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# Can we manage coastal ecosystems to sequester more blue carbon?

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To promote the sequestration of blue carbon, resource managers rely on best-management practices that have historically included protecting and restoring vegetated coastal habitats (seagrasses, tidal marshes, and mangroves), but are now beginning to incorporate catchment-level approaches. Drawing upon knowledge from a broad range of environmental variables that influence blue carbon sequestration, including warming, carbon dioxide levels, water depth, nutrients, runoff, bioturbation, physical disturbances, and tidal exchange, we discuss three potential management strategies that hold promise for optimizing coastal blue carbon sequestration: (1) reducing anthropogenic nutrient inputs, (2) reinstating top-down control of bioturbator populations, and (3) restoring hydrology. By means of case studies, we explore how these three strategies can minimize blue carbon losses and maximize gains. A key research priority is to more accurately quantify the impacts of these strategies on atmospheric greenhouse-gas emissions in different settings at landscape scales.

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As the world begins its transition to a low-carbon economy, removing atmospheric carbon dioxide (CO<sub>2</sub>) through biosequestration will be necessary to keep global warming under 2°C. Among the most efficient systems that provide biosequestration services are vegetated coastal habitats (VCHs), which include seagrasses, tidal marshes, and mangroves (Figure 1) and are known

as “blue carbon” ecosystems (McLeod *et al.* 2011). VCHs occupy only 0.2% of the ocean surface, yet contribute 50% of the total amount of carbon buried in marine sediments (Duarte *et al.* 2013). They have the ability to accumulate carbon without reaching saturation, and can store it in sediments over millennial timescales (McLeod *et al.* 2011). As with important terrestrial carbon sinks (eg Amazonian forests, permafrost regions), ecosystem degradation can shift blue carbon ecosystems from carbon sinks to carbon sources (Pendleton *et al.* 2012).

Approximately one-half of the Earth’s blue carbon ecosystems have disappeared due to anthropogenic activities, including direct impacts (such as dredging, harvesting, filling, dyking, and draining) and indirect impacts via climate change (such as sea-level rise and extreme weather events), thereby releasing ancient carbon (Macreadie *et al.* 2013, 2015; Lovelock *et al.* in press). In terms of carbon emissions, losing one hectare of a blue carbon ecosystem is equivalent to losing between 10 and 40 hectares of native forest. This difference can mostly be attributed to the long-term storage of carbon in the sediments of blue carbon ecosystems (McLeod *et al.* 2011). Protecting and maintaining vulnerable but important carbon stocks to avoid emissions is a high priority for climate-change mitigation efforts, with ecosystem restoration as a secondary aim.

From a scientific and resource-management perspective, we raise the question of whether existing VCHs could be better managed to sequester more blue carbon and minimize CO<sub>2</sub> emissions. There are many environmental processes that control carbon sequestration (stock accumulation and efflux) in VCHs (WebTable 1). With an emphasis on existing VCHs, our attention is directed to those processes that are amenable to management

## In a nutshell:

- Vegetated coastal habitats (seagrasses, tidal marshes, and mangroves) are important global sinks of organic “blue carbon”
- Carbon markets tend to focus on carbon offsets achieved through restoration, with much less attention on optimizing the efficiency of existing ecosystems
- We investigated key environmental processes that influence blue carbon sequestration and identified three catchment-level processes controllable through resource management: nutrient inputs, bioturbation, and hydrology
- We argue that reducing nutrient inputs, avoiding unnaturally high levels of bioturbation, and restoring natural hydrology (freshwater flows and tidal exchange) will maximize blue carbon sequestration and minimize blue carbon losses

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intervention in two ways: (1) actions that lead to emissions reduction (ie preventing carbon losses due to “business as usual” management activities) or (2) removal of atmospheric emissions (ie net sequestration gains achieved via habitat expansion or to enhance sequestration efficiency through management actions). Our focus is on coastal zones; however, because we recognize that human activities strongly influence the lateral transfer of carbon from land to the ocean (Regnier *et al.* 2013), we stress that management of global carbon stocks needs to happen at landscape scales.

