
Five critical questions of scale for the coastal zone

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Abstract :

Social and ecological systems around the world are becoming increasingly globalized. From the standpoint of understanding coastal ecosystem behavior, system boundaries are not sufficient to define causes of change. A flutter in the stock market in Tokyo or Hong Kong can affect salmon producers in Norway or farmers in Togo. The globalization of opportunistic species and the disempowerment of people trying to manage their own affairs on a local scale seem to coincide with the globalization of trade. Human-accelerated environmental change, including climate change, can exacerbate this sense of disenfranchisement. The structure and functioning of coastal ecosystems have been developed over thousands of years subject to environmental forces and constraints imposed mainly on local scales. However, phenomena that transcend these conventional scales have emerged with the explosion of human population, and especially with the rise of modern global culture. Here, we examine five broad questions of scale in the coastal zone :

- (1) How big are coastal ecosystems and why should we care ?
- (2) Temporal scales of change in coastal waters and watersheds: Can we detect shifting baselines due to economic development and other drivers ?
- (3) Are footprints more important than boundaries ?
- (4) What makes a decision big? The tyranny of small decisions in coastal regions.
- (5) Scales of complexity in coastal waters: the simple, the complicated or the complex ?

These questions do not have straightforward answers. There is no single “scale” for coastal ecosystems; their multiscale nature complicates our understanding and management of them. Coastal ecosystems depend on their watersheds as well as spatially-diffuse “footprints” associated with modern trade and material flows. Change occurs both rapidly and slowly on human time scales, and observing and responding to changes in coastal environments is a fundamental challenge. Apparently small human decisions collectively have potentially enormous consequences for coastal environmental quality, and our success in managing the effects of these decisions will determine the quality of life in the coastal zone in the 21st century and beyond. Vigilant monitoring, creative synthesis of information, and continued research will be necessary to properly understand and govern our coastal environments into the future.

Highlights

► We examine five aspects of “scale” we believe to be important for the coastal zone. ► Conventional definitions of scale include spatial and temporal dimensions. ► The “Homocene” coastal zone is subject to recent pressures of globalization. ► The “tyranny of small decisions” is a major challenge to environmental governance. ► “Scale of complexity” applies to both understanding processes and decision making.

Keywords : scale ; coastal management ; governance ; Fishery management ; regime shift ; biogeochemistry

1 **Introduction**

2 The social and ecological systems that comprise human society and its living space are
3 becoming increasingly globalized. From the standpoint of understanding ecosystem behavior,
4 it is getting harder to model a system within their apparently well-defined boundaries because
5 these are ceasing to be the relevant ones. A flutter in the stock market in Tokyo or Hong Kong
6 can affect salmon producers in Norway or farmers in Togo. Concurrent with the globalization
7 of trade, we are witnessing the globalization of the distribution of opportunistic species and
8 the disempowerment of people attempting to manage their own affairs on a local scale.
9 Climate change, as well as other human-accelerated environmental change, can really
10 exacerbate this sense of disenfranchisement. The structure and functioning of coastal
11 ecosystems has evolved over millennia, subject to environmental forces and constraints
12 imposed mainly by local boundaries of catchment and shore, not human culture. However,
13 phenomena that transcend these local scales have emerged as human populations have
14 increased, and especially with the rise of modern global culture. Much of the science of
15 coastal waters is based on abstract considerations of ecosystem behavior in the absence of
16 human “perturbations”, such as long-distance transport of materials, introduction of new
17 species, and human accelerated climate and land use change. How can we keep up with the
18 change in scales (temporal and well as spatial) associated with such human activities? What
19 tools can we employ to help people and policymakers to remain in charge in a meaningful
20 manner?
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26 **Some critical questions of scale for the coastal zone:**

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29 1) *How big are coastal ecosystems and why should we care?*
30 2) *Temporal scales of change in coastal waters and watersheds: Can we detect*
31 *shifting baselines due to economic development and other drivers?*
32 3) *Are footprints more important than boundaries?*
33 4) *What makes a decision big? The tyranny of small decisions in coastal regions.*
34 5) *Scales of complexity in coastal waters: the simple, the complicated or the*
35 *complex?*
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39 **1) How big are coastal ecosystems and why should we care?**

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41 The short answer to the first half of the question is that coastal ecosystems, and the various
42 entities which comprise and interact with them, span a range of scales, depending upon the
43 definition of “scale” (see Appendix 1, supplementary material) and the issues to be analyzed.
44 For example, an analysis of nutrient inputs and eutrophication might be conducted along the
45 boundaries of the catchment-coast continuum, or include an analysis of agricultural systems
46 and businesses at global, continental (e.g. Europe or at least EU wide) or national policy
47 scales. The question of scale is a fundamental challenge for coastal research necessitating a
48 variety of research approaches and requiring extrapolation from mesocosms in many cases
49 (Boynton et al. 2001). While it has become a truism that “scale” is an important dimension in
50 coastal science and management, it is critical to distinguish its manifestation in different
51 categories of processes (Fig. 1). Physical scale effects are often propagated via intermediate-
52 scale processes, (e.g. energy transferred via turbulent eddies from large areas and time scales
53 to the smallest scales of turbulent mixing). Temporal scales tend to correlate linearly with
54 spatial scales, while ecological effects can “jump” intermediate scales or simultaneously be
55 manifest on different scales (e.g., long-lived species and their structures which tend to result
56 in “memory” effects in ecosystems), so it is more difficult to consider a single time scale
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1 corresponding to the spatial scale of an ecosystem. Governance entities, including
2 government agencies, local communities, and the full range of “stakeholder” groups in the
3 coastal zone, exhibit influence at overlapping scales, and are subject to hierarchies and gaps in
4 coverage. Drivers exhibit overlapping asymmetrical effects (large scale drivers affect small
5 scale systems, but not conversely). These effects make selection of a single scale of analysis
6 problematic, and the result is that we must consider a superposition of scales in most cases
7 involving governance of coastal waters (Solidoro et al., 2010a).

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9 <Figure 1 near here>

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11 The answer to the second half of the question is fairly obvious: “Because the response of
12 coastal ecosystems to various pressures (changes in material inputs, freshwater discharge,
13 temperature, etc) depends on how big they are.” Studies of coastal ecosystems frequently
14 attempt to relate physical or biological processes within the systems to characteristic scales,
15 (volume, area, residence time). During the first decade of the Land Ocean Interactions in the
16 Coastal Zone program (LOICZ), coastal nutrient budgets were developed for coastal systems
17 spanning six orders of magnitude in surface area (Smith et al., 2005; Swaney et al., in press).
18 Based on some statistical analyses of LOICZ coastal nutrient budgets, it appears that the net
19 ecosystem metabolism of coastal systems varies inversely with system size, i.e., large systems
20 with long residence times have relatively low metabolic rates, possibly because they are
21 colder, deeper, darker, and may have lower nutrient inputs/volume on
22 average than smaller systems (Fig. 2). This *allometric* relationship (1, supplementary
23 materials) appears to be true whether the systems are heterotrophic (ecosystem respiration
24 exceeding production) or autotrophic (production exceeding ecosystem respiration). Robust
25 statistical analyses using the Olmstead-Tukey test (Olmstead and Tukey, 1947; Sokal and
26 Rohlf, 1995) indicate that such inverse relationships are significant for net-autotrophic
27 systems using either residence time or area as a scale measure, and for net heterotrophic
28 systems using residence time. Other studies have noted that small land margin systems (e.g.
29 coastal lagoons) have relatively high primary and secondary productivity and fish catches
30 compared to larger coastal systems (Houde and Rutherford, 1993). If the productivity of a
31 coastal system varies strongly with its size, then it is likely that management of the system
32 should also vary with size, i.e., one management or decision-making approach should not
33 apply to coastal systems across all scales (Kannen et al 2008). So it seems that for coastal
34 systems, one size does not fit all.

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44 The size question is also relevant to the globally-aggregated productivity of coastal regions. It
45 is well known that coastlines vary in length depending upon the resolution with which they
46 are measured. This fractal property may also apply to the distribution of sizes of various
47 coastal features: for example, Pareto (power law) distributions are well-known to describe
48 island areas, lakes, and other natural features. If they apply to coastal seas, embayments,
49 estuaries and lagoons, it suggests that small systems are numerically dominant, and possibly
50 critical to overall coastal productivity. The nonlinear nature of the response of these systems
51 (Folke et al., 2004), and their associated ecosystem services (e.g., Barbier et al., 2008) as well
52 as their spatial and temporal variability (Luisetti et al., 2011) implies that there should be a
53 strong scale-dependence in many of the benefits humans obtain from coastal ecosystems as
54 well (Koch et al., 2009). The combination of an uneven distribution of the size of coastal
55 ecosystems, and the nonlinear variation of ecological processes and ecosystem services to
56 ecosystem scale implies that simple area-based extrapolations of estimates of the global
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1 contribution of coastal regions probably underestimate their value to human society (Duarte et
2 al., 2008)..

3 While the above can be considered a variation of the well-established idea that localized
4 ~~hotspots~~ or ~~patches~~ provide most of the activity in most ecosystems, it suggests that
5 hotspots are dominant features of the coastal zone. Another view is that the cumulative value
6 of a collection of many small, highly-variable autotrophic and heterotrophic systems is simply
7 the (relatively low) productivity of the mean value of the collection. Averaging out the
8 extremes of productivity of the components of a large system is just a property of the central
9 tendency of the statistics, and so the apparent inverse relation between size of a system
10 (measured in various ways) and magnitude of processes (metabolism, percent nutrient export,
11 etc) is the result. Are these fundamental issues relevant to the governance of coastal systems,
12 or is it simply another manifestation of environmental heterogeneity of which we must be
13 mindful in management?
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19 **2) Temporal scales of change in coastal waters and watersheds: Can we detect shifting** 20 **baselines and regime shifts due to economic development and other drivers?** 21

