of functional groups. Large scale habitat structures, with attendant impact on biomass distributions and trophic interactions, were represented only by an presence/absence habitat use pattern. This formulation has been particularly troublesome for models with strong “sub-grid” spatial structures of key habitat types, e.g., small but productive structures such as reefs and coastal zones that are smaller than a single grid cell but cannot be represented as entire cells.

Decreasing the cell size of an Ecospace scenario to mitigate this shortcoming adversely impacts the speed of computations and the amount of memory needed at runtime, and eventually yields unrealistic results by over-representing modelled phenomena (Fulton et al., 2004). Further, the complex gradient calculation required by the traditional Ecospace calculations greatly slows simulations of changing habitat usage over time, requiring re-calculation of gradients whenever species habitat preference changes occur.

To overcome these problems the Ecospace model has been recently re-structured to represent habitat quality as a ratio in its calculations. In this new model, called the habitat foraging capacity model, this ratio represents the fraction of a cell that is accessible for species to forage, and is determined by multiple environmental factors other than traditional habitat. This modification enables the Ecospace model to capture the fact that large forage areas have lower local impacts, while small forage areas will have higher local impact.

The new model is compatible with older EwE models by providing the option to derive capacity directly from presence/absence habitats which ensures that earlier Ecospace scenarios, built before the habitat foraging capacity model was introduced, will function unaffected under the new computations. In this case, the capacity map for a functional group is populated to full capacity for every cell that contains a habitat that a species uses, and minimum capacity for every other cell.

In addition, the new Ecospace model is extended to accept spatial maps for any environmental effect that is known to limit the ability of species to thrive. Using user-defined response functions for individual groups to these factors, the Ecospace model calculates the cumulative impact to spatially distribute Ecopath groups, overcoming the limitations of the original habitat description in Ecospace.

A logical next step in this development will be to calculate cell capacity for every functional group at every time step, taking varying environmental maps into account. Then, Ecospace will become fully temporal and spatially dynamic, integrating envelope environmental models and ecosystem food-web models (Jones et al., 2012), progressing towards the capability to predict changes in marine ecosystems under scenarios of climate change and explicitly taking into account food-web direct and indirect interactions.

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Annex B GIS toolkit evaluation

Table B-1 - Overview of evaluated free and open source GIS toolkit libraries for implementing the prototype of the spatial temporal data framework

GIS toolkit	Main purpose	License	Language	Capabilities					Support structures				
				File access	GeoDB access	Web services	Opera-tions	Visuali-zation	Extendable	Ref. docs	User community	Developer community	Last release
Geospatial Data Abstraction Library	Data access	MIT/X	C	+++	+	-	++	-	++	++	+++	+	2012
FWTools	Geoprocessing	MITX	C++ python	+++	++	+++	++	++	+++	++	+++	+	2011
PROJ.4	Projection conversion	MIT/X	C	-	-	-	+	-	+	+++	+++	+	2012
Orfeo	Remote sensing	CeCILL	C++	+++	+	-	+	+++	+++	+++	+++	+++	2012
Mapnik	Visualization	LGPL	C++ python	+++	+	-	-	+++	++	+++	+++	+++	2012
Feature Data Objects	Data access	LGPL	C++	+++	+++	-	+++	-	+++	+++	-	-	2007
OpenEV	Visualization, Raster analysis	LGPL	Python	+++	+	-	++	++	?	+	+	-	2004
Open Source Software Image Map	Image processing	LGPL	C++	+++	-	-	+++	+++	+++	++	?	+	2009
Insight Toolkit	Image processing	BSD	C++	-	-	-	+++	-	+	++	++	++	2011
Geometry Engine, Open Source	(See JTS)	LGPL	C/C++	+++	+++	-	+++	-	++	++	++	+++	2012
Shapely	Geoprocessing, Editing	LGPL	Python	++	++	-	+++	+	+++	+++	?	+	2012
TerraLib	GeoDatabase Access	LGPL	C++	-	+++	-	-	-	+++	++	+	+++	2012
Whitebox GAT	Spatial statistics	GPL	Java	+	-	-	+++	+++	++	+++	?	++	2012
Java Topology Suite (JTS)	Geoprocessing, Spat. querying	LGPL	Java	+++	+++	-	+++	++	++	++	?	++	2006
OpenJUMP	Visualization, Editing	GPL	Java	+++	+	+++	+++	+++	+++	+++	+++	++	2012
Java Map Projection Library	Projections	Apache	Java	-	-	-	+	--	++	+	?	+	2012
NTS	(See JTS)	LGPL	C#	+++	+++	-	+++	+	++	-	-	+	2012
DotSpatial	Geoprocessing	LGPL	C#	+++	+	+	+++	+++	+++	+++	+++	+++	2012
Proj.NET	(See PROJ.4)	LGPL	C#	-	-	-	+	-	+++	-	+	-	2009
SharpMap	Spat. Querying, visualzation	LGPL	C#	+++	++	++	-	+++	+++	+++	++	+++	2012
GeoAPI.NET	Metadata, interoperability	LGPL	C#	-	-	-	-	-	+	+++	?	+++	2012
Gecko.NET	Visualization	?	C#	+	-	++	+	++	+	-	?	-	2008