### ■ Key environmental processes influencing blue carbon sequestration

Organic carbon that is produced or captured by VCHs may be: (1) broken down (remineralized by microbes) and converted into atmospheric CO<sub>2</sub> or methane (CH<sub>4</sub>), (2) assimilated into microbial biomass, or (3) sequestered within sediments where it might be locked up for millennia and thereby counter the atmospheric CO<sub>2</sub> pool. If the processes that control breakdown of carbon within VCHs can be elucidated (Figure 2), then it may be possible to manage coastal areas in a way that maximizes carbon gains and minimizes carbon losses.

In WebTable 1, we summarize key environmental processes that influence blue carbon sequestration (including mechanisms and examples from the literature), and their amenability to being controlled by resource managers. The latter – “amenability to management control” – is discussed from a theoretical/logistical viewpoint, with the assumption that boosting blue carbon sequestration is the only goal. Yet, in most cases, there are broader political, ethical, and environmental implications; in some situations, such interventions could result in complex trade-offs. For instance, removal of hard barriers such as dykes and levees from the coastal zone may improve conditions for VCHs and have long-term benefits for coastal protection, but could lead to short-term loss of coastal properties and other human infrastructure until VCHs become established.

From the broader list of possible candidate strategies described in WebTable 1, we identified three that are suitable for management intervention and have the potential to make meaningful differences to global carbon sequestration by VCHs: reducing nutrient inputs, controlling bioturbator activity, and restoring estuarine hydrology (Figure 3). These are discussed in the following sections and summarized in Table 1. Two of these strategies – reducing nutrient loading and restoring hydrology – have recently been recognized in the Verified Carbon Standard 2014 Methodology for Tidal Wetland and Seagrass Restoration (VCS 2015), reflecting sufficient scientific knowledge to allow for implementation. The third – reducing bioturbator populations by restoring top-down control – is much newer and has not yet been fully



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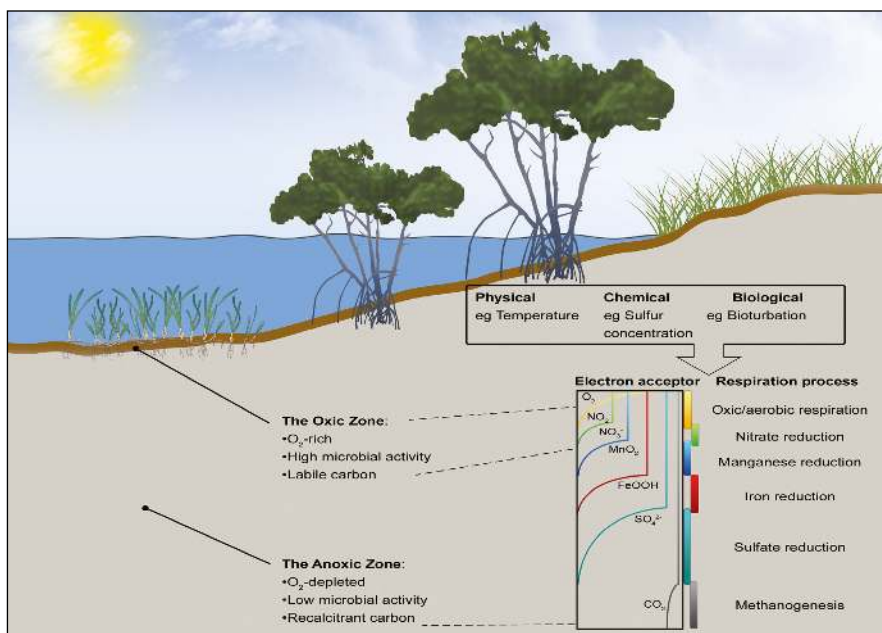
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**Figure 1.** The most important vegetated coastal habitats for “blue carbon” sequestration are (a) seagrass meadows, (b) tidal marshes, and (c) mangroves.

considered, but warrants attention based on its potential to alter carbon accumulation and retention within VCHs (Atwood *et al.* 2015).