22 History is long; human memory is short. For most of their history, coastal ecosystems have
23 evolved and developed under the joint influence of their local (though sometimes large)
24 coastal watersheds and oceanic influences. Human accelerated environmental change,
25 particularly landscape transformations, typically beginning with settlement of colonial
26 regions, but also associated with the rise of new technologies, has dramatically increased the
27 influence of terrestrial drivers. These changes include increased nutrient loads and pollutants
28 from a variety of sources; altered hydrological and sediment transport regimes caused by
29 impoundments, other hydraulic engineering structures, and increased impervious surface; and
30 introduced invasive species from microbes to mammals. Many of these effects have been
31 shown clearly in the Chesapeake by Brush (2008) using paleoecological methods and
32 historical records (Fig. 3), and similar impacts are widely recognized in other watersheds
33 (Meybeck, 2003; Turner and Rabalais, 2003; Swaney et al., 2006; Billen et al., 2007;
34 Humborg et al., 2007; Nixon et al., 2008; Solidoro et al., 2010b). Many changes are due to
35 increases in infrastructure – impervious surface, land drainage, damming, hardened coastline,
36 dredging to facilitate shipping, and consequent modification of watershed and estuarine
37 hydrological, biogeochemical and biological processes. For example, the joint effects of
38 dams in reducing sediment transport and projected sea level rise in increasing inundation
39 poses a major threat to the world's major deltaic systems (Ericson et al., 2006; Woodroffe et
40 al., 2006; Syvitsky et al., 2009). Several studies (e.g., Restrepo et al., 2006; Richmond et al.,
41 2007) have demonstrated the negative impact of runoff and sediment loading to seagrasses
42 and coral systems, even beyond what is typically perceived to be the immediate receiving
43 waters of coastal watersheds, and the need for incorporating watershed management in
44 dealing with these impacts.
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51 While the increase in nutrient loads caused by changes in agriculture practices and land use
52 which occurred during last century triggered eutrophication phenomena over most European
53 and American coastal areas, a reversal in eutrophication trends (so called oligotrophication) is
54 being seen in recent decades in many areas (Stockner et al. 2000, Nixon et al., 2009; Mozetic
55 et al, 2010), probably because of the enforcement of new environmental protection legislation
56 in these regions. This suggests on the one hand that eutrophication trends are reversible, but
57 on the other opens the question of unintended consequences for secondary production,
58 including fisheries (Nixon et al., 2009)
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2 Direct human modification of coastal lands and waters also continues to increase. Lotze et al.
3 (2006) showed patterns of species and habitat loss, species invasions, and water quality
4 degradation in estuaries and coastal seas around the world. Fifty-five percent of the mangrove
5 areas on the coast of Thailand were lost between 1961 and 1996 through the development of
6 shrimp farming, urban development, mining and other factors, though in recent years there
7 has been some recovery (Giesen et al., 2006). The increasing prevalence of fin- and shellfish
8 aquaculture in coastal waters has significantly modified their nutrient regimes in some cases,
9 either through the direct introduction of nutrients in food or the removal of nutrients with
10 harvest (e.g., Yamamuro et al., 2006). Increased port development and shipping activity
11 associated with the growth of trade has affected coastal water quality in and near ports,
12 including the dredging of channels for increasingly large cargo vessels (Wolanski, 2006).
13 Such disturbance may cause increases in turbidity, alter the flows and flowpaths, and
14 adversely affect fish nursery areas.
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19 Oceanic and climatic influences are also changing and will continue to do so. The coastal
20 zone in the sense of LOICZ (-200 m depth to +200 m) has been shaped by global (eustatic)
21 sea level variations and associated cycles of transgressions and regressions over geological
22 time scales. Reconstructions of (eustatic) sealevel change over the last few hundred thousand
23 years suggest that the present sea level is near the maximum reached over the last 450,000
24 years. Isostatic (regional) sea level varies in present-day coastal zones, but there is now
25 unequivocal evidence for a small, but crucial, eustatic sea level rise caused mainly by thermal
26 expansion of sea water (Bindoff et al. 2007). Projections of sea level change through 2100 AD
27 predict an increase of between 20 cm and 50 cm in global mean sea level, not including
28 expected regional effects of increased storm surge height or frequency (Fig. 4. Bindoff et al
29 2007). While this increase may not seem to be dramatic, it could have consequences for
30 coastal protection, and severe ones for extant tidal flats. Whether situated in estuaries, deltas,
31 or on tidal coasts, these play important roles as specific coastal habitats, biodiversity hot
32 spots, and for mitigation of nutrient fluxes from land to sea in the coastal zone. It is
33 particularly dangerous to sinking deltas (Syvitsky et al., 2009). In the geological past, the
34 coastal zone was effectively a "ramp" that accommodated rising/falling sea level by
35 landward/seaward displacement of individual sedimentary and coastal regimes. That degree of
36 spatial freedom is reduced when the coast is enforced by dikes and other structures ("habitat
37 squeeze"). In the narrowing strip between an advancing sea and a fixed coastline, energy of
38 the water increases and results in preferential selection of coarse sediments; fine particles and
39 organic matter are less effectively retained, and are advected to adjacent deeper water. Among
40 other effects, this can decrease areas of tidal flats, and modify river deltas (Fagherazzi et al.
41 2006).
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50 The addition of increased storm activity and flooding superimposed on sea level rise
51 projections is problematic. For example, combined storm surge and sea level rise is projected
52 to pose a risk of flooding to the Mekong Delta, despite extensive damming upriver in China
53 (Hoa et al., 2007). Increasingly, large-scale linkages are being recognized between
54 atmospheric phenomena (such as the Southern Oscillation, ENSO, or the North Atlantic
55 Oscillation, NAO) and the variation of intensity of regional weather patterns (so called
56 "teleconnections"; Wallace and Gutzler, 1981).
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1 Floods and droughts are not the only outcomes of teleconnections. Winter temperature, which
2 is correlated with the NAO in northern Europe (Fig. 5) has a primary role in the development
3 of zooplankton blooms in the subsequent spring and summer (Alheit et al, 2005). Other direct
4 impacts of climate on coastal waters include effects of temperature (air temperature, sea
5 surface temperature (SST), extremes, and gradients), precipitation (e.g. its seasonality) and
6 hydrological regime (flushing rates and circulation) on changes in productivity (Cossarini et
7 al. 2008) and the seasonal timing of its onset and decline (phenology), as well as the degree of
8 benthic-pelagic coupling (Nixon et al., 2008).
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10 A problem shared by many coastal ecosystems subject to changes in terrestrial, oceanic or
11 climatic influences is the lag between cause and effects: we lack early warning indicators of
12 sudden ecological responses to change. Many coastal ecosystems are exposed to gradual
13 changes (climate change, nutrient loading, fishing pressure etc) and are conventionally
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18 assumed to respond smoothly to these changes. However, this is not always the case.
19 Examples of abrupt ecological responses to environmental change include:
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- 21 • Human-supported species invasions, especially through ballast water transfer (Carlton,
22 1999; 2001).
- 23 • Invasions driven by climate change favoring one species over another, as when a new
24 species is able to displace existing species (Schluter et al., 2008; Cheung et al., 2009)
- 25 • Natural cycles which involve drastic changes, such as long-term cycles in fish stocks
26 (Silvert and Smith 1981, Silvert 1983, Silvert and Crawford 1988; Alheit and Hagen,
27 1997).
- 28 • "Regime shifts" driven by climate change, pollution or overfishing (deYoung et al.,
29 2008).
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36 Increasing numbers of studies show that smooth changes can be interrupted by abrupt
37 transitions to a new state (e.g., Folke et al., 2004; Duarte et al., 2008), so called regime shifts,
38 One perception of regime shifts is that they are transitions from one quasi-stationary state of a
39 system persisting for several years and characterised by low-frequency variability to another
40 stable state with a transition period of a few years. Gradual and possibly disparate changes
41 have little effect until they surpass a threshold, at which the nature and extent of feedbacks in
42 the system change, leading to an abrupt transition. The availability of data of sufficient
43 duration to see these effects has severely limited the identification of regime shifts in the past.
44 However, both theoretical and empirical observations suggest that increased variance of one
45 of several of the variables characterising ecosystems serves as an early warning indicator for
46 an impending threshold (Brock and Carpenter, 2006). And although there are suggestions that
47 regime shifts can be triggered by immediate human action, most regime shifts reported so far
48 appear to be linked to underlying climatic changes.
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52 Research into the non-linear dynamics of ecosystems has implications for
53 management frameworks (Duit and Galaz, 2008), which still tend to manage ecosystems as
54 steady-state or smoothly changing systems and assume that such changes are reversible. Such
55 policies lead to unsustainable futures. Both natural and anthropogenic regime shifts are
56 important to delineate: indicators are needed in order to design governance structures that
57 permit adaptive management and an ecosystem approach.
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59 Temporal scales related to lag times between cause and effect (in DPSIR terminology
60 between pressures, state changes and impacts) can play a critical role in dynamics and abrupt
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1 transitions in natural processes, but the same can be said for the institutional response, i.e., the
2 time delay between problem recognition, policy development and political
3 commitment/support to implement a new policy. This can be illustrated by the Multiple
4 Streams framework developed in political sciences (see Zahariadis 2007 on the framework or
5 Meijerink 2005 for an example).

6 Here, the assumption is that a “problem stream” (the shifting baseline) develops over
7 time. Some scientists might initially recognize it, and subsequently recognition could grow
8 (building a so-called “epistemic community”, see Haas 1989 on epistemic communities or
9 Meijerink 2005 for an example). In response to the problem stream and partly in parallel to it,
10 a policy stream develops, e.g. civil servants or NGOs developing proposals for a new policy,
11 but unable to implement it for lack of political support, funding and resistance to change and
12 its implications, a situation termed “ecosocial anomie” (Limburg and Waldman, 2009)
13 develops. The situation lasts until either the new ideas become mainstream or – typically due
14 to a crisis/catastrophe – a Window of Opportunity (WO) opens. Examples can be found in the
15 development of Dutch coastal defense strategies (Meijerink and Dicke, 2008, Meijerink
16 2005). In the Netherlands, the need for strengthening coastal defense structures had been
17 recognized, including development of implementation plans, for two decades before a 1953
18 flood triggered the opening of a WO for implementation.

19 Such processes, in which a problem stream, a policy stream and a political stream
20 must converge before policy changes can take place, are fairly common. Other examples
21 include the fight against eutrophication of the North Sea, the ban of open access clam fishing
22 and the initialization of a clam aquaculture system in the lagoon of Venice, and the
23 establishment of National Parks in the German Wadden Sea.

24 **3) Are footprints more important than boundaries?**

25 There is an increasing awareness in the ICZM community of the importance of
26 catchment/coast coupling: the recognition that in many coastal areas, coastal management
27 cannot be separated from watershed management. (In the context of estuaries and related
28 coastal systems, Wolanski (2007) refers to the processes that bear on these questions as
29 “estuarine ecohydrology.”). The catchment boundary is a well-defined, natural boundary for
30 understanding hydrological and nutrient linkages between catchment and coast, and even to
31 island or reef systems proximal to the coast (Richmond et al., 2007).

32 However, infrastructural changes within coastal watersheds can blur or otherwise modify
33 watershed boundaries. Demands for water for agriculture or drinking water can effectively
34 capture parts of neighboring catchments via impoundments and pipelines (as in the New York
35 City reservoir systems) or more dramatically by effectively rerouting major river systems
36 (e.g., in China). Increases in impoundment volumes of dams typically results in increased
37 evaporation, effectively reducing the net precipitation to the watershed and subsequent river
38 flow. Increased storage and “aging” of riverine water affects sediment and nutrient loads as
39 well (Vörösmarty et al, 1997); dams are typically associated with decreased sediment load
40 downstream of the dam due to sediment retention, and the reduced flow downstream also has
41 a lower capacity for sediment transport, which can result in both increased siltation and
42 starved deltas. Impoundments also are often responsible for nutrient trapping, notably silicon,
43 and can severely alter downstream nutrient ratios and associated plankton species
44 distributions (Humborg et al., 2006).

