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***1 Cover Letter**

Dear Editor,
I am submitting my revised manuscript, taking into consideration the reviewer's relevant comments.
I appreciate the rapid turnaround on your part and on the reviewer's.

Note that I have also made minor edits to the highlights.

Cheers,
Gail Chmura

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What Do We need to Assess the Sustainability of the Tidal Salt Marsh Carbon Sink?

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***Highlight**

highlights

Carbon crediting systems require sinks be sustainable for ~100 yr.

Increasing sea levels threaten tidal marsh sustainability and Blue Carbon sinks.

Assessment of marsh sustainability requires high resolution elevation data.

Lidar technology uniquely provides this data, but we need to fund its acquisition.

What Do We need to Assess the Sustainability of the Tidal Salt Marsh Carbon Sink?

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Abstract

Tidal salt marshes provide a range of ecosystem services. The most recently recognized is their provision of highly effective sinks for atmospheric carbon dioxide, a characteristic they share with mangroves swamps which largely replace salt marshes in the intertidal zones of tropical regions. Efforts are emerging to use salt marsh preservation or restoration in carbon offset programs, similar to the REDD initiative for tropical forests, but a number of issues first must be addressed to determine if a site meets the requirements of these programs. As intertidal systems, both salt marshes and mangrove swamps are threatened by increasing rates of sea level rise, and it will be essential to determine their sustainability, thus meeting the requirement of permanence of the carbon sink. In many areas the vegetation responsible for marsh soil accretion may not survive increased flooding periods, resulting in submergence of the marsh in its present location or inability to restore a marsh at its previous elevation. However, the marsh and its carbon sink, may survive if allowed to migrate inland. Thus assessment of permanence requires a determination if inland migration will be hindered by barriers such as high slopes or development, i.e., if the ecosystem is in a coastal squeeze. Presently, the only technology that can provide elevation models at the required vertical accuracy is Lidar, which also is extremely valuable for assessing vulnerability of coastal communities to flooding. Yet, Lidar data is not available for all coastlines, even those in

the developed world. To effectively plan for the future of our coastlines requires Lidar coverage on all sensitive coastlines and its free availability for impact assessments.

Introduction

Tidal salt marshes, which are found predominantly along protected coastlines with temperate climates provide many ecosystems services, paralleling those of mangrove swamps which occur in similar settings along tropical coasts (e.g., Costanza et al. 1997, Millennium Ecosystem Assessment 2005, Chmura et al. in press). The support salt marshes provide to coastal fisheries through export of energy for coastal fisheries and provision of refugia for juvenile fish is well recognized (e.g., Boesch and Turner 1984, Deegan et al. 2000). Marshes also provide valuable habitat for plants, birds and other animals, many of which serve as food resources. These same functions can stimulate indirect economic benefits to communities which provide services and supplies to recreational waterfowl hunters and fishers. In some regions marsh plants are harvested for subsistence consumption or commercial sale, like the glassworts of Europe. Native vegetation of salt marshes is also harvested as fodder or simply used as natural pastures. The salt tolerance of tidal salt marsh vegetation makes them potential candidates as alternative crops and forage in salinized soils (Gallagher 1985), which are likely to become more problematic as rising sea levels cause salinization of groundwater.

Indirect benefits from marshes may be more valuable. The utility of tidal marshes for protection from storm surges has been noted for decades, and recent modelling studies have helped highlight characteristics that enhance this value (Barbier et al. 2008, Morgan et al. 2009, Koch et al. 2009). Another long recognized value is the capacity of marshes to reduce nutrient loading to coastal waters. However, recent studies have shown that an increased supply of nutrients will reduce root production of marsh grasses (Darby and Turner, 2008) which plays an important role in accretion of the marsh soil (see below). Fertilization experiments in both mangroves and salt marshes have shown that addition of nitrogen can enhance the release of nitrous oxide from the soil (Muñoz-Hincapié et al. 2002, Moseman-Valtierra 2011), a greenhouse gas with 298 times the global warming potential of carbon dioxide (Forster et al. 2007). Thus, the service provided by nutrient regulation may be offset by a reduction in the potential for greenhouse gas regulation of salt marshes.

Carbon Storage in Tidal Salt Marshes

The recognition that tidal salt marshes are significant carbon sinks is the most recent ecosystem service recognized (Connor et al. 2001, Chmura et al. 2003). Although the potential of freshwater wetland soils as a carbon sink has been recognized for some time, many studies had overlooked soils of tidal salt marshes and mangrove swamps, perhaps due to the intensive research focus on carbon export in support of coastal fisheries (Nixon 1980; Odum 2000) and the assumption that % soil carbon reflected carbon quantity. However, the quantity of carbon is a product of the % soil carbon and the overall soil bulk density (e.g., grams soil per cubic centimeter). Carbon quantities were assumed to be lower on coasts where tidal floodwaters contribute large quantities of inorganic sediment to tidal wetland soils. These inputs simply dilute organic matter with mineral sediments that are three orders of magnitude heavier than organic matter. Thus, a tidal salt marsh soil that contains 5% carbon but has a bulk density of 5 kilograms per square meter can hold the same amount of carbon as a soil that contains 50% C, but has a bulk density (mass/volume) 0.5 kilograms per square meter.

Rates of carbon dioxide sequestration in salt marshes are probably an order of magnitude higher that in terrestrial forests (figure 1), but uncertainties exist in the global area of salt marsh and the rates of carbon dioxide sequestration throughout each marsh. The carbon burial rates reported for tidal salt marshes range from 18 to 1713 g C m^{-2} yr^{-1}. Considering that the global area of marshes likely ranges from 22,000 to 400,000 km^2, these wetlands could be storing 4.8 to 87.2 Tg C yr^{-1} (Mcleod et al. 2011).

Reports by the United Nations Environment Programme (Nelleman et al. 2009) and the International Union for the Conservation of Nature (Laffoley and Grimsditch 2009) have stimulated international interest in the carbon stored in tidal salt marshes and other coastal ecosystems, termed "Blue Carbon", and highlighted threats to the sustainability those ecosystems that serve as Blue Carbon sinks. Mcleod et al. (2011) have since identified key areas of uncertainty and specific actions needed to address them, and Crooks et al. (2011) have proposed a research agenda to prepare a greenhouse gas offset protocol for tidal wetlands restoration and management and an " Action Plan to Guide Protocol Development". One of the requirements they identified is that sites used for offsets (carbon credits) be in appropriate landscape settings that allow the spatial migration required to accommodate sea level rise. Crooks et al. note that registries and agencies will require a high degree of confidence that a carbon offset project will be successful over at least 100 years.

