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TAILORED RESTORATION RESPONSE: PREDICTIONS AND GUIDELINES FOR WETLAND RENEWAL

RESEARCH ARTICLE

An Australian blue carbon method to estimate climate change mitigation benefits of coastal wetland restoration

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Restoration of coastal wetlands has the potential to deliver both climate change mitigation, called blue carbon, and adaptation benefits to coastal communities, as well as supporting biodiversity and providing additional ecosystem services. Valuing carbon sequestration may incentivize restoration projects; however, it requires development of rigorous methods for quantifying blue carbon sequestered during coastal wetland restoration. We describe the development of a blue carbon accounting model (BlueCAM) used within the *Tidal Restoration of Blue Carbon Ecosystems Methodology Determination 2022* of the Emissions Reduction Fund (ERF), which is Australia's voluntary carbon market scheme. The new BlueCAM uses Australian data to estimate abatement from carbon and greenhouse gas sources and sinks arising from coastal wetland restoration (via tidal restoration) and aligns with the Intergovernmental Panel for Climate Change guidelines for national greenhouse gas inventories. BlueCAM includes carbon sequestered in soils and biomass and avoided emissions from alternative land uses. A conservative modeled approach was used to provide estimates of abatement (as opposed to on-ground measurements); and in doing so, this will reduce the costs associated with monitoring and verification for ERF projects and may increase participation in blue carbon projects by Australian landholders. BlueCAM encompasses multiple climate regions and plant communities and therefore may be useful to others outside Australia seeking to value blue carbon benefits from coastal wetland restoration.

Key words: blue carbon, carbon credits, climate change mitigation, coastal wetlands, tidal restoration

Implications for Practice

- Restoration of coastal wetlands (mangroves, seagrass, saltmarsh, and supratidal forests) through removal and modification of tidal barriers can result in significant greenhouse gas mitigation benefits.
- Modeled approaches for estimating carbon sequestration and greenhouse gas emissions with restoration of coastal wetlands are available for a range of climate regions in Australia.
- The Australian modeled approaches may be broadly applicable in similar climatic regions globally.

Introduction

Restoration of coastal wetlands provides climate change mitigation benefits through enhancing carbon sequestration in soils and biomass, and by avoiding greenhouse gas (GHG) emissions associated with prior land uses (Crooks et al. 2018; Macreadie et al. 2021). Restoration provides additional benefits including support of fisheries and biodiversity, enhancements in water quality, climate change adaptation, and sustaining community livelihoods (Barbier et al. 2011; Huxham et al. 2017). While the

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benefits of restoring coastal wetlands are clear, the costs of coastal wetland restoration can be high (Bayraktarov et al. 2016). Therefore, payments for ecosystem services have the potential to increase uptake of coastal wetland restoration. Payments for carbon sequestration services through international voluntary carbon trading schemes have supported management of coastal wetlands in many countries (Wylie et al. 2016; Kuwae et al. 2022).

Australia has a national voluntary carbon market scheme, the Emissions Reduction Fund (ERF) under the Carbon Credits (Carbon Farming Initiative) Act 2011 (https://www.legislation.gov.au/Details/C2020C00281), that has carbon accounting methods for restoring natural forest vegetation and soil organic carbon (SOC) stocks. In 2019 the Australian Government began work on developing a blue carbon accounting methodology for restoration of coastal wetlands where Australian Carbon Credit Units (ACCUs) could be issued. Scoping of potential restoration activities that involved stakeholder engagement, indicated that restoration of tides onto land where tidal influences have been reduced to facilitate land use change, through construction of bund walls, tidal gates, or other barriers, was a restoration activity that had high potential for abatement and thus method development (Kelleway et al. 2020). The Clean Energy Regulator of the Australian Government developed the *Tidal Restoration of Blue Carbon Ecosystems Methodology Determination 2022*, which legislated the method a proponent must use to gain ACCUs (which can be sold) for these activities.

To register a blue carbon project under Australia's ERF, proponents must describe the management activity undertaken to increase carbon storage and reduce GHG emissions from restoration of tidal flows (i.e. tidal restoration activity that removes or modifies structures that restricts tidal flows), and estimate and verify how much carbon has been accumulated in soils and biomass, and GHG emissions reduced over time in a manner consistent with the ERF offset integrity standards (Kelleway et al. 2020). In the ERF carbon abatement from land use activities is estimated (often using models) based on changes in the area of different land uses and vegetation types over time. ACCUs generated under an ERF method can be sold or used as offsets, e.g. for achieving carbon neutral certification. Under the ERF, estimates of changes in carbon pools and GHG emissions over time considers the difference between carbon stocks and emissions under baseline business-as-usual conditions (i.e. prior to tidal restoration taking place), and the carbon accumulated and abated emissions following restoration of tidal flows. Prior to project commencement, anticipated carbon abatement can be modeled to assess the economic feasibility of commencing a project, and as the project progresses, carbon abatement can be calculated and verified at prescribed intervals (e.g. up to 5-year intervals for ERF sequestration projects).

Here we describe the blue carbon accounting model ("BlueCAM") approach for estimating carbon abatement under the Australian Government's ERF for the *Tidal Restoration of Blue Carbon Ecosystems Methodology Determination 2022*. This new approach along with previous methods (e.g. Verra VM0033; Needelman et al. 2018; Kuwae et al. 2022) can inform method development for other activities in other nations and jurisdictions.

