Global Environmental Change 32 (2015) 87–95

Contents lists available at ScienceDirect

Global Environmental Change

journal homepage: www.elsevier.com/locate/gloenvcha

Estimating the value of carbon sequestration ecosystem services in the Mediterranean Sea: An ecological economics approach

Donata Melaku Canu [a], Andrea Ghermandi [b], Paulo A.L.D. Nunes [c], Paolo Lazzari [a], Gianpiero Cossarini [a], Cosimo Solidoro [a,d,*]

[a] *Istituto Nazionale di Oceanografia e di Geofisica Sperimentale, Trieste, Italy*
[b] *Department of Natural Resources and Environmental Management, Faculty of Management, University of Haifa, Israel*
[c] *Ecosystem Services Economics Unit, Division of Environmental Policy Implementation (DEPI), United Nations Environment Programme - UNEP P.O.Box 30522, United Nations Avenue 00100 Nairobi, Kenya*
[d] *International Centre for Theoretical Physic, ICTP, Trieste, Italy*

ARTICLE INFO

Article history:
Received 13 June 2014
Received in revised form 16 February 2015
Accepted 25 February 2015
Available online 1 April 2015

Keywords:
Blue carbon
Carbon sequestration
Ecosystem services
Integrated assessment
Mediterranean Sea
Regulating services

ABSTRACT

Ocean and marine ecosystems provide a range of valuable services to humans, including benefits such as carbon sequestration, whose economic value are as yet poorly understood. This paper presents a novel contribution to the valuation of carbon sequestration services in marine ecosystems with an application to the Mediterranean Sea. We combine a state-of-the-art biogeochemical model with various estimates of the social cost of carbon emissions to provide a spatially explicit characterization of the current flow of values that are attributable to the various sequestration processes, including the biological component. Using conservative estimates of the social cost of carbon, we evaluate the carbon sequestration value flows over the entire basin to range between 127 and 1722 million €/year. Values per unit area range from -135 to 1000 €/km^2 year, with the exclusive economic zone of some countries acting as net carbon sources. Whereas the contribution of physical processes can be either positive or negative, also depending on the properties of incoming Atlantic water, the contribution of biological processes to the marine "blue carbon" sequestration is always positive, and found to range between 100 to 1500 million €/year for the whole basin.

1. Introduction

Marine systems are known to play a crucial role in the global carbon cycle by absorbing an important quota of anthropogenic carbon dioxide (CO_2) from the atmosphere. The world's oceans are estimated to absorb up 2 ± 0.8 billion tons of carbon annually, corresponding to about 25 percent of the total anthropogenic emissions to the atmosphere every year (Sarmiento et al., 1998; Sarmiento and Wofsy, 1999) and about 48 percent of the total fossil-fuel and cement-manufacturing emissions in the period from 1800 to 1994 (Sabine et al., 2004a). The temporary storage of large quantities of CO_2 in the various components of marine systems provides an important service in regulating atmospheric CO_2 concentration since it prevents the absorbed CO_2 from immediately contributing to the greenhouse effect thus slowing climate change (Sabine et al., 2004b).

The relevance of sinks and reservoirs of ocean and marine ecosystems for climate change mitigation is acknowledged by the United Nations Framework Convention on Climate Change (UNFCCC, 1992), which in Art. 4.1(d) calls for all Parties to promote and cooperate in their conservation and enhancement, as appropriate and along with biomass, forests and other terrestrial and coastal ecosystems. Over the past decade, there has been a substantial progress in the development of mechanisms for financing the restoration, conservation and sustainable management of forest and, more recently, coastal carbon sinks. The Reduced Emissions from Deforestation and Forest Degradation (REDD+) mechanism has provided a widely accepted international policy foundation for ecosystem-based management, which has been proposed as a blueprint for the management of coastal "blue carbon" sinks, including mangroves, seagrass beds, salt marshes and kelp forests (Crooks et al., 2011; Nellemann et al., 2009). The

---

[*] Corresponding author at: Istituto Nazionale di Oceanografia e di Geofisica Sperimentale, Trieste, Italy. Tel.:+39 0402140619.
E-mail address: csolidoro@inogs.it (C. Solidoro).

http://dx.doi.org/10.1016/j.gloenvcha.2015.02.008

development of reliable carbon accounting methodologies that rely on scientific measures and sound biogeochemical modeling of carbon fluxes has proved crucial for both REDD+ and blue carbon initiatives (Crooks et al., 2011; Tamelander et al., 2010). Against this background, the contribution of the marine biota to blue carbon sequestration remains poorly understood (Reid et al., 2009). Policy development aimed at characterizing the potential of marine-based mitigation strategies is lacking (Tamelander et al., 2010). According to all available estimates, however, the uptake of CO_2 by marine organisms is not negligible. Although phytoplankton constitutes merely 0.2 percent of the photosynthetically active biomass on Earth, marine photosynthesis accounts for about 50 percent of the world's total primary productivity (Falkowski et al., 1998; Beardall and Raven, 2004). Furthermore, even if it is estimated that only 0.1 percent of the organic carbon fixed by phytoplankton at or near the sea-air interface attains long-term storage in the seafloor sediments, about 30 percent of the biologically fixed carbon sinks into deep waters and only reemerges in upwelling regions after traveling large distances and over time scales of decades or longer (Sabine et al., 2004b).

From a welfare perspective, the regulating service of carbon sequestration by marine and coastal systems generates positive welfare impacts that are felt globally in the form of nature-based mitigation of climate change. Because of its public good nature, however, the current markets and respective price signals fail to capture these benefits to society. In other words, the current market prices, in their wide range of market goods and services, fail to embed the contribution that marine and coastal systems have in terms of carbon sequestration. The absence of information in the existing market prices with respect to the benefits generated by these systems may be incorrectly interpreted as indicating that the value of this ecosystem service is zero. Since many decisions, in both the private and public sectors, are based on market information, this information failure may fuel inefficient decision-making with respect to the management of marine and coastal ecosystems. In this context, the present paper provides an attempt to estimate empirically the benefits of marine systems in terms of carbon sequestration services. We followed an integrated, ecological-economic, spatially explicit approach with an application to the Mediterranean Sea.

The paper is structured as follows. Section 2 provides the details of a two-step biogeochemical/economic methodology for a comprehensive and spatially explicit valuation of carbon sequestration flows in the Mediterranean Sea. In Section 3, the proposed methodology is applied to the biogeochemical and economic assessment of the carbon sequestration service under present conditions. Section 4 discusses the policy implications of our findings for the management of carbon sinks in the Mediterranean Sea, with particular reference to blue carbon sinks.

2. An integrated model of marine carbon sequestration services

2.1. Setting the scene

This section describes the method consisting of an integrated biogeochemical-economic assessment of the carbon sequestration services in marine ecosystems, including their contribution to human welfare—see Fig. 1. In this setting, a high-resolution biogeochemical model is applied to provide a sound natural science characterization of the net CO_2 fluxes at the air-sea interface. A key aspect of the analysis, in view of the management implications of the study, involves the ability to separately account for the contribution of abiotic (physical and dissolution pumps) and biotic processes (biological pump) in terms of carbon sequestration services. Then we proceed with an economic valuation exercise of these services. Among the different methods that have been used to assign a value to carbon sequestration, one may count the analysis of prices in regulatory and voluntary carbon markets, the analysis of marginal abatement and marginal damage costs, and stated preference techniques (DECC, 2009; Jerath et al., 2012). Furthermore, we apply this integrated model with a spatially explicit approach and apply it to Mediterranean basin, directly allocating blue carbon tags to the Mediterranean countries and their Exclusive Economic Zones (EEZs).

