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Recovery or decline of the northwestern Black Sea: A societal choice revealed by socio-ecological modelling

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ABSTRACT

During recent decades anthropogenic activities have dramatically impacted the Black Sea ecosystem. High levels of riverine nutrient input during the 1970s and 1980s caused eutrophic conditions including intense algal blooms resulting in hypoxia and the subsequent collapse of benthic habitats on the northwestern shelf. Intense fishing pressure also depleted stocks of many apex predators, contributing to an increase in planktivorous fish that are now the focus of fishing efforts. Additionally, the Black Sea's ecosystem changed even further with the introduction of exotic species. Economic collapse of the surrounding socialist republics in the early 1990s resulted in decreased nutrient loading which has allowed the Black Sea ecosystem to start to recover, but under rapidly changing economic and political conditions, future recovery is uncertain.

In this study we use a multidisciplinary approach to integrate information from socio-economic and ecological systems to model the effects of future development scenarios on the marine environment of the northwestern Black Sea shelf. The Driver–Pressure–State-Impact-Response framework was used to construct conceptual models, explicitly mapping impacts of socio-economic Drivers on the marine ecosystem. Bayesian belief networks (BBNs), a stochastic modelling technique, were used to quantify these causal relationships, operationalise models and assess the effects of alternative development paths on the Black Sea ecosystem. BBNs use probabilistic dependencies as a common metric, allowing the integration of quantitative and qualitative information.

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Under the Baseline Scenario, recovery of the Black Sea appears tenuous as the exploitation of environmental resources (agriculture, fishing and shipping) increases with continued economic development of post-Soviet countries. This results in the loss of wetlands through drainage and reclamation. Water transparency decreases as phytoplankton bloom and this deterioration in water quality leads to the degradation of coastal plant communities (*Cystoseira*, seagrass) and also *Phyllophora* habitat on the shelf. Decomposition of benthic plants results in hypoxia killing flora and fauna associated with these habitats. Ecological pressure from these factors along with constant levels of fishing activity results in target stocks remaining depleted. Of the four Alternative Scenarios, two show improvements on the Baseline ecosystem condition, with improved waste water treatment and reduced fishing pressure, while the other two show a worsening, due to increased natural resource exploitation leading to rapid reversal of any recent ecosystem recovery. From this we conclude that variations in economic policy have significant consequences for the health of the Black Sea, and ecosystem recovery is directly linked to social–economic choices.

1. Introduction

During recent decades anthropogenic activities have dramatically impacted the Black Sea ecosystem. High levels of riverine nutrient input during the 1970s and 1980s caused severe eutrophic conditions resulting in extensive algal blooms and changes in phytoplankton community composition (Bodeanu, 2002). Increased pelagic productivity also led to increased water column turbidity and hypoxia on the northwestern shelf (Cociasu et al., 1996). These conditions resulted in the decline of coastal macrophyte communities, including the brown alga *Cystoseira barbata* and seagrasses. On the shelf, the area and biomass of the *Phyllophora* field (*P. crispa*, *P. truncata*) declined (Minicheva, 2007) and as did *Mytilus galloprovincialis* eventually. These species provide key habitats for a diverse group of associated species, many of which consequently declined in abundance (Zaitsev and Mamaev, 1997).

The Black Sea's ecosystem changed further still with the introductions of the comb jelly *Mnemiopsis leidyi* and the sea snail *Rapana venosa*. *Mnemiopsis* outcompeted small fish while also preying on their larvae and eggs, thereby further altering the structure of the pelagic food web (Shiganova, 1998). *Mnemiopsis* had no natural predators until another gelatinous species, *Beroe ovata*, was introduced in 1997, which decreased the biomass of *Mnemiopsis* significantly (Kideys, 2002). *R. venosa* has destroyed mussel communities (Zaitsev, 1992), and continues to have an impact, but in addition, is now an important target species for Black Sea fisheries.

Intense fishing pressure has depleted stocks of many apex predators; some species have effectively disappeared from catches in the Black Sea since the 1970s (such as tuna, *Thunnus thynnus*; swordfish, *Xiphias gladius*; and mackerel, *Scomber scombrus*; Prodanov et al., 1997). Stocks of planktivorous pelagic species such as sprat (*Sprattus sprattus* and *Clupeonella cultriventris*) and anchovy (*Engraulis encrasicolus*) have increased since the early 1990s and are now the focus of fishing efforts (Daskalov, 2002). Demersal fisheries have expanded as the target has changed from fish stocks such as the almost depleted mullet (*Muglidae*), whiting (*Merlangius merlangus*) and turbot (*Scophthalmus maximus*) to the invasive sea snail *R. venosa*.

The economic collapse of the surrounding socialist republics in the early 1990s resulted in decreased nutrient loading which has allowed the Black Sea ecosystem to begin to recover (Yunev et al., 2002; Bodeanu et al., 2004; Mee, 2006). The Black Sea has also experienced increased trade and shipping traffic, and with the economies of the previous communist states now in a period of transition and growth, industries such as tourism, urbanisation, and infrastructure development are again increasing pressure on the Black Sea coastal zone (BSERP—Black Sea Ecosystem Recovery Project, 2007). However, under rapidly changing economic and political conditions, future recovery is uncertain. Environmental management of the Black Sea is further complicated by the fact that 9 of the 16 countries comprising the majority of its catchment are non-EU states.

This research aims to improve our understanding of the relationship between European lifestyles and the state of marine ecosystems through modelling of consequences of Alternative Scenarios for human development in post-accession Europe on the Black Sea marine environment.

