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The role of economic, policy, and ecological factors in estimating the value of carbon stocks in Everglades mangrove forests, South Florida, USA

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ABSTRACT

Old growth mangroves in existing protected areas store more carbon than restored forests or plantations. Carbon storage in such forests has economic value independent of additionality, offering opportunities for policy makers to ensure their maintenance, and inclusion in climate change mitigation strategies. Mangrove forests of the Everglades National Park (ENP), South Florida, though protected, face external stressors such as hydrological alterations because of flooding control structures and agriculture impacts and saltwater intrusion as a result of increasing sea level rise. Moreover, decreased funding of Everglades' restoration activities following the recent economic crisis (beginning 2008) threatens the restoration of the Greater Everglades including mangrove dominated coastal regions. We evaluate several economic and ecological challenges confronting the economic valuation of total (vegetation plus soil) organic carbon (TOC) storage in the ENP mangroves. Estimated TOC storage for this forested wetland ranges from 70 to 537 Mg C/ha and is higher than values reported for tropical, boreal, and temperate forests. We calculate the average abatement cost of C specific for ENP mangroves to value the TOC from \$2–\$3.4 billion; estimated unit area values are \$13,859/ha–\$23,728/ha. The valuation of the stored/legacy carbon is based on the: 1) ecogeomorphic attributes, 2) regional socio-economic milieu, and 3) status of the ENP mangroves as a protected area. The assessment of C storage estimates and its economic value can change public perception about how this regulating ecosystem service of ENP mangrove wetlands (144,447 ha) supports human well-being and numerous economic activities. This perception, in turn, can contribute to future policy changes such that the ENP mangroves, the largest mangrove area in the continental USA, can be included as a potential alternative in climate change mitigation strategies.

1. Introduction

Mangrove wetlands provide a wide array of ecosystem services that benefit society including coastal protection, wood for fuel, water quality improvement, and support of fisheries (Nagelkerken et al., 2008; Alongi, 2011; Barbier et al., 2011). Furthermore, mangrove forests have the potential to store carbon in above and belowground biomass and in the soil (Kauffman et al., 2011). Previous studies (Donato et al., 2012; Alongi et al., 2015) indicate that the mean carbon storage in mangrove forests located in the Indo-Pacific region (i.e., 1023 Mg/ha) could exceed the mean carbon storage attributed to tropical upland, temperate, and boreal forests (200–400 Mg/ha) (Pan et al., 2011).

Carbon storage (i.e., the stock of carbon stored in plant biomass and soil) and sequestration (i.e., the rate of removal of atmospheric carbon per unit of time by plants and soils) (Chapin et al., 2006) are recognized ecosystem services that contribute to climate change mitigation (Alongi, 2012; Caldeira, 2012; Siikamäki et al., 2012). Deforestation and land-use change account for 8–20% of the total global anthropogenic CO_2 emissions (IPCC, 2007) including the loss of a third of the global mangrove area over the last 50 years (Valiela et al., 2001). Despite occupying only 0.7% of tropical forest area,

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mangrove deforestation contributes 10% (0.02–0.12 Pg per year) of the global CO_2 emissions from deforestation (Donato et al., 2011; Siikamäki et al., 2012).

One of the mangrove forests least affected by direct deforestation in subtropical latitudes is the Everglades Mangrove Ecotone Region (EMER) in southern Florida, USA (Rivera-Monroy et al., 2011a). Despite being located in a protected area, the EMER is exposed to several external stressors (e.g., hurricanes, freshwater diversion). Hydrological changes in the past 100 years have altered drainage patterns and reduced fresh water flows into Everglades estuaries by more than 50% (Smith et al., 1989), affecting nutrient and salinity gradients regulating mangrove structure and productivity (Castañeda-Moya et al., 2013). Although relative sea level has increased by approximately 0.3 m over the last century in South Florida (Ross et al., 2009; Zhang et al., 2012), it is seawater intrusion into the main regional aquifer along the Everglades coastline that has altered the spatial distribution and diversity of plant communities, including mangrove forests (Saha et al., 2012).

The Everglades is undergoing a large spatial-scale restoration as part of the Comprehensive Everglades Restoration Plan (CERP) which is expected to increase the quantity, quality, and timing of fresh water throughout the mangrove ecotone, thus potentially altering its productivity and spatial distribution (Rivera-Monroy et al., 2011b; Sklar et al., 2001). CERP is also expected to enhance other significant ecological and economic benefits arising from a range of ecosystem services such as groundwater purification, real estate, park visitation, open space and fishing (McCormick et al., 2010). Yet, the recent economic downturn (beginning in 2008) along with policy changes has led to a significant decrease in funding to continue restoration activities as initially planned (Sklar et al., 2005), threatening the restoration of the Everglades including the EMER. Assessing the quantity and economic value of the legacy C stored in the EMER, which has not yet been investigated, can (a) send a strong signal to concerned policy makers of the importance of long-term allocation of CERP funds for ENP preservation, (b) establish a baseline for future comparisons to evaluate restoration goals, and (c) present opportunities for U.S.A. to include the value of the C stored in ENP mangroves in long-term climate change mitigation strategies, thus fulfilling its commitment to the 2015 Paris Agreement under the United Nations Framework Convention for Climate Change. Carbon storage in protected areas has an economic value independent of additionality (Zarate-Barerra and Maldonado, 2015), offering opportunities for policy makers to ensure their maintenance, and inclusion in climate change mitigation strategies. Strengthening of these stocks within existing protected areas, especially in old growth forests such as the ENP mangroves, can be an important part of a country's strategy to combat climate change (Campbell et al., 2008; Alongi, 2011).