Marsh Accretion, Sustainability, and Permanence

Considering threats of rising sea levels, permanence is the first criterion that should be addressed and can be combined with planning programs that assess vulnerability of coastal communities to sea level rise. The high rate of sea level rise associated with climate warming threatens the permanence or sustainability of the marsh and the carbon it stores. Rising sea levels require that marsh soils accrete vertically to maintain their position in the tidal frame and they have done this for millennia. However, there is a threshold above which marshes are not able to keep up, so that to persist, the system must migrate to higher elevations found on adjacent uplands to persist.

A major factor in marsh accretion and migration is plant growth which also is responsible for carbon dioxide fixation from the atmosphere. The carbon stored in tidal salt marsh soils comes from plant production, as plants fix atmospheric carbon dioxide during photosynthesis and store it in leaves, stems and roots. Rates of plant production vary considerably (Table 1). In North America aboveground production ranges from 60 g C m^{-2} yr^{-1} in northern Canada and Alaska to averages as high as 812 g C m^{-2} yr^{-1} in the north central Gulf of Mexico (Mendelssohn and Morris 2000). However, most productivity studies have been limited to biomass produced by vascular plants aboveground, missing two important components of carbon stores: below-ground production of roots and rhizomes (Table 1) and microflora (cyanobacteria and eurkaryotic algae such as diatoms) that live on the soil surface (Sullivan and Currin 2000). In many salt marshes belowground production is significantly greater than aboveground (Table 1). This soil biomass is much less available for export to detrital food chains that support coastal fisheries, thus remains stored in soil as organic matter.

This accumulation of soil organic matter, primarily through root production, is key to the continued vertical accretion of marsh soils. If rates of soil accumulation are adequate, the marsh soil thickness will increase, maintaining its surface elevation with respect to rising sea level. Paleoenvironmental studies of marsh soils (e.g., Shaw and Ceman, 1999) have documented not just an increase in surface elevation, but also lateral accretion of marsh soils as marsh plants colonize mudflats to the seaward side and adjacent terrestrial or wetland environments to the landward side. The slow rate of sea level rise over the last 5,000 years has allowed development of carbon-rich deposits as much as 6 m thick in some estuaries. Organic matter in those deposits is preserved as tidal floodwaters saturate the soil and reduce the potential for aerobic decomposition. Anaerobic decomposition is much less efficient (Buol et al. 2003), enabling accumulation of organic matter in the soil, and the effective carbon sink.

Vegetation provides another positive feedback to marsh accretion by enhancing the deposition of suspended sediment from tidal floodwaters (Figure 2, Fitzgerald et al. 2008). In some estuaries that carry little suspended sediment marsh soils can develop nearly solely through accumulation of organic matter (Chmura 1986), but when suspended sediment is available it can greatly enhance marsh accretion. During the eighteenth and nineteenth centuries land clearance associated with European settlement of North America increased suspended loads in waters along some coastal reaches causing expansion of tidal marsh areas in locations such as Chesapeake Bay on the mid-Atlantic coast and Plum Island Estuary on the Massachusetts coast (Kirwan et al. 2011). Results of modelling experiments by Kirwan et al. (2011) support this cause and effect. Their model results also suggest that an expansive marsh platform could replace a landscape dominated by ocean water in <100 yr if suspended sediment concentrations were increased by one to two orders of magnitude. Even after sediment loads are reduced the level of these marsh platforms could continue to track sea level at the rates of sea level rise experienced in the last 100 years. Unfortunately, these same modelling experiments indicate that if lost, these marshes cannot be restored under present conditions.

Other experiments with models and manipulated field conditions show that, to a point, increased sea levels actually can stimulate production of one of the dominant marsh species on the western Atlatnic, *Spartina alterniflora,* producing a further ecogeomorphic feedback (Morris et al. 2002; Mudd et al. 2009). The increased hydroperiod provides greater opportunity for suspended sediment to settle and denser vegetation provides greater capacity to trap the sediment. There is a threshold, however, above which the increased tidal submergence becomes a stress on marsh vegetation. Saturated soils present challenges to nutrient uptake and drain plants energy stores, resulting in decreased production (e.g., Burdick and Mendelssohn 1990). With this negative feedback comes a continued deficit in marsh vertical accretion, degradation of the marsh, and loss of the carbon sink. Erosion of the marsh soil could then result in shifts of carbon to other parts of the estuary, where it might be redeposited or even oxidized, resulting in return of the stored carbon to the atmosphere as carbon dioxide. On many coasts projected increases in rates of sea level rise are likely to push marsh vegetation beyond the critical threshold (Kirwan et al. 2010).

Threat of Accelerated Sea Level Rise

Anthropogenic activities have eliminated or damaged tidal salt marsh ecosystems (e.g., Silliman et al. 2009), but the most pervasive threat to the remaining area of salt marsh is probably accelerated sea level rise (Fitzgerald et al. 2008; Nicholls et al. 1999). In many regions a combination of natural and anthropogenic factors is causing tidal marshes to experience high rates of sea level rise such that an accretion deficit already exists. An example is the marshes of the Mississippi Delta's Barataria Basin which, from 1947-2006, experienced a rise in sea level of 0.92 cm yr^{-1}. The pattern of sea level rise was closely paralleled by loss of wetland area - at rates as high as 28 km^2 yr^{-1} during the same period (Fitzgerald et al. 2008). In fact, Sivitski et al. (2009) reported that, with the exception of Australia, deltas were at serious risk in all climate zones and on all continents, as natural processes that result in subsidence (compaction of sediments) were compounded by anthropogenic factors (e.g., changes in hydrology and sediment loads) so that a number of deltas are sinking at rates many time faster than global sea level is rising.

In their fourth assessment report, the IPCC projected that global sea level would rise from 0.18 to 0.59 m by the end of the century (Bendoff et al. 2007). Such an increase will further hasten marsh loss in those areas already experiencing accretion deficits and threaten additional sites. The sustainability of the additional sites will increase with tidal range and concentration of suspended sediments in local tidal floodwaters (Kirwan et al. 2010). For instance, models by Kirwan et al. (2010) indicate that a salt marsh with a tidal amplitude of 3 m and suspended sediment load of 3 mg L^{-1} and one with a 0.5 m amplitude and suspended sediment load of 10 mg L^{-1} both could be sustainable at rates of sea level rise of 5 mm yr^{-1}, close to the maximum predicted by the IPCC.

More recent research indicates that the rates of sea level increase may have been significantly underestimated by the IPCC. Vermeer and Rahmstorf (2009) have suggested that sea level could increase 0.75-1.90 m by 2100 (figure 3). If rates of sea level rise increased linearly over this time, marshes would experience rates of 7 to 17 mm yr^{-1}, leaving only those marshes with both high suspended sediment supplies and high tidal ranges likely to survive. The present area of vulnerable marshes will be transformed to subtidal environments, but if suitable low lying land is available in bordering terrestrial reaches they may be displaced inland.