Annex C Additional case study results and discussion

This annex provides supplementary material to the discussion and results of the case study as discussed in section 5.3.

The scenarios were run from 1975 to 2008 using Ecosim fitted to the original time series data, followed by the Ecospace module afterwards. These results were then analysed looking at the temporal and spatial dynamics of phytoplankton and other specific components of the food web (Figure C-1). The groups were chosen by taking into account the ecology of different functional groups of the model and their direct or indirect relationships with phytoplankton (Coll et al., 2007, 2009):

1. Phytoplankton, which serves as the nutritional basis for the food web;
2. Zooplankton, which primarily consumes phytoplankton, and should thus be severely affected by fluctuations in phytoplankton;
3. Sardine, with a diet that consists mostly of zooplankton, supplemented with phytoplankton;
4. Anchovy, with a diet that consists entirely of zooplankton;
5. Seabirds, that consume mostly sardine, and some anchovy;
6. Large pelagic fish, with a diet that consists largely of anchovy;
7. Adult hake, with a diet that consists largely of anchovy and sardine, and demersal organisms.

In addition to the diet dynamics, anchovies, sardines, large pelagic fish and adult hake were nominated for consideration as they are highly commercial species and have been subjected to large fishing effort from historic times to the present (Coll et al., 2009; Lotze et al., 2011).

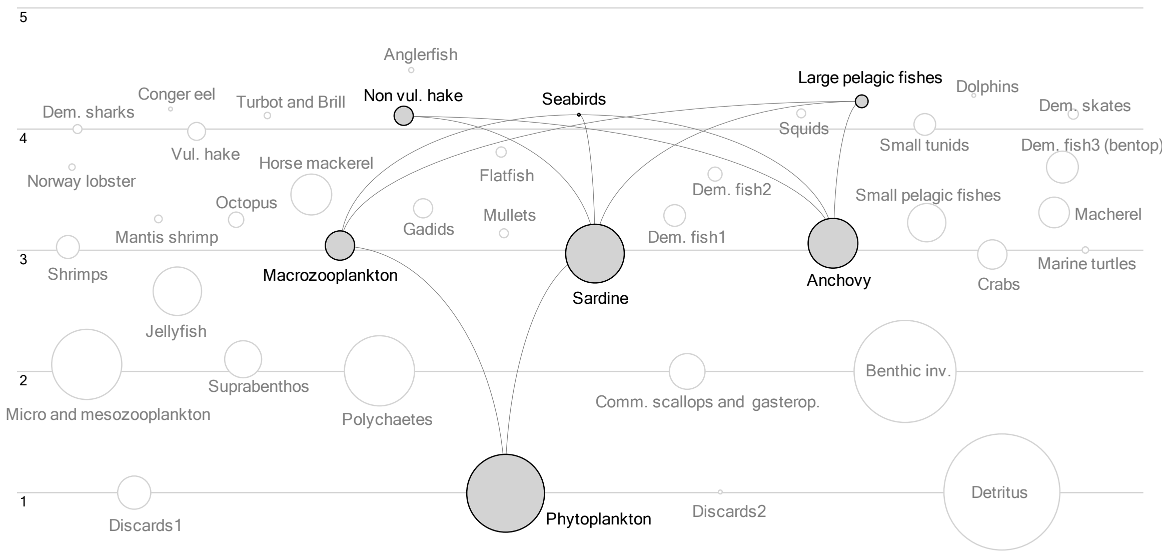

Figure C-1 - Food web of the North and Central Adriatic model, based on Coll et al. (2007, 2009). This figure highlights the groups that were used to analyse the impact of the new spatial framework on the Adriatic food-web model, their tropic levels, and dietary links between the highlighted groups. Dietary links to and between other groups are not drawn. The y-axis represents trophic level from lowest (TL = 1, for primary producers and detritus) to highest (TL >4).

C.1 Temporal food web effects of phytoplankton biomass changes

The three different scenarios produced important temporal results in the food web (Figures C-2, C-3 and C-4).