### ■ Managing nutrients to increase carbon storage

Nutrient levels (particularly of nitrogen and phosphorus) are elevated around much of the world’s developed coastline, primarily due to the use of fertilizers for agriculture in coastal watersheds and the discharge of human sewage effluent from coastal cities (Smith and



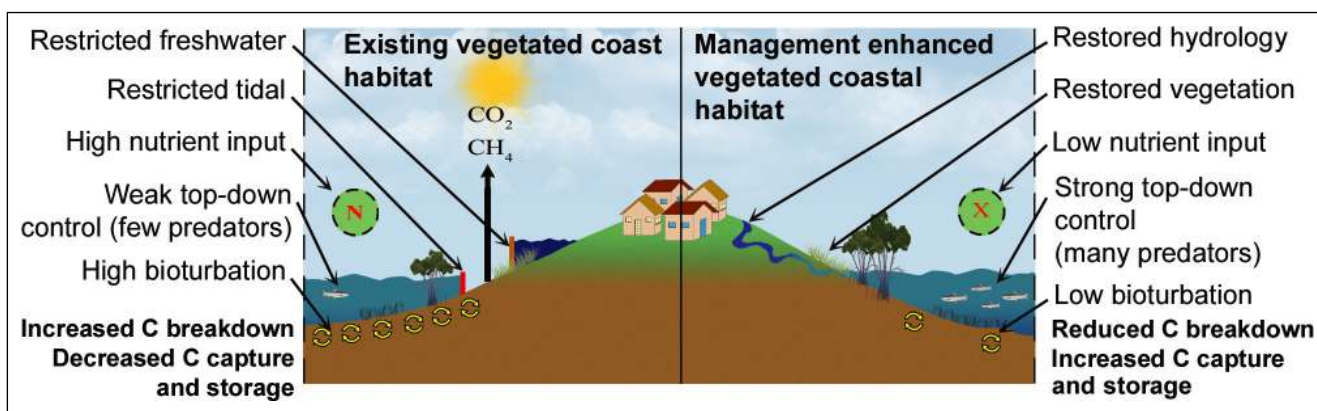
**Figure 2.** Key factors that mediate sequestration of blue carbon within vegetated coastal habitats (left to right: seagrasses, mangroves, tidal marshes). Within the surface layer of sediments – the oxidic zone – aerobic heterotrophs gain energy by oxidizing carbon, using  $O_2$  as the electron acceptor. Below that, in the anoxic zone, diverse microbial populations use alternative electron acceptors for catabolic reactions. Physical, chemical, and biological processes can influence which microbial communities and respiration processes dominate the sediments at different depths, with concomitant implications for the rate of carbon breakdown. The inset showing the electron acceptors and respiration processes is stylized; the depth and overlap of the various zones can vary widely in nature. Also, the distribution of the habitat types can vary (eg tidal marshes can occupy the entire intertidal space in areas where there are no mangroves).

Schindler 2009). A common assumption is that nutrient addition will improve coastal carbon sequestration by enhancing VCH plant productivity. At this stage, however, the balance of evidence is pointing to likely decreases in carbon storage under nutrient addition. For example, experimental evidence shows net losses of carbon either through plant mortality and gaseous efflux (eg in mangroves; Lovelock *et al.* 2009, 2014), or through erosion and loss of sediment (eg in salt marshes; Deegan *et al.* 2012). These effects of nutrient addition in mangrove and tidal marsh habitats also interact with porewater (water within the sediment) salinity and shifts in plant communities, and additional research is needed to better understand how the relationship varies regionally. The results of long-term studies on the impacts of experimentally applied nutrients on seagrasses are mixed; López *et al.* (1998) reported that organic content declined by one-third in surface sediments with nutrient addition, which stimulated microbial activity and thus carbon remineralization (Antón *et al.* 2011). On the other hand, Howard *et al.* (2016) found no effect of nutrients on blue carbon stocks but noted that working at small spatial scales may have limited their ability to detect an impact.