Increasing sea levels have already placed marshes bordering steep slopes or on developed coastlines in what has been termed a “coastal squeeze” (Doody 2004). On many coasts the ability of marshes to expand inland is severely restricted by urban development or embankments associated with “reclamation” (figure 4). Walls, dikes, and paved surfaces present physical barriers to marsh expansion inland, and the seaward edge of salt marshes is expected to retreat. This situation will ultimately result in loss of tidal salt marshes. Increased rates of sea level rise will increase the duration of tidal flooding, limiting vegetation production at the lower elevations along the seaward edge of the marsh. If landward lateral accretion is not possible, these marshes will eventually disappear.

Requirement to Assess Sustainability and Permenance

Since accretion rates of many marshes are unlikely to keep up , survival of the marsh (and the carbon sink) will depend upon its displacement inland. The ability of a marsh to migrate will be dependent upon the slope of bordering terrestrial lands and whether human development has posed any barriers to such migration, placing the carbon sink in a coastal squeeze (Doody 2004). Buildings, roads, walls and even pavement can serve as barriers.

The first information needed to determine if a site is appropriate for a greenhouse gas offset program is if the marsh is sustainable. That is, will it continue to accrete vertically and laterally as sea level rises?. Determination of the carbon sequestration rates of a marsh will have little value if it is not sustainable and does not meet the requirement for permanence. In fact soil accumulation rates of marsh undergoing submergence can be quite high (Cahoon et al. 1995) - a condition which could result in high rates of carbon sequestration, but for a limited period.

Assessment of future marsh sustainability requires a digital elevation model developed from spatial data collected at a resolution relevant to the marshes. Several methods are available for inferring elevations of land close to sea level, but most have a resolution too coarse to properly assess tidal salt marsh sustainability. Topographic maps conventionally have been used to examine elevations and slopes. These are available for most coastlines, but contour intervals are commonly on the order of 3 to 10 m (Titus and Richman 2001). Yet, the predicted increases in sea level and the entire vertical range of many marshes is 70 to 260 cm (table 2), less than a single contour interval. Assessing the potential for marsh migration requires other resources that can produce a digital elevation model accurate to within centimeters.

The Need for Lidar Coverage of Coastal Lands

Over the last decade a new technology has been proven to provide the vertical resolution required for the needed DEMs. Light detection and ranging systems, referred to as Lidar, successfully have been used to determine elevation in tidal areas with vertical resolution as fine as 0.16 m in North Carolina (Poulter and Halpin 2008) and 0.05 m in Venice (Marani et al. 2004). Lidar technology uses radio-frequency waves, firing pulses of highly coherent, narrowly focused light generated with a laser (Monmonier 2008). For topographic work it is mounted on an airborne platform equipped with a GPS, an inertial measurement unit, and a computer. A receiver unit located on the aircraft collects the returning energy from the interaction of the laser pulses with the land or water surface in the surveyed area. The received laser pulse is recorded as a function of time, and the positioning of the laser measurement is calculated using information such as aircraft positioning and altitude, scan angle, and time of the transmitted pulse. A series of filters is used to isolate vegetation surface from actual ground surface (Lefsky et al. 2002). "Topographic" Lidar, appropriate for determining elevations of marsh and adjacent uplands, operates at infrared wavelengths, while "Bathymetric" (or ALB) Lidar operates at a green wavelength allowing it to penetrate coastal waters to depth as great as 60 m, but this is dependent upon turbidity (Monmonier 2008; Pe'er and Long 2011). Both are expensive to acquire, edit and process, but there presently is no other alternative to topographic Lidar that can support the high resolution modelling required for analysis of marsh migration potential.

Lidar also provides better horizontal resolution compared to many remote sensing techniques. Topographic Lidar has a horizontal footprint of 15 to 20 cm, and error is greater in the horizontal than vertical component. However, the horizontal error can be reduced by combining Lidar with hyperspectral imagery from remote sensing which, depending upon the imagery, can provide information on vegetation and constructed surfaces, as well as help to identify the nature of barriers to marsh migration, such as roads or dikes (Millette et al. 2010; Klemas 2011). The vertical uncertainty of other methods translates into greater uncertainty in determination of areas within critical elevation zones, highlighting another advantage of Lidar.

Gesch (2009) compared the uncertainty of Lidar to elevation data available from GTOPO30, SRTM, and NED (DEM source), using coastal North Carolina as an example. He demonstrated that (at the 95% confidence level) there was as much as a three-fold difference in the area inundated by a <1 m rise in sea level. Maps derived from the three more commonly used data sources showed considerably greater areas of uncertainty associated with delineation of the 1 m contour, challenging the ability of planners to assess vulnerability of terrestrial lands or potential for marsh migration (Figure 5, from Gesch et al. 2009).

Considerable funds of governmental, private and non-governmental organizations are devoted to conservation of tidal salt marshes, yet some may not be sustainable. Wise use of private and public funds requires that sustainability of existing marshes be assessed, justifying the investment in obtaining Lidar coverage. Over a decade ago Nicholls et al. (1999) noted the inevitable loss of some wetlands to sea level rise and urged selective planning to minimize wetland losses rather than attempting to maintain the existing stock. Fine scale DEMs developed from Lidar will help us to make those hard choices.

In jurisdictions where tidal marshes are already protected, investment in greenhouse gas offset programs is best made in initiatives to restore tidal salt marshes and high resolution elevation data is needed to assess sustainability of restored marsh areas. However, salt marsh restoration programs are fairly opportunistic. For example, the Gulf of Maine Council (GOMC, with jurisdiction over waters of the US and Canada) has identified sites where salt marsh area has been lost and provides grants to local organizations who come forward with proposals for restoration. The GOMC requires that successful proposals address a number of issues, but there is no assessment as to whether the restored marsh is likely to be sustainable under any scenario of sea level rise. Organizations such as the GOMC which have limited funds may want to reconsider how these are spent and divert some to utilize existing Lidar data to assess which sites are sustainable and partner in programs to obtain Lidar imagery where it is not yet available.