The temporal results of the original run of the model showed increasing sardine biomass due to higher biomass of phytoplankton, their prey, and a decrease in zooplankton due to higher predation mortality by sardines (Figure C-2) (Coll et al., 2009). On the contrary, and due to high fishing pressure, anchovy firstly increased due to prey availability but then continued its historical decline. The seabirds, and to a lesser extent the large pelagic fish, increased due to higher abundance of prey, mainly small pelagic fish, predominantly sardine, while hake continued to decline due to high fishing impact over time (Coll et al., 2009, 2010; Fouzai et al., 2012).

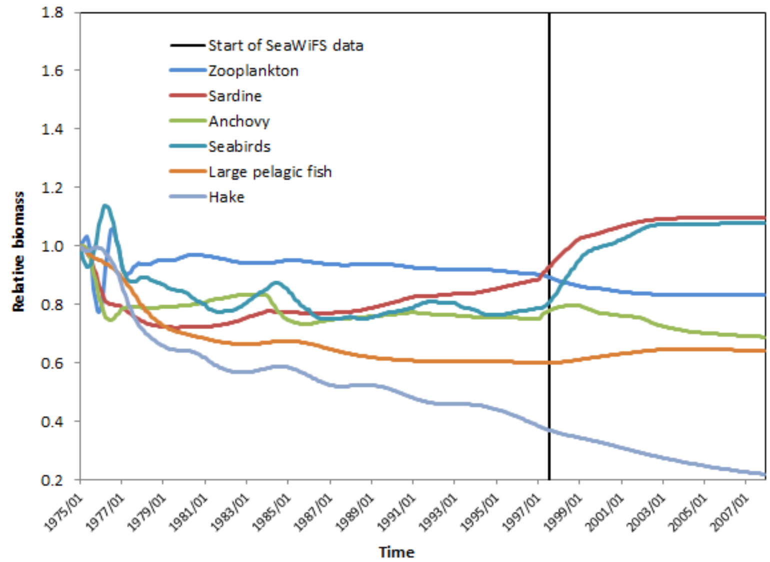

Figure C-2 - Relative biomasses in the Northern and Central Adriatic, as computed by Ecospace, when the spatio-temporal simulation was executed without any external primary production data.

Under the second scenario, with monthly spatial-temporal PP data, the model showed high variation in the biomass of zooplankton after 1997 following the variation in phytoplankton (Figure 33) that was translated into high variation in the biomass of sardine, anchovy and seabirds (Figure C-3). Sardine and seabirds, in contrast to the first scenario and due to the pattern observed in phytoplankton biomass under this scenario (Figure 33), showed first an increase and afterwards a decline, which was also observed in the patterns of large pelagic fish, but with much less variability. Anchovy and hake continued to decline due to fishing impact (Coll et al., 2009; Fouzai et al., 2012) (Figure C-3), although anchovy showed a slight increase in biomass late 1990s, due to higher phytoplankton biomass, and overall larger variability than hake.

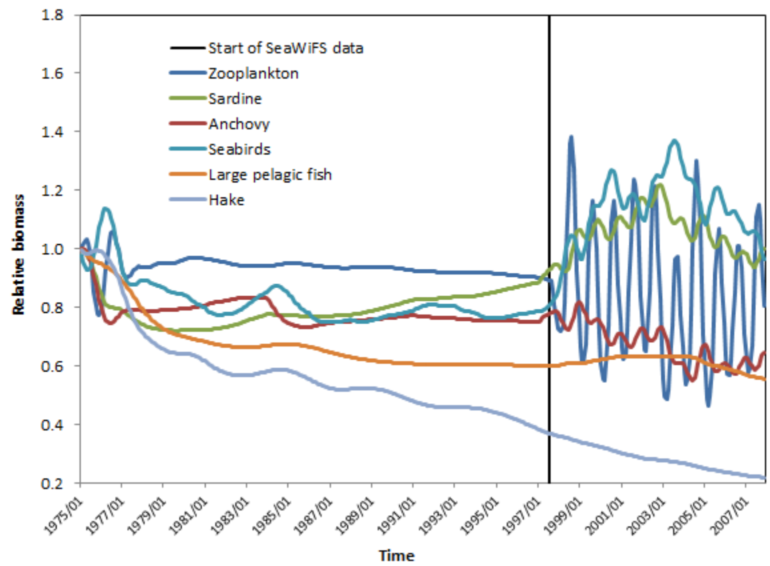

Figure C-3 – Relative biomasses in the Northern and Central Adriatic, as computed by Ecospace, when forced with monthly JRC primary production data from 1997 to 2007.

