Sustain Sci (2013) 8:11–24
DOI 10.1007/s11625-012-0168-2

ORIGINAL ARTICLE

From frontier economics to an ecological economics of the oceans and coasts

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Received: 4 September 2011 / Accepted: 12 April 2012 / Published online: 6 May 2012

Abstract Ecological economics is a field of enquiry that has had, with a few exceptions, an almost entirely terrestrial focus. Given the fundamental ecological and economic importance of oceanic and coastal ecosystems, and the accelerating deterioration of these ecosystems, we argue that there is an urgent case to redress this imbalance. In so doing, the scope of ecological economics will be extended and compelling insights developed and applied to better understand and govern marine systems. Although we acknowledge that there is no unequivocal or unitary view of what might constitute an ecological economics of the oceans and coasts, we assert that it should consist of at least 'four cornerstones': (1) sustainability as the normative goal; (2) an approach that sees the socio-economic system as a sub-system of the global ecological system; (3) a complex systems approach; and (4) transdisciplinarity and methodological pluralism. Using these four cornerstones, we identify a future research agenda for an ecological economics of the oceans and coasts. Specifically, we conclude that ecological economists must work with other disciplines, especially those involved in marine policy and practice, to move from a 'frontier economics' (which has dominated marine management) to entrench an 'ecological economics' of the oceans and coasts as the dominant paradigm.

Keywords Ecological economics · Oceans and coasts · Coastal management

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Introduction

Despite an emerging awareness of the importance of oceans and coasts,[1] scientific discovery in marine systems still lags behind that in terrestrial systems, with much of the ecology of these systems still poorly understood. Calls for us to become more 'oceans literate' have led to international and national policy initiatives to help manage our oceans and coasts; indeed, in recognition of the importance of the marine environment, the United Nations (UN) declared 1998 'The International Year of the Ocean', thus, providing organizations and governments with an important opportunity to raise public awareness and understanding of the oceans and related issues. In this paper, we discuss the critical role that ecological economics has to play in guiding these policy initiatives towards a sustainable future for our oceans and coasts.

Why an ecological economics of the oceans and coasts?

Why are the oceans and coasts important; why should they be studied by ecological economists; and what contribution can ecological economics make to marine policy and practice? We suggest three main reasons: (1) they are vitally important; (2) they are being degraded by economic activity; (3) and they are the focus for policy and management interventions from global to local levels.

[1] We use: (1) 'oceans' to refer to the seas and oceans below the low tide mark; (2) 'coasts' to refer to estuaries, mangroves, tidal marshes, seagrass beds, kelp forests, coral reefs, and beach shores above the low tide mark; and (3) 'marine' as a collective term referring to both oceans and coasts.

Oceans and coasts have a fundamental ecological and economic importance

The oceans cover 70 % of the earth's surface and are critical to the healthy functioning of the planet's biogeophysical systems. They contain 97 % of the earth's water (Trenberth et al. 2007), hold almost 50 times more carbon than the atmosphere (Houghton 2007), and absorb perhaps half the carbon released from economic activity (Sabine et al. 2004). Ocean currents transport and redistribute heat, thereby, affecting global climate patterns and dynamics. Sudden shifts in these currents are thought to have triggered past ice ages, while future shifts could prove catastrophic. Furthermore, the oceans are uniquely important for biodiversity. Much marine biodiversity remains unknown (e.g., Black 2006), despite its importance in being strongly correlated with ecosystem productivity, ecosystem stability, and ecosystem service delivery (Worm et al. 2006; Danovaro et al. 2008).

Similarly, although coastal ecosystems cover just 1.2 %[2] of the earth's surface, they are vitally important in the global ecological system, having a disproportionate influence by accounting for 4.1 %[3] of global productivity (photosynthesis). The diversity of coastal ecosystems provides a wide range of ecological functions, many of which are interconnected. Coastal wetlands act as a natural buffer between the land and ocean, absorbing flood waters and dissipating storm surges (Nellemann and Corcoran 2006; Pérez-Maqueo et al. 2007; Costanza et al. 2008). The loss of coastal wetlands along the Louisiana coastline has contributed significantly to making this region vulnerable to coastal erosion and hurricane-induced storm surges [National Aeronautics and Space Administration (NASA) 2005, 2008]. Coastal wetlands are also important in nutrient cycling and processing. Much of the terrestrial nitrogen flux (from agricultural runoff, sewage, and other sources) is intercepted, stored, and processed by coastal ecosystems (Howarth et al. 2006; Chen et al. 2008). These systems are major producers of detritus and provide nurseries for numerous commercially, recreationally, and culturally important species. In addition, they can filter sediments and toxins from the water. Coastal ecosystems provide a habitat for species of a sometimes extraordinary diversity (Carpenter and Springer 2005; Allen 2008), with warm-water coral reefs rivaling tropical rainforests in their species diversity (Hinrichsen 1998; Nellemann et al. 2008).

Oceans and coasts are important not only ecologically, but also economically. As terrestrial sources of raw materials are depleted, the oceans are increasingly seen as a source. Much of the world's tourism industry is based on coastal attractions and activities, and the oceans still provide the major means of international transport for cargo. For many, oceans are the 'new frontier' of economic development, offering seemingly endless potential for exploitation. They are already a major source of fossil fuels, and they provide 16 % of the world population's protein and are a major food source in parts of Asia, Africa, and the Pacific. In total, raw materials and food from the marine environment had a market value of US\$1.6 trillion in 1994, representing 6.4 % of the global GDP of US\$25 trillion (Patterson 2008). In addition to this direct use of these raw materials (which have a market value), coastal–marine ecosystems also provide 'ecosystem services' that contribute to human welfare but do not have a market value. The total economic value (market plus non-market) of coastal and marine systems has been estimated at US\$22.6 trillion[4] (Costanza et al. 1997). This is equivalent to 68 % of the global GDP_{1994} and is over twice the total economic value of terrestrial ecosystems (US\$10.7 trillion). Ecological economics analyses like these demonstrate the unequivocal importance and value of marine ecosystem goods and services. Moreover, decision-makers are more likely to relate to and appreciate the need to manage these complex systems prudently when relative ecosystem values are expressed in the predominant 'language of dollars'.

