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Review

Carbon offset market methodologies applicable for coastal wetland restoration and conservation in the United States: A review

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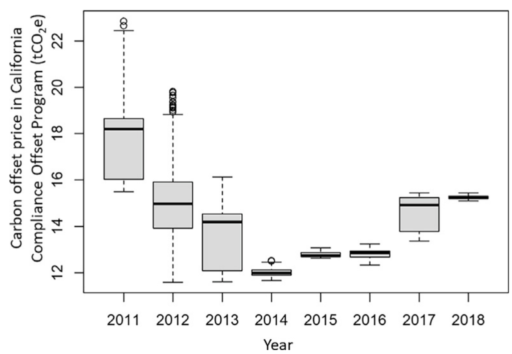
HIGHLIGHTS

- The carbon market is growing.
- Four carbon offset methodologies have been approved for wetland restoration.
- Very few wetland restoration carbon offsets transected to date.
- Simplification of existing methodologies may facilitate adoption of blue C offsets.

GRAPHICAL ABSTRACT



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ABSTRACT

Coastal wetlands have been valued for a variety of ecosystem services including carbon sequestration and long term storage. The carbon sequestered and stored in coastal habitat including mangroves, salt marshes, and seagrass beds is termed as blue carbon. However, these systems are threatened mainly due to sea level rise, limited sediment supply, edge erosion, and anthropogenic influences. These habitats require restoration and conservation to continue providing ecosystem services. The incentive for emission reductions, referred to as carbon offsets, is well established for other ecosystems like forestry and agriculture. Some blue carbon offset methodologies or protocols have been certified by various voluntary carbon markets; however to date, a few wetland restoration carbon offset in the US has been transacted. Thus, the goal of this paper is to discuss the existing carbon market and carbon market methodologies applicable to coastal wetland restoration and conservation in the US. Currently, four wetland carbon offset methodologies have been approved in the carbon market. These methodologies are site and/or project-specific depending on the type of the wetlands, vulnerability to loss, and restoration need. The appropriate carbon stock and Green House Gas (GHG) emission assessment is the basis of determining carbon offsets. Simplification of the existing methodologies and development of new site and project-specific methodologies could potentially help to realize blue carbon offsets in practice. The slowly growing demand for carbon offsets in the carbon market could potentially be fulfilled from the blue carbon pool. While this carbon offset is in the early stages, this review may help the inclusion of carbon offset component in the coastal restoration and conservation projects in United States and potentially across the globe.

Abbreviations: CO_2, Carbon dioxide; tCO_2e, Ton carbon dioxide equivalent; C, Carbon; GHG, Green House Gas; ACR, American Carbon Registry; CAR, Climate Action Reserve; VCS, Verified Carbon Standard (now referred as Verra); ARB, Air Resources Board of California; CPRA, Coastal Protection and Restoration Authority of Louisiana; USGS, United States Geological Survey; SOC, Soil Organic Carbon.

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Contents

1. Introduction

The dramatic increase in the atmospheric concentration of greenhouse gases (GHGs) is a serious concern worldwide due to the potential imbalance on the earth system. Globally, several efforts are underway to address excess carbon emissions, however, the increased anthropogenic influence due to the rising global population and growing demand for energy and food are continuing to drive carbon dioxide emissions up worldwide. Emission reduction can be addressed for specific industries or even entire countries where one can either install emission reduction technologies themselves or purchase carbon offsets in the market place. The emission reduction technology might be more costly than paying for cheaper emission credits available in the global market (Van der Gaast and Spijker, 2013). Thus, providing a financial incentive became more globally accepted in the mid-1990s as a carbon market, where credit is earned through payment for emission reduction strategies (Van der Gaast and Spijker, 2013).

The carbon offset, measured in ton carbon dioxide equivalent (tCO_2e), is defined as the amount of emission reduction of carbon dioxide and carbon dioxide equivalent of other GHGs and/or sequester additional carbon to compensate for an emission made elsewhere (Lane et al., 2016; Murray et al., 2011). The carbon offset is measurable, quantifiable and trackable units of GHG emissions reductions (Hamrick and Gallant, 2018). Currently, it may be less expensive and sustainable to utilize the earth's ecosystems to sequester carbon from the atmosphere rather than the use on artificial carbon sequestration plant or installation of GHG emission reduction technologies for industries. The credit for the restoration, management, and non-exploitation of the ecosystem has been established in several sectors including forestry, agriculture, and wetland restoration/conservation.

1.1. Carbon market

Currently, two types of markets are in existence for carbon trading; the compliance market and the voluntary market. Compliance market deals with the mandatory emission reductions imposed by regulations and is driven by the demand for allowances and offsets from regulated GHG emitters (Mack et al., 2015). The European Union and other developed countries like Canada and South Korea have Emission Trading System (ETS) under the 'cap and trade' principle (World Bank, 2019). Some US states have imposed regulations, either statewide or through the regional initiatives, to reduce GHG emissions (Fig. 1). California has a compliance offset program for approved carbon credit projects. The Air Resources Board of California (ARB) has approved carbon offset protocols for six types of projects: forest, urban forest, livestock, mine methane, ozone-depleting substances and rice cultivation (CAR, 2019). Two compliance instruments are issued by ARB- California Carbon Allowances (CCA) for GHG emitters and California Carbon Offsets (CCO) for the qualified carbon offset projects throughout the contiguous United States (Mack et al., 2015). The market price of carbon offset (tCO_2e) in California decreased from 2011 to 2014 and is gradually increasing with the current price of $15.25 in early 2019 (Fig. 2). The other compliance regulations in the US include the Oregon carbon dioxide standard (Oregon and Washington) for new power plants and the Regional Greenhouse Gas Initiative comprising of nine U.S. Northeast states (Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New York, Rhode Island, and Vermont) (Fig. 1) (Ecosystem Marketplace, 2019).

