

Carbon Sinks in Nearshore Marine Vegetated Ecosystems

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Introduction

To reduce the rate of global warming due to rising CO₂, the potential for sequestering carbon by oceanic phytoplankton has received considerable international attention, which has culminated with a research agenda (Longhurst 1991). The potential for using terrestrial systems as carbon sinks is also under study (Sampson 1992). Although limited work on the use of kelps as a global carbon sink has been reported, very little work has focused on nearshore coastal systems as a carbon sink. The coastal system needs to be added to carbon cycle models because this sector (particularly in the tropics) has a high rate of carbon sequestration that has not been accounted for in terrestrial and oceanic carbon models. In addition, we believe that coastal ecosystem restoration should be carefully evaluated as a potential strategy within the nation's carbon management strategy.

Objectives

The objectives of our paper are to (1) review potential processes that would affect carbon sequestration in coastal ecosystems, and (2) present some data on coastal marsh and seagrasses systems that illustrate the potential for these systems to store carbon. We rely on data from estuarine and coastal ecosystems and habitats in the Pacific Northwest, and draw from published information on processes affecting sequestration from published sources.

Review of Processes

Carbon cycle models include terrestrial, coastal, oceanic, and atmospheric systems. In this paper, the "coastal system" refers to the region between the terrestrial and ocean systems. The land/sea interface defines the coastal margin and the continental shelf and shelf slope physically defines the ocean margin of the coastal system.

Coastal Margin

Oceans play a key role in the global carbon cycle. Because of high primary productivity rates, relatively high nutrient concentrations, and coverage of the earth surface, coastal margins are an important component of the oceanic carbon cycle. In turn, coastal margin productivity provides the basis of energy for fishery production worldwide. An understanding of the sources, sinks and fates of carbon within this system is highly relevant to the global carbon budget, and to the effects of alterations such as global warming and increased CO₂ on this budget. Summarizing the results of the “Natural Sinks of CO₂” conference held in 1992, Wisniewski and Lugo (1992) state that it is critical to include “the coastal system along with the terrestrial, oceanic, and atmospheric systems in models of the carbon cycle because this sector of the biosphere (particularly in the tropics) has a high rate of carbon sequestration that has not been accounted for in terrestrial and oceanic carbon models”.

Carbon Sources

The major types of primary producers in near coastal systems include phytoplankton, benthic microalgae, seaweeds, kelp, seagrasses, tidal (fresh, brackish, salt) marshes and mangroves. Other carbon sources along coastal margins include terrestrial, estuarine, and marine sources. In coastal margins, the most important external sources of carbon include diffusion of CO₂ (dissolved), death of marine producers (particulate), and terrestrial and estuarine debris (dissolved and particulate) (Valiela, 1984). The relative contribution of terrestrially derived carbon (C/N >10) and marine-derived carbon (C/N <6) varies along the coastal margin, depending largely upon the volume of riverine input and distance from the source. Internal sources of dissolved and particulate carbon include recycling of dead particles, exudation from producers, release from broken cells, and excretion by consumers (Valiela, 1984). During periods of upwelling, resuspension of very light particulate organic carbon becomes another potential carbon source.

A series of papers within a symposium at the 1990 INTECOL meeting demonstrated the key control that watersheds have in the functioning of biological systems in coastal waters (Valiela 1992). Changing CO₂, temperature, wind and rainfall patterns and other factors would influence the rate and pattern of forest processes and succession (Agren et al. 1991). For example, increased temperature is expected to result in forest areas being replaced by grasslands (Anderson 1991). Carbon processing and storage and nutrient dynamics will also be affected (Anderson 1991). Furthermore, land use has been shown to be highly important in affecting nutrient transport to coastal systems (e.g. Correll et al. 1992). Large amounts of carbon enter estuarine and coastal systems from watersheds, and it is clear that the rates and mass of nutrients, organic matter and sediments reaching estuaries will be altered. Logging, road construction, river channelization and development in watersheds have resulted in considerable increases in suspended sediments in streams and rivers. In turn, estuarine sedimentation and turbidity are the result of sediment from logging operations (Kehoe 1982). In Grays Harbor estuary, located in Washington State, sediment inputs are three to five times greater following logging and road building activities in the Chehalis River watershed. High turbidity has resulted in limitation in the distribution of seagrasses in that system. The influence of increased sedimentation and turbidity on estuarine systems due to anthropogenic activities has not been addressed in detail (Houghton and Woodwell 1983, Smith and Hollibaugh 1993).

Metabolism

Metabolic processes in coastal systems can be summarized as follows:

$$\text{GCP} = \text{NPP} + \text{AR} + \text{HR}$$

where,

GCP	=	gross community productivity
NPP	=	autotrophic net primary productivity
AR	=	respiration by autotrophs
HR	=	respiration by heterotrophs.

Related definitions are:

CR	=	community respiration	=	AR + HR
GPP	=	gross primary productivity	=	NPP + AR.

It is important to keep these definitions and relationships in mind when discussing system metabolism. They become particularly useful in the calculation of carbon fluxes. For example, when $\text{GPP} > \text{CR}$ the system is autotrophic and a net source of carbon. When $\text{GPP} < \text{CR}$, the system is a net sink of fixed carbon. Unfortunately, for the purposes of evaluating sources and sinks of carbon, most studies provide only some of these measures and therefore total carbon flux cannot be accurately calculated.

Carbon Fixation

Benthic aquatic vegetation roughly accounts for 6% of global NPP (Table 1), of which coastal system production comprises about one-half of this amount. Coastal systems including upwelling areas account for approximately 7% of the global carbon fixation. These systems tend to have a high production to mean annual biomass (P:B) ratio, which means that turnover, and export is relatively important on a global scale (e.g., Thom 1990). P:B ratios range from about one to as high as 300, which indicate that the biomass is replaced from one to 300 times annually (Valiela 1984). Rooted angiosperms occur in shallow depths over major areas of freshwater systems and coastlines globally. These systems are both highly productive and harbor large number of fisheries resources. Annual rates for tidal freshwater marshes, salt marshes, mangroves and seagrasses range from about 300-1000 gC m^{-2} (Mann 1982). Algae, including seaweeds and kelps have NPP rates on the order of 400-1900 $\text{gC m}^{-2} \text{y}^{-1}$ (Mann 1982).