2. Methods

2.1. Study area

The Black Sea drains a catchment area containing parts of 23 countries, covering a land area of 2.4 million km^2 and receiving waste water from >190 million people (daNUbs, 2005). The Black Sea is a nearly enclosed body of water, with only a narrow inlet to the Mediterranean through the Bosphorus Strait. In its northwestern region, the Black Sea has a wide and biologically active continental shelf while the open sea is permanently anoxic below 100–150 m (Sorokin, 2002). Hydrographically, the Black Sea is divided into two distinct regions: the shallow (<200 m) northwestern shelf and the deep (>1000 m) central sea (Fig. 1). The northwestern shelf receives most of the nutrient load to the Black Sea through riverine inputs from the Dniester, Dnieper and Danube rivers and is therefore the region most severely impacted by eutrophication (Cociasu and Popa, 2004). A large portion of the terrestrial nutrients entering the Black Sea originate in central and western Europe, particularly those transported by the Danube,

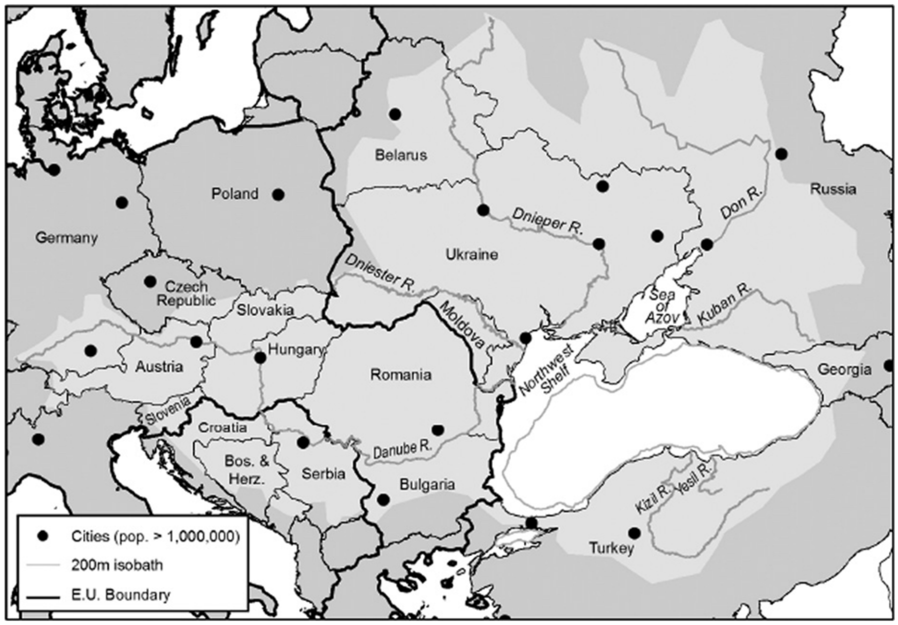

Fig. 1 – The Black Sea. Nine of the 16 countries comprising the majority of its catchment are non-EU states.

which alone is responsible for 75% of total nutrient input to the Black Sea (Mee, 1992; Zaitsev and Mamaev, 1997).

2.2. *Modelling approach*

A modified DPSIR (Driver–Pressure–State-Impact-Response) framework (see Fig. 2, and Mee et al., in preparation, for full description) was used to construct conceptual models of coupled socio-ecological systems, explicitly mapping impacts of socio-economic Drivers on the marine environment. The DPSIR framework provided a way of organising and integrating information on current major State changes in the Black Sea, the Pressures on the environment producing these changes and the social and economic Drivers leading to these Pressures.

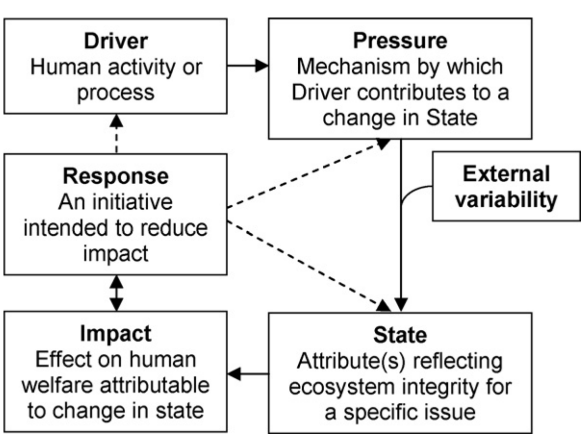

Fig. 2 – Modified DPSIR (Driver–Pressure–State-Impact-Response) framework (Mee et al., in preparation). This was used to organise social and ecological information and map pathways from proximal Drivers (human activities) to changes in ecological States.

Bayesian belief networks (BBNs) were used to quantify the causal relationships between DPS components and operationalise models. BBNs, based on Bayesian statistics, arose in the 1980s (Pearl, 1988). Bayesian statistics use probability theory, developed by Reverend Thomas Bayes (1702–1762), as a measure of uncertainty. Beliefs about variables are expressed as probability distributions; the higher the uncertainty of the real value the wider its distribution. In BBNs, each variable is represented as a node in the network and causal relationships are represented as arcs between them. Each variable has one (in the case of marginal nodes) or several probability distributions associated with it, for each of every possible combination of the values of its parents (upstream variables). Bayes Theorem is then used to compute all probabilities aside from the marginal distributions, that, in this study, were preconditioned by development scenarios.

Probabilistic dependencies act as a common metric, allowing the integration of quantitative and qualitative information, including time-series data, metadata analyses, model-derived data, economic indices, environmental diversity measures and expert knowledge (Jensen, 2001). This was one reason why BBNs were used in this study, but in addition, BBNs do not require specific understanding of the complex systems linking two causally related variables because State changes are represented as probabilities and uncertainties are implicit in their distributions.

Conditional probability distributions specify the belief that a variable will be in a particular predetermined condition given the states of the upstream variables. Thus changes in the state of upstream variables cascade through the model, and are reflected in the conditional probability distributions of those downstream. A commercially available Bayesian belief network software package, Netica™ (version 3.17), was chosen for this investigation. Netica uses the Lauritzen and Spiegelhalter algorithm (Lauritzen and Spiegelhalter, 1988) to calculate

Fig. 3 – The scenarios were developed along two dimensions reflecting fundamental characteristics of social systems: values (consumerism vs. community) and level of governance (interdependence vs. autonomy) (see supporting online material, S1, for descriptions of each scenario).

binary pair-wise correlations of all possible combinations of linked variables.

2.2.1. *Model development*

The Black Sea simulation model was constructed by initially creating comprehensive broad scale conceptual models of several thematic issues addressed (habitat loss, eutrophication, fisheries). This was an iterative process undertaken by experts in Dahlem-style workshops (Freie Universitat Berlin, 2006) and resulted in identification of Drivers, Pressures, States, and mapping of pathways through which these are interlinked. Then pathways and variables were prioritised by perceived importance and potential indicators and data sources identified, resulting in a refined simulation model (Fig. 3). Different environmental problems affecting the Black Sea required different approaches. For example, fisheries were characterised using a typology approach, as information could not be gathered for every fishery in the northwestern Black Sea region; a small pelagic (anchovy and sprat) and a demersal (turbot) fishery were included. Similarly, fishing effort was separated into demersal (dredging and trawling) and pelagic (all gears aggregated) to enable the destructive impacts of demersal fishing activity (for example dredging for *Rapana*) on benthic marine habitats to be mapped through BBNs.