2.2. The biogeochemical model

The biogeochemical model is a state-of-the-art 3D coupled transport-biogeochemical model purposely developed and validated for describing plankton productivity and carbon biogeochemical cycle in the Mediterranean Sea (Lazzari et al., 2012). Here it is used to assess the CO_2 fluxes at the air-ocean interface under present climate conditions. The ocean general circulation model is based on the Ocean PArallelize system (OPA, Madec et al., 1999). For these specific simulations, the transport is computed with a horizontal resolution of 1/8 of degree (which corresponds to about 12 km) and with a vertical z-coordinate discretization that is coarser in the bottom layers and increases in resolution at the surface layers, where plankton activity occurs: in total there are 43 levels with a grid spacing ranging from 3 to 350 m (MED16 OGCM model, Béranger et al., 2005). The biogeochemical dynamics are simulated using the Biogeochemical Flux Model (BFM, Vichi et al., 2007; Lazzari et al., 2012); a model in which chlorophyll and carbon dynamics are based on the parameterization of chlorophyll synthesis proposed by Geider et al. (1997) and on a Plankton Functional Type (PTF) representation of the planktonic food web that includes nine plankton pools, subdivided in photosynthetic producers (phytoplankton), consumers (zooplankton), and decomposer (bacteria). These broad functional classifications are further

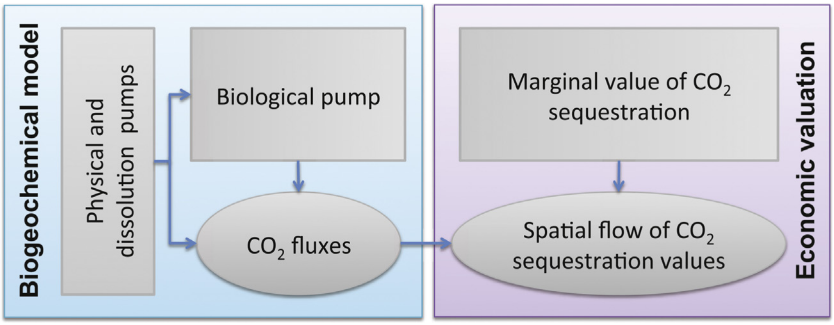

Fig. 1. Scheme of the hybrid ecosystem economic approach to valuation of carbon sequestration.

subdivided into functional subgroups to create a planktonic food web, so to have four phytoplankton groups (representative of diatom and of non-diatoms of different size), heterotrophic bacteria, two microzooplankton groups (preying on bacteria and on smaller phytoplankton groups), and two mesozooplankton groups (feeding on microzoo and on larger phytoplankton groups). Each PFT is described in terms of the interlaced biogeochemical cycles of carbon, phosphorus, nitrogen, and, for diatoms only, silicate. The descriptions of dissolved organic matter (labile, semirefractory, and refractory) and particulate matter are included, as well as the dynamic of the microbial loop, which is known to play an important role in Mediterranean Sea (Thingstad and Rassoulzadegan, 1995). The physical and biogeochemical models are coupled through a modified version of the OPA transport model (Foujols et al., 2000), named OPATM-BFM (OPA Transport Model–Biological Flux Model, Lazzari et al., 2012) now embedded in the MyOcean/Copernicus infrastructure and routinely used to produce short term forecast of the Mediterranean Sea since 2007 (http://www.myocean.eu).

The BFM model is online coupled to a state of the art carbonate system module (see Fig. 2), which computes the concentration of CO_2 dissolved in water (pCO_2) as a function of dissolved inorganic carbon (DIC) and alkalinity (ALK) (Orr, 1999). DIC is the sum of carbonate, bicarbonate, carbonic acid and dissolved CO_2, and accounts for all dissolved forms of inorganic carbon. Alkalinity is a measure of the capacity of the sea to buffer acidification. Together, ALK and DIC exactly determine both pH and pCO_2. The relationships among these variables are complex, but fully defined. In a nutshell, an increase in ALK (all rest being equal) causes an increase in pH (decrease in acidity) and a decrease in pCO_2, whereas an increase in DIC causes a decrease in pH (acidification) and an increase in pCO_2. Finally, the exchange of CO_2 between the atmosphere and the ocean depends on the difference between pCO_2 and the partial pressure of CO_2 in atmosphere (pCO_2air): if the pCO_2 in water is higher (lower) than in atmosphere there is an outgassing (solubilisation) and the sea acts as a source (sink) for the atmosphere. Biological activities influence these processes by modifying both DIC and ALK. Photosynthesis decreases DIC, while respiration increases it. Alkalinity is modified by nitrification, denitrification, and uptake and release of nitrate, ammonia and phosphate by plankton cells (Wolf-Gladrow et al., 2007). The dissolution of CO_2 changes DIC, but does not alter ALK. Water temperature influences pCO_2, too, namely an increase in temperature decreases the solubility of CO_2, i.e. increases pCO_2 (so favouring the release of CO_2).

The initial conditions and boundary conditions are based on Medar Medatlas datasets (MEDAR Group, 2002). The nutrient loads (nitrates, phosphates, and silicates) from terrestrial inputs are derived from Ludwig et al. (2009). Atmospheric inputs of phosphates and nitrates are also included (Ribera d'Alcalà et al., 2003).

In order to account for uncertainties in our estimates of CO_2 fluxes at the air-sea interface, we performed also a second set of simulations by using a different model, obtained by coupling of the same state of the art biogeochemical and carbonate models with a different physical transport model, (Madec, 2008, Oddo et al., 2009, see also http://www.nemo-ocean.eu) also already used in the Mediterranean Sea (Lazzari et al., 2014) and a slightly different boundary condition at the border with the Atlantic Sea (carbonate variables in agreement with Huertas et al., 2009 and Vichi et al., 2011). A third set of simulations was performed by considering the ingression of pCO_2 richer water from the Atlantic sea. The comparison of the simulations provides an indication on the range of variability of our estimates regarding both the total annual flux over the whole Mediterranean basin and the repartition of this flux among different regions.