Voluntary markets were developed to credit actions in reducing GHG emissions (Van der Gaast and Spijker, 2013; Van der Gaast et al., 2018), primarily by private sector companies, to reduce a company's environmental footprint, demonstrate corporate social responsibility and enhance public relations (Mack et al., 2015). The Verra (formerly Verified Carbon Standard; VCS), American Carbon Registry (ACR), Climate Action Reserve (CAR), Gold Standard and Plan Vivo are the major voluntary organizations that approve carbon offset methodologies, certify GHG reduction projects and register carbon offsets globally (van der Gaast et al., 2018). In addition, ACR, CAR, and Verra are approved by California ARB as an Offset Program Registry (OPR) for the California Cap-and-Trade Program. The offset demand in the voluntary market is variable, uncertain, and depends on the buyer's perception and how closely

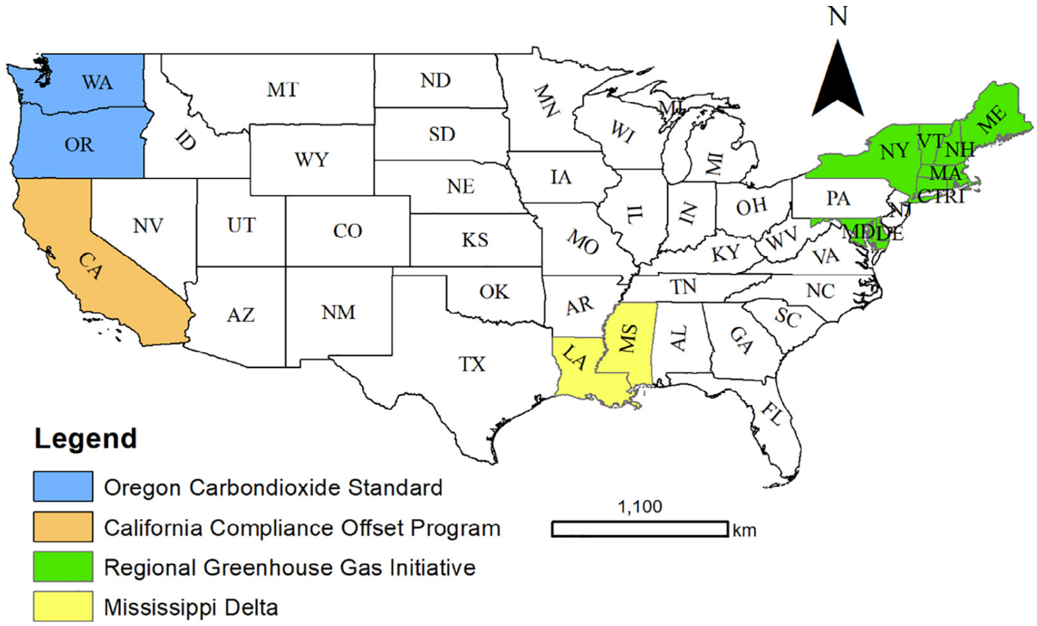

Fig. 1. Distribution of three carbon offset compliance market system (Oregon, California and RGGI) in United States. California has also carbon offset methodology developed for coastal wetland restoration. Mississippi delta is known for the development of two of four coastal wetland restoration methodologies.

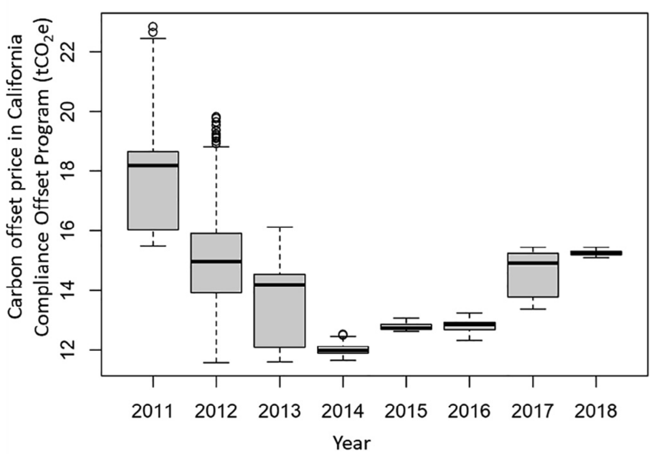

Fig. 2. Box plot of carbon offset price in California Compliance Offset program from 2011 to 2018. The offset price decreased until 2014 and is continuously increasing thereafter. (Data retrieved from http://calcarbondash.org/ on 13 January 2019).