2.2.2. *Selecting variable indicators and proxies*

Appropriate indicators were selected to populate each Driver, Pressure, and State variable in the simulation model. Indicators were chosen based on representativeness, temporal dataset length, and data availability. Where data were unavailable or unsuitable for a particular indicator, proxy datasets were identified. For example, fishing effort data were not available but fishing capacity (gross tonnage of fleet) was used as a proxy. Nutrient concentrations in the water column are not explicitly represented in the model. This is because available time-series were not spatially representative, coming from a single station off the coast of Romania. Hence nutrient-related Drivers were connected directly to phytoplankton biomass (a State variable). For habitat loss, specific examples were chosen as case studies. The selection criteria included perceived importance, data availability, and representativeness. As data are very sparse, metadata analyses were used to populate *Phyllophora* habitat (a keystone red alga) and a sufficiently long time-series measuring total zoobenthos abundance and biomass was not available, but it was possible to construct a time-series for *Mytilus galloprovincialis* biomass, as a proxy for benthic invertebrate fauna.

Including introduced species proved problematic since no time-series of sufficient length were available for the two species with the greatest impact to date: *Mnemiopsis leidyi* and *Rapana venosa*. Thus a risk-based approach was taken, applying data on the number of species introduced, and since the impact of any individual species is highly variable, an assumption was made that increasing numbers of introduced species elevates the risk of a highly invasive species damaging the ecosystem. Since neither *M. leidyi* nor *R. venosa* were included explicitly, their impacts on the pelagic and benthic systems could not be modelled directly. However these are implicit in the probability density functions describing the relationships of, for example, pelagic catch and stock (where uncertainty represents other factors influencing stock such as *Mnemiopsis* predation).

2.2.3. *Discretisation and thresholds*

Each variable was assigned a number of states (i.e. indicators were transformed from continuous to discrete data). Most variables had two states (e.g. 'low' and 'high'; 'present' and 'absent'; 'negative' and 'positive'), as the number of possible states was constrained by the short time-series available. Thresholds between these states were selected by one of three methods: (1) Where a threshold was known it was used. (2) Where a variable had a legislative value associated with it above which its state would be in breach of law, this value could be used as the threshold; however, this was seldom practical as such values were rarely significant to ecosystem functioning. (3) The median value was the most appropriate threshold in most cases, allowing the greatest possible overlap between linked datasets.

2.2.4. *Data*

Simulation model data were extracted from a diverse range of sources, including time-series measurements, extensive novel metadata analyses of reports and peer reviewed publications, model-derived data, indices, interpolated data, and expert opinion (Table 1). A common data format was needed to allow pair-wise assessment of between-variable probabilities using BBNs; annual time-series were chosen as this type of data maximizes comparability of datasets within a model. Where necessary, data were spatially aggregated to increase their representativeness and to match spatial scales. Area spatial-weighting of certain data on catchment-mediated Drivers based on the relative proportion of a country in the Danube catchment was also applied to harmonize spatial scales. Gaps

Table 1 – Black Sea simulation model data sources.

	Variable	Indicator	Data type	Source	Geographic coverage	Temporal coverage
Drivers	Shipping activity	Tanker traffic through Bosphorus Strait (*n* vessels)	Time-series	Turkish Maritime Pilots Association[a]	Bosphorus Strait	1996–2003
	Fishing effort	Gross tonnage of fleet (Mt)	Time-series	FIGIS[b]	Bulgaria, Romania, Ukraine	1970–1995[c]
	Dredging and trawling effort	Gross tonnage of dredging and trawling fleet (Mt)	Time-series	FIGIS	Bulgaria, Romania, Ukraine, Turkey	1970–1995[c]
	Climate change	SST (°C)	Time-series	NCEP/NCAR[d]	Romanian waters	1978–2005
	Livestock production	Meat production (Mt)	Time-series[e]	FAOSTAT[f]	Danube catchment	1961–2001
	Fertiliser usage (P)	Consumption (Mt)	Time-series[e]	FAOSTAT[f]	Danube catchment	1961–2002
	UWWT	Waste water ≥2 °C treatment (% of population connected)	Time-series[e]	EUROSTAT[g]	Danube catchment	1970–2000[c]
	Municipal waste	Municipal waste generated (kg $person^{-1}$)	Time-series	EUROSTAT[g]	Bulgaria, Romania, Turkey	1995–2004
	Landclaim	Agricultural area (10^3 ha)	Time-series[h]	FAOSTAT[f]	Romania	1972–1988
Pressures	Pelagic catch	Anchovy and sprat landings (Mt)	Time-series	GFCM (1997)	Black Sea	1950–1992
	Demersal catch	Turbot landings (Mt)	Time-series	GFCM (1997)	Black Sea	1964–2004
	Hypoxia	Area of hypoxia (km^2)	Time-series	Mee (2006)	NW shelf	1961–1997
	Transparency	Secchi depth (m)	Time-series	NIMRD[i]	Romanian waters	1964–2000
States	Phytoplankton	Total summer density (cells l^{-1})	Time-series	NIMRD[i]	Romanian coast[j]	1986–2003
	Introduced species	Number of introduced species (*n*)	Interpolated time-series	IO-BAS[k]	Black Sea	1950–2005[c]
	Pelagic predator stocks	Mackerel, bonito, and bluefin biomass (Mt)	Standardized time-series	Daskalov (2002)	Black Sea	1952–1992
	Small pelagic stocks	Sprat and anchovy spawning biomass during early May (10^3 Mt)	Time-series	GFCM (1997)	Black Sea	1967–1993
	Demersal stocks	Turbot spawning stock biomass (Mt)	Time-series	GFCM (1997)	Black Sea	1970–1988
	Zoobenthos	*Mytilus* biomass ($g\,m^2$)	Metadata analysis	GeoEcoMar[l]	NW shelf	1954–2003[c]
	Seagrass habitat	Seagrass habitat status (% lost/degraded)	Expert opinion	Consultation	NW shelf	
	Phyllophora habitat	Area of *Phyllophora* meadow (km^2)	Time-series	Minicheva (2005)	NW shelf	1964–1989[c]