A long-term study of tidal marshes indicates that nutrient addition results directly in community shifts in plant species assemblages, and that rates of sediment accretion and concentrations of living and dead carbon in sediment interact with the types of plant species present (Valiela 2015). Excess nutrient loading, when severe, can also cause a complete community shift in the dominant primary producers of shallow-water ecosystems, such as from seagrass to micro- and macroalgal dominance (Antón *et al.* 2011). This may not greatly change the gross primary productivity (ie gross  $CO_2$  fixation rate), but because microalgae are less structurally complex and have higher overall nutrient content than seagrass rhizomes, and because there is enhanced microbial activity, turnover of carbon incorporated into microalgae occurs quickly. The fast carbon turnover results in a smaller carbon reservoir (Antón *et al.* 2011). Community shifts can therefore have a profound impact on the fate of the carbon produced and total carbon sequestered. In addition, increased water-column productivity from a nutrient-driven community shift also leads to light

limitation for benthic plants. As a result of increased microbial activity, hypoxia may also occur at the sediment surface, negatively influencing sediment biogeochemistry (Howarth *et al.* 2011) and benthic organisms.

While more research is needed to quantify the long-term effects of nutrient loading on net carbon flux, particularly in tidal marshes and mangroves, the few existing studies (discussed earlier) suggest that nutrient reduction programs may have a favorable effect on carbon sequestration. Reducing nutrient loading in coastal systems should help to maintain the natural competition between macrophyte production, microalgae, and bacterial activity, thereby limiting the release of stored carbon and facilitating the carbon sequestration capacities of VCHs. Substantial effort is already being expended around the world to limit or reverse eutrophication (Smith and Schindler 2009). Measures to control nutrient loads include reducing fertilizer use, improving wastewater treatment, and altering land practices (soil conservation, wetland restoration, the handling of manure, and planting or protection of riparian buffers). Recent improvements in wastewater treatment technologies that reduce phosphorus and nitrogen inputs have proven particularly effective, although inputs of the latter nutrient



**Figure 3.** Managing catchment-level processes to enhance blue carbon sequestration. Three strategies are suggested: (1) reducing nutrient inputs, (2) reinstating top-down control of bioturbator populations, and (3) restoring hydrology by removing tidal flow restrictions and restoring fluvial inputs. Each of these will directly or indirectly control the burial efficiency and longevity of carbon within sediments through their effects on microbial activity. Though the goal is carbon enhancement, there are broad conservation benefits.

from diffuse catchment sources have been more difficult to control (Howarth *et al.* 2011).

The many nutrient reduction programs being implemented worldwide provide an opportunity to rapidly refine current knowledge about the magnitude of changes in carbon sequestration rates. Increased collaboration among biogeochemists and coastal managers can help to determine the scenarios and habitats offering the greatest gains in carbon storage relative to efforts to decrease nutrient inputs. Nutrient reduction can be quite simple and might include strategies as straightforward as avoiding the installation of stormwater pipes and outfalls near VCHs.

#### ■ Controlling bioturbator populations to prevent carbon losses

Defined as the disturbance of sediments by living organisms, bioturbation is a fundamental ecosystem process that controls how carbon flows in and out of a carbon reservoir (Kristensen *et al.* 2008). Bioturbation in VCHs is associated with a wide range of organisms that live both above and below the sediment surface (eg crabs, shrimp, polychaete worms, and many others). These organisms influence carbon cycling in VCHs through diverse, often competing processes and reactions that alter plant growth and the redistribution and release of gaseous (eg  $\text{CO}_2$ ; Kristensen *et al.* 2008), particulate (Coverdale *et al.* 2014), or dissolved carbon.