the carbon project aligns with corporate goals and communications (Mack et al., 2015). In 2016, the global carbon offset price ranged from almost \$0.50 to \$50 per tCO_2e (only a small proportion above \$12) with a global average of \$3 per tCO_2e. The global average price of credit from the forest and land-use sector was \$5.1 per tCO_2e (Hamrick and Gallant, 2017). In early 2018, the global average price of the offset fell to \$2.4 per tCO_2e (Hamrick and Gallant, 2018). The offset price in voluntary market is low and highly variable, however offset issuance and retirement (offset that can't be resold) are continuously increasing globally with a record value of 62.7 tCO_2e and 42.8 tCO_2e respectively in 2017 (Hamrick and Gallant, 2018). The offset price in the voluntary market is mainly determined by demand and supply. In some cases, the price is also determined by the willingness of the buyer to pay a higher price in order to promote carbon market for environmental sustainability.

In addition, the emerging concept of adding aviation CO_2 emissions, Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), into carbon market may help to widen the carbon market increasing demand of voluntary carbon offsets. There is a need for new offset projects to fulfill the growing demand of voluntary carbon markets. The coastal restoration projects may yield benefits from growing carbon market.

1.2. Forest carbon offset

The carbon offset for the forestry sector is well established and is traded under both compliance and voluntary carbon markets (Vacchiano et al., 2018). Forests absorb about 12% of annual carbon emissions globally (net sink: 1.1 ± 0.8 Pg C year^{-1}) and are increasing. The carbon sink in the US forest was increased by 33% from the 1990s to 2010 (Pan et al., 2011). Deforestation accounts for 17% of anthropogenic carbon emissions. The credit for preventing deforestation, Reduced Emissions from Deforestation and Forest Degradation (REED+), are currently being transacted under forestry methodologies (Bosello et al., 2015). Thus, forest-based carbon sequestration is a well-recognized cost-effective means to offset anthropogenic carbon emissions, mitigate global climate change and provide monetary incentives to the forest landowners (Soto et al., 2016; Miller et al., 2012). Forest landowners have been willing to participate in the carbon offset program depending on revenue (Kelly et al., 2017; Soto et al., 2016; Miller et al., 2012). Reforesting agricultural land could increase carbon sequestration; however, farmers are interested in forest conservation only if the land has limited productivity or if they are motivated by social reward rather than economic rewards (Nelson and Matzek, 2016).

In addition to the forestry sector, the methodologies (eg. biochar) for generating carbon offset from a byproduct of forest and waste have been approved. The carbon sequestered in biomass (forest or through waste diversion) can be converted to biochar through pyrolysis, which prevents decomposition and stores carbon from hundreds to thousands of years. Application of biochar in soil reduces nitrous gas emissions and also reduces the need for chemical fertilizer application in farming (Van der Gaast and Spijker, 2013). Likewise, Farmers are adopting carbon farming techniques, including no-till, agroforestry, methane-reducing feed supplements or plant stubble retention, that increase the carbon sink of the soil (Das and Avasthe, 2015), thus helping to support the livelihood of people in the developing world through the carbon offset program (Lee et al., 2016). The carbon offset program on forestry and agriculture in developing countries have been implemented mainly under Clean Development Mechanism (CDM) of Kyoto Protocol (UNFCCC, 2018). The CO_2 emission and offset generation can occur anywhere in the world making the carbon market global.

1.3. Blue carbon offset

Salt marshes, mangroves, and seagrass meadows are the major coastal wetland and aquatic habitats that provide various ecosystem services including carbon sequestration and storage of this "blue" carbon (Mcleod et al., 2011; Murray et al., 2011; Lovelock et al., 2017) with an area approximately 50–80 million hectares (Murray et al., 2011). Though the global area of the coastal habitat is smaller than terrestrial forest, the per unit area contribution to carbon sequestration and storage is much higher (Mcleod et al., 2011). These systems are a hot spot for carbon storage and show great potential for participation in carbon markets (Theuerkauf et al., 2015; Carr et al., 2018). The estimated global carbon burial rate (Table 1) is 6.3 ± 4.8 t CO_2 e ha^{-1} yr^{-1} (ton of CO_2 equivalent ha^{-1} y^{-1}) for mangroves, 8.0 ± 8.5 t CO_2 e ha^{-1} y^{-1} for salt marshes, and 4.4 ± 0.95 t CO_2 e ha^{-1} y^{-1} for seagrass meadows (Murray et al., 2011) and the total carbon buried in these ecosystems is comparable to all terrestrial forest despite their small area (Mcleod et al., 2011). In the top one meter of sediment (Table 1), soil organic carbon is 500 t CO_2 e ha^{-1} for seagrasses, 917 t CO_2 e ha^{-1} for saltmarshes, 1060 t CO_2 e ha^{-1} for estuarine mangroves and almost 1800 t CO_2 e ha^{-1} for oceanic mangroves (Murray et al., 2011). Likewise, Hansen and Nestlerode (2014) reported that wetlands in the northern Gulf of Mexico coastal region (area in 2004 = 5,308,468 ha) potentially store 124–172 t CO_2 e ha^{-1} and could potentially accumulate 42.15 million t CO_2 e y^{-1} regionwide due to the low sloping coastline.