Table 1 (*Continued*)

Variable	Indicator	Data type	Source	Geographic coverage	Temporal coverage
Cystoseira habitat	*Cystoseira* habitat status (% lost/degraded)	Expert opinion	Consultation	NW shelf	
Wetland habitat	Wetland habitat status (% lost/degraded)	Expert opinion	Consultation	NW shelf	

[a] Turkish Marine Pilots Association. 2007.
[b] FIGIS: Fisheries Global Information System. 2008. FAO: Food and Agriculture Organisation of the United Nations.
[c] Indicates incomplete time-series.
[d] NCEP/NCAR Reanalysis Project. 2008. NOAA: National Oceanic and Atmospheric Administration.
[e] Weighted by land area of each country in catchment (Austria, Bulgaria, Germany, Hungary, Romania, and former Republics of Czechoslovakia and Yugoslavia).
[f] FAOSTAT. 2008. FAO: Food and Agriculture Organisation of the United Nations.
[g] EUROSTAT. 2008. European Union.
[h] Only used as a proxy until 1988.
[i] NIMRD: National Institute for Marine Research and Development.2008. Dataset. Constanta, Romania.
[j] 1 station off Constanta.
[k] IO-BAS: Institute of Oceanology – Bulgarian Academy of Sciences. 2008. Dataset. Varna, Bulgaria.
[l] GeoEcoMar: National Insitute of Marine Ecology and Geo-Ecology. 2006. Dataset. Constanta, Romania.

within time-series were not problematic as long as sufficient overlap existed between indicator datasets.

When quantitative indicator data were not available, expert opinion was solicited by questionnaire. Conditional probability distributions (the probable condition of a variable based on the possible states of related variable(s)) were then calculated from the questionnaire results. This technique was used to obtain information on seagrass (*Zostera* spp.), *Cystoseira* (a brown macroalga) and wetland habitats, for which no quantitative time-series data are available, but declines have taken place (BSEP—Black Sea Environmental Program, 1996; BSERP—Black Sea Ecosystem Recovery Project, 2007).

2.3. Model validation

Leave-one-out cross validation (Martens and Dardenne, 1998) was used to estimate model performance for two reasons: (1) since data were sparse this technique allows all of the available data to be used in model training and (2) this method avoids bias in error rates that can inevitably occur when datasets are split for training and testing, especially since these datasets are most complete for the last decade and become sparser in preceding decades.

The model was trained with the entire dataset bar 1 year, which it was tested against. This was repeated for every year through the dataset between 1970 and 2001. The cumulative error rate was calculated by variable to estimate model performance. The variables that were based on expert opinion (seagrass, *Cystoseira* and wetland habitats) could not be validated in this way since there were no time-series data to validate against.

2.4. Scenarios

2.4.1. Scenario characterisation

The scenarios employed in this study were designed to provide a general overview of alternative states of the world so as to highlight the differences that result. These were adapted from well-established precedents (IPCC SRES (Intergovernmental Panel on Climate Change, 2001), ACACIA (ACACIA—A Concerted Action towards a Comprehensive Impacts and Adaptations Assessment for the EU, 2000), UKCIP (UK Climate Impacts Programme, 2001), AFMEC (CEFAS—Centre for Environment Fisheries and Aquaculture Science) since no individual study addressed the scales and issues relevant here (full details can be found in Mee et al., in preparation).

The Alternative Scenarios are defined at the extremes of two dimensions: governance and values. Each is a description of the underlying values and policies that define it, and their broad socio-economic implications (Langmead et al., 2007). In these descriptions the communitarian scenarios do not necessarily lead to or are driven by environmental improvement, a key difference between these scenarios and their precedents. In addition, a Baseline Scenario was defined, depicting developments that reflect current expectations in demographic, economic and technological terms, taking into account all implemented and adopted policies (although inherent targets are not assumed to be achieved a priori), and thus representing a “business as usual” development path. This was based on current expectations from publicly available predictive

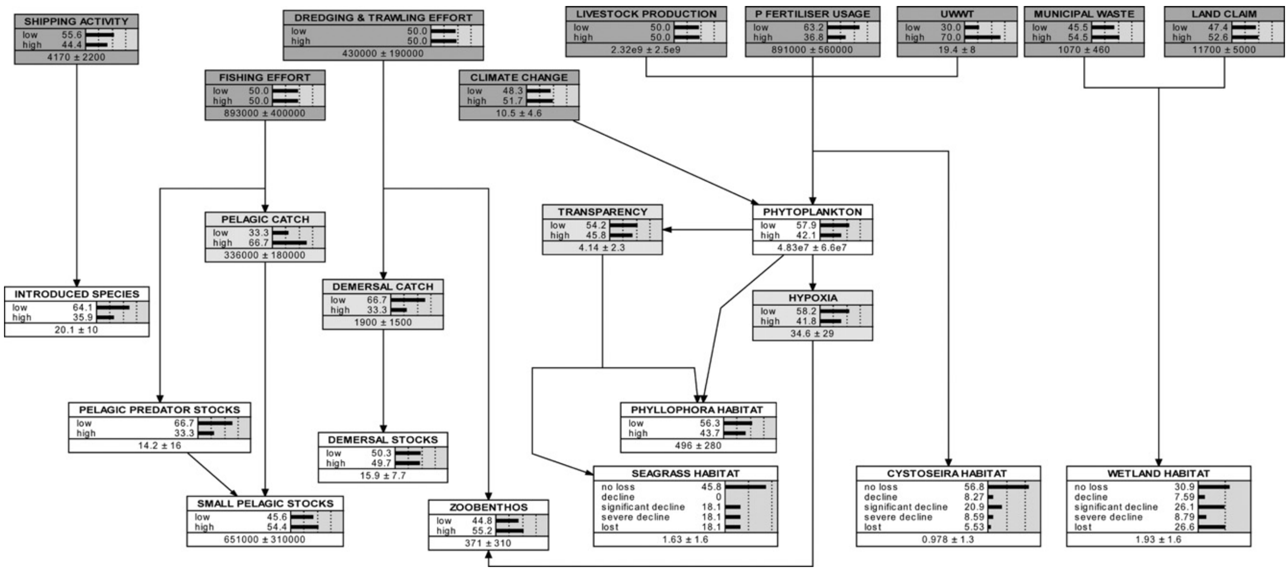

Fig. 4 – Bayesian belief network model structure. Driver variables are shaded in dark grey, Pressures in light grey, and ecological States are unshaded. Full details of the indicators for each variable and supporting data are given in Table 1.

information such as that from the European Environment Agency (EEA—European Environment Agency, 2005). The relative position of this Baseline Scenario is depicted in Fig. 4, and descriptions of the four Alternative Scenarios are summarised and presented in supporting online material, S1).