Plant growth is important for soil carbon accumulation and preservation, because plants provide structure that traps particles and acts as a fresh source of carbon to sediments. At relatively low densities, bioturbators often have positive effects on the growth of VCH plants (Kristensen *et al.* 2008). Feeding and burrowing activities (eg leaf litter processing, irrigation of burrows) of bioturbators increase nutrient and oxygen concentrations in the sediment, and these enhanced conditions help stimulate plant growth (Smith *et al.* 2009). In mangroves, for

instance, studies have reported a positive correlation between tree growth and crab burrow density (Smith *et al.* 2009). However, while some level of bioturbation is necessary for maintaining a healthy VCH, high densities of bioturbators can have negative impacts, generating cascading effects on soil carbon accumulation and preservation (Coverdale *et al.* 2014).

Bioturbator burrowing and feeding activities can both enhance plant growth and stimulate microbial breakdown of soil carbon to  $\text{CO}_2$ . When bioturbators rework sediment, for example, their burrowing mixes relatively young carbon with ancient carbon (Papadimitriou *et al.* 2005). Sediment mixing during burrowing also increases electron receptor (eg oxygen, nitrate) availability to deeper microbial communities (Kristensen *et al.* 2008), with oxygen penetration increasing by several orders of magnitude (Ziebis *et al.* 1996). As a result, microbial abundance can be more than tenfold higher (Papaspyrou *et al.* 2005) and  $\text{CO}_2$  production may be twofold greater in sediments with bioturbators as compared to those without (Kristensen *et al.* 2008). Furthermore, intense burrowing can alter the physical properties of the sediment and weaken plant roots, resulting in bank erosion and the loss of carbon associated with those sediments (Coverdale *et al.* 2014).

Increasing evidence of trophic cascades in VCHs has altered the earlier belief that consumer control in these communities is unimportant, and raises concerns that trophic cascades may be influencing the sequestration capacity of these ecosystems (Atwood *et al.* 2015). In Cape Cod, overharvesting of predatory fish has led to a fourfold increase in *Sesarma* crab populations, causing widespread tidal marsh die-off from overgrazing and erosion, and an estimated release of  $248.6 \pm 4.8$  gigagrams of belowground C (Coverdale *et al.* 2014). Across tidal marshes globally, an overabundance of bioturbators and large-scale bank erosion could be leading to an estimated release of  $\sim 2100\text{--}8500$  metric tons of  $\text{CO}_2$  per year (Coverdale *et al.* 2014), although the fate of carbon after