Despite their profound importance, coastal wetlands are threatened due to sea level rise, local subsidence, edge erosion, hurricanes and human development (Theuerkauf et al., 2015; DeLaune and White, 2012). In addition, the high costs of wetland restoration, increasing incentives for landowners to convert wetlands to other uses, inability or unwillingness of governments to enforce environmental regulations (Murray et al., 2011), anthropogenic activities in coastal areas, and natural disasters are major causes leading to decline of coastal habitats. Almost one-third of coastal ecosystems have been lost globally over the past several decades (Pendleton et al., 2012; Wylie et al., 2016). The estimated annual loss of the global coastal habitats is between 340,000 to 980,000 ha (Murray et al., 2011). Out of 1.6 million ha of salt and brackish marshes in the United States, almost 13,450 ha were lost between 1998 and 2004, mostly converted into open water in coastal Louisiana (Dahl, 2006). The wetland loss rate in Delaware Estuary is 1.03 km^2 y^{-1} (Carr et al., 2018). However, in Louisiana, the wetland loss rate is almost 48 km^2 y^{-1} which converted almost 25% (4833 km^2) of the total coastal wetland area into open water from 1932 to 2016 (Couvillion et al., 2017).

Table 1
Carbon burial rate and carbon stored in the top 1 m soil in coastal habitats across the globe (Murray et al., 2011).

Coastal habitats	Global carbon burial rate (t CO_2 e ha^{-1} yr^{-1})	Carbon stored in top 1 m soil (t CO_2 e ha^{-1})
Mangroves	6.3 ± 4.8	1430
Salt marshes	8.0 ± 8.5	917
Sea grasses	4.4 ± 0.95	500

There are two main impacts to the loss of these coastal wetlands on the C cycle. The lost wetland area is no longer available for the annual C sequestration rate accreted into the soil. In addition, eroded wetland systems can lose the stock of the wetland soil C previously preserved over the past 100 to 1000 years (Sapkota and White, 2019; Parkinson et al., 1994). This soil C can be physically exhumed, remineralized, and emitted as CO_2 back into the atmosphere (Delaune and White, 2012; Pendleton et al., 2012; Lovelock et al., 2017; Steinmuller et al., 2019; Steinmuller and Chambers, 2019). The annual global release of CO_2 from coastal ecosystems is 150–1020 million t CO_2 e y^{-1} (Pendleton et al., 2012). If the majority of the stored carbon is released, their contribution to GHG emissions from a hectare could be as high as the emissions from two to five hectares of destroyed tropical forest (Murray et al., 2011). Lane et al. (2016) in a study of wetland loss found that greater GHGs were emitted from the brackish and salt marshes treated with herbicide in comparison to reference plots demonstrating negative effects of anthropogenic activities on CO_2 emissions. However, these results were inconclusive in freshwater wetlands.

2. Carbon offset methodologies for wetland restoration and conservation

Coastal wetlands could be monetarily valued for their role in the global carbon cycle and mitigating atmospheric CO_2 concentration, thus generating an economic incentive for the conservation and restoration of coastal wetlands. The idea of a monetary incentive for blue carbon is analogous to the payment for REDD+ (Reduced Emissions from Deforestation and Degradation) which is a part of global climate policy that encompasses a reduction in deforestation (Murray et al., 2011). The carbon offset methodologies developed under CDM for the afforestation and reforestation (AR) of degraded mangrove habitats (AR-AM0014 V3, 2013) and AR project activities on wetlands (AR-AMS0003, V3, 2013) have been implemented in the participating countries of Kyoto Protocol and in the developing countries (UNFCCC, 2018). The Intergovernmental Panel on Climate Change (IPCC) has developed wetland specific guidelines for GHG inventorying (IPCC, 2014) that may be applicable for carbon stock and GHG emission assessment for a carbon offset project.

Beginning in 2012, several efforts have been made in United States to introduce wetland restoration to carbon markets. DeLaune and White (2012) presented the monetary annual value of carbon accreted in Louisiana coastal wetlands as well as the value of preserving the older, previously sequestered C. Four wetland carbon offset methodologies (Table 2), with different applicability rules for spatial coverage and restoration activities, have been developed and certified by various markets. Besides these specific methodologies, other methodologies (Table 3), e.g. forestry, can also be applicable to some types of wetlands and peatlands.

The blue carbon from mangrove forest plantings has been transected under AR methodologies in Asia, Africa, and South America by different voluntary organizations including Plan Vivo and Worldview International Foundation. However, despite the effort to introduce wetland restoration to carbon markets, only a few wetland restoration carbon offsets have been transacted to date. To our knowledge, the only project that has currently been registered and under development in the US is in the state of Louisiana. The project that is registered by Tierra Resources with the American Carbon Registry (ACR) as "Forested Wetland Assimilation in the Mississippi Delta" is still undergoing verification after 1.5 years. This project utilizes the ACR wetland methodology-"Restoration of degraded wetlands of Mississippi Delta". This project was implemented in 1439 ha of cypress-tupelo forested wet-

Table 2
Major coastal wetland carbon offset methodologies currently applicable for wetland restoration in United States.

