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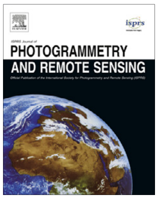

A remote sensing-based model of tidal marsh aboveground carbon stocks for the conterminous United States

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ABSTRACT

Remote sensing based maps of tidal marshes, both of their extents and carbon stocks, have the potential to play a key role in conducting greenhouse gas inventories and implementing climate mitigation policies. Our objective was to generate a single remote sensing model of tidal marsh aboveground biomass and carbon that represents nationally diverse tidal marshes within the conterminous United States (CONUS). We developed the first calibration-grade, national-scale dataset of aboveground tidal marsh biomass, species composition, and aboveground plant carbon content (%C) from six CONUS regions: Cape Cod, MA, Chesapeake Bay, MD, Everglades, FL, Mississippi Delta, LA, San Francisco Bay, CA, and Puget Sound, WA. Using the random forest machine learning algorithm, we tested whether imagery from multiple sensors, Sentinel-1 C-band synthetic aperture radar, Landsat, and the National Agriculture Imagery Program (NAIP), can improve model performance. The final model, driven by six Landsat vegetation indices and with the soil adjusted vegetation index as the most important ($n = 409$, $\mathrm{RMSE} = 310\ \mathrm{g/m^2}$, 10.3% normalized RMSE), successfully predicted biomass for a range of marsh plant functional types defined by height, leaf angle and growth form. Model results were improved by scaling field-measured biomass calibration data by NAIP-derived 30 m fraction green vegetation. With a mean plant carbon content of 44.1% ($n = 1384$, 95% C.I. = 43.99%–44.37%), we generated regional 30 m aboveground carbon density maps for estuarine and palustrine emergent tidal marshes as indicated by a modified NOAA Coastal Change Analysis Program map. We applied a multivariate delta method to calculate uncertainties in regional carbon densities and stocks that considered standard error in map area, mean biomass and mean %C. Louisiana palustrine emergent marshes had the highest C density (2.67 ± 0.004 Mg/ha) of all regions, while San Francisco Bay brackish/saline marshes had the highest C density of all estuarine emergent marshes (2.03 ± 0.004 Mg/ha). Estimated C stocks for predefined jurisdictional areas ranged from 1023 ± 39 Mg in the Nisqually National Wildlife Refuge in Washington to $507{,}761 \pm 14{,}822$ Mg in the Terrebonne and St. Mary Parishes in Louisiana. This modeling and data synthesis effort will allow for aboveground C stocks in tidal marshes to be included in the coastal wetland section of the U.S. National Greenhouse Gas Inventory. With the increased availability of free post-processed satellite data, we provide a tractable means of modeling tidal marsh aboveground biomass and carbon at the global extent as well.

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1. Introduction

The soils and vegetation of coastal wetlands, including tidal marshes, mangroves and seagrasses, represent significant long-term standing carbon (C) pools that cumulatively sequester atmospheric carbon at annual rates comparable to terrestrial forest types despite their small global coverage (McLeod et al., 2011).

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These C stocks and fluxes in intertidal environments are collectively referred to as “coastal wetland blue carbon” (Pendleton et al., 2012). In particular tidal marsh C stocks sequester carbon at rates of 1–2 Mg C per hectare per year on average (IPCC, 2014), though are being converted to open water or other land cover types at rates of 1–2% globally (Bridgham et al., 2006; Duarte et al., 2005). Conversion is primarily due to increasing coastal populations, agriculture and the effects of climate change, including sea-level rise and extreme weather events (Kirwan and Megonigal, 2013; Wylie et al., 2016). Collectively, these contribute to greenhouse gas (GHG) emissions of 21–760 million Mg CO_2eq per year (Howard et al., 2017).

Given their large C stocks and high carbon sequestration rates, as well as the potential for increased GHG emissions due to human conversion and degradation, coastal wetlands have in recent years received significant attention for their potential role in climate change mitigation (Duarte et al., 2013). Entities interested in utilizing “coastal wetland blue carbon” as a management asset include voluntary C markets such as the Verified Carbon Standard (VCS). Approved VCS coastal wetland restoration and conservation projects can now receive carbon credits for reduction of GHG emissions (American Carbon Registry, 2017; Verified Carbon Standard, 2015).

In 2017 the U.S. EPA for the first time included coastal wetlands in the Agriculture Forestry and Other Land Use (AFOLU) sector of the national GHG inventory (USEPA, 2017), based on guidelines in the Intergovernmental Panel on Climate Change (IPCC) 2013 Wetlands Supplement (IPCC, 2014). Because of human use and level of regulatory oversight, all coastal wetlands in the conterminous U.S. (CONUS) were considered as managed lands similar to AFOLU guidelines for U.S. forest and cropland accounting (USEPA, 2017). As a result monitoring annual change in GHG emissions and removals within all 2.7 million Ha of CONUS tidal wetlands is now a component of annual U.S. GHG inventories. While five C pools must be reported in the inventory (soils, above- and belowground biomass, dead wood and litter), the first coastal wetlands inventory only included C stock changes for soil carbon, the largest C pool for tidal marshes, due to insufficient data on biomass, dead wood and litter. Given emergent marsh represents 80% of all CONUS tidal wetlands (U.S. Fish and Wildlife Service, 2014), its biomass can play an important role in C accounting for the coastal lands sector.