**Table 1. Key strategies for managing vegetated coastal habitats for blue carbon outcomes**

Strategy	Examples (case studies)	Management recommendations	Research needed to fill critical knowledge gaps
Reducing anthropogenic nutrients to increase carbon storage	In a 12-year study of an oligotrophic salt marsh in South Carolina (Morris and Bradley 1999), soil respiration increased and carbon inventories decreased as a result of long-term nitrogen and phosphorus fertilization, resulting in a 40% loss of carbon from the top 5 cm of the soil profile, equivalent to ~0.4 metric tons of C ha <sup>-1</sup> yr <sup>-1</sup> . The increase in sediment respiration was attributed to an increase in primary productivity, resulting in enhanced microbial activity and turnover of stocks.	Accept and communicate that nutrient status of coastal waterways affects provision of the VCH ecosystem service Implement or reinvigorate point-source reduction of nutrients (nitrogen, phosphorus) Implement best-practice agricultural methods (eg reducing fertilizer waste, restoring riparian vegetation) to reduce diffuse nutrient inputs to coastal waters	Work with managing agencies to measure short- and longer-term changes in carbon sequestration where nutrients are being reduced Synthesize findings linking nutrient status to rates of carbon storage and model scenarios to assist managers in regions with limited empirical data
Controlling bioturbator populations to prevent carbon loss	In New England, depleted predator populations were linked to large-scale salt marsh erosion resulting from a fourfold population increase in the bioturbator <i>Sesarma reticulatum</i> populations, an important bioturbator in these systems (Altieri <i>et al.</i> 2012; Coverdale <i>et al.</i> 2014). In Cape Cod, the recovery of <i>Spartina</i> marshes has in part been attributed to the release of the predatory, invasive crab <i>Carcinus maenas</i> , which consumes and competes with <i>S. reticulatum</i> (Bertness and Coverdale 2013). Within affected marsh sites, <i>C. maenas</i> abundance was positively correlated with <i>Spartina</i> regrowth and up to 50–100% <i>C. maenas</i> recovery (Bertness and Coverdale 2013). Furthermore, recovered marsh sites in Cape Cod with low abundances of <i>S. reticulatum</i> are estimated to sequester 30 ± 26 megagrams of organic carbon per hectare per year (Mg OC ha <sup>-1</sup> yr <sup>-1</sup> ), while sites with high abundances of <i>S. reticulatum</i> are estimated to lose 60 ± 0.4 Mg OC ha <sup>-1</sup> yr <sup>-1</sup> (Atwood <i>et al.</i> 2015).	Identify locations where top-down control has been lost and bioturbator populations are increasing as a consequence Implement “no-take” reserves and more stringent catch limits in areas where overfishing is the cause of predator losses Consider opening fisheries and other biological controls to harvest over-abundant bioturbator populations	Investigate food webs that are most likely to negatively affect carbon stocks in the event of loss of top-down control For bioturbator taxa of most concern, identify target densities that are optimal for carbon capture and storage
Restoring hydrology to increase carbon accumulation	In a study comparing natural and tidally restored wetlands in the Hunter estuary in SE Australia, Howe <i>et al.</i> (2009) reported a rapid response of soil carbon accumulation in tidally restored mangroves and tidal marshes. The increased carbon sequestration rate of the restored wetlands was driven by substantially higher rates of vertical accretion (345% higher for salt marsh; 95% higher for mangrove), relative to the natural reference site. This resulted in soil carbon accumulation rates 114% and 18% higher than natural values in restored salt marsh and mangrove areas, respectively.	Reinstate freshwater inputs via strategic environmental flows to restore the supply of carbon to VCHs (as well as ameliorate salinity stress, etc) Remove coastal barriers that limit natural tidal exchange, carbon supply, and VCH shoreward migration	Identify locations where impoundments and coastal barriers limit the supply of carbon (and other nutrients and sedimentary materials) to VCHs Develop case studies (eg demonstration projects) to quantify the costs and benefits (social, environmental, and economic) of restoring hydrology

such disturbances, and thus its potential to be remineralized to CO<sub>2</sub>, is unknown. Similarly, the loss of top-down control has resulted in documented cases of overgrazing, defoliation, and extreme bioturbation events in seagrasses and tidal marsh systems, and there is indirect evidence of such events in mangroves (Atwood *et al.* 2015). Once VCHs are transformed to bare sediment, revegetation can be hindered by propagule-eating bioturbators and the reworking of sediment through burrowing and feeding activities. If a wholesale transformation of VCHs were to occur worldwide, these activities could reduce the

global CO<sub>2</sub> uptake by natural ecosystems by several million metric tons (Atwood *et al.* 2015). As a result, the effects of trophic cascades on carbon stocks in VCHs have the potential to be severe and long-lasting.

Within the ecosystem restoration field there is a common perspective that enabling the recovery of natural ecological processes leads to successful long-term results (Landres *et al.* 1999). In the case of bioturbators in VCHs, reinstating top-down control of bioturbator populations may have the most sustainable outcomes, and studies from other ecosystems suggest that this tactic can

lead to increases in carbon sequestration (Wilmers *et al.* 2012). We acknowledge that in some circumstances, increases in bioturbator populations are the result of vegetation loss, not the initial cause (Valdemarsen *et al.* 2011). In these instances, a more successful management strategy may be to address the root cause of vegetation loss, although some direct actions on bioturbators may still be necessary if they inhibit re-vegetation (see below).