45 In contrast to the catchment boundaries of coastal systems, the last decade has seen the
46 ubiquitous “carbon footprint” emerging as a touchstone of the environmental movement to
47 alert people to their impact on atmospheric CO₂ levels and earth’s climate (Wiedmann and
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1 Minx, 2008). The ecological footprint (Wackernagel and Rees, 1996) has been used more
2 broadly to emphasize the dependence of individuals on ecosystem services globally. The
3 “foodshed” (Wedden, 1929) or “foodprint” (Billen et al., 2009) takes into account the area
4 required to produce agricultural goods required to meet the food requirements of a population,
5 and is thus related directly to the nutrient demands of cities and other concentrations of human
6 population (Fig. 6). A benefit of the footprint concept is its emphasis on bringing awareness
7 of the relationships between local, individual material consumption and distant, diffusely
8 distributed production. A peculiarity of the ecological footprint concept is that it doesn’t
9 translate directly into a specific geographic location, but rather represents a hypothetical area
10 of land required to sustain an ecosystem, produce food, or absorb CO₂. In contrast, the
11 “foodprint” attempts to associate a “real” region with the food supply of an urban population
12 (Billen et al., 2009). Historically, the “foodprint” of most cities was largely based on local or
13 regional food production. For some cities (e.g. Paris; Billen, 2009) this may still be true; for
14 others (e.g. New York), food supply is inseparable from the global transportation system.
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20 From the standpoint of nutrient loading, watershed nutrient accounting methods have been
21 used to infer the net cross-boundary nutrient inputs to watersheds from the most significant
22 sources (net food/feed transport, fertilizer, and in the case of nitrogen, atmospheric deposition
23 and biological N-fixation) that have been related to nutrient export from watersheds to coastal
24 waters (Howarth et al., 1996; Boyer et al., 2002; Russell et al., 2008; Fig. 7). These methods,
25 cousins of the various footprint methodologies in that they relate local impacts (both within-
26 watershed and coastal nutrient loads) to transboundary fluxes, reveal the increasing
27 importance of these fluxes in this age of globalization (aptly termed “the Homogocene” in the
28 context of biotic homogenization and reduced biodiversity; Rosenzweig, 2001; Rooney,
29 2007). Nutrient inputs to coastal watersheds are seen to be increasingly related to changes in
30 food preferences and other market trends (more meat/less grain, corn for processed food and
31 biofuels, etc), long-distance transport of nutrients in food and feed across catchment
32 boundaries, and associated increases in atmospheric N deposition related to vehicular
33 emission sources.
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38 Some material flows to coastal waters (water, sediment, silica) seem to be largely constrained
39 by catchment boundaries and human activities therein. Others (nitrogen, phosphorus) may be
40 more tied to trade and other transboundary effects. In addition, the structure and responses of
41 coastal ecosystems themselves may be changing in response to species flows and resulting
42 changes in biodiversity associated with the onset of the Homogocene (Lotze et al., 2006;
43 Levrel, 2007); one example is the transformative effect of the zebra mussel in North
44 American waters and their biogeochemistry. How can we adapt our thinking and management
45 strategies for coastal waters to these realities?
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52 53 **4) What makes a decision big? The tyranny of small decisions in coastal regions**

54 “Scale” applies to other dimensions beyond time and space. Human decision making is also
55 characterized by a range of scales, from deciding what to have for lunch, to deciding whether
56 or not to go to war. However, most human decisions are small, made by individuals, and are
57 often assumed to have few obvious consequences beyond the decision at hand. Kahn (1966)
58 examined the consequences to the market of cumulative effects of apparently independent
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1 individual decisions and concluded that they can yield undesirable consequences. William
2 Odum (1982) discussed the phenomenon in the context of the environment, noting the
3 example that no one decided to eliminate 50% of coastal marshlands of Connecticut and
4 Massachusetts between 1950 and 1970, though this is what happened. Ehrlich and Kennedy
5 (2005) noted that the ethics of decision making is unclear, that there is a need for a focus on
6 how people make decisions affecting the environment, and called for a “Millennium
7 assessment of human behavior.” A recent, provocative piece in the New York Times (Gertner,
8 2009; Marx, et al., 2007), suggesting that the human brain may be “wired” to give
9 environmental issues like climate change relatively low priority, only increases the urgency of
10 such work. Regulations and governance presumably should protect environments from gross
11 negligence and irresponsible decisions, but is it possible to safeguard vulnerable regions from
12 these incremental effects of small decisions?
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15 Coastal regions seem disproportionately vulnerable to the cumulative effects of unintended
16 “bad” choices because of their relatively high population densities (45% of the world’s
17 population lives in the 10% of land area defined by LOICZ as the “coastal zone”; Crossland et
18 al., 2005). Probably more to the point, the rate of migration to coastal regions is higher than to
19 other regions, the result of millions of individual decisions with potentially disastrous
20 consequences. In addition, choices that were relatively innocuous even a few years ago are
21 today more risky due to combined effects of increased vulnerability (i.e., a shifted baseline)
22 and an amplifier effect on consequences of choices due to the nature of modern trade.
23 Historically, most of the small decisions of daily life had little impact beyond local
24 households. Prior to modern food distribution systems, both were procured from local lands
25 or waters. As nutrient accounting can show, the distribution of food and feed can play a
26 dominant role in the level of riverine nutrient fluxes to coastal waters. Modern transport
27 methods assure the arrival of foods across continental scales in a matter of hours or days,
28 thereby guaranteeing a market for fisheries in (previously) remote regions. Fish or fowl for
29 dinner? The fish may have been swimming in coastal waters on the other side of the world a
30 few days before (Berkes et al., 2006). The fowl may be raised in a factory farm, fed on
31 fishmeal from thousands of kilometers away, but the farm discharges waste to local coastal
32 waters.
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38 The world’s coastal ecosystems see the direct effects of human activity for the simple reason
39 that more humans live near coastlines, or along major rivers, than in continental interiors far
40 from waters, and are thus especially sensitive to them. This is not an accident of history, but
41 the collective result of individual decisions over time, based on proximity to jobs and other
42 economic opportunities, quality of life, and many other factors all ultimately related to the
43 proximity to coastal waters and their services to humans. Whether the waters support
44 transport and trade, fishing/aquaculture, recreation, serve as a disposal system for sewage and
45 industrial waste, or all of the above, they provide value (i.e., ecosystem services) to the earth’s
46 coastal lands, and thus concentrate human populations (UNEP, 2006).
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50 However, the decision to live in coastal areas can ultimately have a dark side, as recent
51 experience with natural disasters in Banda Aceh, New Orleans, Haiti, and Japan has shown.
52 Highly populated coastal regions are especially vulnerable to extreme events of geological or
53 meteorological origin. When the catastrophic, magnitude 8.7 Lisbon earthquake of 1755 rang
54 church bells all over Europe, they tolled for the tens of thousands of lives lost in the quake,
55 the accompanying tsunami and fires, which leveled most of Portugal. The January, 2010
56 magnitude 7.0 earthquake that struck Port au Prince, Haiti, killed hundreds of thousands and
57 caused devastating damage to infrastructure and personal property in the billions. Both of
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1 these coastal cities were local centers of population and commerce. While Port au Prince saw
2 no post-quake tsunami, the relative increase in devastation caused by the less powerful
3 Haitian quake (compared to the Portuguese quake) can be seen as a direct result of the relative
4 increase in population density and development in this coastal city. The more recent
5 magnitude 9.0 earthquake and tsunami in northern Japan, and associated nuclear plant
6 catastrophe, shows that even the world's most technologically sophisticated countries are
7 vulnerable. Tsunamis and hurricanes can wreak catastrophic destruction in the modern day,
8 densely populated coastal zone simply by virtue of the number of people deciding to live
9 there; risk to life and property in coastal regions increases in proportion to population density
10 and development even in regions of quality infrastructural engineering and design.

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13 Increasingly, coastal zone governance turns to engaging "stakeholders" at the local scale as
14 well as scientific expertise (e.g. Tompkins et al., 2008) in the hope of equitable solutions and
15 grass roots support. Stakeholder participation has helped to mitigate or solve many conflicts
16 in coastal areas, particularly at local scales, but Billé (2006), in his discussion of the
17 "illusions" of coastal zone management, notes that one illusion is the notion that consensus in
18 human groups is prevalent at small scales. Stojanovic and Barker (2008) discuss several
19 problems of coastal governance through "coastal partnerships" of institutional stakeholders.
20 If consensus is an illusion even in small groups which are deciding questions of governance
21 for small systems, what chance is there for larger systems?

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25 In fact, governance of small coastal systems may be especially difficult because of the
26 numbers of institutions involved. Murawski (2007) refers to this as the "paradox of scale": the
27 smaller the geographic scale used to define an ecosystem, the more entities are involved in
28 decision making (Fig. 8).

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31 <figure 8 near here>

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34 In addition to scale issues, spatial disconnections, e.g. between decisions upstream and distant
35 environmental consequences downstream, often complicate governance, much as lags
36 between actions and consequences do in the time dimension. Major policy decisions, such as
37 undertaking the massive redistribution of river waters to serve the needs of irrigation and
38 drinking water as is being done with the Changjiang River in China (Xue et al., 2007), can
39 have fairly direct environmental implications downstream. Reducing river flows in coastal
40 areas changes the salinity regime, moving the salt front upstream and potentially increasing
41 the risk of groundwater intrusion of salinity and contamination of drinking water supplies
42 (Xue et al., 2007). Reduction of river flow means a concomitant reduction of sediment
43 transport from upland soils, potentially starving river deltas of sediment. The episodic nature
44 of sediment transport (Xu et al., 2005) and its redistribution in the river network is an
45 especially problematic aspect of sediment management and a source of uncertainty.
46 Woodroffe et al. (2006) point out that while sediment processes are well understood at small
47 time scales because of reliable short-term fluid dynamics, and long time scales (> 1000 years)
48 due to the availability of stratigraphic analyses, uncertainties are highest at the intermediate
49 time scales most relevant to managing sediment. Indirect effects can be subtler: introduction
50 of invasive species, shifts in nutrient ratios and corresponding ecosystem changes can easily
51 result from changes in flow regime (Li et al., 2007). All of these flow-related catchment
52 phenomena illustrate the obscuring effect of the spatial dimension on relationships between
53 decisions (large or small) made upstream and consequences (often large) in downstream
54 coastal waters.
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5) Scales of complexity in coastal waters: the simple, the complicated or the complex?

As pointed out by Dennison (this volume) Glouberman and Zimmerman (2002) have differentiated between simple, complicated and complex classes of problems and management in the context of the Canadian medical establishment. This distinction between categories of problems also applies to the tools available to deal with them. Simple problems can be characterized by simple models (recipes); complicated problems by more complicated models. Truly complex problems or phenomena often transcend the capability of current models, or decision processes.

Ecological modelers have recognized for years that models can exhibit nonlinear and often counterintuitive behavior, and so must be created and used judiciously (e.g., Silvert, 2000; Sterman, 2002). Solving the “Goldilocks problem” of matching the appropriate level of model detail to the question at hand is a Holy Grail of modeling; on the one hand, simple models are desirably parsimonious, even though many can exhibit complex behavior (Swaney et al., 2008). On the other hand, models that are too simple (e.g., not “biogeochemical” in the sense of Tett and Wilson, 2000) run the risk of being unrealistic and, if used as a guide for management, conceivably dangerous. Calls for new integrated modeling tools (e.g., Kroeze, et al., 2008) are appropriate and necessary, but probably not sufficient.