2.3. The economic model

The air-sea CO_2 exchanges are regarded in this study as additional, spatially distributed, sources (or sinks) of the ecosystem service which translate into a cost (or benefit) for society by

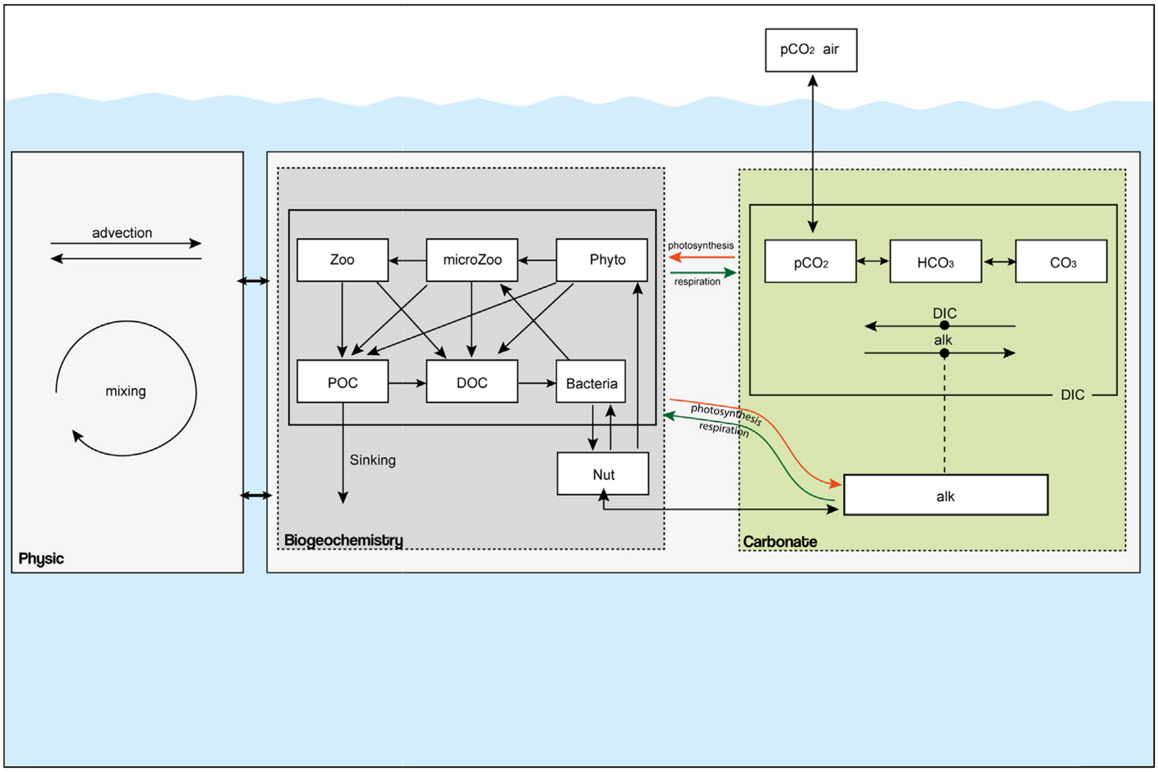

Fig. 2. Scheme of the coupled Biogeochemical Flux Model (BFM) and the carbonate system for the simulation of the CO_2 budget in the Mediterranean Sea.

building up (or reducing) the concentration of greenhouse gases in the atmosphere that are responsible for climate change (please note that due to the customary usage of the terms in the carbon literature, we refer in this paper to “sources” and “sinks” of carbon, respectively as areas of carbon release and storage. Strictly speaking, however, an area of carbon storage (release) is a source (sink) area for the ecosystem service of carbon sequestration). The microeconomic valuation of the benefits of carbon sequestration relies on the use of values per unit of carbon, which are multiplied by the carbon flux estimates resulting from the biogeochemical model to obtain a spatially explicit estimate of the flow of values. The flow of economic value obtained from carbon sequestration (V_0) during a specific period of time (t_0, t_1) and in a specific sea surface area (A) can thus be calculated as follows:

$$V_0 = \int_A \int_{t_0}^{t_1} \mathrm{Flux}(x,y,t) \times \mathrm{SCC}(t)\,dt\,dA \tag{1}$$

where Flux(x,y,t) is the flux of CO_2 at the point of geographical coordinates (x,y) and time t, measured in ton/km^2/day, and estimated by means of the coupled physical-biogeochemical model described in Section 2.1 whereas SCC(t) is the social cost of emitting one additional ton of carbon at time t, measured in €/tonCO_2.

The social cost of carbon (SCC) can be defined as the net present value of the cumulative, worldwide impact of one additional ton of carbon emitted to the atmosphere today over its residence time in the atmosphere (Watkiss et al., 2005). Following Pearce (2003), SCC can be defined as:

$$\mathrm{SCC} = \int_0^T \frac{\partial D_t}{\partial E_t} (1+s)^{-t} dt \tag{2}$$

where $\partial D_t/\partial E_t$ is a measure of the incremental damage of CO_2 emission and s is the social discount rate. Since CO_2 resides in the atmosphere, on average, for a long period, T is usually chosen to be 100 years or longer. The SCC can be interpreted as the value of resulting climate damages, measured at the margin, and is thus an indicator of the global incremental damage done by emitting one more ton of carbon today or at some point in the future, or, alternatively, the marginal benefit of carbon emission reduction (Pearce, 2003). Since the marginal damage of CO_2 emissions at a certain point in time depends in general on the atmospheric concentration of CO_2 at the time of emission and on future emission patterns, the value of the SCC is not constant over time (see Eq. (1)) and is expected to vary between different climate change scenarios (Stern, 2007). In particular, the SCC will tend to increase over time as population and per capita income grow. Since the benefits of CO_2 sequestration are not limited to a specific region but are felt globally, on the other hand, the SCC does not have a spatial variation, as shown in Eq. (1).

The underlying statistical magnitudes for the calculation of the SCC are the outcome of Integrated Assessment Models (IAMs), which capture the complex linkages between greenhouse gas emissions, greenhouse gas atmospheric concentrations, temperature change and monetary costs (or externality) of climate change damage to a society. Well-known IAMs in the literature include the Model for Estimating the Regional and Global Effects of Greenhouse Gas control policies (MERGE, Manne et al., 1995), the Integrated Model to Assess the Greenhouse Effect (IMAGE, Alcamo, 1994), the Climate Framework for Uncertainty Negotiation and Distribution model (FUND, Tol, 2006), and the Dynamic Integrated model of Climate and the Economy (DICE, Newbold, 2010). IAMs in the literature differ on the level of detail in modeling, and the respective capacity to deal with climate-economic-atmospheric complexity, capacity to deal with uncertainty, economic modeling strategy, and ability of incorporating an economic response (van Vuuren et al., 2011). All these aspects affect the final estimates of the social costs of carbon. Tol (2008) highlights the large uncertainty about the social costs of climate change. In a review and meta-analysis of 232 published SCC estimates, he finds a mean estimate of 35 €/tonCO_2 (33 US\$/tonCO_2) for a fitted distribution with a 1% pure rate of time preference. More recently, van den Bergh and Botzen (2014) take a critical look at the current range of SCC estimates, focusing in particular on cost categories that are as yet omitted from past studies, discounting, and uncertainties about damage costs and risk aversion. They conclude that most previous estimates grossly underestimate the true SCC and propose a lower bound value of 97 €/tonCO_2 (125 US\$/tonCO_2) for climate policy appraisal (all carbon value estimates in the paper are expressed in 2011 prices. Currencies other than EUR are converted using the five year average of the nominal exchange rate. The conversion between €/tonCO2e and €/tonC is based on the conversion to CO_2 from C using the ratio of molecular weights (44/12)).

To account for the uncertainties in the damages caused by different degrees of climate change and modelling of the social cost of carbon, we also looked at the range of estimates of carbon prices from regulatory and voluntary emission trading schemes worldwide (see Table 1). The carbon price estimates from the voluntary agreements presented in Table 1 range over a wide spectrum of magnitudes, from 2–4 €/tonCO_2 in the China Green Carbon Foundation scheme to 73–101 €/tonCO_2 in the Japan Verified Emissions Reduction Program (J-VER). In this context, we proceed with the economic valuation of the carbon sequestration services in the Mediterranean Sea by selecting as benchmark the estimate of the SCC produced by the European Commission (2008), under

Table 1
Overview of voluntary carbon markets.