Under the third scenario, with annual averaged spatial-temporal PP data, the model showed lower variability but similar results to scenario 2 (Figure C-4). Sardine increased first and then declined following phytoplankton biomass patterns, and this trend cascaded up the food web to seabirds and in to a lesser extent to large pelagic fish. Zooplankton declined due to declines of the prey (phytoplankton) and higher predation mortality, while anchovy and hake continued their historical declines due to the impact of fishing (Coll et al., 2009; Fouzai et al., 2012) (Figure C-4). A slight increase of the biomass of anchovy biomass in the late 1990s can be attributed to higher phytoplankton biomass with the higher variability observed in zooplankton dynamics.

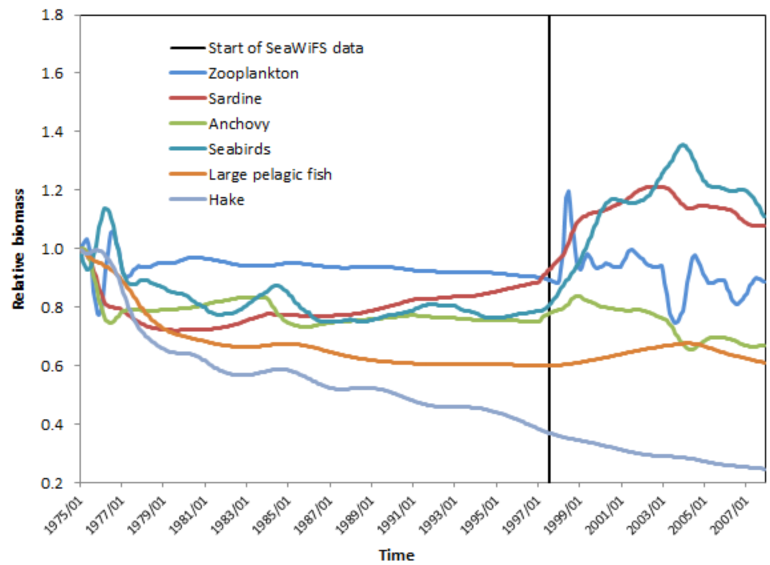

Figure C-4 - Relative biomasses in the Northern and Central Adriatic, as computed by Ecospace, when forced with annual JRC primary production data from 1997 to 2007.

From these results it is evident that changes at the phytoplankton level cascaded up the food web reaching first the zooplankton, then the small pelagic fish, and finally their predators (mainly seabirds and large pelagic fish). Adult hake, the demersal predator, did not show clear signs of responding to this cascading effect, but this may be due to high fishing impact on this species and the historical decline that has been observed in the area (Coll et al., 2009; Fortibuoni et al., 2010; Lotze et al., 2011).

C.2 Temporal and spatial food-web effects by functional group

C.2.1 Zooplankton

The temporal dynamic of zooplankton biomass on the three scenarios analysed was similar (Figure C-5), mainly showing a decline from early 1990s to the end of the simulations. Over the duration of the simulation period the original model showed an almost stable biomass level while the monthly data showed higher fluctuations than annual data.

The spatial dynamics of zooplankton biomass of the original model captured some of the phytoplankton spatial dynamics (Figure C-6a), although the spatial patterns were more realistic when the external data under the second and third scenarios were used (Figures C-6b and C-6c) showing higher zooplankton biomass in northern and western coastal areas of the study region. Differences in spatial distributions between the second and the third scenario were small (Figures C-6b and C-6c), showing that both monthly and annual averaged data produced similar results at the end of the modelling runs.

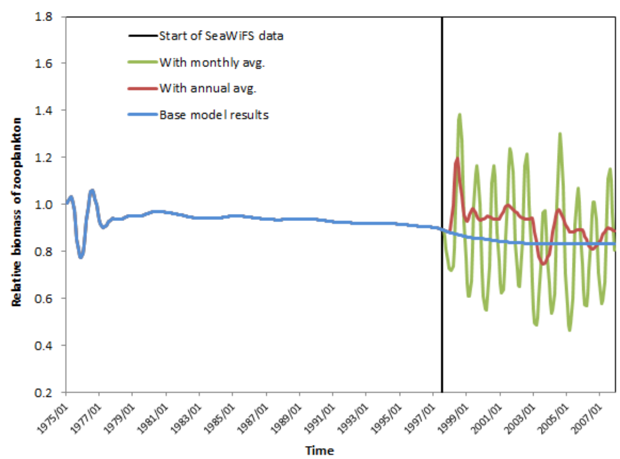

Figure C-5 –Ecospace relative dynamics of zooplankton biomass, relative to the start value, for the three scenarios analysed.