The appropriate level of model complexity depends on the problem to be addressed, and the data available to drive it. While in many cases complex models are needed for use in predicting environmental status of coastal waters (e.g., oxygen levels, trophic status, etc; Kroeze et al., 2008; Solidoro et al. 2005), simpler models may be adequate to serve as functional descriptions of ecosystem services (Barbier, 2008; Russo and Kareiva, 2009) or first-order responses to environmental change (Rahmstorf, 2007). Intermediate complexity tools may be sufficient to serve as screening models, and statistical relationships may be adequate to detect changes in flows (Kunzewicz et al 2009), or to establish relationships between specific human activities and coastal impacts (Howarth et al., 1996). However, examples of coastal waters in which “complicated” models fail to address the scope of the problem are increasingly common; the Baltic Sea is one example of a complex system subject to changes in terrestrial nutrient loads (Humborg et al., 2007), abrupt transitions (i.e. apparent regime shifts) in its biogeochemical cycles and oxygen conditions (Vahtera et al., 2007; Savchuk et al., 2008) and in food web structure (Osterblom et al., 2006). Its governance is further complicated by international boundaries and multiple, hierarchical management bodies with a conventional steady-state perspective of the relationship between loading and ecosystem response (Österblom et al. 2010). New theories of governance that incorporate ideas of complex adaptive systems may be useful in such cases (Duit and Galaz, 2008).

Datasets used for coastal classification are also scale-dependent. Coastal typologies intended to characterize regional to global-scale variation of ecosystems and their drivers in coastal waters have typically relied on global datasets of half-degree or greater resolution, and have discriminated coastal regions based on static properties of coastal or associated terrestrial or oceanic grid cells. This “Aristotelian” approach to coastal typology has limitations (see Appendix 2, supplementary material). It seems increasingly likely that attempting to categorize the controls on eutrophication at local to regional scales will require more highly resolved data in time and space. Duarte et al. (2008) have shown several examples of nonlinear response of eutrophication to nitrogen loading in coastal waters, including hysteresis and apparent shifts in “baseline” response, suggesting that a return to previous trophic status (i.e., “restoration”) may not be possible. However, these phenomena would probably be overlooked if the analyses were performed at a larger scale. Coastal typologies

1 that aim to resolve controls on ecosystem responses have different data requirements than
2 those resolving gross regional patterns of climate or land cover. Clearly, there is no sense in
3 trying to characterize complex responses of coastal waters without sufficiently highly
4 resolved datasets to both drive and validate the models. For example, Yamamuro et al. (2006)
5 have described shifts from submerged aquatic vegetation (SAV) to phytoplankton dominance
6 in Japanese coastal lagoons, in one case resulting in a catastrophic loss of the fishery and in
7 another, an increase of commercial mollusk production. Yamamuro and Icelly (this volume)
8 describe conflicts in governance at different scales which result in similar problems. What is
9 the appropriate level of model complexity to characterize such behavior? This represents a
10 modeling as well as a data management challenge.
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13 Finally, the revolution in technology that has brought us GIS, satellite-based remote sensing,
14 and the capability to follow tracers and biomarkers through ecosystems has also streamlined
15 trade and transportation in the business world, making it simpler to move and track materials
16 globally. Now that we have entered the Homogocene, it is clear that the same revolution is
17 responsible for the homogenization of culture, the creation of material flows between distant
18 ecosystems, and the associated degradation of the environment. Modern tracking systems,
19 such as those used in business to follow shipments door-to-door, remain unused, or at least
20 underutilized, in research, possibly due to privacy concerns and other legal issues. Do these
21 represent a new class of tools appropriate for addressing the unique problems of
22 environmental impacts of globalization? Cutting edge technologies, including so called “smart
23 dust” (<http://en.wikipedia.org/wiki/Smartdust>) and other networks of environmental sensors
24 integrated with analytical software (e.g. Harmon et al., 2009; Galaz et al 2010) have the
25 potential for monitoring spatiotemporal change in coastal ecosystems. Beyond research, can
26 they inform coastal decision making and governance? And, if so, at what scale?
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31 **Preliminary answers from LOICZ experience in coastal science**

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34 The questions posed above don't have obvious single answers – if they did, they would not be
35 very fundamental questions. In addition, we are equipped with incomplete understanding
36 based on limited knowledge, which changes as time goes on, corresponding to the ongoing
37 dynamic of change in the coastal zone. This is true of most questions related to the science
38 and management of the coastal zone. However, we can propose a few partial answers:
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41 *1) How big are coastal ecosystems and why should we care?* While there is no single
42 “size” or scale to coastal ecosystems, we know that they are influenced by activities well-
43 beyond their immediate boundaries. Human activities in their watersheds have degraded
44 coastal ecological communities, increased areas of eutrophication and dead zones, and
45 reduced abundance of fish and shellfish (Bricker et al., 2007). Critical scaling parameters,
46 such as mean residence time and other measures, can provide bases for multidimensional
47 classification of coastal water bodies, inform us as to the sensitivity of a given water body to
48 various loadings, and thus suggest appropriate management action (Bricker et al. 2003;
49 Buddemeier et al 2008; Swaney et al. 2008).
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51 *2) Temporal scales of change in coastal waters and watersheds: Can we detect shifting*
52 *baselines due to economic development and other drivers?* This is a tough one. Human
53 memory is tied to its own relatively short time scales, ranging from the duration of the work
54 day, to the length of a political cycle, to the time between human generations. Time delays in
55 societal and political response to (recognized) regime shifts add to those in the cause-effect
56 relations in ecosystem change. Together, these delays pose a particular challenge for the
57 dynamics of societal response which demand new forms of management which account for
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1 unpredictability of system behavior as well as ambiguity within the society in framing the
2 responses. Without concerted effort to document change in the environment, gradual
3 degradation escapes our notice, as can the gradual, cumulative impacts which can lead to
4 relatively swift transitions in ecological communities (references). This is why monitoring
5 our coastal waters and their watersheds is of paramount importance. Collecting, curating, and
6 synthesizing monitoring data, and analyzing it with the new insights and novel techniques that
7 science continually provides us, is essential to preserving the quality of coastal environments.
8 Establishing common, accessible datasets for general use (such as those developed by the
9 FAO), and developing accessible tools to analyze data is a start. We must share our results
10 with our peers and students, but also with the coastal governance community, as clearly,
11 straightforwardly and with as little bias as possible. As data-collecting technologies
12 proliferate, we must continue to develop new ways of assimilating, interpreting and
13 visualizing the data, including illustrative models and material budget methods, GIS, coastal
14 typologies, and other methods of synthesizing information, so that it is informative for
15 stakeholders, educators and decision makers. In addition, different modes of communication
16 and dialogue between scientists, policy makers and the public need to form part of the
17 evaluation of shifting baselines in order to include societal valuation and perception of the
18 detected changes.

21 3) *Are footprints more important than boundaries?* Because of modern technologies, we
22 have made the world a smaller place. Prior to the industrial revolution, the long-distance
23 transport of materials associated with trade and other human activities was a negligible
24 component of coastal material cycling. Today, ~~footprints~~ matter as much as the boundaries
25 on a map which define coastal water bodies and their watersheds because they represent the
26 dominant role of human activities in biogeochemical cycling, and we will have to recognize
27 the spatial and temporal scales at which decisions are made that influence footprints. Global
28 decisions (e.g. at the WTO) can create local impacts on footprints at many locations.
29 Therefore, both boundaries and footprints are important for planning and management. More
30 efforts must be made to develop global datasets at finer resolution, e.g. better than country-
31 wide totals or averages, or half-degree grid cells), and developed for natural boundaries
32 (watersheds, water bodies) rather than political or administrative ones. This is especially
33 crucial for understanding watershed interactions with coastal waters. For the practical
34 management of nutrient loads to coastal waters, relatively simple nutrient accounting
35 methods, such as the Net Anthropogenic Nitrogen Input (NANI) methodology (Hong et al.
36 2011; Boyer et al. 2002) can estimate the magnitudes of net inputs to coastal watersheds and
37 show the relative importance of local versus distant sources. On the governance side, careful
38 analysis of decision making ~~actors~~ and the scales at which they operate requires integrated
39 assessments and a range of methodologies and tools from both natural and social sciences. A
40 global example of an integrated assessment is the Millennium Ecosystem Assessment
41 (www.millenniumassessment.org); a regional example is the Coastal Futures project, which
42 examined impacts of offshore wind farms in the German North Sea, including perceptions of
43 the local population, effects on regional economic development and impacts on ecosystem
44 services (Lange et al. 2010). Such assessments rely on GIS-based tools to assess physical
45 characteristics as well as actor-oriented analytical frameworks used in political science (e.g.
46 Scharpf 2000).

53 4) *What makes a decision big?* It is fairly clear that the joint impact of small, individual
54 decisions can have as much or more impact on coastal waters than ~~large~~ executive decisions
55 made by those charged with coastal governance, though the difficulty of assigning individual
56 responsibility to the many decisions that can collectively amplify into environmental
57 catastrophe is the root of what Hardin called the ~~tragedy~~ of the commons". Attempts by
58 governing bodies to provide structure and accountability to decision making over the range of
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1 issues affecting coastal regions are fraught with pitfalls and limitations, as discussed above,
2 though there have been some partial successes in grappling with multiple scales of coastal
3 governance. An example is the Resource Management Act (RMA) in New Zealand. The
4 RMA has been deemed, to some extent, a success both nationally and internationally
5 (http://en.wikipedia.org/wiki/Resource_Management_Act_1991). The Act established one
6 single framework in place of separate frameworks divided between different agencies and
7 sectors (e.g., land use, forestry, pollution, water, etc), and was the first national scale statutory
8 planning strategy to adopt sustainability as a core principle, and “sustainable management” as
9 the basis of regulations. The RMA is based on the concept that decisions made locally about
10 a proposed activity are to be made on basis of effects, putting forward the expectation that
11 science-based knowledge be applied to management issues. Unfortunately, the RMA has had
12 failures, including in the area of water quality, which has continued to degrade in New
13 Zealand during the recent period of land development. This appears to be rooted in the
14 inability of regional bodies to prepare and implement standards consistent with the aims of the
15 Act in the face of development. For other environmental issues (e.g., aquaculture) the Act has
16 been more successful. Overall, the Act has provided a unified framework for local bodies to
17 work toward, and some progress has been evident. Such attempts at coordinated decision
18 making over local, regional and global levels (Olsen et al, this volume) represent the best
19 hope for sustainable governance of the coastal zone.

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23 5) *Scales of complexity in coastal waters: the simple, the complicated or the complex?*
24 Scale matters in coastal waters, for a variety of reasons, as we have seen. We also need to
25 communicate this to those who manage the waters and mediate between stakeholders, and to
26 help provide them with methods to manage appropriately to the scales of the problem at hand
27 on a case by case basis. We may be aided in management by new sensor technologies and
28 monitoring networks for coastal environments, but we also must learn to live with uncertainty
29 in decision making and develop governance systems that are flexible and quickly adaptable in
30 the light of new insights or observations of unintended changes in systems (e.g. through
31 monitoring). We need to recognize that coastal governance has scale issues of its own, and
32 that constraints imposed by institutions at various scales are part of the problem. An
33 awareness of the issues of scale is a first step towards avoiding simplistic “off the shelf”
34 solutions to complex problems. Transdisciplinary approaches incorporating natural and social
35 sciences within integrated problem assessments may improve understanding of problems
36 (including interaction between scales), that might help decision makers frame solutions to
37 complex multiscale problems.
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50
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List of figures, with captions

Figure 1: Relationships between time and space scales for a) physical factors, b) biological factors, c) governance and d) drivers of ecosystem change in coastal waters and watersheds.

Figure 2: Apparent net ecosystem production for LOICZ budget sites as a function of system area (log-log plots). a) Net heterotrophic systems ($p-r < 0$; absolute value used). b) Net autotrophic systems ($p-r > 0$). (Smith et al. 2005).