Economic activities are increasingly degrading our environment

The Millennium Ecosystem Assessment (Brown et al. 2006) and a recent UN Environment Programme (UNEP) report (Nellemann et al. 2008) leave little doubt that coastal–marine ecosystems are among those most affected by the expanding global economy. Population growth adjacent to the coast has been prolific, with 21 of the world's 33 megacities being coastal (Martínez et al. 2007),

[2] This percentage refers to the surface area of the world's coasts as defined by note 1. If the continental shelf is included in the definition of 'coastal ecosystems', then the percentage increases to 6.3 % of the earth's surface (3267×10^6 ha) (Costanza et al. 1997).

[3] Data for these calculations are from Costanza et al. (1997, 1998), Field et al. (1998), Gattuso et al. (1998), and Falkowski et al. (2003).

[4] Costanza et al. (1997) calculated the total economic value of the world's marine–coastal ecosystems for 1994 to be: open ocean (US\$8.366 trillion), continental shelf (US\$4.283 trillion), estuaries (US\$4.110 trillion), seagrass and algal beds (US\$3.801 trillion), coral reefs (US\$0.375 trillion), and tidal marshes and mangroves (US\$1.648 trillion). This adds up to US\$22.597 trillion for all coastal and marine–coastal ecosystems. Patterson (2008, Table 3.1) further disaggregated these data to quantify the value (US\$) of each type of ecosystem services derived from these marine–coastal ecosystems types.

and about 41–45 %[5] of global economic activity occurring in coastal regions. This has, inevitably, had ever-increasing direct environmental impacts on coastal ecosystems; for example, much of the loss of estuaries can be directly attributed to port development, infilling, and civil engineering works required to support economic activity in the coastal zone, and more than 80 % of coastal pollution comes from the land (Nellemann et al. 2008). Coastal industries release a wide array of point-source pollutants (nitrogen, phosphorus, oil/oil by-products, heavy metals, and persistent organic substances) into the near-shore environment. Moreover, ecological impacts from non-nutrient pollutants have various unintended impacts, including effects far away from the place and time they first entered the environment (e.g., organochlorine pesticides affecting food chains in the Arctic). Human sewage is another colossal coastal pollutant, as are agricultural and urban runoff. This highly concentrated flow of water pollutants ends up in the mere 1.2 % of the globe occupied by coastal ecosystems. Ironically, the impacts do not arise solely from increases in pollutants: coastal zone geomorphology and ecosystems are being significantly affected by *decreased* sediment loads (resulting from sediment interception by dams and other engineering works).

Greenhouse gas emissions from the economy are more diffuse, but, by influencing climate change, they cause or threaten impacts such as: (1) greater CO_2 absorption by seas and oceans, thereby, causing a decrease in pH, which, *inter alia*, contributes to coral bleaching; (2) losses in biological productivity due to less nutrient supply in the upper ocean, caused by less mixing of warmer waters; (3) potential loss of coastal ecosystems (wetlands, salt marshes, mangroves) and low-lying land resulting from the rising sea level.

Together, these impacts largely explain why marine ecosystems are deteriorating faster than any other ecosystems (Brown et al. 2006) and why this degradation may already be more severe than any land-based equivalent (Nellemann et al. 2008).

Further exacerbating the environmental effects of the growth of the coastal economy has been the even more rapid growth of the coastal tourism industry and associated ecosystem alteration. Environmental impacts of the coastal tourism industry include coastal erosion, increased discharges of pollutants into the sea, natural habitat loss, and increased pressure on endangered species. These developments have caused considerable loss of habitat in marine ecosystems, particularly mangroves, estuaries, and coral reefs (Brown et al. 2006; Nellemann and Corcoran 2006), and have strained water resources in arid areas such as the southern Mediterranean (Essex et al. 2004; Iglesias et al. 2007).

The ever-increasing demand for food for the world's expanding population is an important economic driver of change in coastal–marine ecosystems. Nutrient runoff from agricultural land into the world's oceans has dramatically increased over the last 50 years and is now the primary cause of the over-enrichment of marine–coastal environments; its consequences include the proliferation of hypoxic or 'dead zones' (Nellemann et al. 2008), loss of habitat and biodiversity, and even indirect effects on climate change by influencing marine rates of carbon sequestration.

A critical driver of change in the marine environment is the increasing demand for fish and fish products. Demand for seafood products has doubled over the last 30 years and is projected to continue to grow at 1.5 % per annum to 2020 (World Bank 2005). However, this is demonstrably unsustainable, with 366 (24.1 %) of the world's 1591 fisheries in the Fisheries and Aquaculture Department (FAO) database having collapsed since 1950, mainly due to over-fishing (Mullon et al. 2005); the prognosis is even gloomier unless the current level of fishing effort is substantially reduced (Pauly et al. 2003). This collapse of fisheries not only curtails food supply, but leads to the overall loss and deterioration of marine ecosystem services (Worm et al. 2006). Fishing practices such as bottom trawling (which destroys benthic habitat) and drift netting (notorious for catching non-target species) also have significant, direct, negative environmental impacts (Nellemann et al. 2008). Moreover, although worldwide demand for fish products is increasingly met from aquaculture, this also causes detrimental impacts on the marine environment (FAO 2005).

About 30 % of the world's current oil production and about 50 % of the world's natural gas production are sourced from marine environments. As terrestrial oil and gas are exhausted, increasing attention is given to exploration and production from offshore basins of every continent around the world. Although only a very small amount of minerals is currently taken from the marine environment, many people see the oceans as the 'new frontier' for exploiting minerals, threatening the marine environment with ever-increasing environmental pressures.