The rates associated with coralline reefs can be exceptionally high. Gross community productivities (GCP) can range from 2000-5000 $\text{gC m}^{-2} \text{y}^{-1}$ (Mann 1982), with NPP being about 60% of GCP. Because many rooted macrophyte systems have organically rich sediments, nutrient limitation may be less important as compared to terrestrial systems in moderating the effect of higher CO_2 levels on plant production (e.g., Drake and Leadley 1991). Rooted macrophyte systems can be sources of CO_2 , CH_4 and other gases through microbial processing of organic matter in the sediments and direct emission from leaves (Delaune et al. 1990).

Table 1. Total net primary production (NPP) from world systems. Modified from Valiela (1984).

	Area 10 ⁶ km ²	NPP gC m ⁻² y ⁻¹	Tot. NPP ¹ X10 ⁶ mTC y ⁻¹	% of Total System	% of Total Global
Marine System:					
Open Ocean	332	46	15,355	74.1	24.1
Upwellings	0.4	185	74	0.4	0.1
Continental shelf	27	111	2,997	14.5	4.7
Algal Beds & reef	0.6	925	555	2.7	0.9
Estuaries (exc. marsh)	1.4	555	777	3.7	1.2
Tot. Marine	361.4	57	20,726	100.0	32.5
Continental System:					
Terrestr. Env.	145	273	39,540	91.7	61.9
Swamp and Marsh	2	1,110	2,220	5.1	3.5
Lakes and Streams	2	148	296	0.7	0.5
Tot. Continental	149	289	43,112	100.0	67.5
Total Global			63,838		
Total Benthic Aquatic Vegetation (i.e., algal beds, reefs, seagrasses, mangroves, swamps and marshes)			3,552		5.6

¹ This is (NPP in gC m⁻² y⁻¹) x (area).

Carbon Limitation and Enriched CO₂

There are very limited data on carbon limitation and/or the effects of enriched CO₂ on the photosynthetic rates of coastal plants. However, at least five lines of evidence suggest that C-limitation is occurring in nearshore macrophyte dominated systems. First, a general indication of C-limitation can be derived from a summary of C:N:P ratios from marine macrophytes (Atkinson and Smith 1983). The mean C:N was 22, and approximately 13% of the plant species presented in the review had a C:N ratio of between 5 and 10. Atkinson and Smith stated that the lowest C:N ratios were found under conditions of high nitrogen concentrations. Duarte (1992) also reviewed nutrient contents of aquatic plants and found that, among macrophytes, macroalgae had a low percentage of carbon in their tissues, seagrasses had higher values and freshwater angiosperms had the highest values. Higher values may be related the higher amounts of cellulose and lignin in these latter macrophytes. Either very low C:N ratios or high levels of carbon that are unavailable for use by the plant, suggests physiological conditions of C-limitation. Second, Drake (1992) and his co-workers, using long-term (i.e. five year) enrichment treatments, have shown highly elevated production of the C₃ plant *Scirpus olneyi* and not for the C₄ plant *Spartina patens* in Chesapeake Bay. In general, production rates were increased on the order of 30-80%

under doubled-CO₂ concentrations. C₃ plants are common in wet systems (e.g., Drake and Leadley 1991). Furthermore, most of the seagrass species that have been evaluated utilize this pathway (Beer and Wetzel 1982). Third, enriched CO₂ has been used to increase the production of commercially valuable seaweeds such as *Chondrus* and *Gracilaria* (T. Mumford, Washington State Department of Natural Resources, pers. comm.). Fourth, kelp systems can have very high biomass densities, and it is possible that these dense beds have a major requirement for carbon during periods of active growth (reviewed in Foster and Shiel 1985).

Experiments conducted by Battelle also suggest CO₂ limitation in a species of seagrass and kelp (Thom 1996). A series of short-term experiments were conducted at Battelle/Marine Sciences Laboratory, which evaluated the effect of CO₂-enriched seawater on the photosynthetic rate of mudflats, the seagrass *Zostera marina*, and the kelp *Nereocystis luetkeana*. Mudflats contain dense concentrations of epibenthic diatoms, and can have relatively high NPP (actually net community because animals and bacteria are included in the mud cores). *Zostera marina* is a widespread seagrass species in the world and dominates many subtropical to subarctic nearshore systems (Phillips and Meñez 1988). *Nereocystis luetkeana* occurs from central California through the Aleutian Islands where it forms the major forests.

In single dose experiments: (1) mudflats did not show a significant response; (2) eelgrass showed a significant increase in one experiment and no effect in the second experiment; and, (3) kelp NPP was approximately doubled by the enrichment. A serial enrichment showed a rise in NPP for eelgrass and kelp up to a saturation point. It appeared, in these preliminary experiments, that both species were CO₂-limited. Autotrophs on mudflats may not be, but this system is more problematic due to the high amount of respiration associated with the sediments. The data in Atkinson and Smith showed that *Z. marina* and *N. luetkeana* had relatively low C:N ratios of 13.1 (average of three values) and 9.7, respectively.

Fate of Fixed Carbon

Of importance to the global carbon cycle is the ultimate fate of fixed carbon. In near coastal systems, carbon may be lost to the sediments through burial, recycled within the systems, consumed by herbivores, acted on by microbes and consumed within the detrital food web, exported off shore or to adjacent uplands by currents as particulate and dissolved organic matter, or released to the atmosphere as aerosols. Heterotrophic microbes and animals respire CO₂, and leave solid organic wastes, and these compartments of a carbon cycle may be great in heterotrophic systems (e.g., depositional mud bays).

Estimates of rates of burial of carbon in coastal marsh systems vary widely, with 0.2 to 1 cm y⁻¹ representing a range for most marsh systems. Because marsh soils are generally organically rich, on the order of 25% of the mass of the accreting material may be organic, with accumulation rates of ca. 4 gC y⁻¹ (unpublished data, and Thom 1992). Carbon sinks as peat accumulation are great in some systems on the East and Gulf coastal where marshes have been forming for 3,000-4,000 yrs (Bricker-Urso et al. 1989). Other marsh systems are very new, and have little surface peat accumulation. For example, salt marshes in the Pacific Northwest are buried on the average of once every 300 yrs by ocean sediments as a result of large earthquakes

and land subsidence (Atwater 1987). This effectively, sequesters marsh carbon forever, and resets the process of marsh establishment. The global importance of this process is in need of study.