Figure 3: (a) The Chesapeake watershed at different historical periods: pre-Colonial up to 1650, showing a forested landscape with a large beaver population; early Colonial, when ~40% of the land was deforested for agriculture; intensive agriculture, when up to 80% of the land was under cultivation; and urbanization, when about half of the watershed is in forest and urban and suburban centers characterize some parts of the watershed. (b) The increase in the human population. (c) The historical record of land use. (d) Sales of fertilizer in the Chesapeake watershed. (e) Historical record of nitrogen fluxes into the Potomac River. (f) The historical record of the crab and oyster harvest. (g) Pollen representation of land use in the upper estuary. (h) Paleoecological record of sedimentation rates in the upper estuary. (i) Pollen profile showing a gradual increase in dry taxa after colonization. (j) Nitrogen influx into the Chesapeake Bay. (k) The change in the ratio of planktonic to benthic diatom species in the central mesohaline section of the estuary (Brush, 2008)

Figure 4. Historical and future estimates of sea level change, relative to the present, from the 2007 IPCC report (Bindoff et al. 2007)

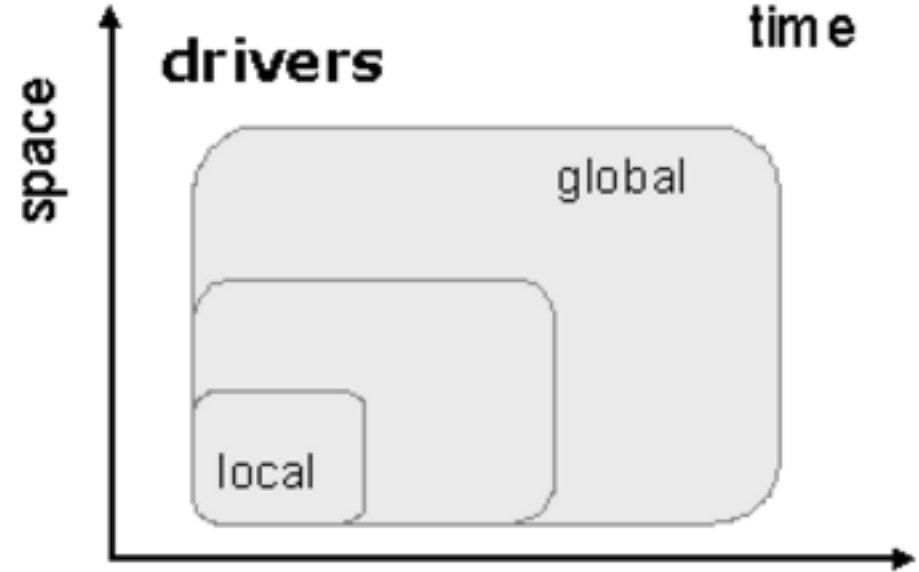
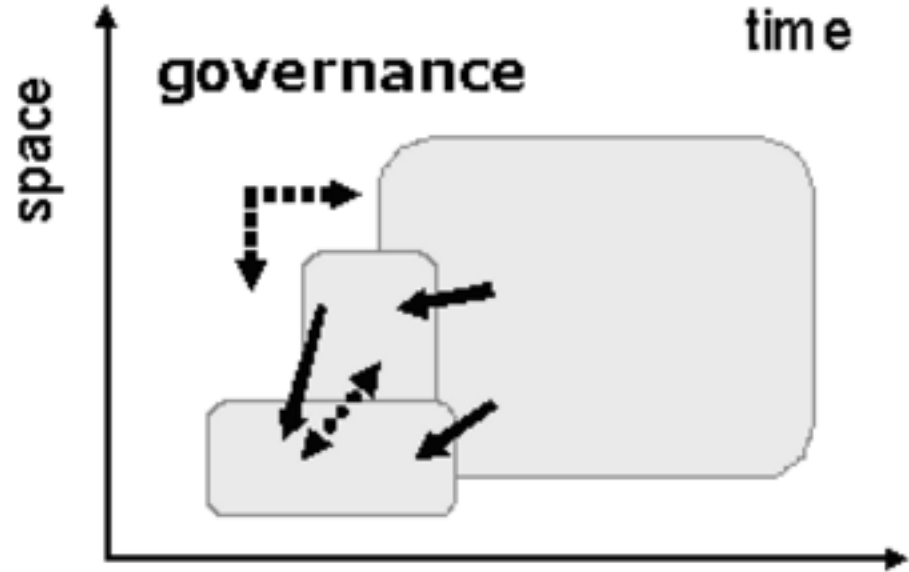
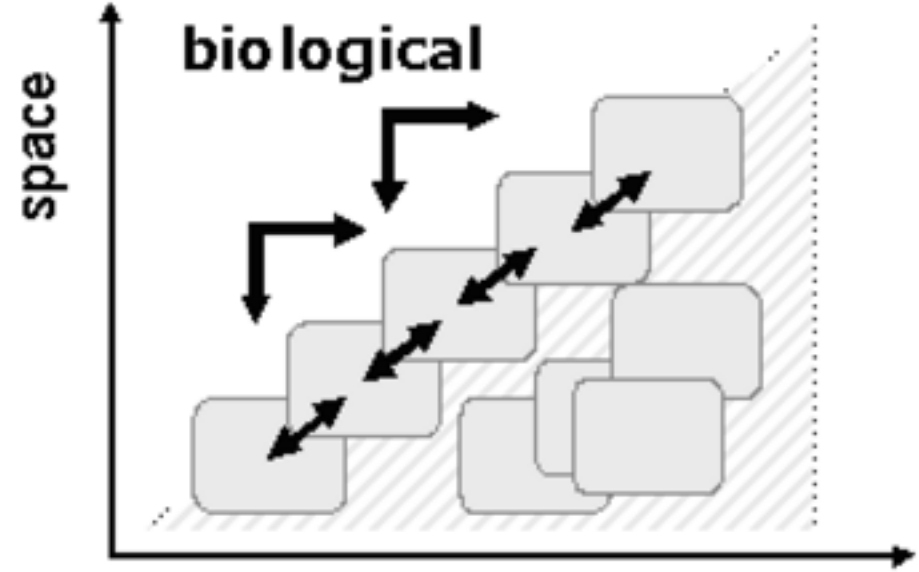
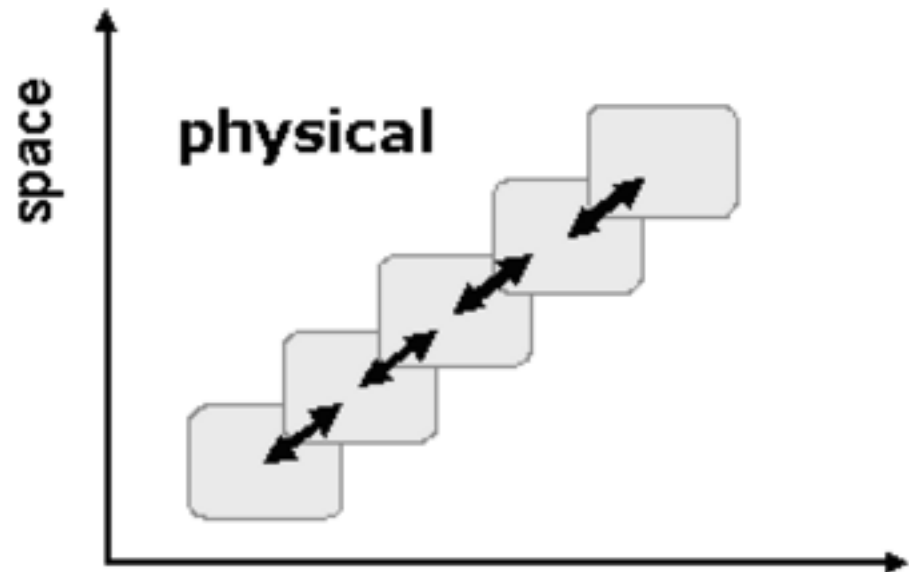
Figure 5. Winter season averages of North Atlantic Oscillation Index (NAO) and average sea surface temperatures in the North Sea and Baltic Sea. (Alheit et al. 2005).

Figure 6: Terrestrial net primary production of agricultural and forested land (Autotrophy) (a), and total heterotrophic consumption by human and domestic animals and by forest communities (Heterotrophy) (b) in the Seine watershed. Distribution of the autotrophy: heterotrophy ratio (c): Yellow areas are in approximate equilibrium; green areas are autotrophic, orange or red areas are heterotrophic (Billen et al 2007). The Paris metropolitan area is highlighted in red, indicating a high net consumption of nutrients, with implications for the downstream waters of the Seine.

Figure 7: Net anthropogenic nitrogen input ($\text{kg-N}/\text{km}^2/\text{yr}$) in a) northeastern US watersheds and b) Hudson River watershed subbasins. The larger scale patterns are driven by latitudinal gradients of population, agriculture, and atmospheric N deposition. Within the Hudson catchment, the intense levels of anthropogenic nitrogen input on the coast correspond to the large food imports of the New York City metropolitan area and local elevated N deposition associated with high automobile densities. (Hong and Swaney 2009)

Figure 8: The range of scale of institutional involvement at for coastal systems of various size scales. The “paradox of scale” is that the smaller the geographic size of the coastal ecosystem, the more entities that “contribute” to its governance (i.e. the largest regions are governed only by international bodies; the smallest by local to international entities) (Murawski 2007).