A broad community of stakeholders should be interested in supporting the collection of Lidar data for their coastal regions. The availability of Lidar-based DEMs enables more insightful and effective coastal planning, so that stakeholders can consider a suite of potential impacts of sea level rise, such as increased exposure to coastal erosion and which socio-economic sectors will be affected by inundation. High resolution topographic data made available in North Carolina enabled an accurate assessment of which lowland habitats were vulnerable to increased sea level and where migration inland was likely to be hindered due to ownership patterns and land management (Poulter et al. 2009). Of course, it has unparalleled value for planning for risks of flooding of coastal property. In North Carolina it has allowed stakeholders to better understand risks of sea level rise, to develop potential response strategies, and increased political receptivity to policy change (Poulter et al. 2009). Coastal communities will be faced with hard decisions and will need accurate maps on a scale that relates to property boundaries to plan where to invest in shoreline protection or relocation of activities. Ironically, those coastal properties most vulnerable to seal level inundation may be the best locations to enable inland migration of tidal marshes. Some protected properties may have less value than the tidal salt marsh that could occur there is barriers were removed. Feagin et al. (2010) were able to examine this dilemma using DEMs developed from Lidar available for the coast of Galveston Island, Texas. They used property values and the value of ecosystem services to calculate economic trade-offs between protection of property and removal of barriers to marsh migration. The Galveston study clearly shows why we need information of the scale of private property holdings to make comprehensive assessments of sea level rise impacts. Merging initiatives to plan for protection of developed property and conservation of coastal habitat will provide greater justification for investment in Lidar, and an economic rationale for it, as well.

Lidar Cost and Availability

Lidar requires a substantial monetary investment, but when large areas are covered it gives an exceptional return for the investment and is less expensive then the alternative that provides comparable resolution, i.e. field based elevation surveys with satellite based survey instruments. Rogers et al. (2007) compared costs for obtaining a digital elevation model for marshes at Wells, Maine in the US. Based upon their project, conducted in

2005, they found no advantage of obtaining Lidar for a target area less than 49 acres, as compared to field surveys, as the minimum cost of a commercial based low resolution Lidar survey was ~US$14,000. The cost of Lidar per unit area decreases considerably with the size of the area surveyed because a single major investment is the cost to get the platform airborne.

It is difficult to determine the extent of Lidar coverage around the coastlines of the world. Despite efforts at developing a clearinghouse for the information (e.g., at http://lidar.cr.usgs.gov/) there is no comprehensive data base. It appears that Lidar has been collected for all coastlines of the UK and Spain (www.02.ign.es/PNOA/vuelo_lidar.html). In the US, Lidar is available for all, or portions of coastlines in the states of Maine, Maryland, Texas, Oregon, Mississippi, Delaware, South Carolina, New York and Florida (www.csc.noaa.gov/digitalcoast/data/coastallidar/details.html). The US government had announced a program to fund and acquire additional imagery, but that program has been stalled (Vierling et al. 2011). In Canada Lidar data has been collected for segments of the coastline along the Gulf of St. Lawrence and Bay of Fundy. In the US and Canada past collection of Lidar imagery has been possible through collaborations of governmental agencies, academia and other partners, funded through targeted grants which do not necessarily ensure free availability to additional users, thus reducing the economic return on this investment. Effective planning for impacts of sea level rise and income from greenhouse gas offset programs will mean long-term savings for all levels of government. Consideration of adequate funding for Lidar coverage to ensure public availability should be a priority policy for all governments with low lying coastal regions.

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Table 1. Rates of above and below ground production of selected tidal salt marsh species from three different plant families in North America and Europe demonstrate the importance of below ground production with varied plant forms.

species		below	above	region	reference
		---g m^{-2}	yr^{-1}---		
Chenopodiaceae					
Arthrocnemum	*macrostachyum*	1260	683	Po Delta	Ibañez et al. 2000
Arthrocnemum	*macrostachyum*	50	190	Ebre Delta	Ibañez et al. 2000
Arthrocnemum	*macrostachyum*	340	840	Ebre Delta	Ibañez et al. 2000
Salicornia	*fructosia*	950	580	Ebre Delta	Ibañez et al. 2000
Atriplex	*portulacoides*	1601	598	Guadiana River	Neves et al. 2007
Plantaginaceae					
Plantago	*maritima*	648	296	Bay of Fundy	Connor 1995
Poaceae					
Spartina	*patens*	1113	500	Bay of Fundy	Connor 1995
Spartina	*patens*	3300	785	Delaware Bay	Roman & Daiber 1984
Spartina	*alterniflora*	1575	718	Bay of Fundy	Connor 1995
Spartina	*alterniflora*	6500	1487	Delaware Bay	Roman & Daiber 1984

Table 2. Tidal amplitudes and elevation range of vegetation in selected salt marshes.

country	coast	tidal amplitude (m)	elevation range of vegetation (m)	source
Italy	Venice Lagoon	0.7	0.2	Silvestri et al. 2005
Italy	Venice Lagoon	0.7	0.3	Silvestri et al. 2005
USA	Drakes Island, Maine	2.1	2.0	Boumans et al. 2002
Canada	British Columbia	2.6	0.9	Hutchinson 1982
USA	Palo Alto, California	2.6	1.2	Hinde 1954
USA	Plum Island, Massachusetts	3.0	2.1	Millette et al. 2010
Spain	Ortigueira and Ldrido Rivers	3.6	2.4	Sánchez et al. 1996
Canada	Bay of Fundy	6.0	>3.0	Chmura et al. 1997

Table 3. Comparison of costs of obtaining Lidar data vs. collecting field data with a real time kinematic Geographical Positioning System (RTK GPS), based upon US $ in 2005 (Rogers et al. 2007)

Type	Cost/Acre	Points/Acre	Cost/Point
Lidar	$2.34	1396	$0.00
RTK GPS	$287.00	62.69	$5.44

Figure captions

Figure 1. Mean long-term rates of carbon accumulation in sediment (g C m-2 y-1) for forests and coastal vegetated ecosystems using a log scale. Maximum rates of accumulation are indicated using error bars. (figure 2 from Mccleod et al. 2011).

Figure 2, Conceptual model of factors that contribute to soil accretion in a tidal salt marsh (from Fitzgerald et al. 2008 fig 17).

Figure 3. Projection of seal level rise from 1990 to 2100 made by Vermeer and Rahmstorf (2009) based upon IPCC temperature projections for three different emission scenarios (labelled on the right). The sea-level range projected in the IPCC AR4 (Bindoff 2007) for these scenarios is shown for comparison in the bars on the bottom right. Also shown is the observations-based global sea-level data (red) including artificial reservoir correction.

Figure 4. Two scenarios of tidal marsh response to rising sea level (dotted line). Elevation of the marsh surface (solid black line) increases as increased tidal flooding allows organic matter and mineral sediments to accumulate. Increasing elevation is accompanied by lateral accretion over inland terrestrial soils, as pictured in the upper diagram. Constructed barriers (e.g., wall, dykes) prevent lateral accretion on the inland edge of the marsh. At lower elevations (dashed-dotted lines), marsh vegetation does not survive increased submergence, resulting in loss of marsh on the seaward edge (from Chmura 2009).