In many cases, controlling for trophic cascades in VCHs is complicated by insufficient knowledge about trophic structure and above- and belowground linkages. Research into the potential for trophic cascades should therefore be a priority. Although in situations where the bioturbator is an invasive species and lacks a native predator (Malyshev and Quijon 2011), or where action is required immediately, harvesting of bioturbators may be required in order to reduce their densities quickly. Along the western and eastern coasts of the US, several agencies have already implemented trapping and tidal marsh transplanting programs to combat the invasive European green crab *Carcinus maenas* (Kern 2002). However, when bioturbators are native species it is important to identify target bioturbator densities that are conducive to high rates of carbon accumulation and preservation for each site, and to identify the extent to which plant growth and recovery can be used as a proxy for the success of blue carbon sequestration strategies. Such information can be obtained by monitoring plant growth, seedling recruitment, and bioturbator and predator populations as components of coastal VCH management.

### ■ Restoring hydrology to increase carbon accumulation

Globally, there is a long history of human modification to coastal waterways through intentional draining of estuarine wetlands, the artificial opening or closing of intermittent estuary entrances, and the building of dams, weirs, barrages, and flood gates. Here, we identify strategies that utilize or modify existing water management structures (as opposed to new geoengineering works) to maximize carbon sequestration by VCHs. While these measures are theoretically simple to implement, their execution may differentially affect the VCH types present (ie seagrass versus mangrove versus tidal marsh). For example, changes to hydrological and sedimentary regimes may promote the expansion of one VCH at the expense of another. Implementation of such measures should therefore be based on their potential net sequestration outcome, and should be preceded by a careful consideration of costs and benefits on a case-by-case basis (VCS 2015).

### Restoring allochthonous inputs

Many of the world's VCHs occur within estuaries (or are at least influenced by coastal rivers), where they

capture mineral sediments required for maintaining surface elevation (Craft 2007; Lovelock *et al.* 2015) and receive contributions of carbon from distant sources (Kennedy *et al.* 2010; Adame *et al.* 2012). The refractory nature of terrestrial carbon transported by rivers, along with the rapid mineral sedimentation rates often associated with runoff, can limit remineralization of this carbon by microbes, resulting in rapid carbon sequestration by VCHs. In-stream barriers such as dams and weirs reduce these important inputs; globally, 20% of suspended sediment loads are now retained in reservoirs (Syvitski *et al.* 2005). Under river regulation, catchment-derived plant materials and riverine carbon generally accumulate behind reservoirs. This accumulation of organic matter can lead to CO<sub>2</sub> and CH<sub>4</sub> release within the dammed, freshwater reservoir (Friedl and Wüest 2002).

The trapping of fluvial inputs behind impoundments may starve downstream VCHs of the sedimentary materials (inorganic and organic) they require for the vertical accretion that helps to cope with sea-level rise. The regulation of the Mississippi River, for instance, has led to significant reductions in sedimentation rates in tidal marshes throughout the river delta and in the northern Gulf of Mexico (DeLaune *et al.* 2003). The resulting gradual subsidence of land, combined with rising sea levels, continues to lead to the loss of tidal marshes and their associated ecosystem services.

In regulated catchments, reinstatement of freshwater inputs via strategic environmental flows may be a feasible method for maximizing VCH carbon sequestration. Changes in common environmental indicators such as VCH extent, open water area, vegetation composition, and elevation (or inundation depth and frequency as inverse measures of elevation) may alert coastal managers to sediment deficiency. Flow may then be used to enhance sedimentation in downstream habitats, and to increase VCH surface elevation. Because many estuarine plants are facultative halophytes (ie they require freshwater), freshwater inputs may also increase belowground production. Such a response is expected to be species- and setting-dependent; but for some mangroves, belowground root growth declines with increasing salinity (Krauss *et al.* 2014). Where belowground production increases, there are likely to be positive outcomes for both surface elevation gain (through root production) and belowground carbon storage. Finally, in some cases an increase in sedimentation rates may also allow rapid burial of labile surface carbon (eg benthic algae and detritus) such that it bypasses the "normal" oxidative processes and therefore escapes microbial remineralization.