Figure(s) 1
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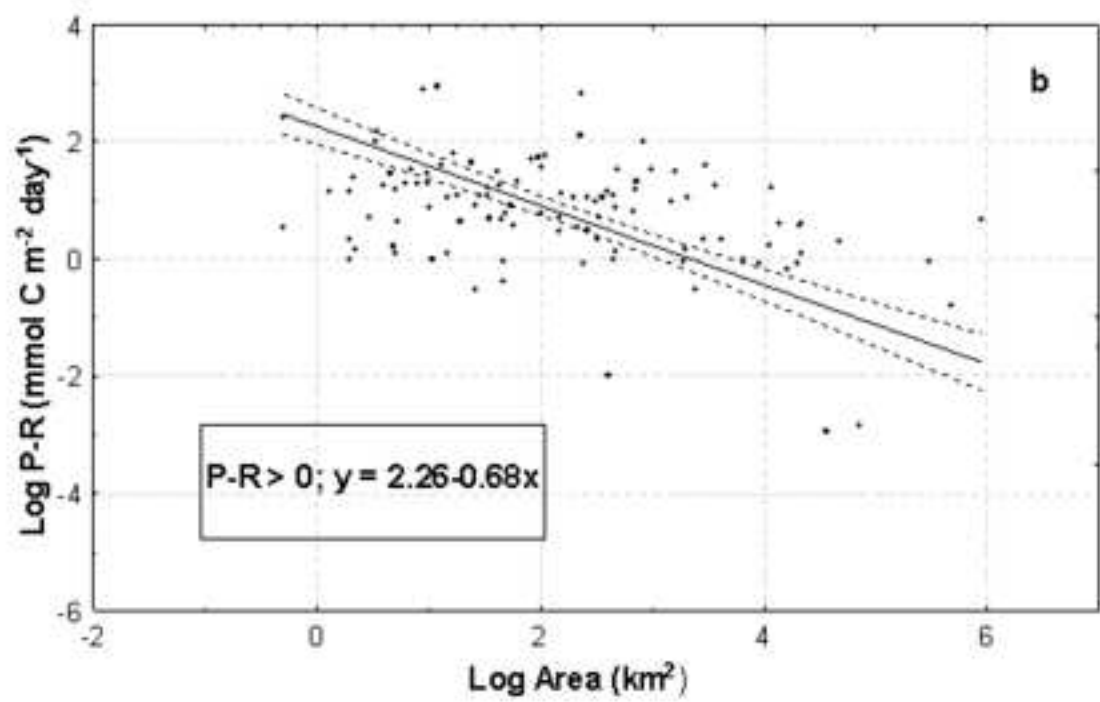
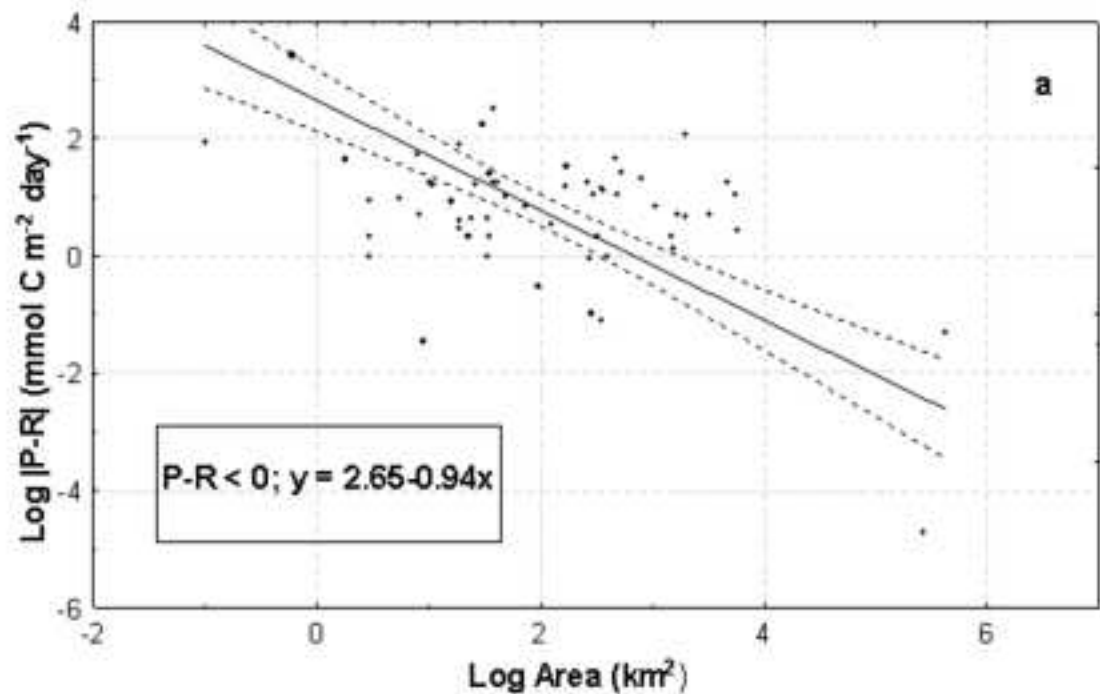


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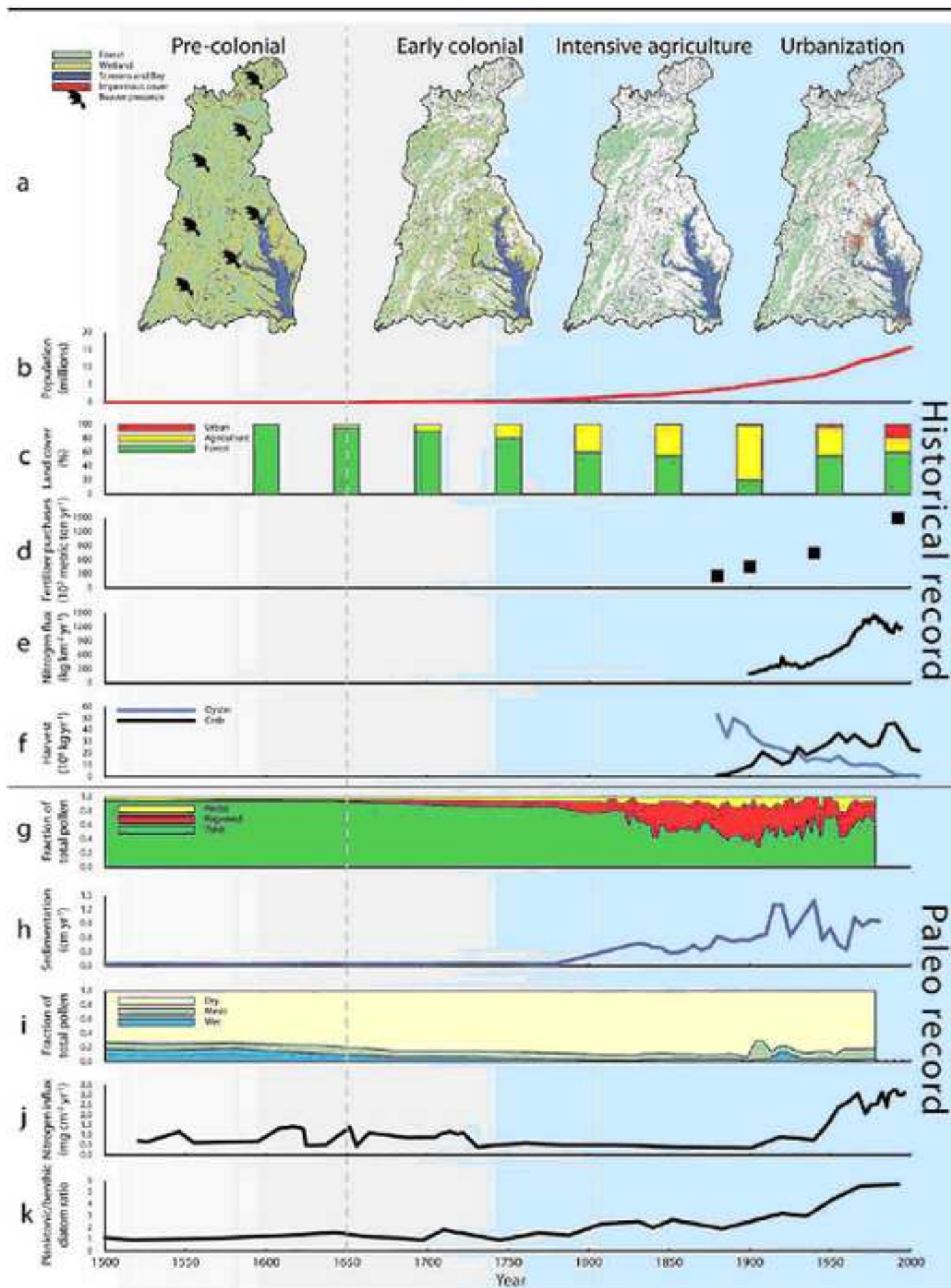
Figure(s) 2

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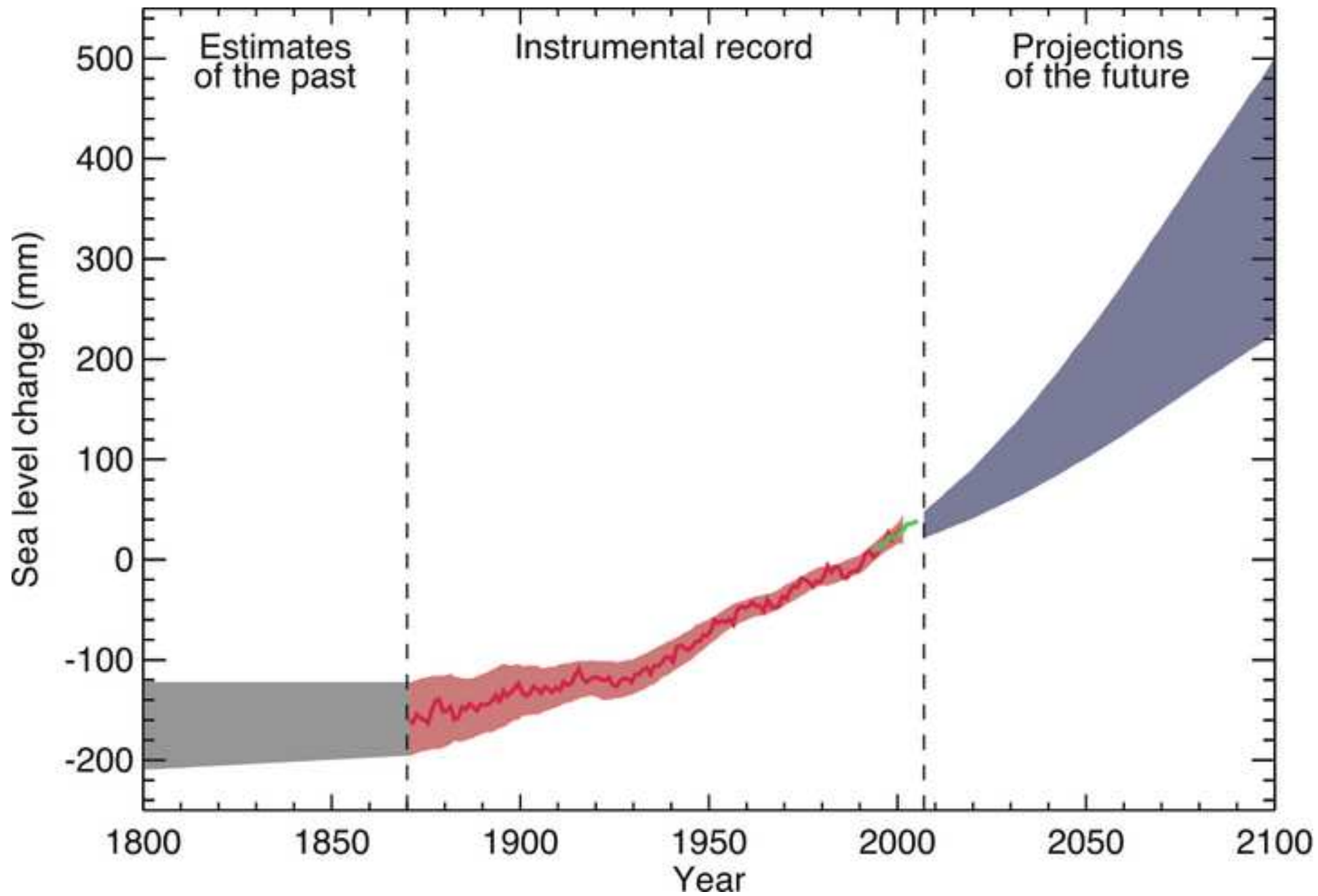