National or sub-national program	Starting date (regime)	Price per credit/certificate (€/tonCO_2, Jan 2012)	Volume transacted in 2011 (ton CO_2)
British Columbia, Carbon Neutral Government	2008 (r)	19	800,000
United Kingdom, Woodland Carbon Code	2011 (v)	5–19	200,000
The Netherlands, Bosklimaatfonds	2011 (v)	25	NA (d)
Italy, Carbomark	2009 (v)	8–43	NA (d)
Oregon, Carbon Dioxide Standard	1997 (r)	5–7	73,225
California, Cap and Trade Program	2012 (r)	5–8	3,000,000
Oklahoma, Carbon Sequestration Certification	2008 (v)	3	26,100
Costa Rica, C-Neutral Standard	2011 (v)	NA (d)	NA (d)
Australia, National Carbon Offset Standard	2010 (v)	NA	937,000
Japan, J-VER	2008 (v)	73–101	50,000
Republic of Korea, KVER	2007 (v)	4	439,837
China, Green Carbon Foundation	2007 (v)	2–4	148,000
Thailand, T-VER	2013 (v)	NA	NA

Notes: Modified from Peters-Stanley (2012) and Portela et al. (2012); (r) = regulatory regime; (v) = voluntary regime; (d) = design phase; NA = not available.

the assumptions discussed in DECC (DECC, 2009; p.44 Table 6.3). In monetary terms this estimate corresponds to 19 €/tonCO$_2$ for the year 2013. This value is in agreement with the figures in Table 1 as well as with the work of Tol (2008), but also specific to this world regional sea. However it still is a very conservative value, in agreement with van den Bergh and Botzen (2014), and significantly lower than the one used by US EPA. Furthermore, we also consider the market price information, including the European Trade Scheme, the largest regulatory emission trading scheme worldwide, which as of November 2013 was equal to 4.36 €/tonCO$_2$. This value is substantially lower than the European Commission's estimate, suggesting that the current market price is a large underestimate of the true cost of carbon, which possibly reflects the fact that markets are only weakly limited by climate regulations. By using the presented values as boundaries, we are able to estimate a range for the carbon sequestration benefits.

3. Results

We applied the BFM and carbonate systems to the Mediterranean Sea under current conditions and aggregated at the level of EEZ as defined in Claus et al. (2013). The results are shown in Table 2 and Figs. 3 and 4. The data are presented both in terms of the total net CO$_2$ flux – which aggregates the value of the physical, solubility and biological pumps – and for the biological pump only. The contribution of the biological pump to the total flux has been estimated running a twin simulation where biological processes have been disabled. The value of the biological pump is calculated by difference between the two simulation runs.

Table 2, Figs. 3 and 5 all refer to the spatial distribution of CO$_2$ fluxes. Fig. 5 depicts the spatial distribution of CO$_2$ fluxes using euro/km^2/year as unit. The same figure, after proper rescaling, would illustrate the distribution of fluxes as kg/m^2/year. The values over the EEZs can be obtained by integration of CO$_2$ fluxes over the EEZ areas, and can be expressed both as total value over a given EEZ (value of an EEZ), or as normalized values over an area (value of a km^2 within a given EEZ). Table 2 gives the list of both the total and the normalized EEZ integrated values expressed as euro, with and without considering biological processes. Fig. 3 illustrates the total values with and without biological activity.

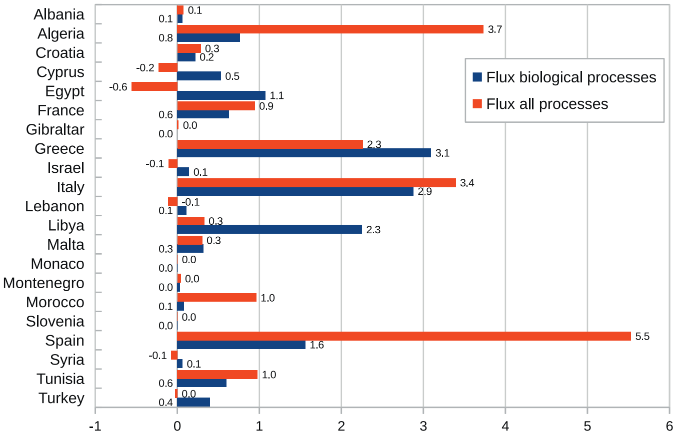

Fig. 3. Average yearly sea-air total net CO$_2$ flux and CO$_2$ flux due to biological processes only under current conditions and for all EEZs in the Mediterranean basin. Negative values represent fluxes from the sea to the atmosphere.

According to our findings, the Mediterranean Sea globally acts as a sink of CO$_2$, with an estimated overall flux of CO$_2$ from the atmosphere to the sea of 17.8 million tonCO$_2$/year, averaged over the period of investigation. The net flux of carbon ranges between −66 and 63 tonCO$_2$/km^2/year, with an average estimated flux of 7 tonCO$_2$/km^2/year.

Under these estimates, the net carbon flux in the Mediterranean Sea accounts for the 0.9% of the global ocean carbon fluxes. The Mediterranean Sea occupies 0.7% of the global water surface, therefore its carbon sequestration flux per surface unit is similar to the average global ocean sequestration flux. The distribution of the CO$_2$ fluxes generally shows a west/east gradient with higher sink fluxes in the west and lowest (negative in some areas) in the east Mediterranean. The EEZs of six countries located in the Levantine and North African regions (Egypt, Cyprus, Lebanon, Israel, Syria and Turkey) currently act as sources of CO$_2$ for the atmosphere. The majority of carbon sequestration occurs over the EEZ of four countries (Spain, Italy, Algeria and Greece) that account for about 84% of the total carbon sequestration flows, although they represent only 56% of the total surface of the Mediterranean.

Table 2
Overall carbon sequestration values and values of carbon sequestration from biological processes in the Mediterranean EEZs, calculated using the SCC value estimate recommended by the EC (DECC, 2009).

Country EEZ	All processes		Biological processes	
	Total value [10^6 €/year]	Value per km^2 [€/km^2/year]	Total value [10^6 €/year]	Value per km^2 [€/km^2/year]
Albania	1.5	130.3	1.1	102.6
Algeria	71.0	550.6	14.5	112.4
Croatia	5.4	96.1	4.2	73.7
Cyprus	−4.3	−43.6	10.1	102.4
Egypt	−10.6	−61.9	20.4	119.6
France	17.9	202.4	12.0	135.1
Gibraltar	0.3	696.8	0.001	2.1
Greece	42.9	86.8	58.8	118.9
Israel	−2.0	−74.4	2.7	100.4
Italy	64.5	119.9	54.7	101.7
Lebanon	−2.2	−113.0	2.1	107.9
Libya	6.2	17.5	42.8	120.5
Malta	5.8	104.0	6.0	108.8
Monaco	0.05	166.0	0.03	111.4
Montenegro	0.8	104.2	0.6	83.8
Morocco	18.3	1013.3	1.6	87.0
Slovenia	0.04	230.3	0.03	186.2
Spain	105.1	404.0	29.7	114.0
Syria	−1.4	−135.9	1.2	116.6
Tunisia	18.6	181.5	11.4	110.9
Turkey	−0.6	−6.9	7.6	90.7
Total	**337.3**	**133.5**	**281.4**	**111.4**