Methodologies	Developer	Approver	Spatial coverage	Applicability	Structure	Baseline conditions	Restoration project activities
Restoration of Degraded Deltaic Wetlands of the Mississippi Delta v2.0 (Mack et al., 2012)	Tierra Resources LLC	ACR (2012)	Mississippi Delta	Degraded Forested and non-forested wetlands	Modular, Empirically based, flexible, Peer reviewed	Degraded wetlands (DW) only, DW with wetland loss (WL), DW requiring hydrologic management (HM) or DW with both HM and WL	Assisted natural regeneration, seeding, and planting of trees (like cypress and mangroves); Hydrologic management (river diversion into wetlands, the introduction of nonpoint source runoff, discharge of treated municipal effluent into wetlands or the combination these activities); and any other activities that prevent wetland loss.
VM0024 Methodology for Coastal Wetland Creation, v1.0 (CPRA, 2014)	Louisiana Coastal Protection and Restoration Authority	Verra (2014)	Louisiana, also applicable to other regions of the US	Wetlands that have been degraded to open water	Empirically based, flexible	Open water	Marsh creation: substrate establishment, vegetation establishment, or combination of both.
VM0033 Methodology for Tidal Wetland and Seagrass Restoration, v1.0 (Emmer et al., 2015a)	Restore America's Estuaries, Silvestrum	Verra (2015)	Worldwide application	Degraded tidal marshes, tidal forests and seagrass meadows	Empirically based, flexible	Degraded tidal wetlands, mudflats or shallow open water	Hydrologic management, altering sediment supply, altering salinity conditions, improving water quality, reintroducing native plant communities, improved management practices (eg removing invasive species) or a combination of any of these activities.
Restoration of California Deltaic and Coastal Wetlands (Deverel et al., 2017)	Sacramento–San Joaquin Delta Conservancy, HydroFocus, University of California Berkeley and Tierra Resources LLC	ACR (2017)	Sacramento-San Joaquin Delta, San Francisco Bay Estuary and coastal areas of California	Agricultural lands and degraded tidal wetlands	Modular, Empirically based, flexible, Peer reviewed	Agricultural land, seasonal wetlands or open water	Rice cultivation (in agricultural land and seasonal wetlands), Managed wetlands (in agricultural land and seasonal wetlands), or tidal wetlands (in all baseline conditions).

Table 3
Other carbon offset methodologies applicable to wetlands and peatlands.

S. No.	Methodologies	Developer	Approver	Applicability
1	VM0027 Methodology for Rewetting Drained Tropical Peatlands, v1.0	World Wildlife Fund-Germany	Verra (2014)	Drained tropical peatlands of Southeast Asia
2	REDD + Methodology Framework (REDD-MF), v1.5	Avoided Deforestation Partners (ADP)	Verra (2015)	Forested wetlands and peatlands worldwide
3	VM0036 Methodology for Rewetting Drained Temperate Peatlands v1.0	Silvestrum Climate Associates and University of Greifswald	Verra (2017)	Drained peatlands in temperate climatic regions worldwide
4	Methodology for the restoration of pocosin wetlands	The Nature Conservancy and TerraCarbon LLC	ACR (2017)	Drained peatlands of the coastal plains of Southeast Virginia, North Carolina, South Carolina, and Georgia in the US
5.	Afforestation and reforestation of degraded land V1.2	ACR	ACR (2017)	Forested wetlands and peatlands worldwide
6.	Forest project protocol V4.0	CAR	CAR (2017)	Forested wetlands of the US and US territories

land by supplying treated municipal effluent to increase tree growth since 2006. The evaluation of the project by Lane et al. (2017) found that additional carbon sequestration under the project scenario compared to baseline scenario was 0.21 tCO_2e ha^{-1} yr^{-1} by trees and 7.86 tCO_2e ha^{-1} yr^{-1} by soil. Likewise, the restoration project reduced emissions of 26.27 tCO_2e ha^{-1} yr^{-1} due to increased flooding. These results demonstrate that restoration projects can sequester a significant amount of additional carbon and reduce emissions.

Most of the wetland restoration methodologies have applicability that is specific to certain wetland types and their corresponding management techniques (Table 2). The focus of restoration activities can vary within the same region. The coastline of the United States is variable in terms of geology, geomorphology, hydrology, climate, relative sea level rise, and restoration needs impacting the net sequestration of a wetland system. Therefore, wetland carbon methodologies tend to be designed for specific regions and restoration activities. There is consistency in some aspects of coastlines along with some site-specific conditions. This fact is well supported by the major coastal wetland methodologies (Table 2) that include a range of wetland types, major problems, and restoration needs.

Methodologies approved by the American Carbon Registry (ACR) are modular and peer-reviewed (Table 2). These methodologies have separate modules for carbon stock and GHG emission assessment under different baseline and project scenarios. The ACR certification process requires a national public comment period followed by a blind peer-review. Verra certification process requires methodologies validated by two separate and independent validation/verification bodies (VVBs). The first VVB is contracted by the methodology developer while the second is contracted directly by Verra (VCS, 2017). The voluntary carbon registries, eg. Verra and ACR, have set standards under which the carbon offset methodologies and the projects are developed. The offset methodologies are developed on the specific templates provided by these carbon registries. Here we briefly discuss the major component of a typical wetland carbon offset methodology based primarily on the existing wetland methodologies approved by Verra and ACR:

2.1. Background and scope

This section typically includes the background information on the methodology including the definitions, spatial scope, and major restoration focus. Some methodologies (eg. CPRA, 2014; Emmer et al., 2015a,b) provide a brief summary of the entire methodology at the beginning. The methodologies approved by ACR (eg. Mack et al., 2012; Deverel et al., 2017) are modular with a methodology framework (MF) module and supporting individual modules. This section of the methodology generally mentions the spatial coverage, modular or non-modular, major baseline and project conditions and definitions.

