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The effect of ocean acidification on carbon storage and sequestration in seagrass beds; a global and UK context

Samantha L. Garrard [a,b,*], Nicola J. Beaumont [a]

[a] Plymouth Marine Laboratory, Prospect Place, The Hoe, Plymouth PL1 3DH, UK
[b] Marine and Fisheries Unit, Ascension Island Government Conservation Department, Georgetown, Ascension Island, South Atlantic ASCN 1ZZ, UK

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ABSTRACT

Ocean acidification will have many negative consequences for marine organisms and ecosystems, leading to a decline in many ecosystem services provided by the marine environment. This study reviews the effect of ocean acidification (OA) on seagrasses, assessing how this may affect their capacity to sequester carbon in the future and providing an economic valuation of these changes. If ocean acidification leads to a significant increase in above- and below-ground biomass, the capacity of seagrass to sequester carbon will be significantly increased. The associated value of this increase in sequestration capacity is approximately £500 and 600 billion globally between 2010 and 2100. A proportionally similar increase in carbon sequestration value was found for the UK. This study highlights one of the few positive stories for ocean acidification and underlines that sustainable management of seagrasses is critical to avoid their continued degradation and loss of carbon sequestration capacity.

1. Introduction

Ecosystem services can be defined as ‘‘the aspects of ecosystems utilized (actively or passively) to produce human well-being’’ (Fisher et al., 2009). As the importance of understanding how the natural world affects human health, wealth, and well-being is recognized, research into ecosystem services has risen exponentially (Fisher et al., 2009). An ISI Web of Knowledge search into the number of papers referring to the term ‘ecosystem services’ found 41 in 1995, whilst 2020 were published in 2013, highlighting the increase in interest in this area of science. The marine environment provides a number of ecosystem services, which are essential for human health and well-being, such as provision of food, coastal protection, water purification, and climate regulation (Liquete et al., 2013). Anthropogenic carbon emissions, which cause climate change, are a concern, as climate change may weaken the provision of some ecosystem services by the natural environment (Schröter et al., 2005).

Anthropogenic CO_2 release primarily comes from two sources: (1) emissions from fossil-fuel combustion and industrial processes and (2) the CO_2 flux from land-use changes (especially forest clearing) (Raupach et al., 2007). The first source is of particular concern as this releases over five times the quantity of CO_2 as the latter (7.9 Gt C y^{-1} versus 1.5 Gt C y^{-1}), and emissions are accelerating rapidly (Raupach and Canadell, 2007). The concentration of CO_2 in the atmosphere has risen from 280 ppm in preindustrial times to levels of 390 ppm in 2010, an increase of approximately 40%. In 2013 levels of 400 ppm were measured at Mauna Loa volcano for the first time in recorder history, the highest levels found on earth in millions of years (Showstack, 2013). If CO_2 emissions continue under the ‘business as usual’ scenario then levels are expected to increase to over 900 ppm by the end of this century (IPCC, 2013).

Increasing CO_2 is of concern as it is a greenhouse gas and alters the energy budget of the earth by changing the net balance of incoming solar radiation and outgoing infrared radiation between the troposphere and the stratosphere, leading to changes in temperature, humidity, clouds and circulation, termed radiative forcing (Kamae and Watanabe, 2013). Greenhouse gases reduce the amount of energy leaving the atmosphere leading to a warming effect (Estrada et al., 2013). Other climatic effects from the increase of these gases include increased intensity of tropical cyclones (Krishnamurti et al., 1998) and increased frequency of El Niño like conditions (Timmermann et al., 1999), alongside conditions of greater precipitation or drought (IPCC, 2007).

The ocean contributes to the key ecosystem service of climate regulation, one aspect of which is the absorption of CO_2 from the atmosphere, acting as a carbon sink. In 2010 it was thought to have absorbed approximately 155 Gt C (Khatiwala et al., 2013), almost

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* Corresponding author at: Marine and Fisheries Unit, Ascension Island Government Conservation Department, Georgetown, Ascension Island, South Atlantic ASCN 1ZZ, UK. Tel.: +44 247 6403.

E-mail address: Samantha.Garrard@ascension.gov.ac (S.L. Garrard).

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30% of the anthropogenic CO_2 released into the atmosphere since the pre-industrial times (Doney et al., 2009; Sabine and Feely, 2007). A portion of the CO_2 absorbed by the oceans is stored in living biomass or sequestered in sediments, whilst a large amount remains in its inorganic form. The increase in inorganic carbon stored in the oceans has led to a decrease in pH and associated changes to seawater chemistry, and has been termed ocean acidification (OA) (Doney et al., 2009). Since the Industrial Revolution (approximately 250 years ago), the pH of ocean surface waters has dropped by 0.1 units from 8.2 to 8.1, representative of a 30% increase in hydrogen ion concentration (Guinotte and Fabry, 2008). To try and predict future climate change and associated changes to ocean chemistry, a number of potential scenarios have been developed, and pH is expected to drop to anywhere between 8.05 and 7.6 by the end of this century (Caldeira and Wickett, 2003; IPCC, 2007, 2013; Prinn et al., 2008, 2011).

Ocean acidification is a ubiquitous stressor which is likely to lead to negative consequences for marine organisms (Kroeker et al., 2010), ecosystems (Fabry et al., 2008), and ecosystem service provision (Cooley et al., 2009) in the future. For example the Pacific oyster (*Crassostrea gigas*) is one of the most cultivated molluscs in the world, being extensively cultured or fished in Europe, North America, Asia and Oceana. In 2011 over 650,000 tonnes were harvested, primarily through cultivation (FAO, 2014). In the UK Pacific oyster cultivation was valued at 10.137 million in 2011/12 (Herbert et al., 2012). Research has shown that ocean acidification will have deleterious effects on this species (e.g. Barton et al., 2012; Kurihara et al., 2007), which may lead to a reduction in food provision, and employment potential in the future in relation to this species.