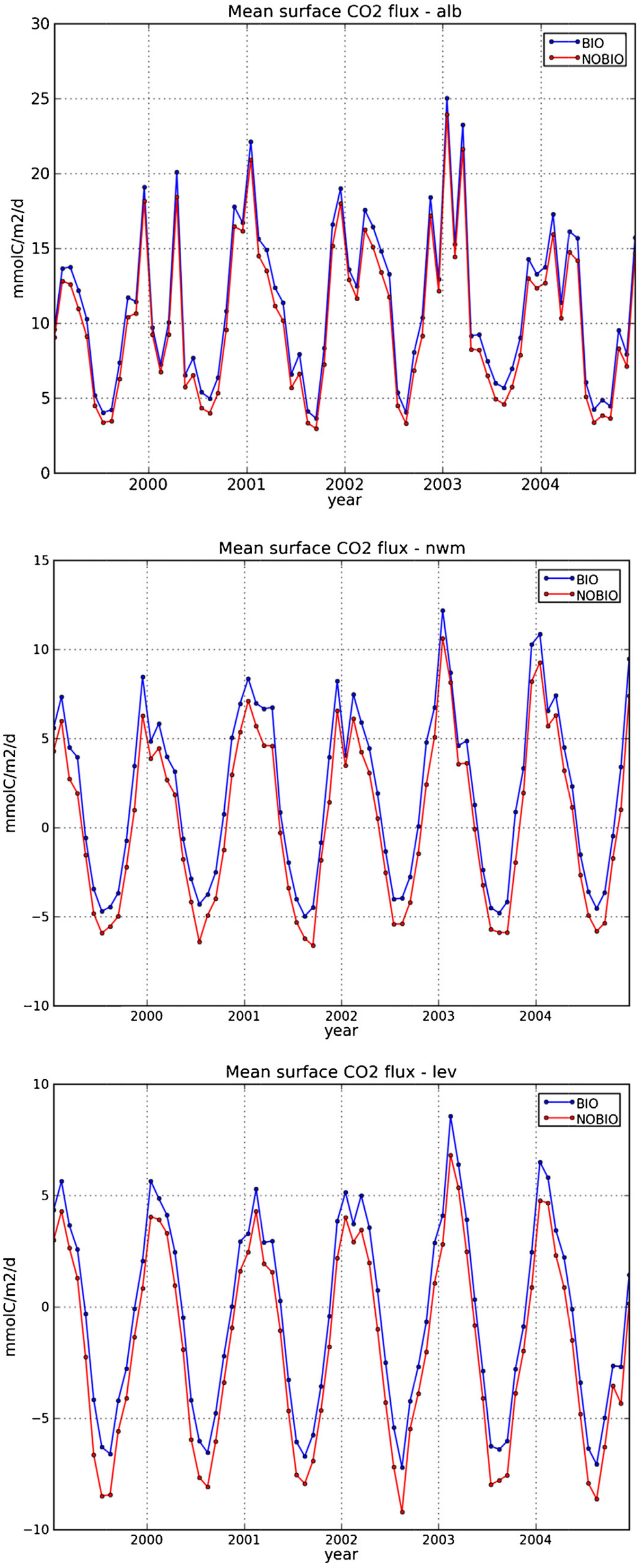

Fig. 4. Time series of CO_2 fluxes averaged over the Alboran Sea basin (alb, left panel), the northwestern Mediterranean area (nwm, central panel), and the Levantine Sea (lev, right panel). The spatial definition of those areas can be found in Lazzari et al. (2012). Blue solid lines indicate the fluxes with biology, red lines indicate the fluxes without biology. Positive fluxes indicate that the sea is absorbing CO_2 (sink), negative fluxes indicate that it is outgassing CO_2 (source). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

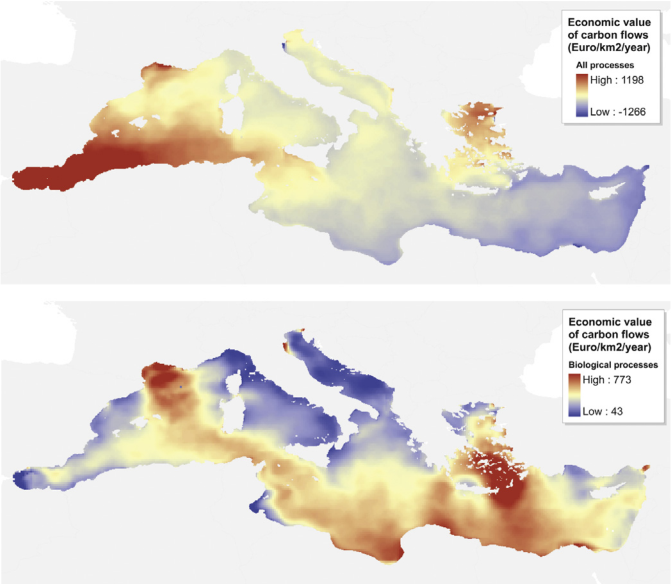

Fig. 5. Maps of average values of air-sea fluxes of carbon expressed in €/km^2/year. In red, carbon sinks, in blue carbon sources (with respect to atmosphere). Top, simulations obtained considering all biogeochemical processes; bottom, effects related to biological activity only. Values are calculated using the SCC value estimate recommended by the EC (DECC, 2009). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

The spatial distribution of CO_2 fluxes results from the superposition of several processes, including: (i) the properties of Atlantic water incoming though the Gibraltar strait and their spreading over the western Mediterranean by physical processes (advection and diffusion), which is the main driver of the above mentioned west-east gradient, (ii) a latitudinal gradient in temperature (and consequent CO_2 solubility), with the eastern part of Mediterranean Sea also being the southern and warmer one, (iii) the role of terrestrial inputs of alkalinity from major rivers, clearly recognizable in the marginal subbasins, (iv) the effects of biological activities. A marked seasonal cycle – related mainly to the seasonal temperature cycle and to the biological activity – also is observed all over the basin, so that all subbasins become sources in summer time and sinks in winter time, as depicted – as selected examples – in Fig. 3 for the Alboran, Northewest, and Levantine sub-basins. The inter-annual variability intrinsic in the above-mentioned processes produces some year-to-year variability in space distribution of yearly CO_2 fluxes, too. However its main features are preserved.

Obviously, a future increase of atmospheric partial pressure of CO_2 would trigger an increase in CO_2 sequestration (or a decrease in its release), partially compensated by the decrease of CO_2 solubility related to warming. However, a projection of the cumulative impact of climate changes on this process requires an ad hoc simulation, also considering changes in circulation, vertical mixing, and other physical processes.

Our simulations highlight the important role of the biological pump in carbon sequestration, which accounts for 14.82 million tonCO_2/km^2/year. The biological fluxes over the Mediterranean follow a clearly different distribution pattern compared to the total fluxes. In particular as shown in Fig. 4, with the exception of the Alboran Sea, the net annual flux is the balance between winter positive fluxes and summer negative fluxes. Biological activity produces a modest effect if compared to seasonal oscillation, but – being always positive – it shifts systematically the oscillation towards higher fluxes, so it is important when accounting for the annual balance. The highest biological CO_2 sequestration (almost twice the flow of the second-highest) is that of Greece, followed by Italy and Libya. Taken together, these four countries account for 56% of the total biological flux. Spain, the country with the highest overall flux (31% of the total Mediterranean flux), accounts for only 10.5% of the total biological flux and only about half of the biological sequestration in the Greek EEZ. In most EEZs, the CO_2 sequestration resulting from the processes of the biological pump is smaller than that of the combined physical and solubility pumps, with the exception of Spain, Algeria, Morocco and Gibraltar, where the biological sequestration amounts to 9.4–39% of the non-biological sequestration in absolute value. In several EEZs, the biological sequestration compensates for a negative sequestration (carbon source) from the physical and solubility pumps. This is the case of Cyprus, Egypt, Israel, Lebanon, Libya, Malta, Syria and Turkey. In the case of the EEZs of Libya and Malta, such positive flux is sufficient to reverse the overall trend from a CO_2 source to a sink.