The estimates for direct consumption through herbivore pathways and detrital pathways are not well known in general for these systems. What is evident is that large proportions of the standing crop of these plants can be removed by animals, which shred material and/or eat the material directly (Adam 1990).

Sea level is rising an estimated 1 to 2.5 mm yr⁻¹ (Gornitz et al. 1982, Peltier and Tushingham 1989), and the rate of rise is predicted to increase substantially over the next century due to global warming (Peltier and Tushingham 1989). Salt marshes accrete sediments and organic matter and can keep pace with sea-level rise as long as sediment supplies are adequate. Increased flooding related to increased rainfall and runoff can bring more sediment to coastal marshes and potentially result in enhanced carbon sequestration (e.g., Reed 1999). However, flooding of marshes alters their chemical conditions (Nyman et al. 1990) and can ultimately result in the loss of marsh area. The loss of 59.5 km² y⁻¹ in the Mississippi River deltaic plain due to reduced sediment input is an extreme example of what can happen (Britsch and Kemp 1990). Increased flooding may initially increase C-fixation, however. Metabolic processes are altered with increased flooding. Morris et al. (1990) showed a strong positive correlation between mean sea level and net annual aboveground production of *S. alterniflora*, and attributed the higher productivities to increased wetland flooding. However, heavy flooding, as is documented on the rapidly subsiding portions of the Mississippi delta, increases benthic respiration and greenhouse gas emissions, and decreases net primary productivity (Delaune et al. 1990).

A rising sea affects the penetration of salt into the estuary, which will affect the distribution of organisms and the rates of processes. It is very difficult to predict the overall affect of a rising sea, along with increased temperatures, altered rainfall and other associated factors on net productivity in coastal systems at this time (Mehta and Cushman 1989).

Ocean Margin

Smith and Hollibaugh (1993) provide perhaps the most comprehensive and directed review of the role of coastal systems in the oceanic carbon budget. Their analysis indicated that net organic metabolism might be an important term in the oceanic budget and that the oceans, in total, may be a source of carbon (as CO₂) to the atmosphere. Oxidative respiration appears to account for a large proportion (i.e., 30%) of the oceanic total. They do caution that the metabolic rates used for their calculations are subject to wide variability and that the difference between net production and respiration for coastal systems is small. Variation now limits interpretation of coastal systems in the oceanic budget. Finally, they point out that coastal systems are highly vulnerable to human perturbations, which can significantly alter metabolic activity.

Carbon Sources and Fixation

Production in the surface layers of the ocean is driven by sunlight and nutrients. Nutrients are supplied via land sources and via remineralization in the surface layer. Carbon that is fixed in the

photic zone sinks to deeper depths where remineralization is intense. The mass of carbon transported to depth is limited by nutrient and available sunlight as well as carbon in the surface waters. In ocean margin systems, dynamical currents and wind driven upwelling events bring remineralized nutrients back to the surface. Productivity, which is often limited by low nutrient concentrations in the photic zone, will be stimulated by these upwelled materials. Hence, as compared with the very deep ocean, coastal margins can receive a large amount of nutrients and carbon from deeper layers. This dynamic linkage between deep and upper layer portions of the water column, along with the proximity to “new” sources of nutrients from land explains the high productivity rates found in coastal margin systems.

Planktonic productivity along coastal margins varies both seasonally and episodically. High production rates are found in inner shelf, upwelling, and sea surface microlayer systems. Carbon fixation rates within frontal eddies off of the North Carolina coast may reach $1\text{-}6 \text{ g C m}^{-3} \text{ d}^{-1}$, while rates in nutrient-poor, outer shelf waters are $5 \text{ mg C m}^{-3} \text{ d}^{-1}$ (Yoder et al., 1983). In the Mid Atlantic Bight, production may remain high ($2\text{-}3 \text{ g C m}^{-3} \text{ d}^{-1}$) from spring to fall, as the plankton populations shift from using upwelled nutrients, in the spring, to using recycled nutrients in the summer (Walsh et al., 1978; Matte and Waldhauer, 1988).

In the sea surface microlayer, the upper millimeter of the water column, neustonic productivity per unit volume may be much greater than that of planktonic productivity in underlying water. Carbon can be enriched 4-16 times over that immediately below (Frew 1992). Microbial populations represent 12-40% of the microlayer biomass (Carlucci et al 1991), and these populations may be 10,000 times greater than those in the bulk water (Hardy 1982). Bacterial activity is often much greater in the microlayer. Off Baja California, dissolved free amino acid (DFAA) utilization and total free amino acid (TFAA) utilization rates were up to four times greater in the microlayer as compared with the subsurface waters. The microlayer, because of its position at the interface between the atmosphere and the ocean and because of the increase microbial biomass and activity, may be a key, but largely ignored, component of carbon flux between the ocean and the atmosphere.

Fate of Fixed Carbon

Loss of carbon is primarily due to settling of particulate organic carbon (fecal matter, carcasses, molts) to the ocean floor. Downward carbon flux can be quite high, nearly 59% ($299 \text{ mg C m}^{-2} \text{ day}^{-1}$) of the water column production falls to the bottom in the New York Bight (Valiela, 1984). The majority of this lost carbon (50% in the Mid Atlantic Bight) is transported off the shelf, to the continental slope. Sinking carbon may then be incorporated into benthic ecosystems, buried in sediments, or resuspended and reincorporated in the water column (Valiela, 1984).