Global economic growth also affects the coastal–marine environment indirectly, even though such growth may occur far from the sea. As already discussed, agricultural

[5] In 2003, 41 % of the global population lived within 100 km of the coast (Martínez et al. 2007), and in developed countries, wealthier people live in coastal areas (Agardy 2004), although this may not necessarily be true for developing countries. Assuming the coastal population throughout the world has a per capita income 10 % higher than average, we conclude that the GDP of the coastal economy could be as high as 48 % of the world's economy (if there is a 10 % higher per capita income for coastal regions) or 44 % (assuming no difference in per capita income between coastal and non-coastal areas).

activity in non-coastal areas can significantly affect the coastal–marine environment by increasing the nutrient load, and greenhouse gas emissions, an important driver of global warming, can profoundly affect the coastal–marine environment. Increased greenhouse gas emissions have a myriad of effects on the coastal–marine environment, ranging from sea level rise and a lowering of pH, to changing ocean currents, and including the loss of biodiversity due to these changing conditions (Nellemann et al. 2008). Because terrestrial, coastal, and marine environments are strongly interconnected through biogeochemical cycles, growth in the global economy, wherever it occurs, will have at least some affect on coastal and marine ecosystems.

Urgent calls for robust and integrative policy to deal with the negative impact of economic activity on marine ecosystems are increasing

Many of these problems have a strong ecological economics dimension, and a move to a more integrative approach for coastal and marine policy (e.g., Cheong 2008; Cicin-Sain and Knecht 1998) has been made across several fronts.

The UN Conference on Environment and Development (UNCED, 'Agenda 21') called for new and integrated approaches to the sustainable development of coasts and oceans (UN 1992). Subsequently, progress has been made to secure agreements and build programmes towards this end, including: the UN Convention on the Law of the Sea (1994); UNEP Global Programme of Action for Protection of the Marine Environment from Land-Based Activities; and the Convention on Biological Diversity's Jakarta Mandate relating to coastal and marine biodiversity. Coasts and oceans assumed a more prominent place on the agenda of the 2002 World Summit on Sustainable Development in Johannesburg, which, among other things, committed to 'Type I' outcomes such as controlling illegal fishing by 2004, managing fishery capacity by 2005, applying the ecosystem approach to marine areas by 2010, and establishing a network of marine protected areas by 2012 (UN 2002).

At a national level, the US Coastal Zone Management Act in 1972 was followed by the establishment of many integrated coastal management (ICM) initiatives. Since the 1990s, ICM has become accepted international practice and has increased dramatically. In 1993, about 75 countries and organizations were involved in about 217 ICM initiatives; by 2002, some 145 countries and organizations were involved in 698 such initiatives (Sorensen 1993, 2002). ICM focuses explicitly on the interconnections that characterize coastal systems and provides a holistic perspective that incorporates the links between inland catchments, the coastal zone, and the marine environment. In particular, it focuses on integrating planning and decision-making processes that have been traditionally compartmentalized into vertical (spheres of government) and horizontal (between sectors) components.

The complexity of marine systems is now well recognized. The UN's high-profile Millennium Ecosystem Assessment called for "an integrated approach to coastal management [that] requires a holistic view that includes land-based and freshwater influences and necessary political, economic and social conditions" (Brown et al. 2006). It recognized that cause–effect relationships in the coastal and marine environment are multidimensional, with many connections across ecological processes and systems, as well as cross-cutting political, social, economic, and institutional dimensions.

In general, the literature on oceans and coasts tends to be artificially divided, with a focus on either oceans or coasts, or on either economics or ecology. Neither division is constructive in developing policy to advance the sustainability of these interconnected systems. An ecological economics perspective on oceans and coasts attempts to transcend these artificial divisions and should bring a fresh conceptual perspective to policy development and implementation.

Defining features of an ecological economics of the oceans and coasts

An ecological economics view overlaps with but necessarily differs from perspectives from marine ecology, neoclassical economics, policy sciences, and several other disciplines. This view is important because it attempts to draw together strands from these other disciplines in a way that focuses on the interconnections between economic and ecological processes.

Ecological economics emerged in the late 1980s as a separate discipline that placed particular importance on economy–environment interactions. However, its roots can be traced to the visionary work of Boulding (1966), Georgescu-Roegen (1971), and Daly (1973), and even further back to the classical economists (particularly Malthus and Ricardo) and the French physiocrats.[6] Much of the initial impetus for ecological economics arose from the perceived failure of conventional (neoclassical) economics to deal with sustainability issues and from the desire for a new approach firmly grounded in an understanding of

[6] Martinez-Alier (1987) also links the development of ecological economics to theorists such as Geddes, Clausius, and Soddy, who came from diverse disciplinary backgrounds ranging from town planning to thermodynamics.

ecological processes and their bearing on the economy and economic growth. Neoclassical economics was considered too narrow, too reductionist, and too 'mono-discipline' oriented in that it often ignored or assumed away the findings from other biophysical and social sciences. In contrast, ecological economists have frequently argued for a more interdisciplinary or transdisciplinary approach.

We suggest four cornerstones of ecological economics that should be at the forefront of our thinking when attempting to define an ecological economics of the oceans and coasts: (1) sustainability as the normative goal; (2) biophysical approach; (3) complex systems approach; (4) transdisciplinarity and methodological pluralism.

Sustainability as the normative goal

The primary focus of ecological economics is achieving the policy goal of sustainability, which encompasses ecological, economic, social, cultural, and governance dimensions (see, e.g., Daly 1990, 2007; Costanza 1991; Common and Perrings 1992; Paavola and Adger 2005; Sneddon et al. 2006; Martinez-Alier and Røpke 2008). It is a transdisciplinary field that seeks to understand the complexities of coupled human–natural systems and develop practical solutions that promote ecological, economic, and social sustainability. This contrasts with the normative goal of neoclassical economics, which is usually seen to be allocative efficiency or, more broadly, economic efficiency. This difference leads to differing approaches in defining policy problems and their solutions. For example, neoclassical economists generally place greater faith in the market mechanism for resolving resource conflicts and policy issues. Gowdy and Erickson (2005) argue that there are signs of some tempering of this view, with recent Nobel Prize winners in economics holding beliefs that would have been heretical in the 1970s and 1980s. However, many neoclassical economists still hold fervently to the Walrasian general equilibrium framework and its role in defining economically efficient outcomes—in spite of its many assumptions about optimizing behavior, perfect information, and so forth.