Figure 5. Comparison of how differences in vertical resolution result in differences in uncertainty of land area flooded in North Carolina. (A) Lands vulnerable to a 1-meter sea-level rise, developed from topographic map-derived DEMs and (B) lidar elevation data. The darker blue tint represents the area at or below 1 m in elevation, and the lighter blue tint represents the additional area in the vulnerable zone given the vertical uncertainty of the input elevation datasets. The more accurate lidar data for delineation of the vulnerable zone results in a more certain delineation (from Gesch et al. 2009).

Dear Editor,
I have taken the liberty to itemize and number the reviewer's comments and place my response directly below each in boldface, italic font. The manuscript revisions also include some technical editing I thought was needed upon rereading it myself (including a missing reference).

Main Comment
The paper highlights the main issue of permanence in coastal wetlands being related to elevation data and that the likelihood of marshes not being able to migrate inland is mainly because of urban barriers. There are other issues, perhaps secondary, associated with the permanence of coastal wetlands that should be raised (at least in list form for this manuscript), including

1)climate change and its effects on species (i.e., marsh die-off or species invasions),

Marsh die-off has been shown not to relate to climate change, but predominantly to cascade effects by overharvesting of predators (e.g., loss of blue crabs on the western mid-Atlantic permitted increased populations of snails that kill off salt marsh grass, or loss of finfish permitting other over population of burrowing crabs that decimate marsh vegetation).
There is no literature on species invasions related to climate change in tidal <u>salt</u> marshes and to suggest this would be simply conjecture.

2) feedbacks from elevated CO2 on productivity,

Research is inconclusive on this and to identify it as a "threat" is preliminary. As compared to C4 plants, C3 plant production may be enhanced by elevated CO_2, which could affect tidal SALT marsh plant community structure if the C3 plants are tolerant of the increased salinities that would probably accompany sea level rise. However, a 2011 paper by Kathilankal et al. in Hydrobiologia vol 669, pages167–181 reports that field studies show that Spartina alterniflora (a dominant tidal salt marsh plant of the western Atlantic) is likely to respond to elevated CO_2 with increased production.

3) changes in erosion (from sea level rise and storminess) and

Erosion was mentioned, but I have added additional mention of it on page 7 - noting that these are climate related...

4) direct human destruction (see Henman and Poulter 2008, for example).

This paper is about freshwater peatlands, particularly the pocosins that could be submerged with rising sea level. Direct human destruction does not threaten permanence of a tidal salt marsh, but simply eliminates it. Nicholls identifies sea level rise as the major threat to tidal salt marshes and this is what we can address with Lidar - the focus of this paper. There are excellent reviews regarding threats to salt marshes, in fact a whole book on it, which I now cite in the following sentence prefacing the beginning of the section Marsh Accretion, Sustainability, and Permanence: "Anthropogenic activities have eliminated or damaged tidal salt marsh ecosystems (e.g., Silliman et al. 2009), but the most pervasive threat to the remaining area of salt marsh is probably accelerated sea level rise (Fitzgerald et al. 2008; Nicholls et al. 1999)."

5) In addition, the resilience of coastal wetlands (related to permanence) to sea level rise has been decreased by human activities (i.e., drainage, dikes etc.) that provide some opportunity for positive management effects on permanence (see Pearsall and Poulter 2005, for example).

This book chapter is about brackish and freshwater wetlands (e.g., cypress swamps) threatened by rising sea level. The opportunities for positive management is outside the scope of this paper.

6) Lastly, the assumption that inland marsh migration could keep pace with marsh loss from sea level rise if there were no urban barriers should be evaluated some more - for example, elevations tend to rise rapidly

(with steeper slopes) beyond the coastal plains that have formed during the Pleistocene, and so the coastal 'squeeze' is not necessarily of urban creation.

The contribution of steep slopes to coastal squeeze already was mentioned in the text. I have added yet another mention - "low lying" to line 5 on page 9 and bordering "steep slopes or" to line 7 on the same page. There are steep slopes bordering some marshes that are the result of fairly recent isostatic change (during the Holocene), so dealing with this in any more detail would require a major geomorphic endeavour, outside the scope of this paper.

Minor

P1: Chmura in press, missing from References

Added

P3: Intro paragraph to 'Carbon storage in Tidal Salt Marshes' needs clarifying

I have made additions, deletions and done some reorganization that I believe increases clarity. These changes are displayed through track changes of the

P4: Prefer 'rates of carbon sequestration' to rates of carbon 'dioxide' sequestration

Changed

P10: First paragraph - would help to clarify what is meant by the marsh being 'sustainable' - I'm assuming its something to do with its resilience to SLR?

I have added the following sentence immediately after: "That is, will it continue to accrete vertically and laterally as sea level rises?"

P11: Another aspect of the vertical uncertainty of lidar is related to the density of vegetation and how this affects the lidar returns reaching the actual soil elevation. It might be useful to have a comment on this (or even a reference) as to how wetland elevations might possibly be biased from dense vegetation.

Most of the articles discussing uncertainty, error, etc. do not discuss problems with marsh vegetation, after some investigation I found the explanation, which I have added along with the supporting reference: "A series of filters is used to isolate vegetation surface from actual ground surface (Lefsky et al. 2002)."

P13: Poulter et al. 2009 missing from References

Added

P14: Could you be 'bold' enough to extrapolate the per acre cost of lidar acquisition to a global estimate.?!

There are compounded uncertainties here as we are certain of neither the global area of tidal salt marsh nor the area of existing Lidar coverage. As it is highly unlikely that any single institution would assume responsibility for the global mapping I don't see the value in such an extrapolation.

P14: An additional area of uncertainty is the vertical datum that lidar uses to reference sea level. in areas where there is a paucity of long-term tide gage records, does this present issues for datum assignment - and could this issue be raised here?

I do not think it is appropriate to raise this issue here. Lidar is useful whether tide gauge records are available or not and all vertical datums are tied into a standard datum, not a local level. Lidar allows us to plan (as noted in the existing manuscript) for various scenarios of sea level rise. The projection of sea level rise is not an uncertainty of the Lidar, but of the response of the ocean. Also, satellite altimetry is replacing tide gauge records for assessment of sea level change and is part of the IPCC assessment of sea level change.

P15: Regarding the comment of the US Government pulling funds for lidar acquisition, because this is somewhat anecdotal, is there more information on this (year, program etc.)