Carbon leaves the shelf environment through entrainment in offshore surface and deep layer water masses. Seaward export of coastal carbon is, however, a controversial subject, especially among those that study temperate estuarine systems. However, there is no question that considerable carbon is exported in fluvially dominated system like the Columbia River (Hedges et al. 1988). Movement of carbon from the shelf to deeper areas is mediated by currents and the dynamics of wind driven events like upwelling. Upwelling brings carbon from deeper areas of the shelf back to shore with the potential for further landward movement under the right conditions. Significant

amounts of carbon fixed very nearshore can end up in windrows of detritus on beaches. This material, which can reach massive levels, is broken down by detritivores, sunlight and physical grinding (Zobel 1971). Some of the material may be buried in beach sediments, marsh soils or be removed to deeper areas by tides. Even buried material may be removed at times, for example during severe storm events.

Shallower shelf waters, such as the Cape Coastal Water (11°C, 34.5-36.5) south of Cape Hatteras and Virginia Coastal Water (13.5°C, 31-34 ppt) north of Cape Hatteras generally feature more variable physical parameters and more terrestrial influence. Riverine input may be high in some regions, as near the mouth of Chesapeake Bay (Matte and Waldhauer, 1988), or negligible, as is the case immediately south of Cape Hatteras (Yoder et al., 1983). Despite regions of high estuarine input, nutrient concentrations remain relatively low in outer shelf waters. Only inner shelf waters close to the mouth of major estuaries exhibit substantially elevated nutrient levels (Matte and Waldhauer, 1988).

The convergence of the shelf and slope waters, the shelf/slope front, meanders from the slope to the outer shelf during summer months, and may move as shallow as the 70m isobath (FRED Group, 1989). More importantly, frontal eddies will spin off the front, encapsulating deeper, nutrient rich waters and bring them near or to the surface. During these periods of upwelling, nitrate levels may reach 15 μM NO_3 within the eddy (Yoder et al., 1983). Mid-Atlantic Bight waters also have periods of upwelling and increased nutrients; however, these are more seasonally controlled events (Matte and Waldhauer, 1988). These periods of upwelling represent the bulk of annual production in coastal margins (Yoder et al, 1983).

Slope waters are generally dominated by stable oceanic currents. Along the Eastern seaboard, the Gulf Stream dominates the slope as far north as Cape Hatteras (Atkinson, 1985). North of Cape Hatteras, slope water is mainly derived from the Labrador Sea, with Gulf Stream water mixed in from warm core rings (Cook, 1988). Gulf Stream waters are characterized by warmer surface temperatures (21-29°C annually), higher salinities (35-36.5 ppt annually), and moderate nutrient concentrations (surface: 1 μM NO_3 , 0.1-0.2 μM PO_4 ; bottom: 20-28 μM NO_3 , 1.0-1.5 μM PO_4). Slope water north of Cape Hatteras features slightly cooler and more variable water temperatures (15-29°C) and salinities (34-35.5 ppt) (Cook, 1988). Nutrients in slope waters north of Cape Hatteras are similar to those of the Gulf Stream waters.

An extremely important component of the global carbon budget is the rate at which gases are exchanged between the atmosphere and the ocean. Research at has shown that an increase in whitecaps area coverage from 0.0 to 0.6% increases gas transport velocity by a factor of five (Asher et al. 1992). In addition, Frew et al. (1990) has shown that phytoplankton-generated surfactants (i.e., surface active organic matter), when present, significantly reduced relative oxygen exchange coefficients. The authors concluded that the details of fundamental processes affecting gas exchange in system containing these types of materials is in need of further evaluation.

Recent evidence has shown that in parts of the Southern Ocean, phytoplankton production is not maximal even in the presence of relatively high nutrient concentrations. Iron limitation has been

proposed as an explanation, and this hypothesis has generated debate within the oceanographic community (ASLO 1991). The debate was driven by the proposal that suggested large-scale introductions of iron in these areas of the ocean could be used to stimulate carbon sequestering from the atmosphere, which would partially mitigate increased atmospheric CO₂. Subsequent experimental additions of iron to the Southern Ocean resulted in modest, short-term increases in phytoplankton biomass (Chisholm 2000).

Project Description

Carbon Sequestration in Coastal Pacific Northwest Systems

Two studies were conducted to characterize carbon sequestration in coastal Pacific Northwest Systems. The first examined organic carbon content of tidal marsh soils of various ages, as well as above and belowground biomass. The second study measured eelgrass biomass in natural and created wetlands

Tidal Marshes

We collected soil organic matter and total organic carbon content data from a wide variety of tidal marsh systems in the Pacific Northwest estuaries between 1990 and 2000. We also sampled above and belowground biomass in many of these systems. Some of the systems were recently (i.e., with the last 15 years) restored either by breaching a dike surrounding the system to reconnect the system to tidal flushing, or by creation of a completely new tidal system by excavation of upland. These data provide an indication of the amount of organic matter in tidal marshes and the rate at which carbon accumulates in these systems over time.

Eelgrass

Eelgrass (*Zostera marina* L.) is one of approximately 50 species of seagrass. *Z. marina* is distributed widely throughout the northern hemisphere. Seagrasses are generally submerged most of the time and fringe virtually all coastlines in the world. They are among the most important primary producers and form critical habitat for fish, invertebrates and birds.

Our experiments (Thom 1996) examined soil carbon content in natural and man-made eelgrass habitats and eelgrass carbon limiting factors. More recently, we sampled eelgrass biomass in Willapa Bay, Washington, and Coos Bay, Oregon, between 1998 and 2000. We also monitored air temperatures during these sampling seasons.

Results

Tidal Marshes

The effect of sediment deposition on organic matter accumulation is shown in Figure 1. The diked system had not received sediment from tidal waters for over 50 years. In comparison to the reference marsh, carbon from vegetation deposition accumulated in the upper 5-10 cm of the soil where decomposition and respiratory processes probably account for relatively rapid losses of organic carbon to the atmosphere. In the reference marsh, carbon accumulation mediated by sediment deposition provides for burial of carbon to depths in the soil profile where respiratory processes are much slower (owing to low oxygen conditions).