Early ecological economists set out the principles and preconditions for a sustainable economy. Boulding (1966) used the metaphor of a spaceship to emphasize the roles of matter, energy, and information in maintaining economic activity and the need for social rather than technical solutions. In more formal terms, Georgescu-Roegen (1971) analyzed the thermodynamic constraints on economic activity and provided insights about how to run an economy more sustainably, albeit not in a steady state. Daly (1973) also set out principles for sustainability in his visionary book *Toward a Steady-State Economy*. He positioned the analysis of sustainability questions in terms of his 'ends-means' spectrum, where 'low-entropy matter-energy' is the 'ultimate means' (or binding constraint on economic activity), and 'higher-level ends' are defined by human needs and ethics and not by the concept of economic efficiency.

More recently, ecological economists have drawn on ecological rather than thermodynamic theory to define sustainability principles. For example, by defining sustainability in terms of Holling's (1978) concept of resilience (the "propensity of the system to retain its organizational structure following a perturbation"), Common and Perrings (1992) showed how ecological theories of communities and ecosystems can help define sustainable development.

Both neoclassical and ecological economists have used the concept of 'natural capital' to define and analyze sustainability. Although their attitudes differ, the general view is that sustainability can be defined as maintaining a constant capital stock (manufactured capital plus natural capital) from generation to generation.[7] Neoclassical economists tend to be more optimistic about the ability of manufactured capital to substitute for natural capital, implying that the depletion of natural capital is not necessarily unsustainable. However, ecological economists, armed with knowledge of ecological systems and thermodynamics, are less optimistic. They often refer to 'critical natural capital', defined as "that part of the natural environment which performs important and irreplaceable functions" (Chiesura and de Groot 2003); so, by definition, critical natural capital cannot be replaced indefinitely by manufactured capital.

Thus, when ecological economists consider how marine systems can be sustainably managed, they must define carefully the critical natural capital functions of those systems. For example, the services of the oceans in maintaining and regulating climate must be recognized in any ecological economic analysis purporting to be concerned about sustainability.

Many concepts of sustainability advanced by ecological economists are important in interpreting how marine systems should be sustainably managed. Oceans and coasts are highly connected with global biogeochemical processes of energy and mass flow, and the accounting and modeling of these processes can illuminate the connections between marine systems and the economy, as well as terrestrial systems. These connections across space and time must be clearly understood. For example, greenhouse gas emissions

[7] Although both neoclassical and ecological economists commonly use capital theory to define sustainability, this approach does have its critics (e.g., Faucheux et al. 1997). Furthermore, there is a view, particularly amongst ecological economists, that there is no one way to define sustainability. Lawn (2006) provides a comprehensive account of other definitions and of sustainability indicators advocated by ecological economists, in addition to those based on capital theory.

and non-point source agricultural pollution arising from terrestrial economic activity strongly affect not just the terrestrial environment, but also the potential sustainability of the oceans and coasts.

More generally, increased attention needs to be focused on the societal dimension of sustainability (see, e.g., Rudd 2000; Lehtonen 2004; Sneddon et al. 2006). According to Norgaard (2007), ecological economists have a special role to play in ongoing deliberations about improving prospects for sustainable governance of the coupled co-evolving human–natural system (see, e.g., Norgaard 1994; Paavola and Adger 2005, 2008; Paavola 2007; Gual and Norgaard 2010). Ecological economists, thus, have a distinctive contribution to make to the widely recognized need for transdisciplinary integrative analysis and practical governance interventions that are imperative for marine sustainability (Cicin-Sain and Knecht 1998; Hanna 1999; Ostrom et al. 1999; Hughes et al. 2005; Fanning et al. 2007; Hilborn 2007; Cheong 2008) (see "Transdisciplinarity and methodological pluralism").

Biophysical approach

Ecological economics aims to promote ecological, economic, and social sustainability. But it generally adopts a biophysical approach to economics. This perspective uses a nested hierarchy model in which the socio-economic system is a sub-system, or 'wholly owned subsidiary' (Daly 2005), of the biophysical system (Fig. 1). It emphasizes the materials, energy resources, technology, information flows, feedback, and production processes underlying economic activity. Attention is paid to physical limits, leading ecological economists to question the notion of indefinite economic growth. As Peet (1992) pointed out, "most physical scientists would agree that [a biophysical approach] is applicable to the physical constraints and long-term *limits* to social activities, not to the day-to-day activities of people within those limits."

This biophysical model of ecological economics has important implications for sustainability, including:

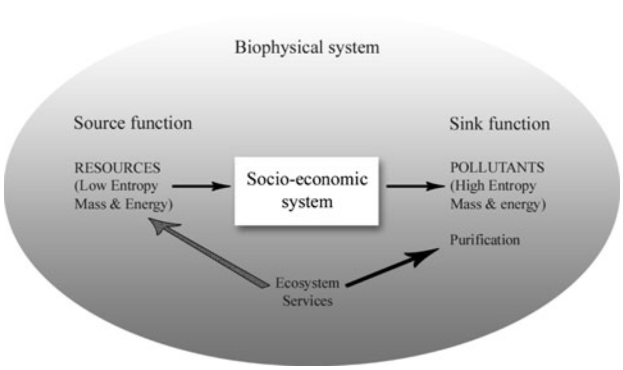

Fig. 1 Ecological economics framework: biophysical system and its socio-economic sub-system

1. The extent to which the socio-economic sub-system occupies the biophysical system. The economy has appropriated about 40 % of the net primary productivity of the terrestrial biosphere (Vitousek et al. 1986); it cannot exceed 100 %, and it is unclear at what point critical thresholds will be transcended and compromise vital ecological functions and life-support systems.
2. The extent to which sustainability of the socio-economic sub-system depends on the biophysical system as a source of resources and ecosystem services. Many resources are clearly finite and depletable, and economic growth cannot be sustained indefinitely if these resources are depleted or degraded. Moreover, ecosystem services like climate regulation, soil formation, and pollination can be compromised and degraded with profound negative consequences for economic activity.
3. The extent to which sustainability of the economy depends on the sink functions of the biophysical system. The biophysical system can efficiently purify and absorb many wastes and emissions, but beyond critical thresholds, it cannot cope with ever-increasing levels of pollutants.
4. The critical limits to our ability to recycle material wastes. The Second Law of Thermodynamics tells us that degraded energy outputs can never be recycled and there are severe limits on the degree of recycling of materials (mass).