### Restoring hydrology and physicochemical conditions

Tidal constriction through the operation of barriers such as flood barrages may convert estuaries – and the VCHs within them – from tidal saline systems into brackish

lakes, with consequent changes to biota (Figure 3). In southeastern Australia, for example, there are 4300 barriers to tidal flow in estuaries and coastal rivers. Of these, a considerable number (1388) could be easily removed or modified, which would allow the re-establishment of tidal exchange (Williams and Watford 1997). Reinstatement of tidal waters has the potential to increase vertical soil accretion resulting from (1) VCH biomass and litter production, (2) increased access to particulate carbon transported during tidal inundation, and (3) restoration of physicochemical conditions that maximize carbon sequestration (Anisfeld 2012).

The conversion of coastal ecosystems through tidal flow restriction can disrupt carbon sequestration by coastal ecosystems and may switch these ecosystems from being net sinks to net sources of carbon (McLeod *et al.* 2011). For instance, conversion of coastal systems to freshwater systems (via diking or impounding coastal areas) can lead to CH<sub>4</sub> emissions by reducing the supply of marine sulfates, which effectively inhibit methanogenesis, which can be greatly reduced by the restoration of tidal flows and the increase in salinity (Chmura *et al.* 2003). Draining wetland soils may result in the loss of soil carbon stocks through the oxidation and enhanced decomposition rates associated with a shift to terrestrial conditions and altered microbial consortia. In contrast, increasing soil moisture has been shown to reduce surface soil CO<sub>2</sub> efflux in VCHs in the short term (minutes to weeks) by as much as 65% when soils become anoxic (Lewis *et al.* 2014). After the early stages of tidal restoration (around 10–14 years), enhanced surface carbon accumulation rates have also been observed (Howe *et al.* 2009). Intervention should therefore be prioritized in tidally restricted sites that currently exhibit high CO<sub>2</sub> and CH<sub>4</sub> efflux and/or slow surface accumulation rates (relative to suitable reference conditions).

Removing existing structures to reintroduce tidal exchange should help with VCH migration in the presence of rising sea levels, thereby facilitating future carbon sequestration. Recent modeling of an estuary in southeastern Australia suggests that opening the floodgates currently in place would allow for effective retreat of coastal wetlands, with potential carbon burial gains of up to 280,000 metric tons by 2100 (Rogers *et al.* 2014). Historical VCH sites (which have since been altered through tidal restriction) and sites that offer the greatest opportunity for VCH expansion in terms of elevation and extent should be prioritized for such changes.

A major challenge for coastal biogeochemists and managers is to combine the process-level research discussed above with biophysical models to provide quantitative estimates of the carbon sequestration capacity that will accompany hydrological restoration. This synthesis of strategy and theory, combined with monitoring of restoration trials and demonstration projects, will improve understanding of the feasibility and effectiveness of hydrology restoration for enhancing carbon sequestration.

## Conclusions

The management strategies discussed above offer the potential to profoundly alter carbon accumulation and retention within VCHs, providing new and previously undervalued strategies for mitigating climate change. The state of the science varies among the three management strategies suggested, with hydrology being the area of research that is most supported by robust science. Table 1 lists suggestions for future research. Regarding the fundamental question about manipulating ecosystems (ie should we do it?), we argue that each of the proposed strategies will push coastal ecosystems toward a less impacted state and will, in many cases, offer ecosystem benefits beyond carbon sequestration. Moreover, these strategies (with the exception of monitoring bioturbator populations) are already featured in most coastal management plans, thus facilitating their broad-scale implementation.

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