When compared to the total annual greenhouse gas emissions in CO_2 equivalents as reported by the UNFCCC Greenhouse Gas Inventory Data for the last inventory year excluding land-use changes (http://unfccc.int/ghg_data/items/3800.php), one observes that the Mediterranean Sea is overall responsible for sequestrating 0.7% of the total yearly emissions of the neighboring countries. On a country-by-country basis, such value is highest for Malta (10.1%), Tunisia (3.9%), and Algeria (3.4%). Marine biological processes are responsible for the sequestration of 10.5% and 5.8% of the total emissions of Malta and Cyprus, respectively.

The spatial distribution of the estimated yearly flows of economic value of CO_2 sequestration and the aggregated average values over Mediterranean EEZs – under current conditions and based on the partial equilibrium approach described in the previous section – are presented in Fig. 5 and Table 2, respectively. The values were calculated using the EC (DECC, 2009) estimate of the SCC. Fig. 5 illustrates the yearly average value flows at a 1/8-degree resolution, i.e., for a grid cell size ranging between 69 and 156 km^2, over the period 2001–2005.

In monetary terms, the estimated current value of carbon sequestration over the entire Mediterranean basin amounts to 337.3 million €/year, out of which 281.4 million €/year can be attributed to the biological pump. At the level of individual EEZ, the highest aggregated values for all considered biogeochemical processes and for the biological processes only are found respectively in Spain (105.1 million €/year) and Greece (58.8 million €/year). On average, one square kilometer of Mediterranean Sea provides carbon sequestration services in the value of 133.5 €/km^2. The value flow for biological processes when estimated separately amounts to 111.4 €/km^2. The highest values per unit of area are found in Morocco (1013.3 €/km^2) and Slovenia (186.2 €/km^2) for, respectively, all biogeochemical processes and biological processes only. Notably, several EEZs in the Levantine Sea present a negative value flow. This should be regarded as the costs related to net carbon emissions in the atmosphere from those zones. Also in these cases, biological activity provides a positive contribution, which mitigate the cost.

The economic appraisal of the flows of carbon under current conditions is strongly affected by the wide uncertainties in the presently available estimates of carbon prices. Fig. 6 shows the aggregated values of carbon sequestration in Mediterranean countries as obtained using various carbon prices (see Section 2). For comparison, the chart also shows the values obtained considering the central range of the probability density function of SCC estimates as produced by Tol (2008).

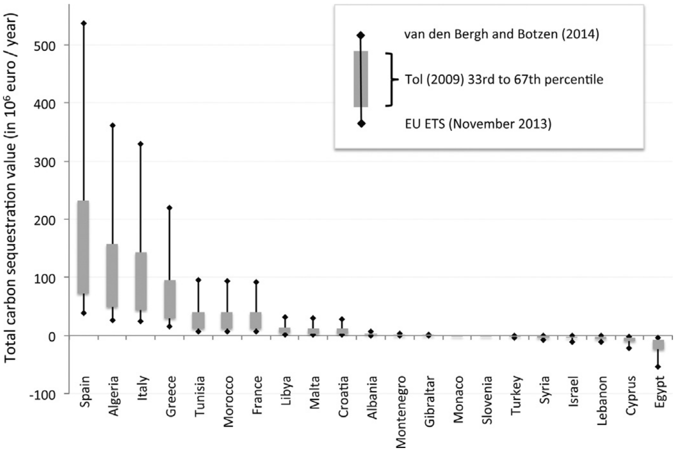

Fig. 6. Aggregated yearly carbon sequestration values for different carbon price estimates in Mediterranean countries. The reported values include the contribution from all biogeochemical processes. Negative values can be seen as cost related to a net carbon emission in the atmosphere from a given zone.

Fig. 6 highlights the wide range of uncertainty that exists in the current SCC estimates and the carbon prices in regulatory and voluntary markets. The average yearly economic value of the aggregated CO_2 sequestration flows in the entire Mediterranean Sea is found to range between 126.9 million €/year when the carbon price of the European Trade Scheme (as of November 2013) is used and 1721.9 million €/year at the lower bound price proposed by van den Bergh and Botzen (2014).

Uncertainties also arise from the natural science estimation side, i.e. from uncertainties in the estimate of carbon fluxes. Results from the second set of simulations return a total CO_2 flux of 18.1 million tonCO_2/year, i.e. very close to the previous estimate. However, the analysis of the spatial distribution of fluxes indicates that there are differences in the estimates of the individual EEZs contributions, especially in the three countries close to the Altantic boundary. The third set of simulations indicates that while the contribution of the biological pump is fairly constant, about 15 million tonCO_2/year (equivalent to about 300 million euro), the contribution of the physical pump over the western part of the Mediterranean is greatly influenced by the properties of the incoming Atlantic water and by how much the physical field (currents) spread this water inside the basin. In fact, in the simulation with pCO_2 rich Atlantic water the physical and solubility pumps in the four countries close to the Gibraltar strait can became as low (in respect to our reference simulation) as to counterbalance the positive contribution to biological fluxes, and return a total value for the Mediterranean Sea close to a neutral situation.

This fact clearly underlines the sensitivity of model output to the properties of inflowing water from the Gibraltar strait, but also increases our confidence in the robustness of results in the area far from the boundaries. Clearly, the variability in the estimates of spatial distribution of CO_2 fluxes also alters the repartition of the total flux among Mediterranean EEZs, up to significantly modifying the total and per area value of different countries. In most of the cases changes in per area values are lower than 50 €/km^2/year, but in a few cases (e.g. Malta, Tunisia) they can be higher, and in the countries close to the Atlantic boundaries, higher than 200 €/km^2/year, for the reasons mentioned above. The uncertainty analysis in biogeochemical properties therefore suggests that the estimates for carbon flux values across the Mediterranean EZZ given above could be – on average – about 25–50% lower, but with relevant spatial differences.

More accurate estimates of countries contributions to specific years, or periods, – if needed – might be obtained by adopting our methodology while constraining model output to updated sets of ad hoc forcing and observations, possibly through the use of data assimilation techniques. Globally, however, the emerging picture appears relatively robust, and the estimates provided by the proposed ecological-economics approach a sound, though rather conservative, contribution to the valuation of carbon sequestration services over the Mediterranean basin, which can be used as a source of information for carbon accounting of different states under present condition.

4. Concluding remarks

The degree to which human activities and wellbeing depend on the oceans as source of many valuable ecosystem services is increasingly well understood. The value of some among these services (e.g. fisheries, tourism and recreational activities, natural resources exploitation) can be assessed in monetary terms but also in terms of how many people depend on the ocean for food or work (Beaudoin and Pendleton, 2012; Ghermandi and Nunes, 2013; Onofri and Nunes, 2013). Nevertheless, there remain services that are more difficult to assess in monetary terms, like the capacity of the oceans to absorb heat or their role as sinks in the global carbon cycle. Moreover, there might be an additional value of the oceans if these carbon sink services can play a role in terms of providing a nature-based contribution to the efforts of climate change mitigation, analogously to the case of "blue carbon" sinks for coastal ecosystems. In this context, the present study constitutes a first worldwide study that sheds light on the pricing of carbon sequestration services in the Mediterranean regional sea.