To achieve greater sustainability from a biophysical perspective, ecological economists such as Goodland and Daly (1993) propose the minimization of energy and material throughput. An ecological economics analysis of the oceans and coasts should emphasize this biophysical approach by first highlighting the source and sink functions. Source functions provide raw materials and deliver ecosystem services, all of which are critical inputs into the economy. Unfortunately, much current economics thinking about the exploitation of these marine resources and their ecosystem is driven by a 'frontier economics', where biophysical limits are axiomatically assumed not to exist, or are, at least, not important. Approaches such as net energy analysis, which can show whether more embodied energy goes into extracting the energy resource than is contained in the extracted resource (Cleveland 1992), need to be used more frequently to test the true viability of energy and mineral exploitation in the seas, while any ecological economics analysis of fisheries must appreciate and incorporate ecological models of the non-linear dynamics of fish populations (Mullon et al. 2005).

The sink functions of the oceans and coasts must be more thoroughly analyzed than in conventional economic analysis. Again, 'frontier economics' must not prevail, because the capacity of the oceans and coasts to continue to sustainably absorb, process, and purify wastes from the terrestrial economy is limited (see "Oceans and coasts have a fundamental ecological and economic importance").

In developing an ecological economics of the oceans and coasts, we must recognize that we are dealing with living systems that are complex, rife with turbulence, surprises, and processes connected across time and space. Consequently, ecological economists must be careful to ensure, first, that they use appropriate tools of analysis such as complex systems thinking, and, second, that they recommend the use of approaches such as adaptive management. All too often, standard economic models assume idealized, smooth behavior of living coastal–marine systems, leading to some spectacular failures, particularly for fisheries.

Another important characteristic of an ecological (biophysical) view of the economy and its relationship with the biophysical environment is *inter-connectedness across space and time*. For the oceans and coasts, this perspective is critical. As previously noted, marine ecosystems are part of, and connected to, global biogeochemical cycles, meaning they can be affected by economic activity that may be situated inland, far from the coasts (e.g., farming, heavy industry). However, conventional economic analysis seldom takes account of these spatial factors[8] and the interconnectivity of ecological processes. Redressing these shortcomings of economic analysis presents a real challenge to ecological economics when it comes to a biophysical view of the oceans and coasts.

Complex systems approach

Ecological economics and neoclassical economics are broadly based on a systems approach, viewing the economy as a system of interdependent processes. Neoclassical economists often use partial equilibrium analytics for pedagogical purposes, but most gravitate to general equilibrium ideas that see interacting markets involving an ensemble of producers and consumers. Ecological economics shares the view of the economy as an interdependent system but extends it to include the biophysical environment, seeing the economy as a sub-system of the biophysical system, necessarily interacting with it through inputs, outputs, and feedbacks across the sub-system boundary (Peet 1992).

[8] Our propensity for spatial 'discounting' is even more problematic when it comes to the oceans than the better known 'time discounting' with which resource economists are often concerned. However, from a sustainability perspective, neither are virtuous—a Not In My Back Yard (NIMBY) attitude towards the disposing of wastes in the oceans (spatial discounting) is arguably just as ethically bankrupt as disregarding future generations (time discounting).

Moreover, ecological economics more fully embraces the idea of complex systems, whereby the economy–environment system and its interactions are characterized by complex systems behavior, including 'emergent properties', 'irreversibility', and 'non-linear dynamics' (e.g., Liu et al. 2007). This contrasts strongly with neoclassical economics, which is based on the Walrasian general equilibrium system that can only predict smooth, reversible behaviors because it is based on mechanical analogies drawn from nineteenth century physics (Mulder and van den Bergh 2001; Ruth 1993).

This complex systems perspective of ecological economics is critical for understanding the sustainability implications of ocean and coastal systems. Of foremost importance is the concept of interdependence: the oceans and coasts must be seen as systems strongly connected to each other as well as to the economy of the terrestrial environment.

Also important is the idea of emergent properties and its relationship to the hierarchy of complex systems. Emergent properties (e.g., disturbance regulation) are not apparent when systems are studied at the level of individual organisms or even populations; instead, they are revealed only when the entire ecosystem is studied at higher levels.

A third important idea of complex systems thinking is that of non-equilibrium behavior. Neoclassical economics centers on equilibrium behavior, but modern ecology increasingly considers ecological systems to be governed by non-equilibrium as well as equilibrium behavior (DeAngelis and Waterhouse 1987). In this view, a system's behavior is, at best, loosely predictable, even chaotic, with bifurcation points where the system may flip into a qualitatively different state or a new trajectory towards an equilibrium point. Wilson et al. (1996) and Mullon et al. (2005) argue that marine systems like fisheries are characterized by this type of non-linear dynamics, which requires a different approach from the conventional one that is heavily centered on predictability and system control.

A corollary of dealing with complex systems is that uncertainty is an inherent property of these systems. This uncertainty occurs at various levels, all of which must be addressed. The first type of uncertainty is risk, where we can statistically calculate the probability of an event—for example, we may be able statistically to estimate the probability of a storm at a specific coastal location. Second, in the marine environment, the uncertainty is generally more deep-seated; we cannot calculate probabilities because either we do not know all the important variables in the system and/or we are dealing with a system so intrinsically non-linear that statistical probabilities cannot be reliably calculated.