Figure(s) 3

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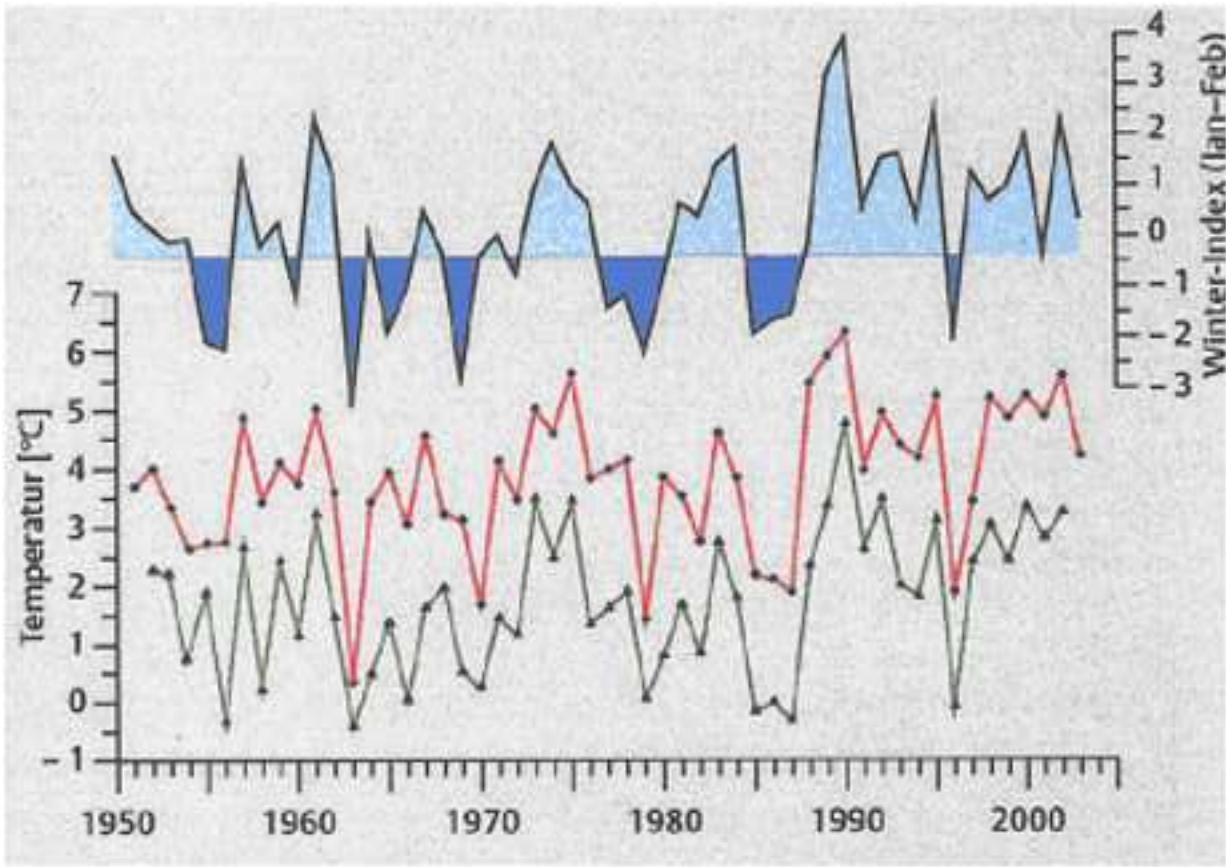


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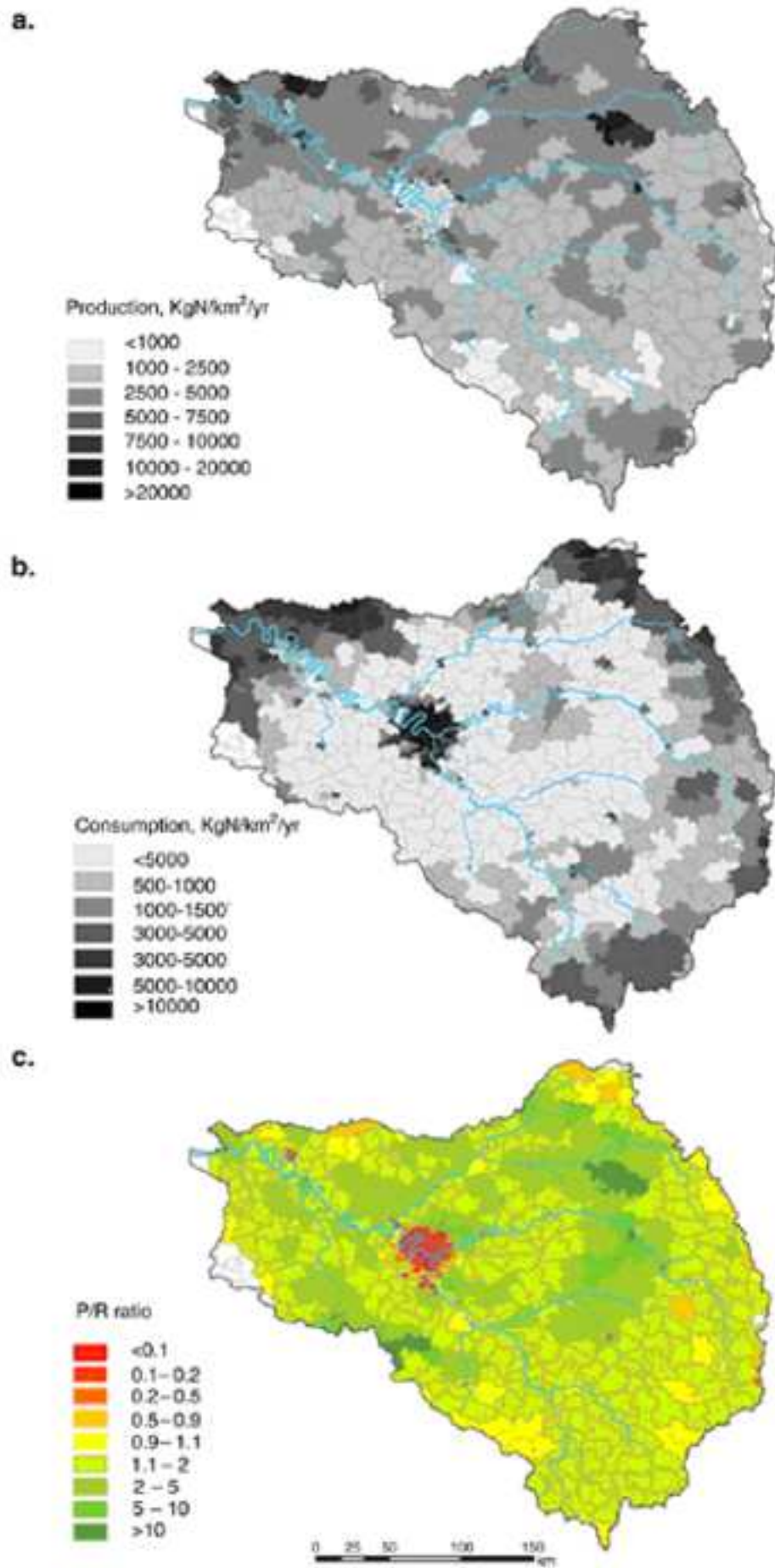
NAO Index

Water Temp. North Sea

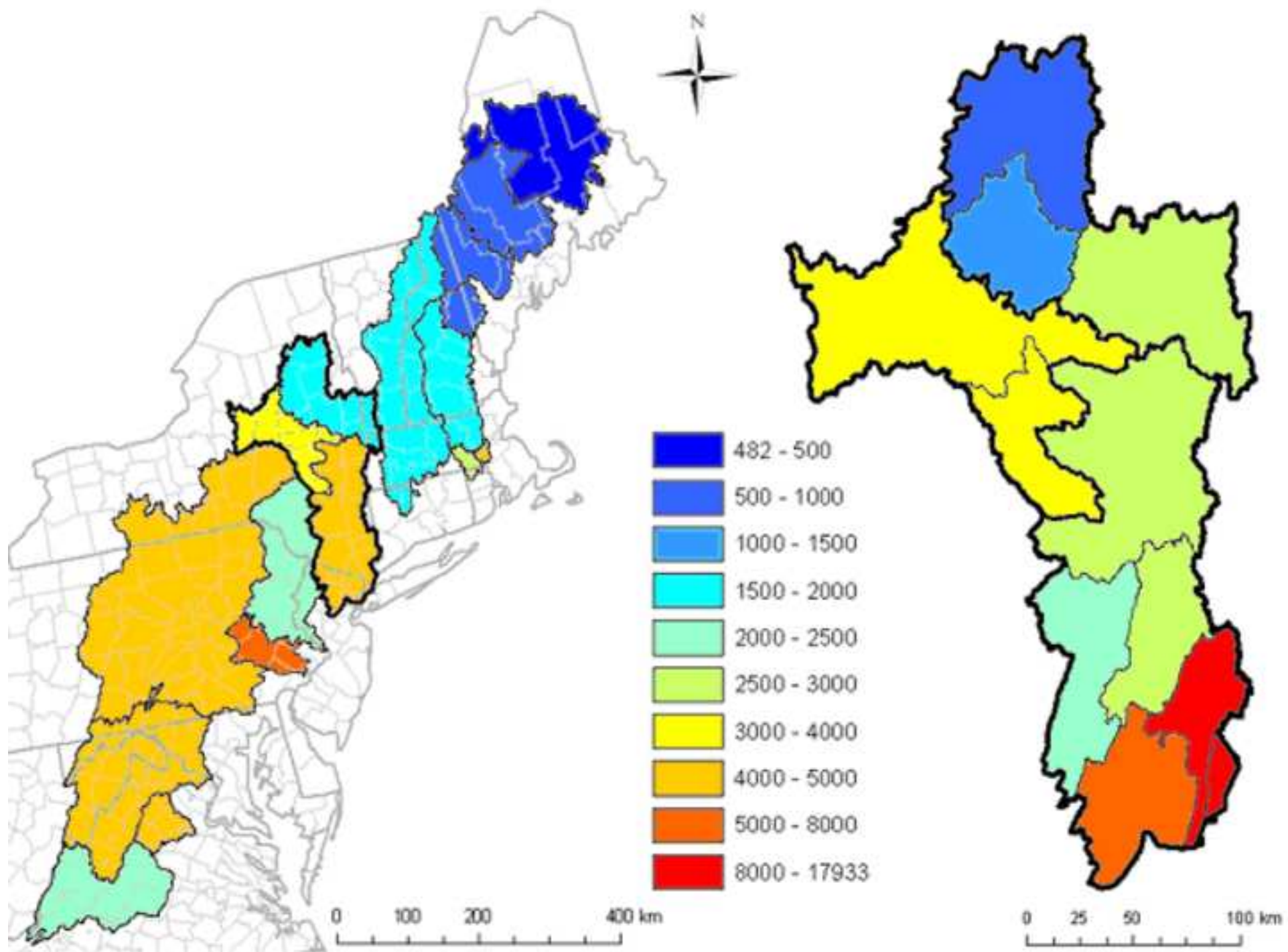
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Figure(s) 6

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Supplementary Material

Appendix 1. Terminology of Scale and Related Concepts (from Boynton et al., 2001)

At a 1997 EPA/MEERC-sponsored workshop on "Scaling Relations in Experimental Ecology, held in St Michaels, Maryland, it was quickly recognized that the use of the terms "scale" and "scaling" varies widely across disciplines. In one of the papers emerging from the workshop, Boynton et al (2001) provide the following definitions, which seem suitable for discussions of coastal ecosystems.