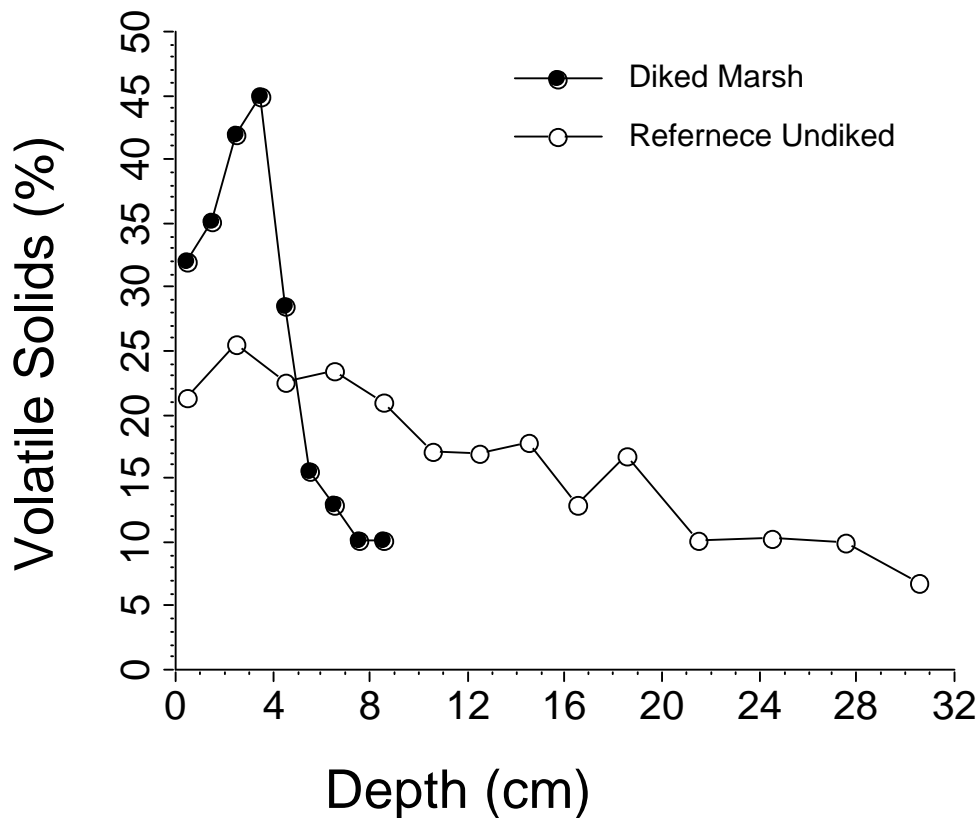


Figure 1. Soil volatile solids versus depth in a diked tidal marsh at Elk River, Grays Harbor Washington and a nearby reference (undiked) marsh (from Thom 1992).

Creation of tidal marshes can result in rapid accumulation of carbon. Figure 2 shows above and belowground biomass in a 10-year old created tidal marsh in the Chehalis River, Washington, and a nearby reference marsh. The data indicate that at this age soil organic matter in the created marsh system is comparable to the natural system. In addition, the data illustrate the most of the total biomass is below ground.

Altered tidal wetland systems show lower soil carbon. Data on soil organic carbon from altered and natural marshes in Sequim, Washington, illustrates that by altering hydrology (drying) and by altering salinity (switching from salt water to freshwater) resulted in a tendency to decrease soil carbon (Figure 3).

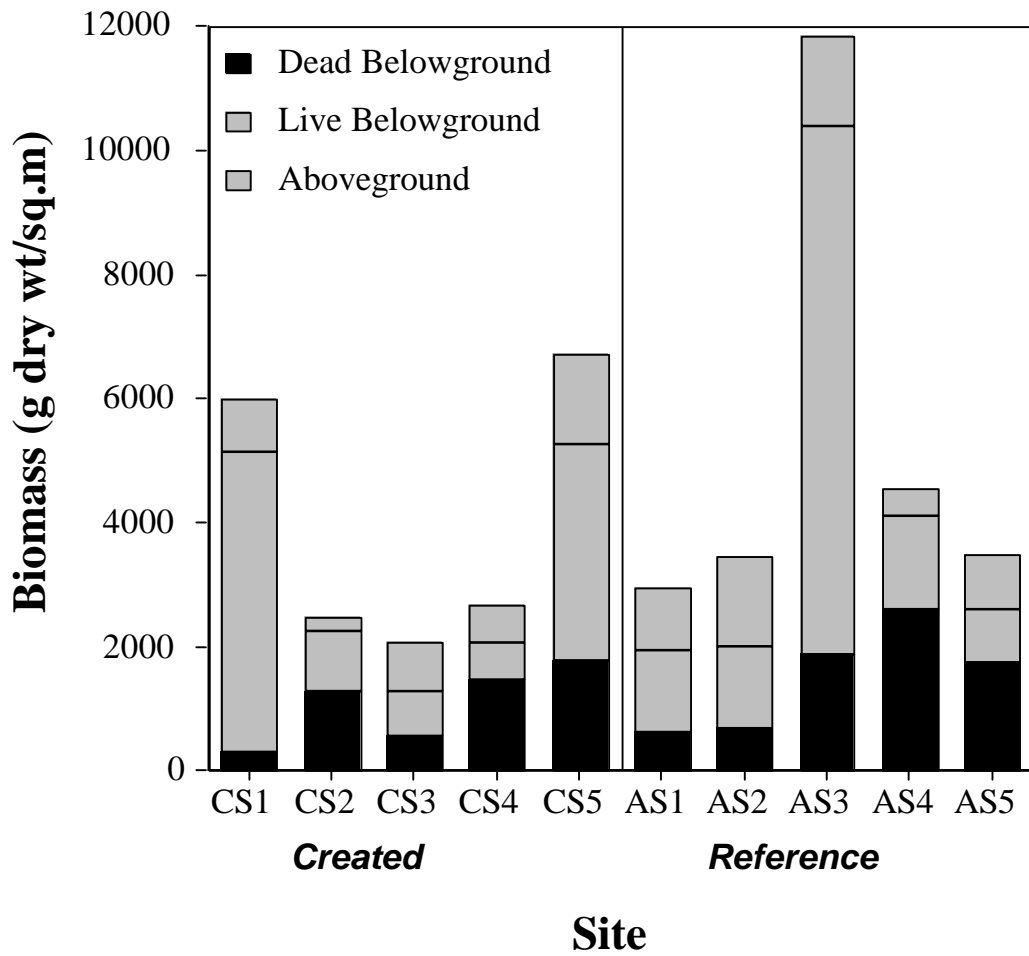


Figure 2. Biomass of Lyngbye's sedge (*Carex lyngbyei*) in at five sites in a created (CS) and five sites in a reference marsh (AS) in the tidal portion of the Chehalis River, Washington.