The third type of uncertainty is ignorance of system processes that we should, but do not, know about.[9] This is prevalent in coastal and (particularly) oceanic environments—even at a general level, our understanding of oceanic processes and biodiversity is mostly very poor. Despite recent advances (e.g., Worm et al. 2006; Levin and Lubchenco 2008), our understanding about the links between biodiversity and ecosystem services is woefully limited by our ignorance.

A fourth level of uncertainty is indeterminacy—that is, the system's behavior is inherently impossible to predict because it incorporates properties such as circularities, incongruities, and recursion. Ecological economists like O'Connor (1994) have appreciated that ecological–economic systems often have indeterminate behavior, with these ecological economists drawing their insight from fields like mathematics, systems theory, and non-equilibrium thermodynamics. Many marine systems may be characterized by such indeterminacy, particularly when the problem is framed in broad terms and over longer time-frames and diverse spatial scales. Moreover, much of our 'knowing' of the sea is inaccessible to rational Western-science analysis, instead falling outside the realm of intellectual endeavors and belonging more to the spiritual dimension. This is particularly true for cultures that still maintain a close connection with the marine environment (Šunde 2008).

Awareness of these categories of uncertainty is critical for an ecological economics of the oceans and coasts—even more so than in terrestrial contexts. Ecological economists must develop methods that can deal with these types of uncertainty, and must learn from other disciplines (such as the policy and planning sciences) with a longer history of dealing with such issues. Rather than abandoning traditional economic methods of dealing with risk and uncertainty, there is a need to move beyond them to embrace processes such as adaptive management (from the ecologist, Holling) and mixed scanning (from the sociologist-planner, Etzioni). More market-oriented methods, such as 'minimum information management' (MIM) (Batstone and Sharp 2008), should be developed to deal with our lack of information about the marine environment. This movement to a wider range of methods and broader appreciation of uncertainty is vital, particularly in relation to the uncertain world of oceans and coasts. Too often, we over-simplify to solve what Cartwright (1973) refers to as 'simple problems' when we are, in fact, dealing with 'messy' or 'metaproblems'.

[9] Patterson (2008) presented a method for making visible the contributory value of species and processes that exist in nature but are not picked up by neoclassical valuation methods due to the lack of knowledge (ignorance) of either the survey respondents and/or survey designers.

Transdisciplinarity and methodological pluralism

Given the complexity of economy–environment interactions and related policy questions, methodological pluralism in ecological economics is a necessity—no single theory or analytical framework is, in itself, deemed to be sufficient. Ecological economists draw on many disciplines, theoretical frameworks, and methodological approaches. Norgaard (1989) established a robust rationale for this approach, and it has been broadly accepted by most ecological economists (e.g., Faber and Proops 1985; Soderbaum 1990; Costanza 1991).

In contrast, neoclassical economics is firmly grounded on a single discipline approach and the assumption that one valid framework (Marshallian economics) can be universally applied independent of context. Such universalism is not uncommon in other disciplines, particularly in the sciences where universal truths are seen as a sign of the 'maturity' and 'rigor' of a discipline. However, ecological economists see such an hegemony as being not only unhealthy and academically stifling, but also as not reflecting the reality of complex, multi-dimensional, multifaceted, and often incongruous systems.

Consequently, ecological economists have attempted to adopt more open approaches in their research, drawing on many disciplines besides ecology and economics. For example, many have integrated social science perspectives into their analyses, particularly when dealing with governance, behavior, and equity (Paavola and Adger 2005; Hezri and Dovers 2006; Sneddon et al. 2006; Liu et al. 2007). Indeed, many consider that ecological economics has not gone far enough in integrating social science dimensions and there is much debate on how ecological economics can be truly transdisciplinary (van Kerkhoff 2003).

Much of this concern for transdisciplinarity and methodological pluralism is motivated by the groundswell of calls for a more integrated and holistic approach to environmental management, an opinion echoed in the coastal and marine governance literature (Sorensen 1997; Cicin-Sain and Knecht 1998). Thus, it is clear that an ecological economics of the oceans and coasts needs to be transdisciplinary[10] (or at least interdisciplinary). It must also be receptive to a variety of interpretations from other disciplines, including coastal and marine ecology, policy

[10] It is often asserted that ecological economics is, or should be, a 'transdiscipline' [e.g., Gill 1997; International Society for Ecological Economics (ISEE) 2006]. With respect, it is unlikely—and even arrogant to think—that any one discipline alone can transcend all others. Instead, ecological economists would do better to embrace transdisciplinary endeavors that involve working with other disciplines and, more importantly, they should remain or become open-minded.

sciences, social sciences, and, indeed, neoclassical economics, which produces valuable insights into questions of optimality and efficiency, market behavior, economic instruments for policy implementation, property rights, growth dynamics, and the valuation of coastal and marine goods and services.

A future research agenda for an ecological economics of the oceans and coasts

By applying the 'four cornerstones' definition of ecological economics (discussed above) to the oceans and coasts, a number of future research challenges for an ecological economics of the oceans and coasts can be identified.

Oceans and coasts are critical natural capital

Our first and most important conclusion is that *the oceans and coasts are facing unprecedented pressure from economic development*. Intensifying economic activity on the coastal margins, as well as the expanding global economy, are degrading the natural capital embodied in oceanic and coastal ecosystems, often irreversibly. The frontier economics attitude that characterizes much thinking about both sink and source functions of marine systems fails to acknowledge that these functions are limited, and, in some cases, the ability of marine systems to provide these functions has already begun to fail. This frontier economics approach must be replaced by sound ecological economics principles, and, until this happens, the outlook remains bleak.