I have added the missing reference: Vierling et al 2011

References

Henman, J and B Poulter. 2008. Sea level rise and potential carbon emissions from freshwater peatlands. Journal of Geophysical Research - Biogeosciences, 113, G01011, DOI:10.1029/2006JG000395.

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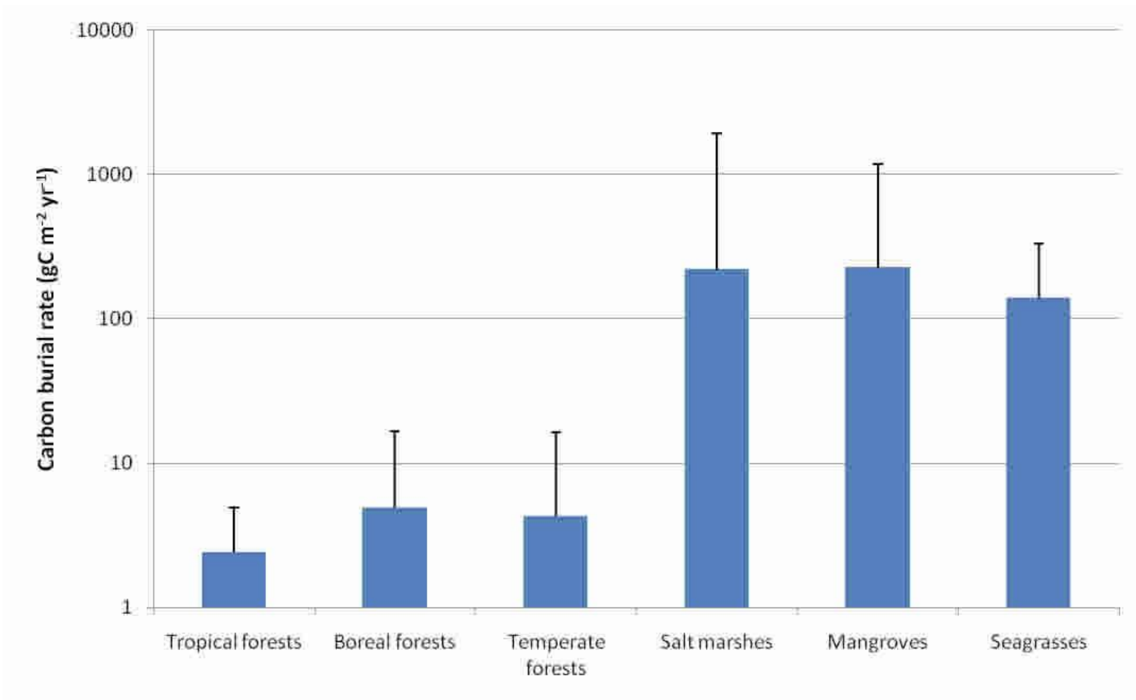
Figure 1



10000
1000
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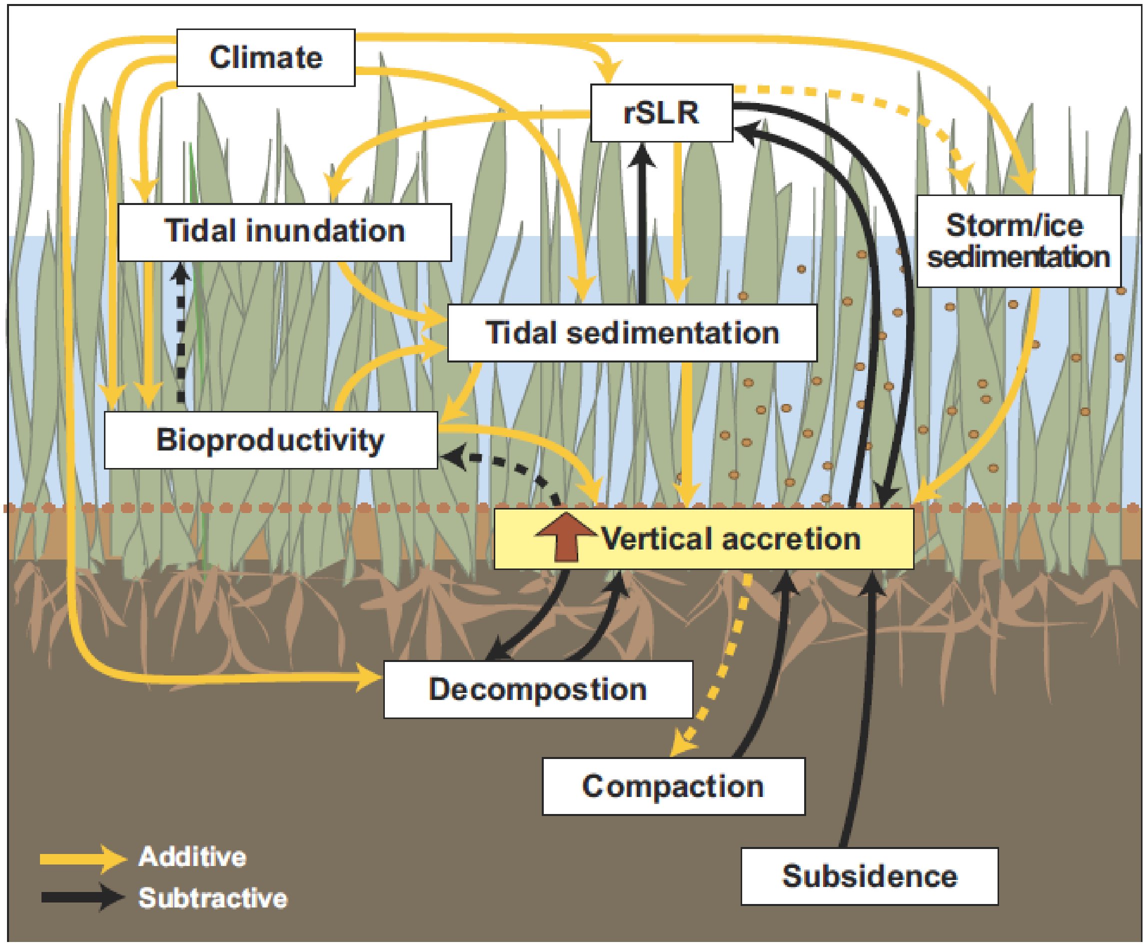
Carbon burial rate (gC m-2 yr-1)
Tropical forests
Boreal forests
Temperate forests
Salt marshes
Mangroves
Seagrasses