From these characterisations, narrative description of changes in basic socio-economic variables and activity in Driver sectors were developed for each scenario at broad EU level. These were translated into a simple categorical representation (+/0/−) to indicate the direction of change in each of the Driver sectors and ultimate activities, which were used to condition the model. Because of the manner in which the Alternative Scenarios were developed, they were represented as changes relative to the Baseline Scenario. From these definitions it is not possible to know whether a positive change from the current situation to the Baseline Scenario is offset by a negative change in any Alternative Scenario, because there is no scale only the direction of change. As the Baseline Scenario was characterised based on current predictions on the state of development in 2025, and the Alternative Scenarios are possible contrasting futures, most confidence is held in the Baseline Scenario.

2.4.2. *Scenario implementation*

The simulation model was conditioned to each of the five scenarios (the Baseline Scenario and four Alternative Scenarios—see above), and responses of downstream variables (Pressures and States) were recorded. This was carried out by manipulating the marginal probability distributions of Driver variables in unique combinations via a three-step process (Fig. 5). Unconditioned, Driver variables are equally likely to be in either the 'high' or 'low' states (Fig. 5). (1) To simulate the current situation, marginal probability distributions (Drivers) were changed by $P = \pm 0.2$. Thus a positive change resulted in an input $P(\text{low}) = 0.3$ and $P(\text{high}) = 0.7$, while a negative change resulted in an input $P(\text{low}) = 0.7$ and a $P(\text{high}) = 0.3$. (2) Under the 25-year time horizon of the Baseline Scenario,

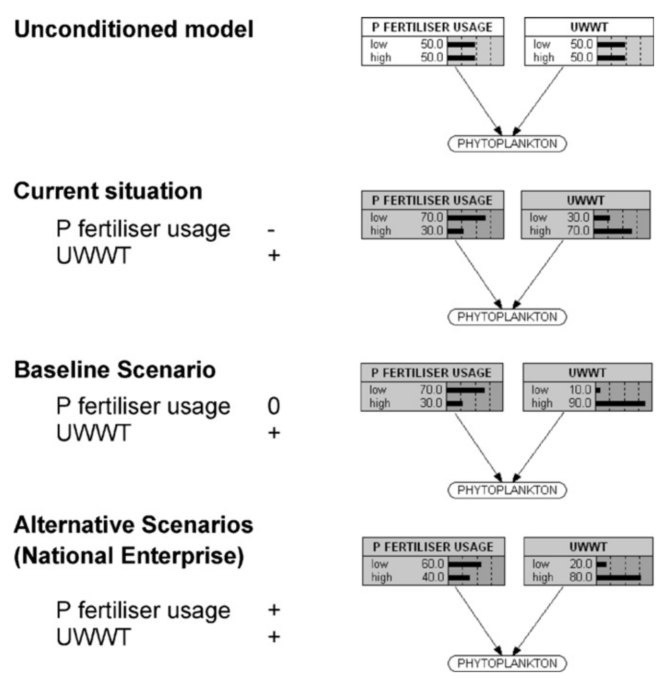

Fig. 5 – Scenario implementation. Scenarios were input as changes to the state of marginal probability distributions of Driver variables. Above are the changes for two Drivers, phosphate (P) fertiliser usage and urban waste water treatment (UWWT) for the current situation, Baseline Scenario and one Alternative Scenario (National Enterprise), as a worked example. The direction of change is relative; the current situation is relative to the unconditioned driver (median of time-series); Baseline Scenario is relative to current and the Alternative Scenarios, including the National Enterprise Scenario, are calculated as deviations from the Baseline Scenario. The full list of scenario conditions can be found in Fig. 8.

changes to marginal probability distributions were made as before ($P = \pm 0.2$), but calculated relative to the current situation (Fig. 5). (3) Alternative Scenarios were calculated relative to the Baseline Scenario, but were conditioned as a change of $P = \pm 0.1$ from the Baseline. Thus the greatest changes occurred during the current and Baseline Scenario steps ($P = \pm 0.2$) and less weight was given to the deviations of the Alternative Scenarios ($P = \pm 0.1$) for reasons outlined in Section 2.4.1.

While climate is included as an exogenous Driver since it has been shown to play a role in structuring the Black Sea ecosystem (e.g. Belokopytov, 1998), it was not conditioned during the scenario analysis since SST is not predicted to be greatly different at the scenario time horizon (2025), although significant changes are predicted for later this century.

3. Results and discussion

3.1. *Novel metadata time-series*

The novel metadata constructs clearly show the pattern of increasing eutrophication and decline in different components of the Black Sea ecosystem and constitute a significant advance for this region where historical data are scarce. Ecosystem conditions in shelf waters deteriorated throughout the 1960s and 1970s before reaching their worst state in the late 1980s (Fig. 6). Water transparency diminished steadily beginning in the 1960s (Fig. 6a). The 1960s, 1970s, and 1980s saw expansive phytoplankton blooms in shelf waters (Fig. 6b) and an increase in the number of mass blooming species, most of which were flagellates; and an increase in the proportion of the phytoplankton community occupied by non-diatoms (Bodeanu et al., 2004). During this period harmful algal bloom, or red tide, events also increased in frequency (Moncheva et al., 2001).