Definitions of Scale

- A change in pattern is determined by the spatial and/or temporal extent of measurements necessary to detect significant differences in the variability of the quantity of interest (Gardner 1998).
- Scale refers to resolution (spatial grain, time step, or degree of complication) and to extent (in time, space, and number of components included) (Costanza et al. 1993).
- Scale denotes the resolution within the range of a measured quantity (Schneider 1994).
- Scale refers to the resolution (grain) and to the range (extent) of research activities and ecological rates (Schneider et al. 1997).
- Scale is defined by the temporal and spatial characteristics of energy and matter within and among ecological systems. The scale of a study is determined by the size and extent of the observations in time and space, as well as by the resolving power of the individual measurements (Hoekstra et al. 1991).

Definitions of Scaling

- Scaling refers to the application of information or models developed at one scale to problems at other scales (Costanza et al. 1993).
- Scaling is that which is needed when the "ballgame rules" change; when relationships break down when size (for example) changes and some other feature does not change in a linear fashion (from workshop notes).
- Scaling pertains to the use of rules to explain the manner in which processes change when extrapolating from short to long and small to large time and space scales; all measurements are related to scale (from workshop notes).

Definitions of Scale-Dependence

- Scale-dependent pattern can be defined as a change in some measure of pattern with a change in either the resolution or range of measurement (Schneider 1994).
- Scale-dependent pattern refers to the way in which statistical summarization of a quantity changes with spatial or temporal scale,
- Scale-dependent processes are those where the ratio of one rate to another varies with either resolution or range of measurement (Schneider 1994).

Other Definitions

- *Extent* is the overall area encompassed by a study.
- *Grain* is the size of the individual units of observation. Extent and grain define the upper and lower limits of resolution of a study (O'Neill et al. 1986).
- *Allometric* relationships are those wherein a part of an organism or a process is related to or scaled to another and the scaling is not a direct proportion (i.e., the scaling factor is not unity); *isometric* relationships are those related by direct proportion (i.e., the scaling exponent is unity) (Calder 1983).
- *Normalization* is scaling that is done with simple direct proportions; identical with isometric scaling.
- The *scope* of a natural phenomenon is defined as the ratio of the upper to lower limit. Scope is thus the ratio of the extent to the grain or the ratio of the largest to the smallest size scale of measurement. Scope also provides an indication of the degree of extrapolation that is needed or used (Schneider 1998).

- *Multiscale analysis* is simply the recognition that there is no single "right" scale for analysis at levels of organization above an individual organism (Schneider 1994).

Appendix 2. Typology, Scale and Data

Rob Nicholls, Roberto Pastres, and Paul Tett

Aristotelian and Newtonian Views of the Coastal Zone

"Classical categorization comes to us first from Plato, who, in his Statesman dialogue, introduces the approach of grouping objects based in their similar properties. This approach was further explored and systematized by Aristotle in his Categories treatise, where he analyzes the differences between classes and objects. Aristotle also applied intensively the classical categorization scheme in his approach to the classification of living beings ... establishing this way the basis for natural taxonomy..." (<http://en.wikipedia.org/wiki/Categorization>)

The European Water Framework Directive (WFD) concerns itself with the ecological and chemical status of water bodies, defined as *"a discrete and significant element of surface water such as a lake, a reservoir, a stream, river or canal, part of a stream, river or canal, a transitional water or a stretch of coastal water."* Chemical status involves comparisons with quality standards but ecological status requires assessment of deviation from **type-specific reference conditions**, and the aim of management is essentially to restore water bodies to something close to these conditions. Thus there are concrete water bodies - exemplified by the Scottish fjord, loch Creran - which instantiate types - Creran is a 'coastal water type 12' in the system made by the UK and ROI (Tett, 2008). The quality status of the phytoplankton biological element in loch Creran will be assessed by comparison with reference data collected in another fjord, Loch Ewe, by an agency of the Scottish Government.

This approach has technical difficulties, e.g., there are some physical differences between loch Ewe and loch Creran: Why should we expect that they would have similar phytoplankton under undisturbed conditions? Such difficulties could be resolved with sufficient data and sub-typing, but the key point is that underlying this sort of categorization the philosophy that nature can be divided into discrete categories, each of which represents an ideal type, so that our management aim should be to maintain or restore the ideal. Key questions for this "Aristotelian" world-view are: what are the spatial limits of the water body or coastal zone system concerned, and, to what type does the water body or CZ system belong?

A contrasting world view, which sees nature as a continuum, could be called "**Newtonian**," because it is best described by the continuous differential equations of the Newtonian calculus. At any point in the continuum, conditions are a function of space, time and each other; the functions capture key features of processes relating each aspect of the local conditions (i.e. relating the state variables that define the system). In such cases, ecological theory can define a state of ecosystem "health", and social theory may be able to do the same for human societies; hence we may be able to characterize each point in the continuum as healthy or unhealthy, with an obvious preference for the first.

The new European Marine Strategy Framework Directive can (and perhaps should) be interpreted in Newtonian terms. The Directive requires good environmental status in 'salt-water' (not estuarine) regions out to the limits of national jurisdictions. This status is defined in part as that of *"marine waters where these provide ecologically diverse and dynamic oceans and seas which are clean, healthy and productive within their intrinsic conditions, marine strategies; ..."*. The units of management are very large - for example, the North Sea is named as a sub-region within the North-East Atlantic region - and it is not yet clear how information on status will be aggregated even over sub-regions. Nevertheless it would be possible to define a set of indicators that could be used to measure ecosystem state and function at arbitrary locations, to define 'good health' for each location on the basis of its environmental conditions, thus to evaluate health at each place, and finally to define an averaging or aggregation procedure to be used over a sub-region.

Typology: static versus dynamic characterization

Defining a typology is important in comparing both system status and the outcomes of

management policies. Typology implies classification, i.e. an Aristotelian view. Unfortunately, a classification usually implies a “static” characterization of coastal waters when, in fact, they are highly dynamic systems receiving fluxes of matter and energy from both local catchments and the sea which subsidize the maintenance of a coherent structure. Coastal ecosystems often rapidly respond to changes in these inputs during both periods of deterioration and recovery phases, so a challenge for typologies applied to coastal systems is to capture their dynamics with creative analysis of readily available data. Signs of change may be evident if we look at some indicators/indices of overall ecosystem functioning.

For example, introduction of invasive alien species marks an irreversible change in an ecosystem structure, but such a “perturbation” may be absorbed and, due to adaptive/evolutionary processes at different time scales, the ecosystem could maintain its functionality. The “alien” bivalve *Tapes philippinarum* was introduced to Northern Adriatic coastal lagoons about twenty years ago. In the lagoon of Venice, this species was successful, since the local species, *Tapes decussatus*, was disappearing due to the severe eutrophication episodes which repeatedly occurred in the Lagoon at that time. The reduction of N and P loads implemented in the 1980s, has markedly lowered nutrient concentrations, particularly P, in lagoon waters, but has not brought back the native species. Overall, however, from the ecosystem point of view, a benthic filter feeder has substituted for a “functionally equivalent” one. Typologies aimed at characterizing ecosystem function must consider different indices than those aimed at distinguishing dominant species.

Because systematic variation in pressures/drivers induce corresponding variations in ecosystem states, typologies based on spatial or temporal “mean” values (or other statistical measures of central tendencies) of biological (phytoplankton density), chemical (nutrients, pollutants) or physical (residence times) variables, i.e. “quality elements” *sensu* WFD, may be misleading. Temporal averages over seasonal variations (temperature) or spatial averaging over “hotspots” (nutrient loads) especially in coastal basins with complex morphology or circulation pattern can miss critical dynamics and structures that define the ecosystem. To adequately characterize such systems, typological systems should address time variation of systems, including indices of the “typical” seasonal evolution of both drivers/pressures on the system, and corresponding “state” indicators (ideally ones that are cheap and easily measured).

Where time series are available for the desired variables, these indices (and their trends) can be identified in a quantitative fashion and potentially can provide relevant information about the cause-effect relationships between systematic changes in drivers/pressures and changes of state. Typology can then be based on both the similarity of mean values and that of the seasonal patterns using Functional Data Analysis and clustering methods. It is worth noting that the most recent generation of typology software developed with support from LOICZ (DISCO, Buddemeier et al, 2008) has aimed to include time series data directly in analysis of typology, though such datasets have not yet been generally available for the coastal zone.

Developing global and regional databases to support coastal science for management

Process-based analyses of coastal zones allow us to understand how coastal systems operate, and move towards prognostic evaluation. Both these activities are important elements in providing the scientific basis for coastal management. Given the broad-scale of many of the drivers of coastal problems, investigations at these broad scales as well as local scales are important for a number of purposes, such as assessing and comparing impacts, as well as assessing the potential benefits of different policy interventions. This requires broad-scale databases with the necessary input data. However, the availability of such databases is generally a major constraint or even precludes application of process-based knowledge, especially for studies that address the land/sea interface (e.g., National Research Council, 2004).

Over the last two decades, the availability of digital spatial data has vastly increased as a result of advances in data capture and input techniques, and this has had a significant impact on coastal science. Fundamental to this is remote sensing. It has provided new and improved data for large parts of the world’s coastal areas for physical factors such as wave climate, water quality, sediment fluxes, and elevation. At the same time, new gridded global datasets on various socio-economic parameters such as population distribution and GDP density are being developed and upgraded in order to satisfy data needs for interdisciplinary analysis. For some factors, global sources are extremely dated as this type of research has not been funded (e.g., the global geomorphic maps of Valentin (1952) and McGill (1958)

which have never been updated). These datasets are normally typological in structure, and improvements are likely to have the same structure. Some factors, such as the long-term baseline rate of shoreline change are simply not known for large parts of the world's coast.

The DIVA, SAUP, LOICZ and CoastBase databases probably constitute the most comprehensive attempts to effectively merge coastal data, to date (see Table A2.1). The DIVA database is worthy of note as it builds on the other three (Vafeidis et al., 2008). It explicitly contains more socio-economic data, digitized sources from the old geomorphic data, and has a unique one-dimensional structure based on 12,148 coastal segments of variable length which captures the data. (This linear data structure is especially efficient for coastlines, compared to a raster structure; this is not true for coastal sea databases). This database feeds the DIVA models, which the database was designed to drive, and collectively this database-model system allows investigation of the potential impacts of sea-level rise. Nevertheless all the models are limited by the absence or limits of data which could greatly improve them.

Continued development of broad-scale data will be required to improve our scientific understanding of the world's coastal zones. Coastal geomorphological parameters are a particular gap in this regard and will require dedicated projects to fill; time series of driver, pressure, and state data are similarly important. These data developments will need to proceed in parallel with model and software development to insure that the critical data are collected; consideration of the best form of the database that encourages flexibility and ease of use will be essential. Coupled database/analysis systems, such as LOICZView and DISCO can facilitate both exploratory typological analyses and rapid refinements in typologies.

Database	Coverage	Data Format	Resolution	Data Sources	Source
DIVA (Dynamic Interactive Vulnerability Assessment)	Coastal areas (coastline)	Vector (one-dimensional)	Variable	Existing datasets, synthesis of sources	public including paper Vafeidis et al (2008)
LOICZ typology	Global	Raster	Half degree	Existing datasets	public Maxwell and Buddemeier (2001)
SAUP (Sea Around Us Project)	Coastal areas and Oceans	Raster	Half degree	Existing datasets, newly developed datasets for SAUP	www.saup.fisheries.ubc.ca ; Alder (2003)
CoastBase (European virtual coastal and marine data warehouse)	Europe	Various	Not specified	Existing datasets	www.coastbase.org

Table A2.1: Example broad-scale coastal databases and their main characteristics.

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