Climate
rSLR
Tidal inundation
Storm/ice sedimentation
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Bioproductivity
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Decompostion
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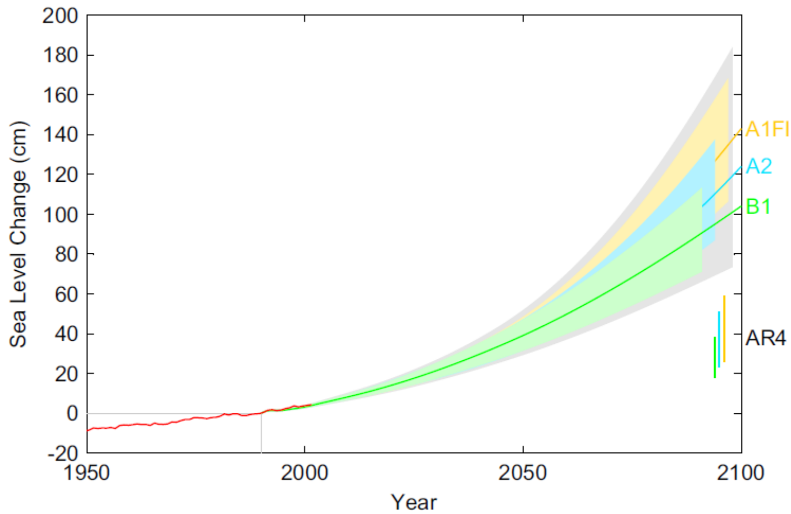

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Sea Level Change (cm)
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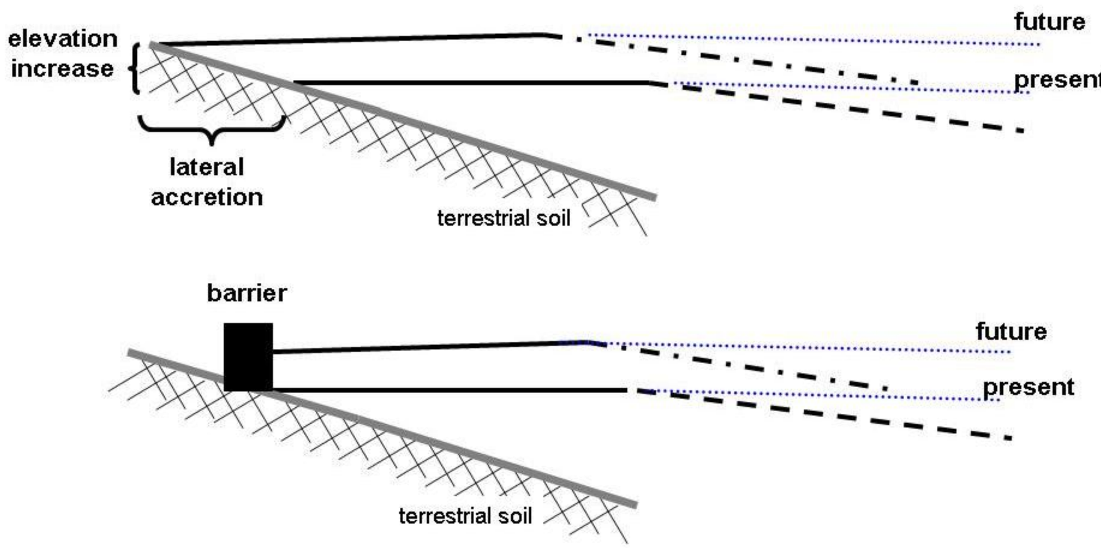
AR4



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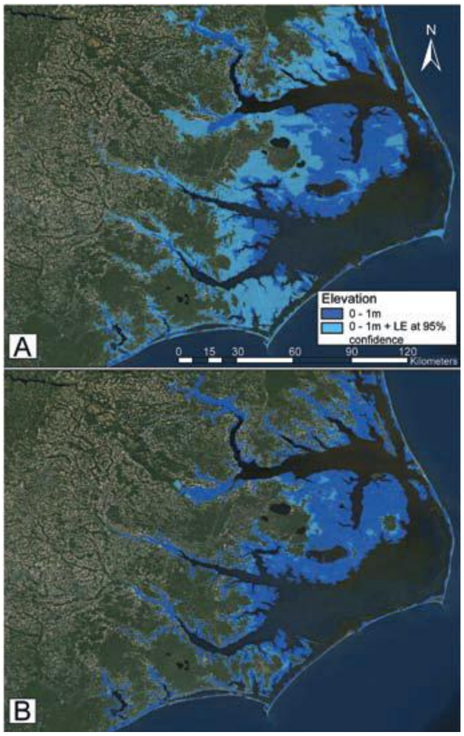
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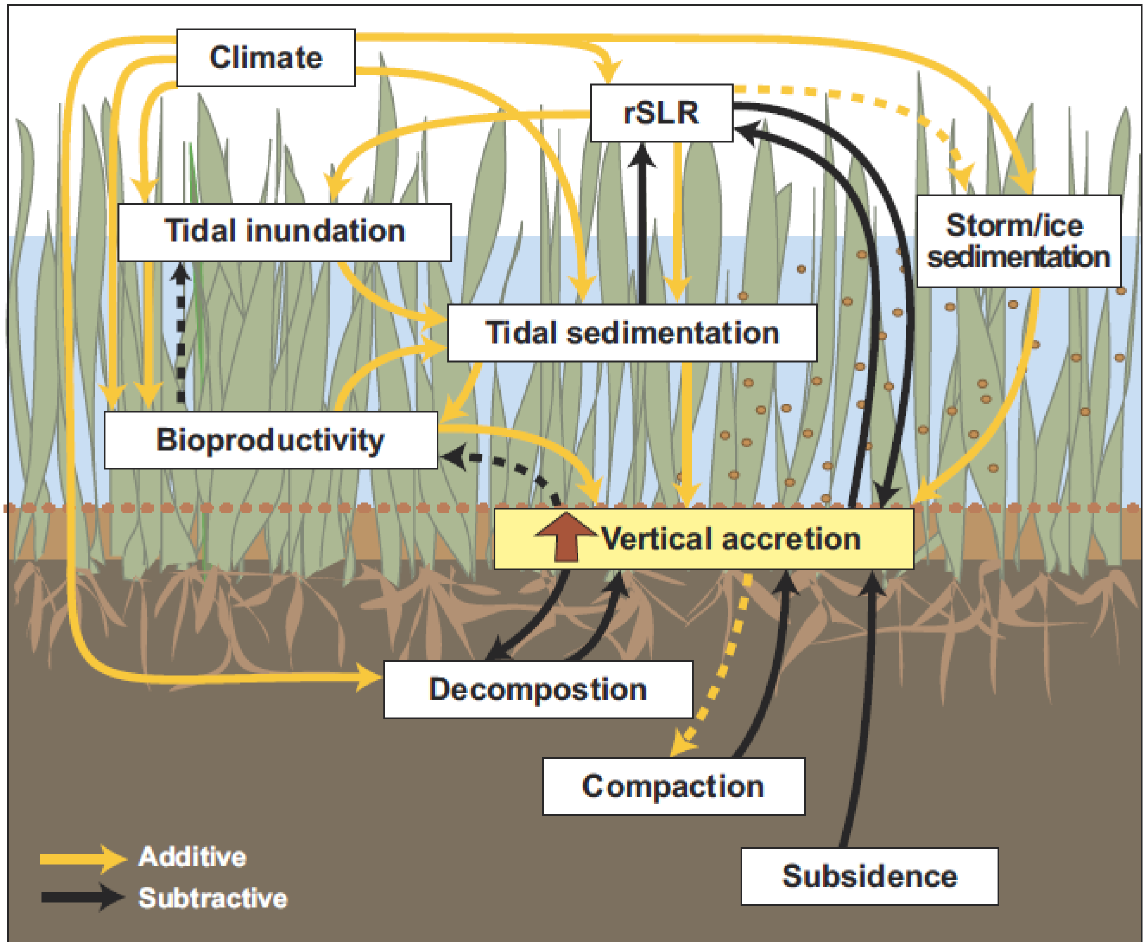
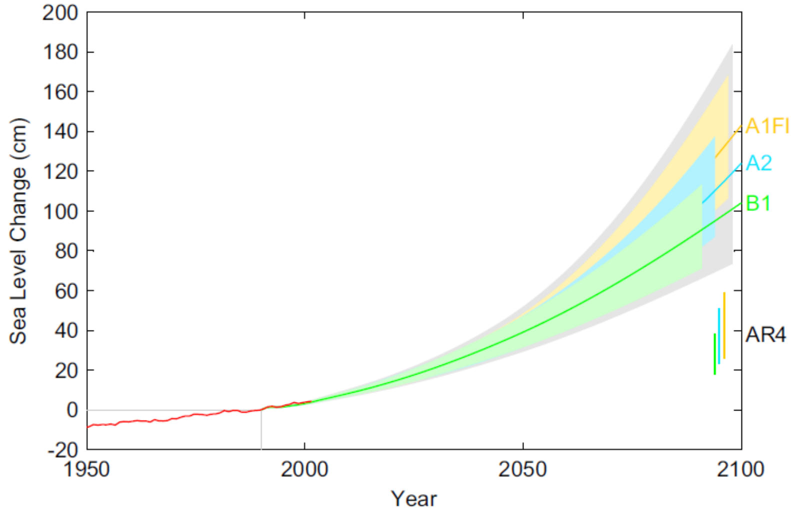
0 - 1m + LE at 95% confidence
A
0 15 30 60 90 120 Kilometers
B