Reduced water transparency along with an increase in organic matter deposition from the pelagic zone had negative effects on benthic macrophyte communities. The extent of the *Phyllophora* field on the shelf decreased from 1000 km^2 in 1964 to 82 km^2 in 1989 (Fig. 6c). A decline in *Cystoseira* and seagrass beds along the northwestern coast was also observed; pressure on these habitats was further compounded by coastal development and agricultural reclamation in the Danube delta (Milchakova, 1999). The increased rain of pelagic

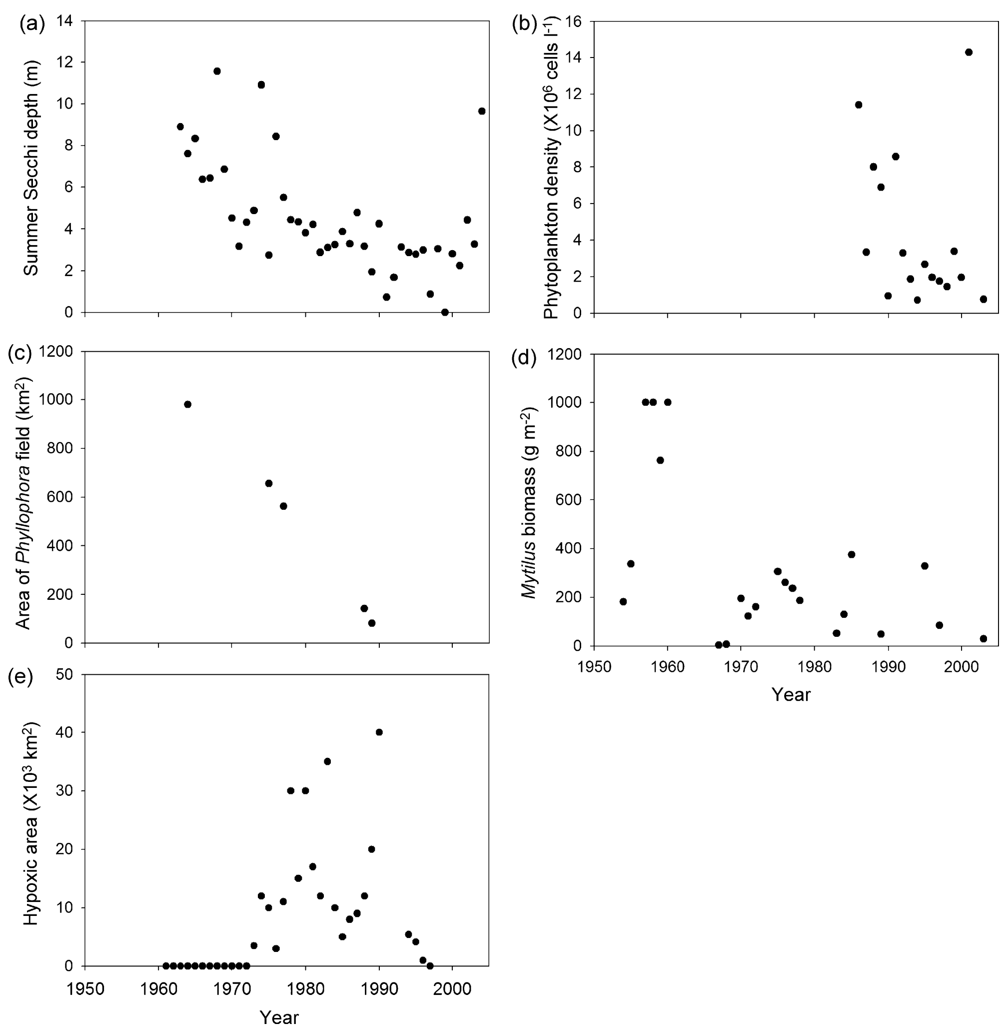

Fig. 6 – (a) Transparency (summer Secchi depth), (b) phytoplankton density, (c) area of *Phyllophora* field, (d) *Mytilus* biomass and (e) hypoxic area in northwestern shelf waters. All time-series show a deterioration of the shelf ecosystem during the 1970s and 1980s.

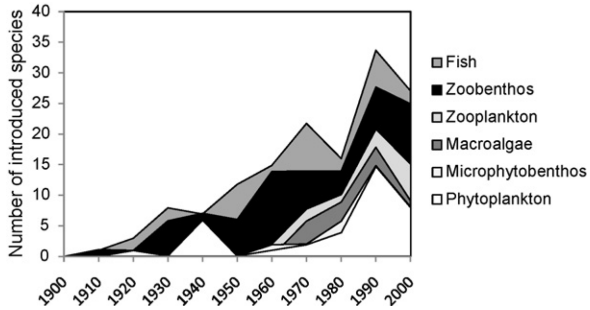

Fig. 7 – Species introduced to the Black Sea over the last century by taxa (after BSERP—Black Sea Ecosystem Recovery Project, 2007).

Table 2 – Results of leave-one-out cross validation exercise (performed using data from 1970 to 2001 (*k* = 31)). As not all datasets extended fully across this range, the number of tests on each variable is also given.

Variable	Error rate %	N-tests
Pelagic catch	15.38	32
Demersal catch	38.46	32
Hypoxia	52.63	21
Transparency	37.83	27
Phytoplankton	15.38	14
Introduced species	16.67	7
Pelagic predator stocks	30.77	31
Small pelagic stocks	5.26	24
Demersal stocks	53.33	19
Zoobenthos	44.44	13
Phyllophora habitat	50	4

organic matter resulted in an initial growth of *Mytilus* biomass during the onset of eutrophication in the 1950s and early 1960s (Fig. 6d). However, as pelagic productivity continued to increase, hypoxic conditions in bottom waters caused extensive loss of *Mytilus* biomass from the late 1960s (Fig. 6d). The hypoxic area spread across the shelf during the 1970s, 1980s, and 1990s, reaching a maximum extent of 100,000 km^2 in 1989. Occurrence of hypoxia was exacerbated by the combined loss of bottom water oxygenation by macroalgae and biofiltration power from the depletion of shelf mussel beds (Mee et al., 2005).

The number of introduced species increased through the twentieth century (Fig. 7), closely matching the rise in maritime transport activity. The increased risk of introduced species heightens the chances that one of the species invading disturbs the ecosystem, and is likely to be exacerbated by the weakened ecosystem resilience due to eutrophication and the effects of overfishing (Mee et al., 2005). The most notable invasion occurred in the mid 1980s when the gelatinous ctenophore *M. leidyi* was introduced to the Black Sea. Lacking predators and finding favourable prey and environmental conditions, its biomass grew rapidly, effectively dominating the food chain and precipitating a collapse in small pelagic fish stocks within 5 years of its arrival (Kideys, 2002). Because *Mnemiopsis* preys on anchovy (*Engraulis encrasicolus*) larvae and eggs and competes with anchovy for food, the amount of non-gelatinous zooplankton available as fish fodder decreased drastically after its establishment (Shiganova and Bulgakova, 2000; Kideys, 2002). As a result, catches of anchovy decreased sharply, economically damaging this important fishery (Kideys, 2002).