Valuation of ecosystem carbon storage faces several challenges. First, there exists a large uncertainty regarding accurate estimations of C storage, particularly in coastal wetlands because of the dynamic nature of C cycling in coastal environments where hydrological conditions regulate the exchange of organic and inorganic carbon between land and adjacent coastal waters (Bouillon et al., 2008; Hopkinson et al., 2012; Rivera-Monroy et al., 2013). Further, these areas are increasingly threatened by human impacts since 10 per cent of the world's population and 13 per cent of the world's urban population live in the coastal zone (McGranahan et al., 2007; Hopkinson et al., 2012). The variability and uncertainty in mangrove primary production and C accumulation through space and time greatly influence the economic valuation of carbon storage (Alongi, 2011). Indeed, C storage in wetland ecosystems, including mangrove forests, could vary between short (month, years) and long (decadal, centennial) temporal scales. This temporal variability is reflected in the role of mangroves as C sinks or sources as a result of dynamic changes in net carbon fluxes that are influenced by the geomorphic setting interacting with latitudinal temperature and precipitation gradients (Barr et al., 2010, 2012, 2013; Fuentes and Barr, 2015; Ho et al., 2014; Maher et al., 2013; Troxler et al., 2015; Rovai et al., 2016). Although the number of studies assessing net C fluxes in mangrove wetlands is limited (e.g., Maher et al., 2013), some studies indicate that mangrove forests could become a net C sink on decadal and centennial timescales if not significantly affected by deforestation or major changes in land use (Alongi, 2011; Kauffman et al., 2014; Ezcurra et al., 2016). In the case of the ENP, its protected nature (i.e., National Park) has the potential to lock the stored organic C longer into the biological pool, in contrast to carbon in an ecosystem that is under direct and compounding human threats.

Second, the economic valuation of C varies with valuation methodologies (Hessen et al., 2004; Stockmann et al., 2013), not all of which are suitable for valuing the carbon in a particular ecosystem. Carbon prices, too, are influenced by several technological, regulatory, economic and social factors, and vary across countries and markets. As C sequestration rate for EMER is not currently available and is uncertain (Troxler et al., 2013; Rivera-Monroy et al., 2013), our goal is to value the legacy carbon stored in the ENP mangrove biomass and soil. We therefore investigated different C valuation methodologies to appropriately value the C storage in the Everglades mangroves. Moreover, global estimates of mangrove C storage or estimates derived from tropical mangroves cannot be directly transferred to the Everglades region because of its distinct geographical location, ecogeomorphic characteristics, and the nature of the presses (i.e., sea level rise) and pulses (e.g., hurricanes) influencing the functional properties of mangroves in the Everglades (Collins et al., 2011; Castañeda-Moya et al., 2010).

While recognizing the above challenges, the purpose of our study is to conduct a first economic valuation of total (vegetation plus soil) organic carbon (TOC) storage in the mangrove forests of the Everglades National Park (ENP). To achieve this goal, we first estimated the physical quantity of stored TOC, and then performed an economic valuation of this ecosystem service. Although a number of mangrove carbon stock assessments are now available for neotropical regions (e.g., Kauffman et al., 2014; Hamilton and Lovette, 2015), there is a lack of information establishing the physical and economic baseline of C values to strengthen emerging carbon mitigation initiatives, particularly given the wide difference in the degree of carbon storage magnitude (above and belowground) provided by different mangrove ecotypes (Ewel et al., 1998; Twilley and Rivera-Monroy, 2009; Rovai et al., 2016). We expect the economic value of the stored organic carbon in mangroves per unit area to be significantly higher than other types of forests. Presently, despite the fact that the Everglades has the largest area of mangroves in the continental USA (1445 km^2) (Simard et al., 2006), there are no regional estimates of the TOC (aboveground, belowground, and soil carbon) stored and its associated economic value (Rivera-Monroy et al., 2013; Troxler et al., 2013). We expect that the estimate of TOC in the Everglades mangroves and its economic valuation will encourage similar quantifications in other mangrove wetlands.

As a protected area, some of the major threats to the ENP and its ecosystem services come from external stressors located outside the park boundaries (e.g., change in the hydrological regimes upstream; Sklar et al., 2005). Managing such external factors is often a complex process and requires a large scale regional assessment study. For instance, as Friess et al. (2015) note, designing a Payment for Environmental Services (PES) mechanism to handle external factors needs to carefully consider a series of complex steps—from the evaluation of onsite large-scale impacts of stressors to willingness on the part of external stakeholders to