Figure 2



Climate
rSLR
Tidal inundation
Storm/ice sedimentation
Tidal sedimentation
Bioproductivity
Vertical accretion
Decompostion
Compaction
Subsidence
Additive
Subtractive

Figure 3



Sea Level Change (cm)
200
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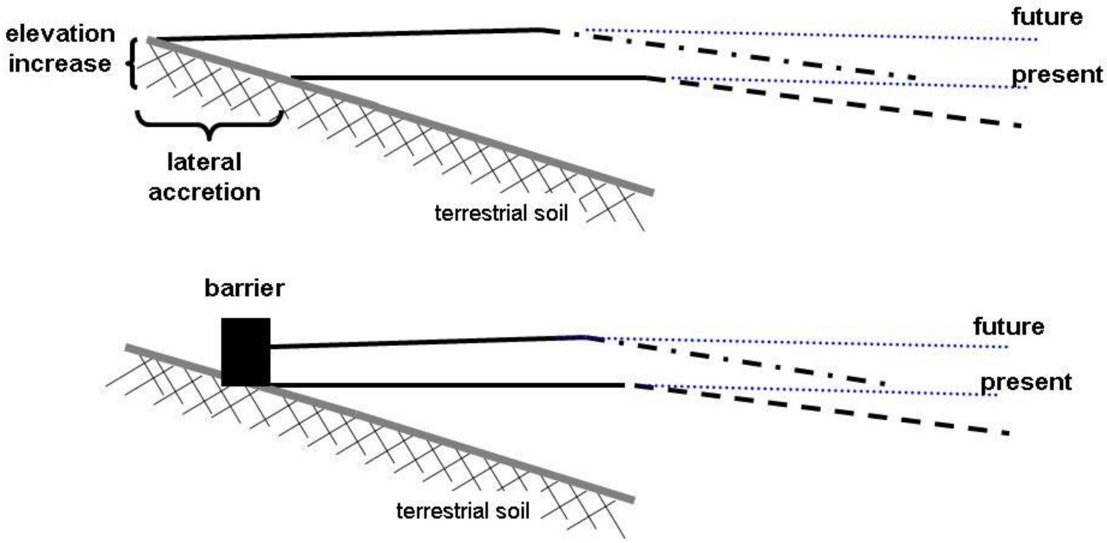
Figure 2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terrestrial soil
future
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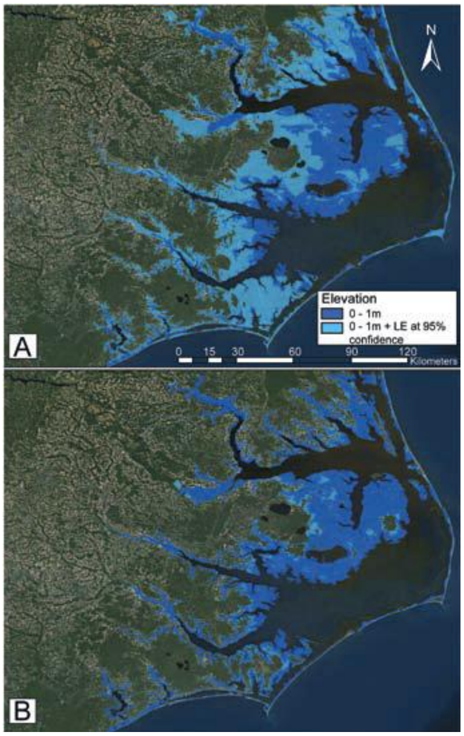
future
present
terrestrial soil

Figure 5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Elevation
0 - 1m
0 - 1m + LE at 95% confidence
A
0
15
30
60
90
120
Kilometers
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***4 Ethical Statement**

Dear Editors,

I am the sole author and affirm I the publication I submit presents no conflict of interest including any financial, personal or other relationships with other people or organizations within three years of beginning the submitted work that could inappropriately influence, or be perceived to influence, their work.

Cheers,

Gail Chmura