To include tidal marsh biomass in the coastal wetlands GHG Inventory, particularly at a Tier 2 level, higher temporal and spatial resolution and more disaggregated data are needed (IPCC, 2003). Information on biomass C stocks will also help to verify emission reductions for projects included in the voluntary C markets (Howard et al., 2017). Remote sensing based maps of tidal marshes, both of their extents and C stocks, can play a key role in meeting these objectives (Gonzalez et al., 2010). Remote sensing data provide a repeatable, standardized approach to assess spatial and temporal changes in biomass over large areas, fulfilling an essential component of GHG Inventories and required monitoring of carbon mitigation activities (Pettorelli et al., 2014).

In the United States the primary spatial dataset being used for tidal marsh GHG inventories is the National Oceanic and Atmospheric Administration (NOAA) Coastal Change Analysis Program (C-CAP) dataset (NOAA Office for Coastal Management, 2015), which was produced for CONUS in four to five year increments (1996, 2001, 2006, and 2010). C-CAP provides wall-to-wall Landsat-based 30-meter resolution maps of coastal lands with wetland classifications for key coastal wetland classes that include forested, scrub-shrub and emergent marsh, subdivided into palustrine (freshwater wetland with salinity less than 0.5%) and estuarine (brackish and saline wetland with salinity equal to or greater than 0.5%). Extraction of additional information on vegetation condition from the Landsat data used to derive the C-CAP maps has the potential to further characterize wetland carbon stocks.

Technical barriers to national scale remote sensing have become greatly reduced in recent years with the availability of free, post-processed satellite and aerial imagery with national to global coverage. The entire catalog of Landsat satellite images is now available georeferenced and calibrated as a surface reflectance product (Vermote et al., 2016) that can be used for biomass estimation in otherwise data scarce regions (Dube and Mutanga, 2015). Sentinel-1A and Sentinel-1B provide global, free C-band quad-pol synthetic aperture radar data approximately every 6 days. The U. S. National Agriculture Imagery Program (NAIP) offers 4-band aerial image data of the U.S. at 1 m resolution approximately every two to three years since 2003 (USDA Farm Service Agency, 2017). These datasets, along with other geophysical, climate and demographic data, are now accessible within Google Earth Engine’s (GEE) platform. The GEE platform consists of a petabyte catalog of satellite imagery and geospatial datasets and a massively parallel, distributed runtime engine (Google Earth Engine Team, 2017). This combination of parallel processing and rich data archive is enabling the production of global products, such as global forest cover change maps and global surface water inundation maps (Hansen et al., 2013; Pekel et al., 2016).

Optical remote sensing of tidal marsh biomass has been performed in multiple regions, including the U.S. Southeast (Schalles et al., 2013), the Gulf of Mexico (Ghosh et al., 2016; Mishra et al., 2012), Argentina (Gonzalez Trilla et al., 2013), the U.S. Pacific Coast (Byrd et al., 2014, 2016) and South Africa (Mutanga et al., 2012) where remote sensing model error is typically below 20%. The application of radar data for tidal marsh biomass mapping has not been well tested, though it can indicate marsh dieback from hurricanes and recovery (Ramsey et al., 2014). Despite these multiple efforts, mapping is conducted using empirical models and the general assumption is that due to differences in marsh ecosystems including plant community composition, water depth and soil types, models are calibrated to specific locations and years, thus posing limitations for scaling (Lobell et al., 2015).

Tidal marsh vegetation is primarily dominated by graminoids, or grass or grass-like plants, including grasses (Poaceae), sedges (Cyperaceae), rushes (Juncaceae), and arrow-grasses (Juncaginaceae). Common genera from these families appear throughout U.S. tidal marshes, though these may vary in dominance, distribution and spatial pattern. In the U.S. Northeast and mid-Atlantic marshes, the perennial, deciduous shrub *Iva frutescens* (high-tide bush or marsh elder) can also occur. Tidal freshwater marshes are more species-rich than saline marshes though commonly include *Schoenoplectus* spp. (bulrushes), *Typha* spp. (cattail), *Polygonum* spp. (smartweed), and non-natives like *Phragmites australis australis* (common reed) (Vasquez et al., 2005).

One reason why empirical remote sensing models of biophysical features like biomass are not transferrable to other regions is that the differences in canopy architecture or leaf traits from one plant community to the other have different optical properties, and so generate different relationships with vegetation indices for the same level of biomass (Glenn et al., 2008; Nagler et al., 2004). For example the vertical stem morphology of many tidal marsh rushes, sedges or grasses increases light scattering and absorption in spaces between vegetation, leading to lower overall canopy reflectance (Mutanga and Skidmore, 2004; Ollinger, 2011). In contrast, the horizontal leaf angle of grass species like *Distichlis spicata* support strong relationships between biomass and vegetation indices like NDVI (Langley and Megonigal, 2012).

Given differences in leaf morphology and plant growth form among emergent marsh species, our primary objective was to generate a single remote sensing model of tidal marsh aboveground biomass and carbon that represents nationally diverse saline, brackish and freshwater marshes. In order to successfully fulfill this, we developed the first national-scale dataset of aboveground

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