To distinguish between the contribution of physical and biological components to the carbon sequestration service is important too. In fact, it contributes to make less invisible the role played by plankton, increases the awareness on the importance of ecosystem services, and – eventually – produce knowledge useful to inform environmental management policies. Our simulations indicate that without biologically productivity, over the Mediterranean Sea CO_2 sinks and sources would roughly balance each other, and that this balance is altered and the Mediterranean acts as a sink of carbon only because of biological activity. In areas that behave as sources, biological activity significantly mitigates this cost, in those that act as sinks, biological activity increases the magnitude of sequestration fluxes.

Accounting for the value of carbon sequestration marine services is of particular significance since this information is not available in any economic statistics datasets. In fact, key information about the natural capital of oceans and the underlying ecosystem services flows that it generates is missing or invisible in the System of National Accounts (SNA), including the Gross Domestic Product (GDP). Since analogous macro-economic indicators are often used to assess a country's economic progress and affects, among others, economic policy measures with respect long term investment decisions, international trade agreements and environmental taxes, flaws in this measurement may lead to distorted decisions. In this context, today there is a strong demand for beyond-GDP indicators, which can measure wellbeing in a more comprehensive way. Among such indicators are natural-capital-based indicators, which also include the role of the oceans. Building on this demand, the recent World Bank-led global partnership WAVES (Wealth Accounting and the valuation of Ecosystem Services) has been working on the value assessment and accounting of natural capital assets in accordance to a statistical standard that allows a direct comparison with the SNA and its aggregates, including GDP. Therefore, the present work proposes a valid methodology that allows physical and monetary measurement of the capacity of the Mediterranean Sea as a carbon sink in the global carbon budget and these estimates can be easily used to populate a National System of Environmental and Economic Accounts, in accordance to UN standards (United Nations, 2014), as well as provide the basis to extend the analysis to other regional seas and, ultimately, to all the oceans on Earth. Overall this paper contributes an improvement in the measurement of the natural capital of marine ecosystems and in building better indicators for monitoring sustainable development.

Acknowledgments

The research leading to these results has received funding from the European Commission's Seventh Framework Programme under grant agreement 265103 (Project MedSeA) and from the italian project Acid.it.

References

Alcamo, J., 1994. IMAGE 2. 0: Integrated Modeling of Global Climate Change Kluwer Academic Publishers, Dordrecht, The Netherlands.

Beardall, J., Raven, J.A., 2004. The potential effects of global climate change on microalgal photosynthesis, growth and ecology. Phycologia 43, 26–40.

Beaudoin, Y., Pendleton, L. (Eds.), 2012. Why Value the Oceans? UNEP/GRID-Arendal and Duke University's Nicholas Institute for Environmental Policy Solutions (A discussion paper. TEEB Discussion Paper), p. 33, http://www.teebweb.org.

Béranger, K., Mortier, L., Crépon, M., 2005. Seasonal variability of water transport through the Straits of Gibraltar, Sicily and Corsica, derived from a high-resolution model of the Mediterranean circulation. Prog. Oceanogr. 66, 341–364.

van den Bergh, J.C.J.M., Botzen, W.J.W., 2014. A lower bound to the social cost of CO_2 emissions. Nat. Climate Change 4, 253–258.

Claus S., De Hauwere N., Vanhoorne B., Hernandez F., Mees J. (2013) Union of the ESRI Country shape file and the Exclusive Economic Zones (version 1). Available online at ⟨http://www.marineregions.org⟩. (Accessed 14.07.13)

Crooks, S., Herr, D., Tamelander, J., Laffoley, D., Vandever, J., 2011. Mitigating Climate Change through Restoration and Management of Coastal Wetlands and Near-shore Marine Ecosystems: Challenges and Opportunities. Environment Department Paper 121 World Bank, Washington, DC.

DECC, Department for Energy and Climate Change, 2009. Carbon Valuation in UK Policy Appraisal: A Revised Approach. Climate Change Economics, Department for Energy and Climate Change. https://www.gov.uk/government/

EU Commission (2008) Annex to the Impact Assessment accompanying the Package of Implementation measures for the EU's objectives on climate change and renewable energy for 2020. Available at: ⟨http://ec.europa.eu/energy/climate_actions/doc/2008_res_ia_en.pdf⟩.

Falkowski, P.G., Barber, R.T., Smetacek, V., 1998. Biogeochemical controls and feedbacks on ocean primary production. Science 281 (5374), 200–206.

Foujols, M.A., Lévy, M., Aumont, O., Madec, G., 2000. OPA 8.1 Tracer Model Reference Manual. Note du Pole de Modélisation, IInstitut Pierre Simon Laplace (IPSL), France, pp. 45.

Geider, R.J., MacIntyre, H.L., Kana, T.M., 1997. Dynamic model of phytoplankton growth and acclimation: responses of the balanced growth rate and the chlorophyll a: carbon ratio to light, nutrient-limitation and temperature. Mar. Ecol.-Prog. Ser. 148, 187–200.

Ghermandi, A., Nunes, P.A.L.D., 2013. A global map of coastal recreation values: results from a spatially explicit meta-analysis. Ecol. Econ. 86, 1–15.

Huertas, I.E., Ríos, A.F., García-Lafuente, J., Makaoui, A., Rodríguez-Gálvez, S., Sánchez-Román, A., Orbi, A., Ruíz, J., Pérez, F.F., 2009. Anthropogenic and natural CO_2 exchange through the Strait of Gibraltar. Biogeosciences 6, 647–662, 10.5194/bg-6-647-2009.

Jerath, M., Bhat, M.G., Rivera-Monroy, V.H., 2012. Alternative approaches to valuing carbon sequestration in mangroves. In: Proceedings of the ISEE 2012 Conference on Ecological Economics and Rio+20, Rio de Janeiro, 16–19 June 2012.

Lazzari, P., Solidoro, C., Ibello, V., Salon, S., Teruzzi, A., Béranger, K., Colella, S., Crise, A., 2012. Seasonal and inter-annual variability of plankton chlorophyll and primary production in the Mediterranean Sea: a modelling approach. Biogeosciences 9, 217–233.

Lazzari, P., Mattia, G., Solidoro, C., Salon, S., Crise, A., Zavatarelli, M., Oddo, P., Vichi, M., 2014. The impacts of climate change and environmental management policies on the trophic regimes in the Mediterranean Sea: Scenario analyses. J. Mar. Syst. 135, 137–149.

Ludwig, W., Dumont, E., Meybeck, M., Heussner, S., 2009. River discharges of water and nutrients to the Mediterranean and Black Sea: major drivers for ecosystem changes during past and future decades? Progr. Oceanogr. 80, 199–217.

Madec, G., Delecluse, P., Imbard, M., Levy, C., 1999. OPA 8.1 Ocean general Circulation Model reference manual. Note du Pole de modelisation Institut Pierre-Simon Laplace (IPSL), France, pp. 91pp (N XX).