2.2. Applicability conditions

This states the applicability criteria for the eligible project including eligible activities, wetlands, and locations. The wetland restoration project activities must comply with federal, state and local regulations and requirements, for example, the policies and legislation related to wetland restoration and the Clean Water Act. The drainage of the wetland is prohibited, and timber harvesting (from forested wetlands) is not allowed. Along with these common regulations, site-specific regulation might be applicable.

2.3. Project activities identification

This component depends on the scope of the methodology. If the scope of the methodology is broad, decision trees (Mack et al., 2012) might be used to identify project activities. If the methodology is developed for certain specific objectives, like marsh creation in the open water resulted from wetland loss (CPRA, 2014), it might be straightforward to identify project activities.

2.4. Project boundaries

Project boundaries include geographic and temporal boundaries, carbon pools, and wetland emission sources. The geographic boundaries are fixed using the United States Geological Survey (USGS) topographic map, aerial map, and geographic coordinates. ACR approved methodologies (Mack et al., 2012; Deverel et al., 2017) specify a crediting period of 40 years.

Defining the eligible carbon pools (Table 4) and wetland emission sources (Table 5) may help to prevent double-counting of carbon stock and GHG emission. In addition, specification of included and excluded carbon pools and emission sources could facilitate efficient carbon offset project development.

A division of the project area into groups or strata (stratification) based on the management regime, vegetation type, hydrology, subsidence rates, land use, and soil properties is helpful to increase the accuracy of measurement. Typically site-specific condition plays a decisive role in determining strata.

Table 4
Carbon Pools and their measurement methods in the different wetland methodologies.

Methodologies	Included carbon pools	Excluded carbon pools
Restoration of Degraded Deltaic Wetlands of the Mississippi Delta v2.0	Aboveground biomass carbon, belowground biomass carbon, and soil organic carbon	harvested wood, dead wood, and litter/surface debris
VM0024 Methodology for Coastal Wetland Creation	Aboveground tree biomass, soil organic carbon	Aboveground non-tree biomass (optional), belowground biomass (optional), litter, deadwood, and wood products
VM0033 Methodology for Tidal Wetland and Seagrass Restoration, v1.0	Above-ground tree biomass, above-ground non-tree biomass, below-ground biomass, soil, and wood products	Litter and dead woods
Restoration of California Deltaic and Coastal Wetlands	Aboveground biomass, belowground biomass, litter, and soil organic carbon. Included only in agricultural baseline: crop residue, harvested biomass	Any of the included pools could be excluded if double-counted.

2.5. Demonstration of additionality

The restoration project activity is an additional effort and generally reduce emission above the business as usual (baseline) condition. Generally, two tests are performed to demonstrate additionality in performance standard based methodologies. 1) Regulatory surplus test: the restoration projects eligible for carbon offset must not be mandated by existing laws, regulations, statutes, legal rulings or other regulatory frameworks and 2) Practice-based performance standard test to show the emission reduction above the business-as-usual situation (Mack et al., 2012; CPRA, 2014;

Table 5
GHG sources in baseline and project activities under different wetland methodologies.

Methodologies	GHG Sources
Restoration of Degraded Deltaic Wetlands of the Mississippi Delta v2.0	Decomposition, Methanogenesis and denitrification (included based on significance test)
VM0024 Methodology for Coastal Wetland Creation	Dredging, transport, and re-handling for maintenance (baseline) or dredging transport or placement (Project): CO_2, CH_4, and N_2O Methane ebullition (baseline): CH_4 Habitat Regeneration (project): CO_2, CH_4, and N_2O
VM0033 Methodology for Tidal Wetland and Seagrass Restoration, v1.	Methane produced by microbes, denitrification/denitrification, burning of biomass and organic soil and fossil fuel use (CO_2).
Restoration of California Deltaic and Coastal Wetlands	Production of methane by bacteria (excluded in baseline but included in project). N-transformation due to fertilizer application or organic matter decomposition (excluded in baseline but included for rice cultivation project). Oxidation of organic soil (included in both). Emissions from fossil fuel combustion (CO_2 required in the baseline, others might be excluded in both condition based on significance).

Emmer et al., 2015a,b; Deverel et al., 2017). Instead of a performance standard test, three-prong additionality test may be performed that includes regulatory surplus test, common practice test and implementation barrier test (ACR, 2018).

2.6. Baseline estimation

The baseline carbon stock and emissions are determined, based on the included carbon pools and emission sources (Tables 4 and 5), prior to the project start date. Generally, separate modules and tools are used for each baseline conditions. The Verra approved methodology for tidal wetland and seagrass restoration (Emmer et al., 2015a,b) have set some default values (discussed in a separate section below) to facilitate baseline and project estimation (Needelman et al., 2018a,b).