In general, appreciation of the oceans and coasts as critical natural capital is poor and underdeveloped. Recently, McNeil (2008) reviewed the fundamental ecological processes and functions of the oceans and coasts (viz. the critical natural capital embodied in the oceans and coasts) in supporting human and non-human life, and Wilson and Liu (2008), building on earlier work by Costanza et al. (1997), showed how these processes and functions could be valued using non-market valuation methods. We need to build on these insights in order to better understand the role of oceans and coasts as critical natural capital. So far, research on marine natural capital and ecosystem services has focused on benefits and value, with little attention given to the risk and cost of irreversibly degrading these ecosystems' services and natural capital. We must also investigate exactly where the critical thresholds lie in degrading the natural capital of marine systems, and try to determine the extent to which natural capital can be substituted with man-made capital.

Also important is a need to understand better the dynamics of economic drivers of change affecting marine ecosystems (natural capital); that is, the dynamics driving: (1) growth in coastal economies, coastal tourism, and coastal urban development; and (2) demand for marine products such as fish and energy resources. Furthermore, we must understand the sometimes complex causal chains that eventually connect these economic drivers of change to impacts on marine ecosystems. Without this knowledge, formulating integrated policy responses that can reduce these impacts of the economy on marine natural capital will prove to be refractory.

Oceans and coasts are irreducibly complex, inherently uncertain, and conventionally unknowable

Our knowledge and understanding of the oceans and coasts face problems of uncertainty and lack of information, particularly compared with the terrestrial environment. Conventional economic analysis is ill-equipped to address this, and it remains for ecological economics to develop approaches that expect and can deal with uncertainty and indeterminacy in the ecological–economics interactions of these difficult-to-manage complex systems.

Value conflicts and valuation

Value has been a central concept in economics, with tensions between schools of economic thought often arising from fundamental differences over theories of value (Cole et al. 1991). Schumpeter (1954) recognized that "the problem of value must always hold the pivotal position as the chief tool of analysis in any pure theory that works with a rational schema". In fact, the neoclassical theory of value (price)[11] is central to the theoretical framework of neoclassical economics and is probably the main reason for its unquestionable success.

However, there is no theoretical consensus on the issue of value in ecological economics. While neoclassical methods showed marine ecosystem services to be far more valuable than those on land (Costanza et al. 1997), ecological economists need to move beyond this preliminary work so as to understand the value of marine systems from a multiplicity of perspectives and methods. Contemporary ecological economics uses a range of valuation methods and approaches, including: neoclassical methods (Wilson and Liu 2008); group-based methods that are often extensions of neoclassical methods (e.g., Blamey et al. 2000;

[11] Neoclassical economics has been dominated by the well-known 'scissors' of Alfred Marshall (1842–1924), comprising supply (marginal cost) and demand (marginal utility) curves, with an equilibrium price where the two curves intersect and at which maximum net economic benefit is generated. This orthodox approach is rarely challenged and is widely applied to public policy issues, including ecological problems.

Wilson and Howarth 2002); multi-criteria methods (Munda et al. 1994; Martinez-Alier et al. 1998); discursive–ethical approaches (O'Hara 1996; Sagoff 1998); conjoint analysis (Stevens et al. 2000); energy-based methods (Costanza and Hannon 1989); and ecological pricing (Patterson 2008). This methodological pluralism should be seen not as indecision and weakness, but as strength.

Valuation is critical in enabling us to make rational decisions about the oceans and coasts. However, the frontier economics of the oceans and coasts all too often disregards or downplays significant costs, resulting in biased decision-making. Spatial discounting is also prevalent, with the negative effects of inland industries on the marine environment being ignored. In this respect, the type of valuation data collected by Wilson and Liu (2008) can help by enabling the true cost of these externalities to be measured in readily understood dollar terms. Nevertheless, valuation in marine contexts must go beyond anthropocentric methods of neoclassical economics to include more biocentric methods, such as ecological pricing (Patterson 2008). Some would argue for more multi-criteria methods, while others would argue for a total abandonment of formal valuation methods in favor of more process-based methods of decision-making to resolve value conflicts. Šunde (2008) issued an even broader challenge to ecological economists to look beyond concepts of externalities and ecosystem services to include non-rational and spiritual ways of valuing oceans and coasts.

Need for a spatial dimension

Neoclassical models of economic behavior and growth are aspatial, with Blaug (1997) noting a "curious disdain of location theory on the part of mainstream theory". In contrast, some ecological economists have attempted to introduce spatial dimensions into their analyses, particularly when tracking the environmental impacts of economic activity (Costanza and Greer 1997). This approach is necessary for an ecological economics of the oceans and coasts because many environmental impacts and their causes have a critical spatial dimension that cannot be ignored or simply assumed away.

First, spatial analysis of ecological impacts is necessary for the integrative management of marine systems. When the cause (e.g., inland farming) and the effect (e.g., nutrient over-enrichment of the coastal zone) are widely separated, spatial analysis using methods such as cellular automata systems is crucial for a whole-system understanding of the problem; for example, to show how, where, and at what rate nutrients move across space from inland areas to the coast. These analyses should recognize the spatial heterogeneity of both terrestrial and marine environments and the differential effects of nutrients (or other pollutants) on biota. Too often, ecological economists measure the output of pollutants into the 'sink' environment without appreciating that it is a highly ecologically and spatially differentiated environment—for example, one tonne of nitrogen will have a markedly different impact when discharged into a mangrove swamp compared with an outfall three miles from the coast.

Second, the drivers of change of economic activity have an unavoidable spatial dimension that is not captured by mainstream growth theories such as those of Solow (1956) or Romer (1990). Because both these mainstream models lack a spatial dimension, they cannot adequately explain the patterns and drivers of economic change on the coastal margins. 'Economic agglomeration' in coastal regions strongly determines growth, with industries tending to co-locate on the coast due to self-reinforcing advantages related to market access, close proximity to other growth industries, and access to finance, innovators, and entrepreneurs (Patterson and Hardy 2008). In short, we are dealing with 'circular and cumulative causation' (Myrdal 1944)—when (coastal) regions experience initially higher growth, the flow of the factors of production from slowly growing regions reinforces the initial advantage many times over. For analyzing the economic growth of coastal economies, this type of economic geography model seems to have greater explanatory power and be of more use than the aspatial neoclassical models. Furthermore, it provides a spatial dimension that can be directly integrated into the ecological–spatial analysis discussed above. Fujita et al. (1999) provided a useful summary of economic geography theories and methods that could be used in such an analysis of the ecological economics of the oceans and coasts.