During the late 1990s and early 2000s the hypoxic area decreased in extent (Fig. 6e); water transparency began to increase as pelagic productivity declined (Fig. 6a) as a result of decreasing nutrient loads with the collapse of centrally planned economies in the early 1990s. The phytoplankton community returned to a pre-eutrophic composition (Bodeanu et al., 2004), while the biomass of *Mnemiopsis* decreased drastically due to the introduction of a natural predator *Beroe ovata*, reducing pressure on zooplankton and fish larvae (Shiganova and Bulgakova, 2000; Kideys, 2002). There are even indications of recovery in *Phyllophora* habitat on the shelf (Langmead and Mee, 2008).

3.2. *Model validation*

The leave-one-out cross validation exercise showed that the model is able to predict with a low error rate (<20%) the state of many variables (pelagic catch, small pelagic stocks, introduced species, phytoplankton, Table 2). However, some variables proved harder to predict and were associated with high error, including *Phyllophora* habitat (50%), demersal catch and stocks (38% and 53% respectively), zoobenthos (44%), transparency (37.83%) and hypoxia (52.63%). In the case of *Phyllophora* habitat this may be related to the low number of records (4). In the other cases, this reflects our confidence in the datasets, which are in many cases constructs from different seasons, locations and researchers. This highlights the paucity of consistent, reliable datasets in this region, but also is reassuring as it demonstrates that the model reflects the known in terms of data quality. It is important to note though that these data represent the best of our knowledge of this sea, and in many cases a significant advancement.

3.3. *Scenario outcomes*

Under the Baseline Scenario the exploitation of environmental resources (demersal fishing, shipping and agriculture) increases due to the continued economic development of post-Soviet countries (Fig. 8). Pelagic fishing effort remains at present high levels as some degree of cross border cooperation to limit fishing effort might be expected as the EU presence in the Black Sea increases, and with it, the impact of a greener Common Fisheries Policy. This overall increase in resource exploitation is partly ameliorated by an increase in infrastructure development, represented here by the proportion of the population connected to secondary and tertiary waste water treatment. These changes in infrastructure also result in the degradation and loss of wetlands through drainage, reclamation and by smothering with municipal waste. Nutrient loads from sewage decrease, and phosphorus loads from agricultural application remain at present levels, but there is growth in intensive livestock farming. This is reflected by increases in phytoplankton abundance and concurrent decreases in water transparency; light is then unable to reach coastal (*Cystoseira*, *Zostera*) and offshore (*Phyllophora*) plant communities, and loss of these habitats is experienced. The expansion

		Baseline Scenario (changes relative to current)	Alternative Scenarios (changes relative to Baseline Scenario): National Enterprise	Local Responsibility	World Markets	Global Community
DRIVERS	Dredging & trawling effort	↑	↗	↘	→	↘
	Shipping activity	↑	↘	↘	↗	→
	Fishing effort	→	↗	→	→	↘
	Landclaim	↑	↘	↘	↗	↘
	Municipal waste	→	↗	↘	→	↘
	Livestock production	↑	→	↘	↗	→
	P fertiliser use	→	↗	↘	→	↘
	Urban waste water treatment	↑	↘	→	↘	→
PRESSURES	Transparency	↓	↘	↗	↘	↗
	Hypoxia	↑	↗	↘	↗	↘
	Demersal catch	↓	↘	↗	→	↗
	Pelagic catch	→	↘	→	→	↗
STATES	*Cystoseira* habitat	↓	↘	↗	↘	↗
	Zostera habitat	↓	↘	↗	↘	↗
	Phyllophora habitat	↓	↘	↗	↘	↗
	Pelagic predator stocks	→	↘	→	→	↗
	Small pelagic stocks	→	↘	→	→	↗
	Wetland habitat	↓	↘	↗	↘	↗
	Demersal stocks	↓	↘	↗	→	↗
	Zoobenthos	↓	↘	↗	↘	↗
	Phytoplankton	↑	↗	↘	↗	↘
	Introduced species	↑	↘	↘	↗	→

Fig. 8 – Outcomes for the Baseline Scenario and four Alternative Scenarios. The Driver component determines the conditions that forced the simulation for each scenario. Outcomes are presented with the Baseline Scenario relative to the current situation (vertical arrows), and Alternative Scenarios as deviations from the Baseline Scenario (diagonal arrows). When conditioning the model to the scenarios, more weighting was given to the Baseline Scenario over the Alternative Scenarios ($P = \pm 0.2$ vs. $P = \pm 0.1$); thus directions of change in the Baseline Scenario are shown as vertical arrows to emphasise this difference. Climate is not included among the Drivers, since it was not conditioned during the scenario analysis for reasons outlined in Section 2.4.2.

of a hypoxic area with the decomposition of plant material impacts zoobenthic communities, as does increases in demersal fishing activity. Ecological pressure from eutrophication together with fishing at higher (demersal) or present (pelagic) high levels of activity lead to decreases in demersal stocks and no recovery of pelagic stocks which remain at current low levels. Furthermore, there is an increased likelihood of the introduction of alien species through ballast water, with increasing shipping activity. This constitutes a reversal of the recent recovery of the Black Sea ecosystem and a return to the conditions experienced in the 1980s.

The outcomes of the Alternative Scenarios fall into two groups (Fig. 8): (1) scenarios that show an improvement on the Baseline condition and (2) scenarios that indicate worsening. The most environmentally damaging is the National Enterprise Scenario, where increased exploitation of natural resources places the greatest pressure on the environment. Under this scenario, fish stocks collapse and eutrophication and hypoxia reach levels not previously experienced, leading to loss and degradation of benthic plant and animal communities. The World Markets Scenario shows an increase in agricultural activity and shipping but with fisheries effort remaining at Baseline Scenario levels due to increasing fish imports. This leads to a situation similar to that experienced under the National Enterprise Scenario in terms of eutrophication but with fish stocks at Baseline Scenario levels. This scenario is strongly reliant on the movement of materials through the region, strengthening the influence of transportation on the ecosystem. The increase in shipping activity also means an increased risk of the introduction of alien species.