The majority of OA research has focussed on the effect of a decrease in pH on calcifying species (Brennand et al., 2010; Courtney et al., 2013; e.g. Gazeau et al., 2007; Iglesias-Rodriguez et al., 2008). The process of calcification is particularly susceptible to a reduction in pH (Fabry, 2008), due to the decrease in carbonate availability and subsequent decrease in calcite and aragonite saturation states. Although non-calcifying photosynthetic organisms are seen as a lesser priority, the ability of marine ecosystems and species to store and sequester carbon in marine sediments under changes in pH and carbonate chemistry is of paramount importance if we are to understand how the ability of the ocean to act as a carbon sink may change under future OA scenarios.

Seagrass beds cover less than 0.2% of the ocean surface, and yet they contribute to a disproportionate amount of marine net primary productivity (NPP) (1%), and are responsible for approximately 15% of carbon storage in the oceans (Kennedy and Bjork, 2012). Seagrasses play an important role in carbon sequestration, partially due to their ability to filter particulate carbon from the water column (Greiner et al., 2013), and to the fact that their belowground component of higher plants is nutritionally poor, unpalatable, and often found in anoxic sediments, so prevents efficient decomposition (Duarte and Cebrian, 1996). The carbon stored in living biomass or sequestered in sediments by seagrasses, alongside salt marsh plants and mangroves, has been termed 'blue carbon' (Nelleman et al., 2009), and the importance of conserving these habitats is increasingly recognised (Laffoley and Grimsditch, 2009; Luisetti et al., 2013; Nelleman et al., 2009).

Carbon storage and sequestration is an imperative component of climate regulation, as this carbon is locked away for either short (living biomass) or long (carbon buried within sediments or in the deep sea) periods of time (e.g. Lo Iacono et al., 2008; Mateo et al., 1997; Passow and Carlson, 2012), rendering it inert. Our definition of marine carbon sequestration has been modified from the OECD definition for biological carbon sequestration (OECD, 2001), to apply to marine environments. Marine carbon sequestration is defined as 'a biochemical process by which carbon dioxide is fixed by living organisms, including phytoplankton, seagrasses and salt marsh plants, and involving the storage of carbon in sediments, or the deep sea, with the potential to reduce atmospheric carbon dioxide levels'. Without the ability of the oceans to sequester this carbon, atmospheric CO_2 concentrations would be higher, leading to climate change occurring at a more rapid pace.

This study aims to detail both current carbon storage and sequestration in seagrass beds, and also how this may change in the face of OA from both a global and UK perspective. The UK has been used as a case study due relatively good data availability, and also to fulfil a real need of the UK's Marine Management Organisation, to inform marine planning in line with the requirements of the UK marine policy statement. A review of the evidence of OA impacts on seagrass will be summarised, alongside a review of current and potential future carbon storage and sequestration of seagrasses. Calculations of standing stock (tC ha^{-1} yr^{-1}) and carbon sequestration (tC ha^{-1} yr^{-1}) have been used to assess these parameters.

2. Carbon storage and sequestration by global and UK seagrass

2.1. Global carbon storage and sequestration by seagrass

Seagrass meadows are estimated to cover between 170,000 and 600,000 km^2 globally (McLeod et al., 2011). They are generally net autotrophic, therefore acting as global carbon sinks (Duarte et al., 2010) This is partially due to their ability to filter sediments and particulate organic carbon from the water column (sestonic particles), through a reduction in flow, wave action and turbulence (Hendriks et al., 2008). Denser meadows trap sediments more effectively than less dense meadows or bare sediment (Greiner et al., 2013), and sediment accumulation in seagrasses is greater than saltmarsh plants (Couto et al., 2013). Carbon storage also comes from a build-up of seagrass necromass (dead roots and rhizomes). Necromass can build-up within the sediment to extremely high volumes, without decomposing, as sediments where seagrasses are found are generally anoxic and therefore prevent efficient decomposition (Romero et al., 1992). Carbon sequestration in seagrass beds ranges from 0.45 to 1.9 tC ha^{-1} yr^{-1} (mean 1.38 tC ha^{-1} yr^{-1}) (McLeod et al., 2011). Approximately 40% of sediment organic carbon comes from seagrass and its associated epiphytes, whilst sestonic particles contribute the other 60% (Gacia et al., 2002). This highlights the importance of seagrass beds in sediment deposition and sequestration of allochthonous inputs of carbon. Increased decay rates occur at higher temperatures (Chmura et al., 2003), therefore carbon sequestration potential may be greater in polar and temperate coastal zones than tropical and sub-tropical zones.

Whilst seagrass carbon sequestration potential and standing stock (quantity of carbon stored within living biomass) is high, it is generally lower than the standing stock and carbon sequestration potential of salt marshes and mangroves, although, due to the higher values of their predicted extent around the globe, their global capacity to store and sequester carbon is comparable (Table 1). Some species of seagrass have a much higher standing stock than others. For example the Mediterranean seagrass *Posidonia oceanica* has a much greater standing stock than smaller seagrass species such as *Zostera noltii* and *Zostera marina*, which have a wide distribution in the Atlantic (Duarte and Chiscano, 1999). Seagrass above: below-ground ratio is variable between species, although a data set comprising of 30 species showed an average balanced distribution between above: below-ground biomass, and *Z. marina* has a 2:1 above: below-ground biomass (Duarte and Chiscano, 1999).

2.2. UK carbon storage and sequestration by seagrass

Whilst mangroves are limited to tropical and sub-tropical zones, salt marshes and seagrass beds provide significant carbon