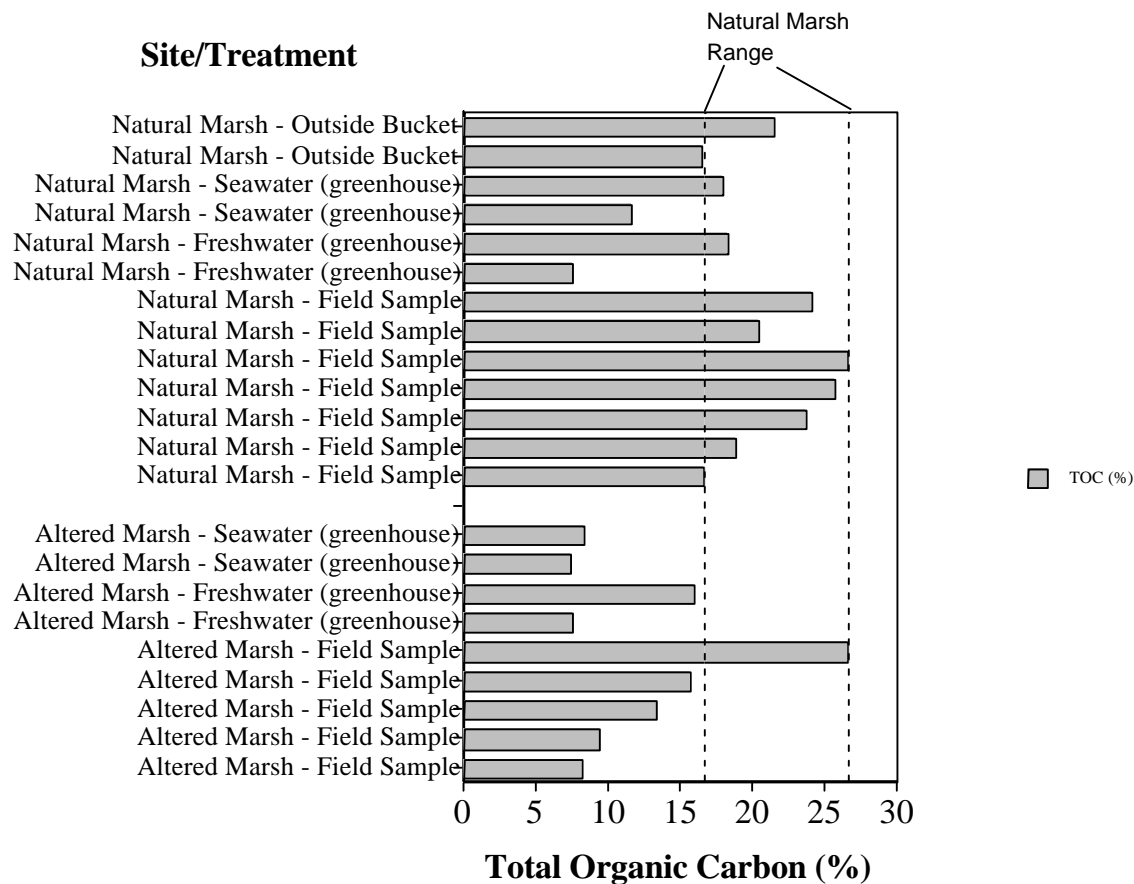


Figure 3. Soil organic carbon from various marsh treatments. The altered marsh is a system that was cut off from tidal inundation. Hydrology and salinity was manipulated in a greenhouse and affected carbon content in the soils.

Based on sampling of restored marshes of various ages and natural marshes, it appears that carbon gain happens rapidly over the first approximately 5-50 years (Figure 4), and then levels off. Because massive vertical land movements coupled with tsunami-generated sand burial, most coastal marshes are relatively new in the Pacific Northwest. The last major land movement occurred in 1700. Hence, we considered the natural marshes shown in figure 4 to be 300 years old or less. The data also illustrate the considerable variation in soil carbon in natural marshes.

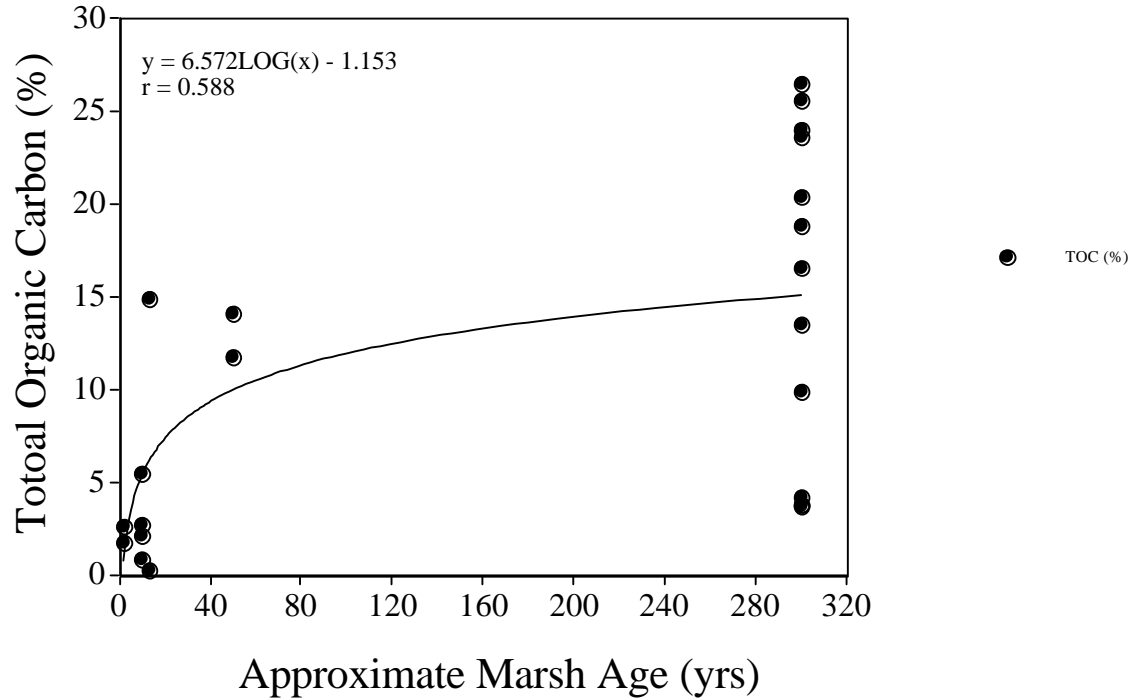


Figure 4. Marsh age versus soil organic carbon for systems in Oregon and Washington.