Both the Local Responsibility and Global Community Scenarios show expected environmental use to be less damaging than the Baseline Scenario. However, whether this represents an overall improvement on current conditions is not known, since the Alternative Scenarios were formulated relative to the Baseline Scenario and not the current situation (Mee et al., in preparation). The main differences between these scenarios are related to pelagic fisheries; while in the Local Responsibility Scenario there is no improvement on the current situation as management is not achieved on a transboundary basis, improvements in terms of stock recovery are experienced under the Global Community Scenario for this reason. A further difference is in the level of shipping activity. This decreases under the Local Responsibility Scenario (an autonomous scenario) but increases under the Global Community Scenario (which is defined by increasing globalisation), so the risk of species introductions is much higher in the latter scenario.

The information from scenarios should be viewed alongside the current political and economic choices being faced in the region. There are three groups of coastal countries, currently moving in somewhat different social and economic directions: (1) Bulgaria and Romania that are now members of the European Union, together with Turkey that is aligning its policies as it aspires to join; (2) Russia, which is reasserting its independent political and economic role, buoyed by revenue from exports of oil and other materials to World Markets; (3) Ukraine and Georgia that continue to struggle with the transition from centrally planned economies. The fate of the Black Sea will be determined by how these three groups exert influence on future Drivers and how they cooperate together. Nutrients and eutrophication, dominated by Danube influx will be heavily influenced by EU Policy that tends to fall between a World Markets and Global Community scenario. The arrival of invasive species however, may depend upon the future attitude of Russia (currently somewhere between World

Markets and National Enterprise) towards international measures. Fishing will depend on the degree of cooperation of all countries and particularly on whether or not the major fishing country, Turkey, joins the EU (and is obliged to follow its Common Fisheries Policy) or continues to follow a predominantly National Enterprise pathway for this activity. Currently, the only integrated policy agreements between Black Sea countries are the inter-related Black Sea Action Plan and 1993 Bucharest Convention for the Protection of the Black Sea against Pollution (Mee, 2002). Though these agreements have identified the environmental issues and their root causes, they have limited power over the key Drivers we have identified. There is also no fisheries agreement in place to guide levels of exploitation. Currently therefore, there are few mechanisms to offset the outcomes that our scenarios describe.

4. Conclusions

The Black Sea is a unique basin with its limited exchange, enclosed nature, large catchment and relatively low taxonomic diversity all contributing to its high sensitivity to human induced disturbance. This study forecasts that if regional development follows as predicted (the Baseline Scenario), the Black Sea ecosystem will likely return to its highly eutrophic (1980s) state and recent recovery will be reversed. From this we conclude that variations in economic policy have significant consequences for the health of the Black Sea, and ecosystem recovery is directly linked to social-economic choices.

The BBN approach proved successful in integrating the different types of information without the data intensive requirements of most mechanistic models. To the authors' knowledge, this study constitutes the first attempt to model the combined socio-economic–ecological system of the north-western shelf of the Black Sea. Previous system models for this region have focused on biogeochemical representations describing the complex ecological cycling of elements in functional groups (phytoplankton, zooplankton, gelatinous organisms and microbes) (e.g. Oguz et al., 2001a,b; Lancelot et al., 2002). However, they have not extended to the socio-economic activities in the catchment from where nutrients originate, or included higher trophic levels of the food web. Similarly, at a basin scale, coupled ecosystem and hydrographic models have been developed to assess the influence of physical processes on the ecological dynamics (Grégoire and Lacroix, 2003; Gregoire and Friedrich, 2004; Grégoire et al., 2004, 2008). Alternative approaches have included trend analysis of historic data to link fish stocks to environmental conditions (Daskalov, 2002, 2003), and mass balance modelling of the pelagic food web under scenarios of increasing eutrophication and fishing effort (Daskalov, 2002). Although these pressures are anthropogenic in origin, this model did not consider the underlying socio-economic Drivers that give rise to these conditions; they were represented simply as increases in primary production and fishing mortality. Thus the model presented here constitutes a significant advancement in crosscutting socio-ecological research.

Also, while BBNs have been applied to many different socio-ecological systems, and to issues ranging from

Table 3 – Properties of some aquatic BBN socio-ecological models compared with the presented model.

Issue	Scale and location	Freshwater/transitional/marine	Data types	Scenario analysis	Reference
Ecosystem degradation	Sub-basin scale (NW shelf, Black Sea)	Marine	Empirical information (time-series), expert opinion	Yes	This paper
Water resource planning	Catchment scale, (Loddon River, UK; Jucar River, Spain; Havelse River, Denmark; and Vomano River, Italy)	Freshwater	Empirical information, model output, expert opinion	No	Bromley et al. (2005)
Wildlife population viability	Catchment scale (Columbia River, USA)	Freshwater	Empirical information, expert judgement, case studies	No	Marcot et al. (2001)
Salmon stock assessment	Basin scale (Baltic)	Marine	Model output, empirical information, expert opinion	No	Varis and Kuikka (1997)
Eutrophication	Catchment scale (Neuse River estuary, North Carolina, USA)	Transitional	Empirical information, model output, expert judgement	Yes	Borsuk et al. (2004)
Surface water quality assessment	Catchment scale (Neuse River, North Carolina, USA)	Transitional	Empirical information, expert judgement	Yes	Reckhow (1999)
Information flow among fishing vessels	Great Barrier Reef (Australia)	Marine	Empirical information	Yes	Little et al. (2004)

eutrophication to fisheries stock assessment, this is the first time the complex issue of systemic degradation has been attempted at a sub-basin scale (Table 3). Its BBN predecessors to date have focused either on a narrow issue at a large scale (e.g. salmon stocks, fishing vessel communication) or a broader problem at the scale of a single river catchment (e.g. wildlife population viability, eutrophication, Table 3).

This approach has limitations; however the lack of historic time-series presented a challenge; no amount of model refinement can counter poor or absent data, and this will continue to be a problem in the future. The extent of our current knowledge of causal links in the complex systems investigated was revealed by model validation. This identified critical information gaps in the socio-economic and ecological domains that pose important imperatives for policymakers. Unless these gaps can be closed by improved monitoring of social and natural system indicators, it will not be possible to develop scenario models that will serve for decision making in the context of the Ecosystem Approach.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.ecolmodel.2008.09.011.

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