2.7. Restoration project estimation

Ex-ante estimation techniques are used to project carbon stock and emissions after the implementation of the project activities for the project term.

2.8. Net GHG emission reduction

This component is the difference between project and baseline.

2.9. Risk and uncertainty assessment

Since the restoration activities for carbon offset purposes are long-term investments and commitments, the risk of reversal is usually due to natural disasters or intentional reversals by landowners. The general and project-specific risk factor could be considered. The risk mitigation strategies like insurance, buffer deduction or approved risk mitigation mechanisms may be applied. The uncertainty exists in the measurement of the carbon stocks and GHG emission, which if it exceeds 5% of the total GHG benefit then it should be considered in the calculation of emission reduction (Needelman et al., 2018a).

2.10. Emission reduction tons (ERTs)

The number of emission reduction tons during the reporting period (t_i) is calculated by the difference of the emission reduction in two time periods (t_2 and t_1) and adjusted to deduct the risk and uncertainty.

2.11. Monitoring plan

The methodologies provide the basis for a monitoring plan. However, the project developer actually develops a monitoring plan in accordance with the methodology for the specific project.

3. Monitoring carbon stock and GHG emission

The carbon stock and GHG emission assessments are completed in the baseline scenario, project scenario, and as stated in the monitoring plan of the carbon offset project. Both Verra and ACR approved methodologies have approved modules and tools to assess carbon stock and GHG emissions in the project areas.

VCS methodologies include emissions (eg. methane and nitrous oxide) in GHG calculation if they account for $\geq$5% of the total GHG benefit generated by the project. The carbon stock and GHG accounting options in VCS methodology for tidal wetland and seagrass restoration (Emmer et al., 2015a,b) includes the use of proxies, field-collected data, published values, default values (Table 6) and models individually or in different combinations (Needelman et al., 2018a,b; Emmer et al., 2015a). This methodology does not have default values for the soil carbon sequestration in seagrass beds and methane emissions from the wetlands with salinity below 18 ppt (Needelman et al., 2018a,b; Emmer et al., 2015a). Likewise, VCS methodology for coastal wetland creation in Louisiana (CPRA, 2014) uses the model from literature, proxy models and some default values for carbon stock and GHG emission assessment. Specifically, the default values are used for nitrous oxide across the salinity gradient from Smith et al. (1983). The allochthonous carbon is excluded in this wetland creation methodology.

Table 6
Default values for soil carbon and GHG accounting under Verra's Verified Carbon Standard (VCS) methodology for tidal wetland and seagrass restoration (Emmer et al., 2015a; Needelman et al., 2018a).

Component	Default values
Soil carbon sequestration	1.46 t C/ha for marshes and mangroves
Mineral protected allochthonous carbon	1.5% C in allochthonous deposited carbon
Fate of eroded carbon	0% mineralization in baseline, 100% mineralization in project condition
Methane emissions	Salinity > 20 ppt: 0.0056 t CH_4/ha/yr Salinity > 18 ppt: 0.011 t CH_4/ha/yr salinity < 18 ppt: no default value
Nitrous oxide emission	0.000157 tN_2O/ha/yr to 0.000864 tN_2O/ha/yr depending on salinity and land use. Do not consider N_2O emission from seagrass beds.

ACR Methodology for Mississippi Delta (Mack et al., 2012) uses field measurement techniques including soil cores collection, Cesium^{137} dating, and feldspar marker horizons to estimate carbon stock. The carbon stock in aboveground tree biomass is calculated using species-specific allometric equations (eg. Megonigal et al., 1997) that use tree biomass as a function of diameter at breast height (DBH) and/or tree height. This assessment can either be done measuring entire trees in a project area or from sample plots. The GHG emission is estimated from direct field measurement of the gaseous fluxes, use of acceptable proxies, published values, and approved local or national parameters. The emissions from fossil fuel combustion during project activities are estimated from the default emission factors provided in the methodology (Mack et al., 2015).

ACR methodology for California deltaic and coastal wetlands (Deverel et al., 2017) uses direct field measurement techniques like soil coring to estimate soil carbon stock and species-specific allometric equations (eg from Miller and Fujii, 2010) or remote sensing data to estimate aboveground biomass. An allochthonous carbon deduction is made if it enters into the project area. The aqueous carbon load is monitored to estimate carbon losses and gains from the project area. The subsidence measurement is done to assess the oxidation of organic soils. Gaseous fluxes are estimated from direct field measurements and biogeochemical models.

These carbon stock and GHG emission assessment techniques are associated with uncertainties that may create obstacles in the development, monitoring, and verification of the project activities. Each of the existing wetland methodologies discusses the uncertainty and includes this component in the calculation. The ACR has a separate module (UNC) to determine the uncertainty associated with the measurement. It is the sum of squared-uncertainty in all selected carbon pools. The confidence deduction in emission reduction/removal in VCS coastal wetland creation methodology (CPRA, 2014) is based on the uncertainty associated carbon stock estimate only and does not include measurement uncertainty of methane and nitrous oxide, expecting them to be negligible. Stratification could reduce the uncertainty of population estimates within each stratum (CPRA, 2014).