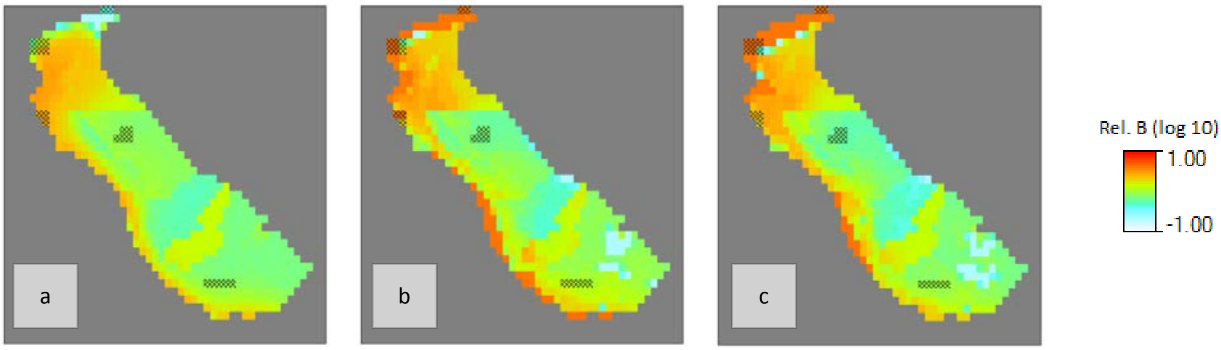

Figure C-6 - Ecospace map showing the distribution of relative biomass of zooplankton for the last year of the simulation, 2007. Results are related with the model (a) without external PP data, (b) with monthly PP data, and (c) with annual PP data.

C.2.2 Sardines

The temporal dynamic of sardine biomass under the three scenarios analysed show differences (Figure C-7) due to a decline of phytoplankton biomass in the second and third scenario that was not reproduced in the first one (Figure 33).

The spatial dynamics of sardine biomass of the original model captured some of the phytoplankton spatial dynamics (Figure C-8a), although the spatial patterns were also clearer when the external data was used (Figures C-8b and C-8c). Differences between the second and the third scenario were also small (Figures C-8b and C-8c), as for the zooplankton functional group.

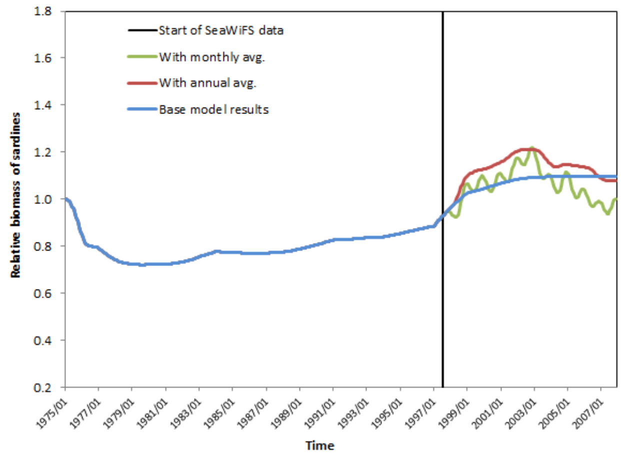

Figure C-7 - Ecospace relative dynamics of sardine biomass, relative to the start value, for the three scenarios analysed.

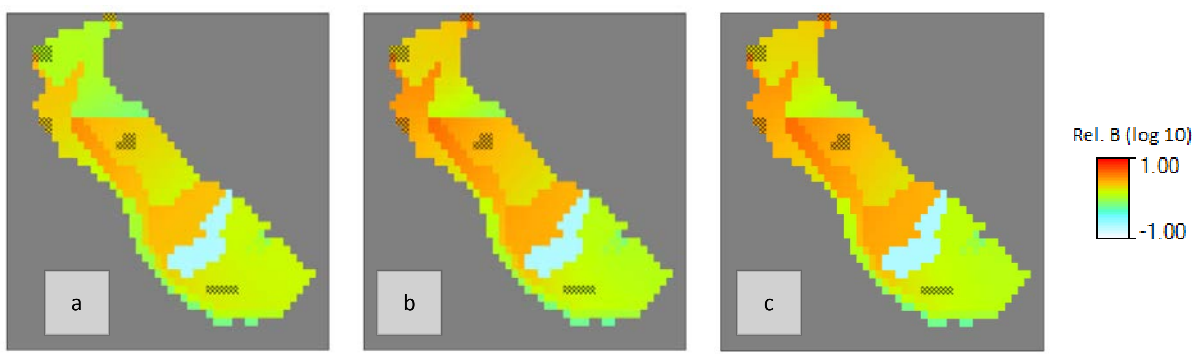

Figure C-8 - Ecospace map showing the distribution of relative biomass of sardine for the last year of the simulation, 2007. Results are related with the model (a) without external PP data, (b) with monthly PP data, and (c) with annual PP data.