Eelgrass

Earlier experiments (Thom 1996) indicated that eelgrass carbon limited and that an increase in dissolved carbon would result in increased growth. Although not quite as high as marshes, eelgrass habitats can contain considerable soil carbon (Figure 5). Our measurements of soil carbon in a large (80 m³) flowing seawater tank that contains dense eelgrass shows that after about two years the soil carbon in the planted tank was within the range of soil carbon in natural eelgrass meadows. This suggests that restoration of these systems can lead to rapid carbon accumulation. We have observed large quantities in deep portions of Puget Sound and in open water offshore of Washington. This indicates that these systems export large quantities of carbon to deeper locations where it may be buried or otherwise sequestered.

The data from 1998-2000 show that there are wide variations of eelgrass biomass between years with a major increase in eelgrass biomass within Willapa Bay over the study period (Figure 6). Temperature monitoring at the sites showed a warming trend over this period, which as not seen in Coos Bay. Our preliminary conclusion is that the increasing water temperature (up to 5°C during spring) has resulted in greater flowering as well as faster growth, both of which result in greater biomass. Like marshes, much of the biomass is below ground, which indicates that a warming environment may result in greater carbon accumulation rates.

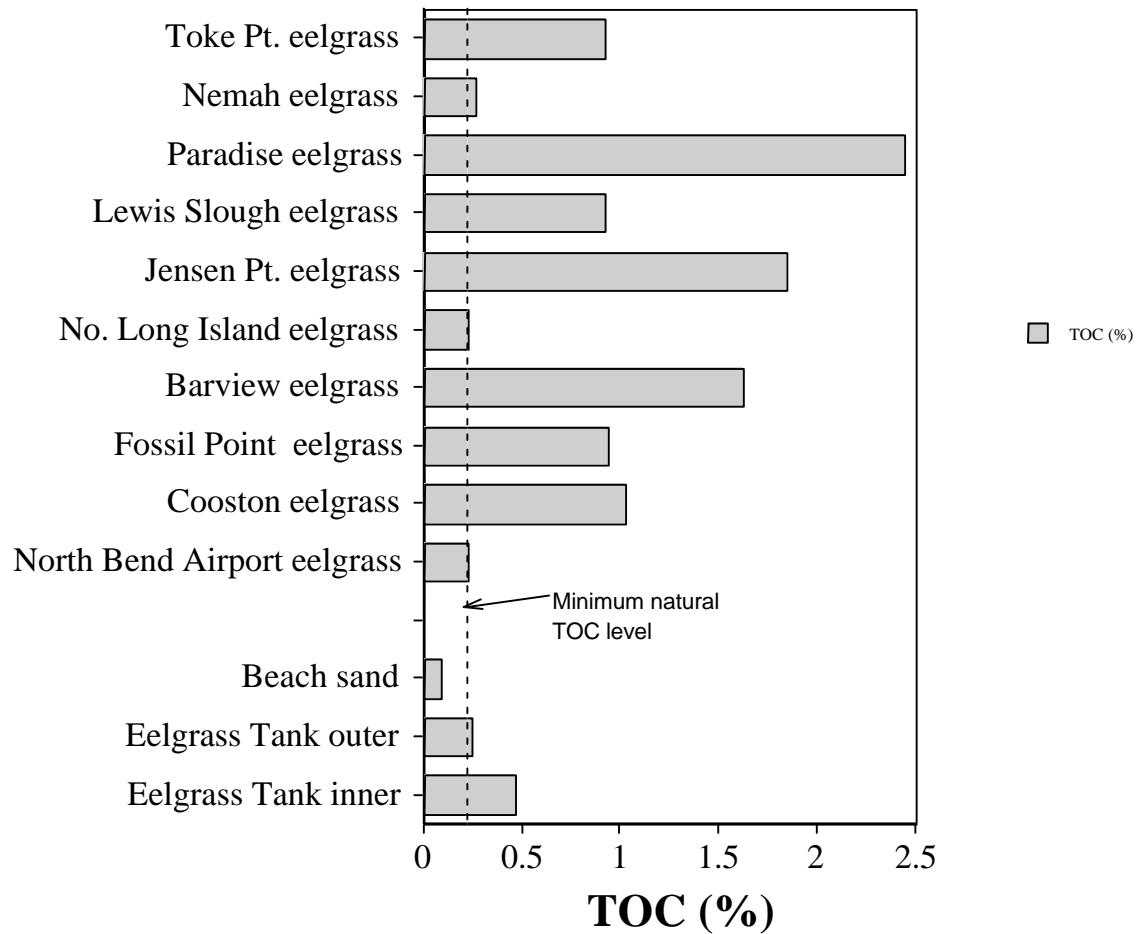


Figure 5. Soil organic carbon in eelgrass systems in the Pacific Northwest and in a large culture tank. The tank was planted with eelgrass approximately two years before soils samples were collected. The beach sand sample provides an approximation of the organic content prior to introduction of the eelgrass.