4. Generating offset from preventing wetland loss

Coastal wetland loss due to erosion is a serious concern worldwide (Sapkota and White, 2019). The soil erosion, and post erosion biogeochemical changes, in the blue carbon ecosystem results in a large loss of soil organic carbon (Lovelock et al., 2017). Holmquist et al. (2018) have identified coastal wetlands as a source of net-CO_2-equivalent emissions mainly due to the large soil loss in the US Gulf Coast, and methane emissions from freshwater tidal wetlands. The wetland loss results in the loss of the century to millennial-aged organic matter (Sapkota and White, 2019). In addition, the lost land is no longer able to sequester additional carbon into the future.

Restoration activities could minimize CO_2 emissions from the existing soil organic carbon stocks (Mack et al., 2012; Lovelock et al., 2017). The Lousiana's Comprehensive Master plan for a sustainable coast has plans to prevent the loss of 2850 km^2 of land in the next 50 years through restoration activities (CPRA, 2017). Carbon credit and carbon financing could generate a greater portion of the revenue needed for the wetland restoration (Murray et al., 2011; Siikamäki et al., 2012; Lane et al., 2016). Establishment of credit for prevented wetland loss might be helpful to increase investments in wetland restoration projects (Mack et al., 2015; Lane et al, 2016; DeLaune and White, 2012). Realizing this fact, some wetland carbon offset methodologies have included prevented wetland loss component in the assessment of the carbon stock and GHG emissions (Emmer et al., 2015a; Mack et al., 2012). VCS methodology for tidal wetland and seagrass restoration (Emmer et al., 2015a) assumes complete oxidation of the eroded soil carbon following the erosion and specify the depth of the erosion (Emmer et al., 2015a,b; Needelman et al., 2018a,b). The ACR methodology for Mississippi Delta (Mack et al., 2012) includes the credit for preserving the top 50 cm of the wetland soil carbon. Some studies have found that the marsh edge erosion potentially results in the loss carbon from up to ~ 1.5 m depth of the wetland soil (Sapkota and White, 2019; Wilson and Allison, 2008). However, the future fate of the eroded soil organic carbon is not well understood (Pendleton et al., 2012; Mack et al., 2015; Wylie et al., 2016; Lovelock et al., 2017). Some recent studies have shown that the eroded carbon undergoes substantial mineralization (Steinmuller et al., 2019; Steinmuller and Chambers, 2019). Opportunities exist to increase the number of offsets generated from preventing loss of carbon stored up to the depth of ~1.5 m (Sapkota and White, 2019; DeLaune and White, 2012).

5. Future steps

The GHG emission assessment requires substantial funding and technical expertise that increase the cost of the project development under all existing wetland carbon offset methodologies (Needelman et al., 2018b). Carbon stock and GHG assessment modules have been developed for simplification of the GHG accounting under existing methodologies. A project development manual has been developed for VCS methodology for tidal wetland and seagrass restoration (Emmer et al., 2015b). Further simplification of the methodologies and GHG accounting modules could help smaller-scale projects benefit from carbon offset (Needelman et al., 2018b). The US coastline, as many coastlines around the world, differs in terms of hydrology, geology, geomorphology, land use, relative sea level rise and hence, potential for coastal restoration projects. Development of methodologies which can be more easily adapted to specific sites and restoration projects may help facilitate efficient project development and move the C market forward. Addressing key research needs in carbon stock and GHG accounting could potentially support the simplification of the methodologies and monitoring plans. The development of site/project-specific models may help to lower the cost and time required for monitoring. The carbon offset generated from wetlands might suffer from the uncertainty of the voluntary market. The offset price differs greatly in the compliance and voluntary market i.e mean price of $10–15 vs $2.4 in early 2018 (Hamrick and Gallant, 2018; Fig. 1). Since, ACR, Verra, and CAR are endorsed by California's ARB for some projects, there is greater potential that wetland projects will be included in California's compliance offset program. However, a sufficient amount of offsets should be created in the voluntary market before blue carbon can be included in the compliance market. A number of current needs include establishment of several restoration projects, registration of offsets in the voluntary carbon market, and advocacy for the inclusion of wetlands as a sector in the compliance offset program. The emerging concept of offsetting aviation CO_2 emissions could potentially significantly increase the demand of carbon offsets in the voluntary market.

6. Conclusion

Wetland restoration and conservation is an ever-present need along nearly the entire coastline of the United States to secure the livelihood and infrastructure of the tens of millions of people and critical economies associated with the coast. Of the many valued ecosystem services of coastal wetlands, the importance of carbon sequestration and GHG emission reduction potential of wetlands is increasing. Several efforts have been made to bring the blue carbon offset into the carbon market including the development of wetland carbon offset methodologies. Blue carbon system could potentially benefit by generating offsets in the growing voluntary and compliance carbon markets. The simplification of the existing methodologies and development of new site-specific and restoration project-specific methodologies could help to facilitate inclusion of the carbon offset component in coastal restoration and conservation activities. This inclusion not only will promote the economic value of wetlands but also generate substantial financial capital to support restoration projects, which ultimately will help reduce overall CO_2 emissions and reduce the impact of an ever-increasing atmosphere CO_2 pool.

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