C.2.3 Anchovies

The temporal dynamic of anchovy biomass under the three scenarios analysed were similar as for the zooplankton group (Figure C-9). This is mainly due to a decline in phytoplankton biomass in the second and third scenarios and higher predation mortality in the first scenario (Coll et al., 2009). Therefore, the increase of phytoplankton during the last 1990s was not captured by anchovies as it was for sardines. This result is most likely due to the fact that anchovies feed exclusively on zooplankton.

The spatial dynamics of anchovy biomass of the original model and the new spatial framework showed similar patterns for anchovy distribution, although these patterns were more evident with the new spatial framework in place (Figure C-10). Differences between the second and the third scenario were also minor (Figures C-10b and C-10c).

Figure C-9 - Ecospace relative dynamics of anchovy biomass, relative to the start value, for the three scenarios analysed.

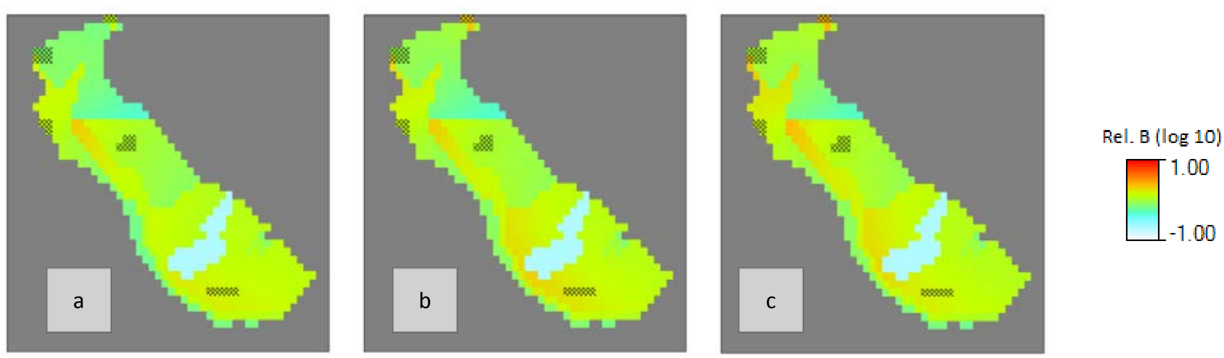

Figure C-10 - Ecospace map showing the distribution of relative biomass of anchovy for the last year of the

simulation, 2007. Results are related with the model (a) without external PP data, (b) with monthly PP data, and (c) with annual PP data.

C.2.4 Seabirds

Seabirds' biomass also showed first an increase and then a decrease of biomass from the early 1990s to late 2000s following sardine's dynamics (Figure C-11) based on the second and third scenarios using the new spatial framework. The original model, on the contrary, showed an increase and stabilization of seabirds with time. This is due to seabirds being parameterized in the food-web model to consume mostly sardine (Coll et al., 2009).

The spatial distribution of seabirds' biomass was similar under the three simulations (Figures C-12a to C-12c). However, the original model predicted less abundance of seabirds in the northern areas of the Adriatic Sea, probably due to less productivity patterns predicted in that area (Figure 35). This is less realistic than results using the new spatial module since seabird populations in the north of the Adriatic Sea are known to be very abundant (e.g. Boldreghini et al., 1997).

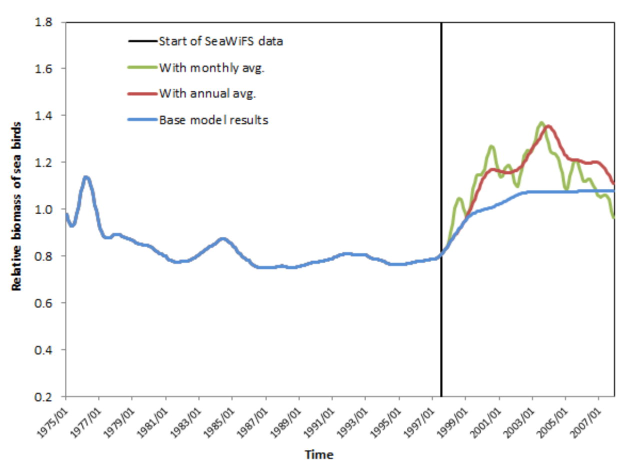

Figure C-11 - Ecospace relative dynamics of seabirds' biomass, relative to the start value, for the three scenarios analysed.