Need for integration to achieve sustainable development

Although the ecological economics agenda necessarily focuses on interactions between the economy and the environment, this alone will not achieve sustainable development of the oceans and coasts. Glavovic (2008a) showed that our efforts to improve economic and ecological outcomes in the coast often overlook issues of equity and poverty, and Šunde (2008) showed that the cultural and spiritual values of indigenous peoples are often compromised or ignored. Although ecological economists have argued about poverty and inequity (Goodland and Daly 1993; Martinez-Alier 2002), in the ecological economics literature, these issues have seldom been discussed (Costanza and King 1999) and, for the oceans and coasts, they have, until recently, been absent. If the goal of sustainable oceans and coastal development is to be advanced, the challenges presented by Glavovic (2008a, b) and Šunde (2008) must be accepted, with these and other social dimensions being considered alongside and connected with ecological and economic dimensions.

However, it is debatable whether ecological economics must integrate these social dimensions into its theoretical frameworks. Achieving an overall integrative economics that includes economic, ecological, and social dimensions is an ambitious agenda. Instead, we suggest that ecological economists (whose expertise lies at the economy–ecology nexus) should work with social scientists and other researchers and practitioners to define viable and preferred policy options, integrating their analyses and working towards sustainable development while embracing their concerns with dimensions such as poverty, equity, spirituality, traditional knowledge, and indigenous peoples.

Another area requiring an integrated approach is the analysis of marine environmental impacts across space and time. All too often, these impacts are compartmentalized—for instance:

- One-species models instead of whole-community or whole-ecosystem models;
- Considering only one spatial location when the cause may be far from the effect (see “Transdisciplinarity and methodological pluralism”);
- Using one-pollutant studies that have one impact when, in the coastal or marine environment, there is often a cascade of interrelated impacts (e.g., nutrient enrichment and climate change);
- Considering only first-order effects when the effects are cumulative across space and time (e.g., bio-accumulation of persistent pesticides in marine food chains).

Not only are these environmental impacts interrelated, but layered on top of them are interactions with the economy and communities. Integrated coastal management and ecosystem-based management regimes are steps in the right direction. Ecological economists need to support such initiatives by providing good quality information, particularly on the connectivity between the economy and the marine environment. Integrative economy–ecology modeling tools (Ruth 2008) are useful for this because they enable interactions and tradeoffs between the economy and the environment to be simulated and tested. Integrative marine management also requires good integration of governance and policy processes that are appropriately mapped onto temporal and spatial scales. Although governance, per se, is not the domain of ecological economists, our perspective can help by providing information, insights, and critiques concerning the appropriateness of governance and policy structure and processes.

Poor governance and policy implementation

Generally speaking, oceanic and coastal governance is failing worldwide. Marine ecosystems worldwide are deteriorating, often delivering economic benefits that are uncertain and/or outweighed by greater poverty and equity dis-benefits.

Arguably, governance structures and processes in the marine environment are poorly developed compared with those on land. Many factors contribute to this, but Glavovic (2008b) listed seven challenges arising from the disconnection between prevailing governance and the distinctive characteristics of marine systems. These include:

- Dealing with one-dimensional and universal solutions that are inappropriate, given the multi-faceted, complex nature of marine ecosystems and their connections with the economy and communities.
- Inability to deal with cross-scale and cross-level interactions due to ignorance, lack of information, or scale mismatch.
- Inertia and inflexibility. Oceans and coasts are dynamic complex systems that require an adaptive approach rather than traditional command-and-control bureaucratic responses.
- Inappropriate discounting of time. Attitudes and time-frames are often short term, working against the long-term viability and welfare of the system.
- Inappropriate reductionism. Analyzing complex systems like oceans and coasts as collections of component parts is unrealistic.
- The frontier mentality, which either assumes few foreseeable ecological, thermodynamic, and economic constraints to developing marine resources, or assumes that these constraints are not relevant.
- The collective action problem. Many marine systems transcend national and regional jurisdictional boundaries. This presents particular governance issues when applying property right systems developed for terrestrial contexts where, *inter alia*, property rights are more private in character.

Many of these governance challenges have a strong ecological economics dimension, relating to issues like intergenerational equity, sustainability, property rights design, economy–environment interactions, economic efficiency dimensions, value commensurability, and tradeoff analysis. Ecological economists should feel obliged to inform the governance debate by offering their particular set of expertise and insights.

Final comment: from frontier economics to ecological economics

Pressures on the coasts and oceans have accelerated over the last 30–40 years, and under the frontier economics that dominates marine management, many of these pressures will continue unchecked in spite of their well-documented and already unsustainable ecological impacts. Ecological economics must work with other disciplines, and with those involved in marine policy and practice in particular, to address these issues; specifically, by:

- Developing and applying new and existing tools of analysis that can evaluate marine policy options in an integrative manner;
- Undertaking in-depth analyses of the role of oceans and coasts as critical natural capital;
- Clarifying the value conflicts and valuation issues underlying marine resource management problems;
- Developing new ways of understanding and dealing with the complexity and uncertainty inherent in marine systems;
- Applying integrative approaches to analyses that track effects across temporal and spatial scales;
- Critically analyzing the connections between poverty, environment, and economy in the marine context;
- Through incisive analysis, helping to inform the ongoing debate about governance structures and processes in the oceans and coasts.

In short, there is an urgent need to develop an ecological economics of the oceans and coasts that is holistic, realistic, useful, and one that, above all, ultimately serves the needs of both current and future generations.

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