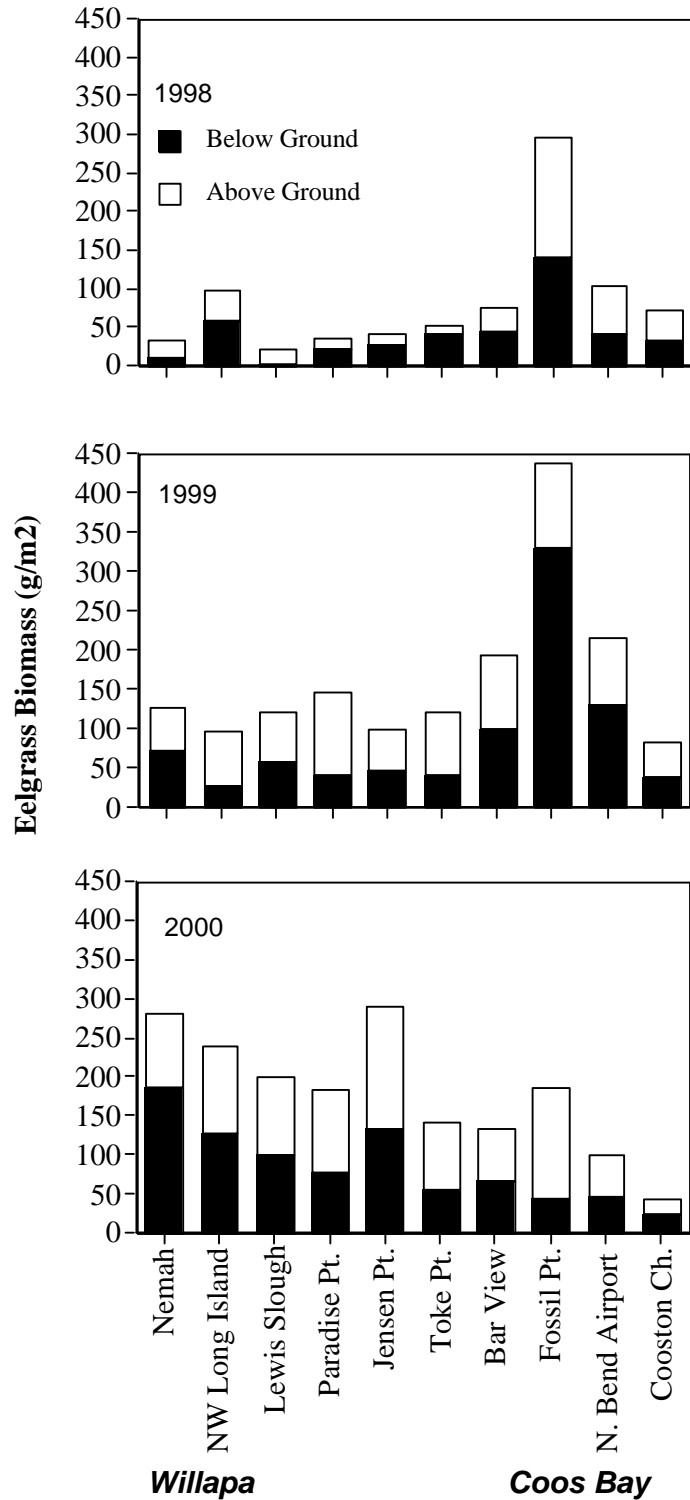


Figure 6. Above and belowground live biomass in eelgrass systems in Coos Bay, Oregon, and Willapa Bay, Washington during summers of 1998-2000.

Applications

In 1999, the U.S. Department of Energy conducted a “road mapping” exercise to plan research on carbon sequestration (Reichle et al. 1999). As part of this exercise, the ability to enhance carbon sequestration in wetlands was evaluated. Wetlands in general were found to contain vast carbon stocks in the soils. However, there was concern that carbon uptake by terrestrial wetlands, especially peatlands, would be offset by methane gas emissions, resulting in a net source of carbon to the atmosphere. This topic requires more research. Methane emissions are generally low in coastal systems because of the salt content in the water and soils (Mitsch and Gosselink 1993). In addition, because of the fact that large areas of coastal wetland have been either destroyed or highly altered, the plan concluded that restoration of coastal systems might be one of several important methods for sequestering more carbon in the biosphere.

Although preliminary, our results corroborate this strategy. Not only does it appear that coastal marshes and eelgrass meadows can build soil carbon if restored, this carbon is stored for long periods. The rate of sequestration appears to be rapid over the first few years and up to 40 years following restoration. Our observations with eelgrass indicate that export of eelgrass biomass to deep areas of estuaries as well as the coastal ocean may further sequester more carbon. The fate of exported carbon needs to be studied to verify this conclusion.

Future Activities

We plan to concentrate our research in the future on further understanding the carbon budgets of the major vegetated systems in the coastal zone. Our efforts presently are concentrated on tidal marshes and eelgrass because of the tractability of experimental and fieldwork.

Several ongoing studies are designed to evaluate carbon sequestration in wetlands. The first study investigates the use of mesocosms for evaluating carbon flux rates and dynamics from wetlands in various conditions. Prototype mesocosms containing natural salt marsh sod will be used to monitor patterns of carbon flux over an extended period of time. Treatments will include sod from natural, restored and altered wetlands. Carbon dioxide flux rate, and parameters such as temperature, salinity, and soil moisture will be monitored over extended periods of time using an automated sampling system. We expect that restoring hydrology will increase wetland carbon sequestration, and that the mesocosms will prove very useful as a tool for assessing ways to increase carbon sequestration. With the mesocosms we also expect to verify that restored wetlands sequester substantially more carbon than do degraded wetlands. This information could be used as a strong basis to support expanded research into the use of restoration as a tool for sequestering more carbon in the biosphere.

We are also evaluating spectral radiance as a useful first indicator of enhanced carbon sequestration. We will explore the use of spectral radiance for detecting changes in carbon sequestration by detecting differences in spectral signatures from various test treatments. A portable spectral radiometer will be used to determine radiances from natural and hydraulically

altered marsh treatments. With these data, we will test whether spectral radiance correlates with carbon stores in sediments. We will make spectral measurements at sites where soil carbon samples are collected. If the technique is viable, this method could be scaled to assess carbon sequestration on a regional scale.

Additional key research issues that remain to be investigated include the effects of temperature and hydrology on carbon fixation and soil carbon accumulation and the short and long-term fate of fixed carbon. Because restoration not only results in enhanced sequestration rates, it also benefits a wide variety of coastal fisheries resources, we believe that restoration of coastal systems should be a key component of the carbon management strategy for the nation.

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