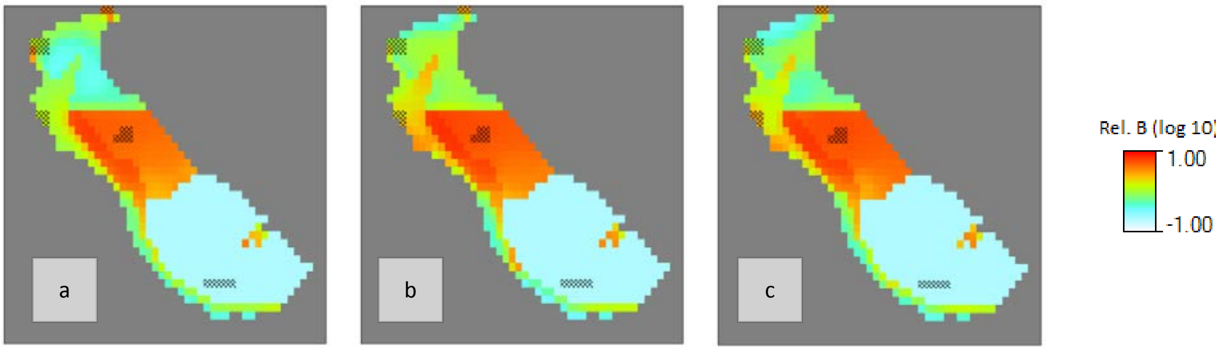

Figure C-12 - Ecospace map showing the distribution of relative biomass of seabirds for the last year of the simulation, 2007. Results are related with the model (a) without external PP data, (b) with monthly PP data, and (c) with annual PP data.

C.2.5 Large pelagic fish

The temporal dynamic of large pelagic fish biomass initially increased slightly and was then maintained under the first scenario, but under the second and third scenarios this group showed a similar trend to sardines following a similar trend to their prey (Figure C-13). However, the decline they showed under the second and the third scenarios after the initial increase also provided evidence of their dependency on anchovy, which declined with time (Figure C-13).

The spatial dynamics of large pelagic fish biomass of the original model and the new spatial framework showed overall similar patterns (Figure C-14a to C-14c).

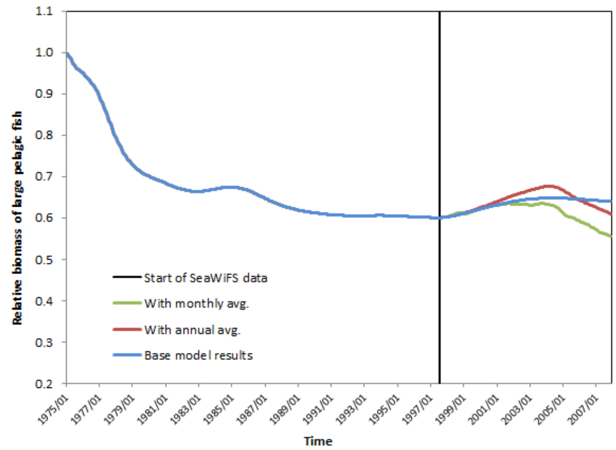

Figure C-13 - Ecospace relative dynamics of large pelagic fish biomass, relative to the start value, for the three scenarios analysed.

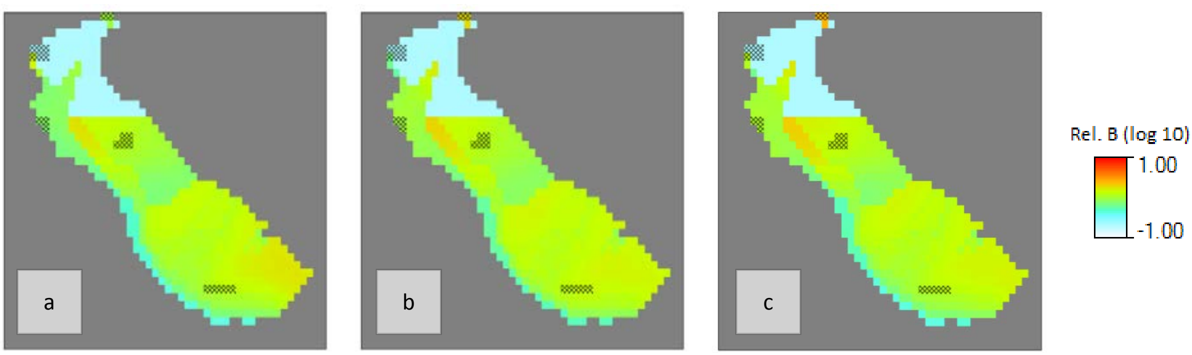

Figure C-14 - Ecospace map showing the distribution of relative biomass of large pelagic fish for the last year of the simulation, 2007. Results are related with the model (a) without external PP data, (b) with monthly PP data, and (c) with annual PP data.