Madec, G., 2008. NEMO Ocean Engine. Note du Pole de Modelisation Institute Pierre-Simone Lapalce (IPSL), France, pp. 1288–1619 (No 27).

Manne, A.S., Mendelsohn, R.O., Richels, R.G., 1995. MERGE—a model for evaluating regional and global effects of GHG reduction policies. Energy Policy 23 (1), 17–34.

MEDAR Group-MEDATLAS/2002 database, 2002. Mediterranean and Black Sea database of temperature salinity and bio-chemical parameters. Climatological Atlas, Edition (4 Cdroms). IFREMER. http://www.ifremer.fr/medar/cdrom_database.htm.

Nellemann, C., Corcoran, E., Duarte, C.M., Valdés, L., DeYoung, C., Fonseca, L., Grimsditch, G. (Eds.), 2009. Blue Carbon. A Rapid Response Assessment. United Nations Environment Programme GRID-Arendal. www.grida.no.

Newbold, S., 2010. Summary of the DICE Model. US-EPA.

Oddo, P., Adani, M., Pinardi, N., Fratianni, C., Tonani, M., Pettenuzzo, D., 2009. A nested Atlantic–Mediterranean Sea general circulation model for operational forecasting. Ocean Sci. 5 (4), 461–473.

Onofri, L., Nunes, P.A.L.D., 2013. Beach lovers and greens: a worldwide empirical analysis of coastal tourism. Ecol. Econ. 88, 49–56.

Orr, J.C. (1999) Ocean Carbon-cycle Intercomparison Project (OCMIP). Phase 1 (1995–1997). IGBP/GAIM Report Series, Report #7.

Pearce, D., 2003. The social cost of carbon and its policy implications. Oxf. Rev. Econ. Policy 19 (3), 362–384.

Peters-Stanley, M., 2012. Bringing it home: taking stock of government engagement with the voluntary carbon market. Ecosyst.Marketpl. (March) , http://www.ecosystemmarketplace.com.

Portela, R., Nunes, P.A.L.D., Onofri, L., Villa, F., Shepard, A., Lange, G.M., 2012. Assessing and Valuing Ecosystem Services in Ankeniheny-Zahamena Corridor (CAZ), Madagascar: A Demonstration Case Study. Wealth Accounting and the Valuation of Ecosystem Services (WAVES) Global Partnership. http://www.pmel.noaa.gov/pubs/outstand/sabi2683/sabi2683.shtml.

Reid, P.C., Fischer, A.C., Lewis-Brown, E., Meredith, M.P., Sparrow, M., Andersson, A.J., Antia, A., Bates, N.R., Bathmann, U., Beaugrand, G., Brix, H., Dye, S., Edwards, M., Furevik, T., Gangstø, R., Hátún, H., Hopcroft, R.R., Kendall, M., Kasten, S., Keeling, R., Le Quéré, C., Mackenzie, F.T., Malin, G., Mauritzen, C., Olafsson, J., Paull, C., Rignot, E., Shimada, K., Vogt, M., Wallace, C., Wang, Z., Washington, R., 2009. Impacts of the oceans on climate change. Adv. Mar. Biol. 56, 1–150 (Chapter 1).

Ribera d'Alcalà, M., Civitarese, G., Conversano, F., Lavezza, R., 2003. Nutrient ratios and fluxes hint at overlooked processes in the Mediterranean Sea. J. Geophys. Res. 108, 8106, 10.1029/2002JC001650, 2003.

Sabine, C.L., Feely, R.A., Gruber, N., Key, R.M., Lee, K., Bullister, J.L., Wanninkhof, R., Wong, C.S., Wallace, D.W.R., Tilbrook, B., Millero, F.J., Peng, T.H., Kozyr, A., Ono, T., Rios, A.F., 2004. The oceanic sink for anthropogenic CO_2. Science 305 (5682), 367–371.

Sabine, C.L., Heimann, M., Artaxo, P., Bakker, D.C., Chen, C.T.A., Field, C.B., Gruber, N., Le Quere, C., Prinn, R.G., Richey, J.E., Romero Lankao, P., Sathaye, J.A., Valentini, R., 2004. Current status and past trends of the global carbon cycle. In: Field, C.B., Raupach, M.R. (Eds.), The Global Carbon Cycle: Integrating Humans, Climate, and the Natural World, 62. Island Press, Washington, DC, USA, pp. 17–44.

Sarmiento, J.L., Wofsy, S.C., 1999. A US Carbon Cycle Science Plan. US Global Change Research Program, Washington DC.

Sarmiento, J.L., Hughes, T.M.C., Stouffer, R.J., Manabe, S., 1998. Simulated response of the ocean carbon cycle to anthropogenic climate warming. Nature 245–249.

Stern, N., 2007. The Economics of Climate Change: The Stern Review. Cambridge University Press, Cambridge, UK.

Tamelander, J., Herr, D., Laffoley, D., 2010. Managing large marine ecosystems for climate change mitigation. In: Sherman, K., Adams, S. (Eds.), Sustainable Development of the World's Large Marine Ecosystems during Climate Change: A Commemorative Volume to Advance Sustainable Development on the Occasion of the Presentation of the 2010 Göteborg Award. IUCN, Gland, Switzerland.

Thingstad, T.F., Rassoulzadegan, F., 1995. Nutrient limitations, microbial food webs, and biological C-pumps: suggested interactions in a P-limited Mediterranean. Mar. Ecol.-Prog. Ser. 117, 299–3065.

Tol, R.S.J., 2006. Exchange rates and climate change: an application of FUND. Climat. Change 75, 59–80.

Tol, R.S.J., 2008. The social cost of carbon: trends, outliers and catastrophes. economics: the open-access. Open-Assess. E-J. 2, 2008–2025.

United Nations, 2014. System of Environmental-Economic Accounting 2012: Central Framework, http://unstats.un.org/unsd/envaccounting/seeaRev/SEEA_CF_Final_en.pdf.

UNFCCC—United Nations Framework Convention on Climate Change, 1771 UNTS 107; S. Treaty Doc No. 102–38; U.N. Doc. A/AC.237/18 (Part II)/Add.1; 31 ILM 849 (1992).

van Vuuren, D.P., Lowe, J., Stehfest, E., Gohar, L., Hof, A.F., Hope, C., Warren, R., Meinshausen, M., Plattner, G.K., 2011. How well do integrated assessment models simulate climate change? Climat. Change 104, 255–285.

Vichi, M., Pinardi, N., Masina, S., 2007. A generalized model of pelagic biogeochemistry for the global ocean ecosystem, Part I: theory. J. Mar. Syst. 64, 89–109.

Vichi, M., Manzini, E., Fogli, P.G., Alessandri, A., Patara, L., Scoccimarro, E., Navarra, A., 2011. Global and regional ocean carbon uptake and climate change: sensitivity to a substantial mitigation scenario. Climate Dyn. 37 (9–10), 1929–1947.

Wolf-Gladrow, D., Zeebe, R., Klaas, C., Körtzinger, A., Dickson, G., 2007. Total alkalinity: the explicit conservative expression and its application to biogeochemical processes. Mar. Chem. 106, 287–300.

Watkiss, P., Anthoff, D., Downing, T., Hepburn, C., Hope, C., Hunt, A., Tol, R., 2005. Social Costs of Carbon Review–Methodological Approaches for Using SCC Estimates in Policy Assessment. AEA Technology Environment, UK.