C.2.6 Adult hake

Finally, the temporal dynamic of adult hake showed a strong declined in the three analysed scenarios (Figure C-15), mainly due to the large historical fishing impact of this species in the area (Coll et al. 2009, Fouzai et al. 2012) and due to the decline of one of its main preys, anchovy (Figure C-9), but also of sardine in the last part of the time series (Figure C-8).

The spatial dynamics of adult hake biomass of the original model and the new spatial framework showed overall similar patterns (Figure C-16).

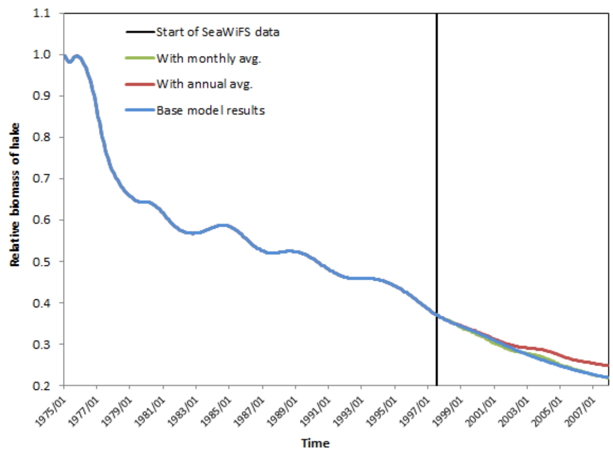

Figure C-15 - Ecospace relative dynamics of hake biomass, relative to the start value, for the three scenarios analysed.

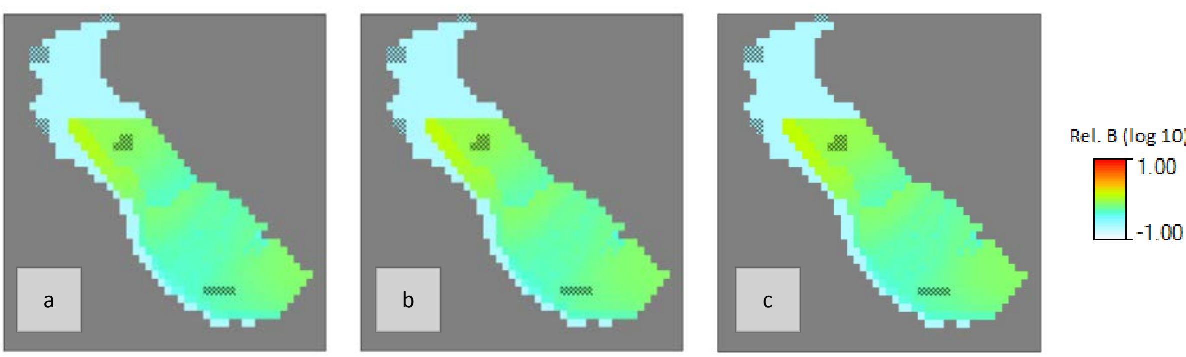

Figure C-16 - Ecospace map showing the distribution of relative biomass of hake for the last year of the simulation, 2007. Results are related with the model (a) without external PP data, (b) with monthly PP data, and (c) with annual PP data.

C.3 Discussion

Overall, changes in the temporal dynamics of phytoplankton biomasses cascaded up the food web and influenced the dynamics of zooplankton and small pelagic fish, which directly feed on phytoplankton or zooplankton (Palomera et al., 2007). The impact on the dynamics of larger predators was also noticeable; although such impact was mitigated by other dietary links in the food web. Seabirds and large predatory fish showed similar patterns as their prey. When the new spatial framework was in place (under the second and third scenarios), these groups showed first an increase, followed by a decrease in abundance due to spatial patterns of first phytoplankton, then for zooplankton, and then small pelagic fish. The dynamics of adult hake, on the contrary, were less affected by the bottom-up effects of the food chain due to the high fishing pressure placed upon this highly commercial species (Coll et al., 2009; Fouzai et al., 2012).

Simulations including the external data reproduced more realistic spatial distribution of phytoplankton and thus yielded more accurate spatial distributions of zooplankton and small pelagic fish. The differences between the three simulations regarding the distribution of predators were less profound and may indicate that real predator distributions are affected by other factors than just the distribution of their prey. Either the chosen model configuration did not include all required factors to adequately predict predator distributions, or the biological dynamics are overshadowed by other impacts such as high fishing pressure.

C.4 References

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