Methods

Components of Estimated Abatement

The restoration of tidal flows to coastal land can increase carbon sequestration through creating conditions that favor the growth and development of blue carbon ecosystems such as mangroves, saltmarshes, seagrasses, and supratidal forests. Supratidal forests are forests that are influenced by interactions among tidal water, groundwater, and rainfall, comprised of *Melaleuca*, *Casuarina*, and other plant genera (Lovelock & Duarte 2019). Tidal restoration can also decrease methane emissions from land through changes in soil water content, increases in soil and water salinity, and changes in biogeochemistry that influence microbial processes (e.g. changes in iron availability), which can decrease rates of methanogenesis and increase rates of sulfate reduction (Poffenbarger et al. 2011; Al-Haj & Fulweiler 2020; Iram et al. 2021). The method we developed considers changes in organic carbon stocks and GHG emissions (carbon dioxide, methane, and nitrous oxide) following a management intervention to restore tidal flows (Table 1).

Stratification of Sites to Establish Carbon Estimation Areas

Australian carbon accounting methods divide project areas into multiple carbon estimation areas (CEAs; https://data.gov.au/data/dataset/erf_project_mapping) for which abatement is calculated and then summed. Individual CEAs have homogenous levels of carbon abatement reflecting similarities in land use and soil and vegetation types. The rules for defining CEAs are developed for each ERF method, and thus we devised an approach to stratification of land into CEAs based on data sources that are typically available, information on the distribution of coastal wetland plant communities in the literature, and consistent with the hydrological assessment of project sites that must be provided at project registration (part C, Carbon Farming Initiative, Supplement to the Carbon Credits [Carbon Farming Initiative—*Tidal Restoration of Blue Carbon Ecosystems*] *Methodology Determination 2022*). Briefly, the hydrological assessment uses maps of features of the project area, including elevation and tidal data, to model inundation of land at the level of the highest astronomical tide at the start of the project, at 25 and 100 years, incorporating sea-level rise.

Regional Approach to Modeling Abatement

Over the Australian continent, variation in climate, including variation in temperature, humidity, precipitation, groundwater, and river flows influences the type (species and community composition) and biomass of coastal wetland communities, and therefore affects organic carbon stocks and fluxes and GHG emissions (Serrano et al. 2019; Young et al. 2021). Land uses in the pretidal restoration baseline conditions, as well as their carbon stocks and fluxes also vary regionally (Viscarra Rossel et al. 2014; Roxburgh et al. 2019). Climatic regions used in BlueCAM follow previous climatic classifications used by the Australian Government in their policies in order to facilitate alignment with environmental planning and the delivery of

Table 1. Carbon pools and greenhouse gases (GHGs) considered in BlueCAM.

Relevant Carbon Pool or Emission Source		*Greenhouse Gas*	*IPCC Guidance*
Carbon pool	Living aboveground biomass	Carbon dioxide (CO_2)	2013 Wetland Supplement
Carbon pool	Living belowground biomass	Carbon dioxide (CO_2)	2013 Wetland Supplement
Carbon pool	Soil	Carbon dioxide (CO_2)	2013 Wetland Supplement 2019 Refinement of 2006 Guidance
Emission source	Fuel use	Methane (CH_4) Nitrous oxide (N_2O) Carbon dioxide (CO_2)	2019 Refinement of 2006 Guidance
Emission source	Flooded land	Methane (CH_4) Nitrous oxide (N_2O)	2019 Refinement of 2006 Guidance
Emission source	Aquaculture	Nitrous oxide (N_2O)	2019 Refinement of 2006 Guidance 2013 Wetland Supplement
Emission source	Agricultural lands	Nitrous oxide (N_2O) Carbon dioxide (CO_2)	2019 Refinement of 2006 Guidance
Emission source	Ecosystem transitions (vegetation death)	Carbon dioxide (CO_2)	2013 Wetland Supplement
Emission source	Excavation	Carbon dioxide (CO_2)	2013 Wetland Supplement

environmental programs, and for projecting the influence of climate change on ecosystems (Fig. 1).

Carbon Accumulation Biomass and Soils

The general approach devised for BlueCAM for estimating abatement from biomass accumulation in woody communities (mangrove forests and supratidal forests) was similar to other ERF methods, where biomass accumulation is modeled using an exponential curve that reaches an asymptote when the vegetation is mature (Paul et al. 2015). BlueCAM does not include carbon in dead organic matter and litter because litter carbon stocks are often small compared to other pools and they may be exported in tidal flows, and data on dead wood (and other necromass) were limited and therefore we used earlier approaches that presumed those pools were included in estimates of aboveground biomass (Lasco et al. 2006; Kennedy et al. 2014).

The approach for estimating changes in SOC stocks was based on the mass of organic carbon and accumulation rates in soils from a national collation of SOC sequestration rates in coastal wetlands (Serrano et al. 2019) updated to include recently published and unpublished datasets, including those for supratidal forests (Adame et al. 2020; Jones et al. 2019; Kelleway et al. 2021) and sparsely vegetated saltmarshes or salt flats (Brown et al. 2021) (Table S1).

Carbon in the Baseline Land Uses

SOC stocks from baseline land uses were extracted from the Australian SOC map (Viscarra Rossel et al. 2014) for grazing and sugarcane land uses on coastal lands in different climatic regions. Coastal land was delineated using the Smartline Coasts Sediment Compartment and Realms data (https://coastadapt.com.au/coastadapt-interactive-map).

Assessment of available published and unpublished soil organic carbon accumulation rate (CAR) data from locations where wetlands have been created due to restrictions to tidal flows (tidal-restricted wetlands; Fennessy et al. 2019) were used to estimate soil CAR in tidally restricted wetlands in Australia (Table S2). These values were derived from estimates of soil CAR in hydrologically modified mangrove forests, saltmarshes, and other herbaceous communities, and are therefore applicable to a range of baseline tidally restricted wetland scenarios.

Annual SOC stock change factors for agriculture (grazing and sugarcane) were from IPCC (2019) for different land use (F_{LU}), inputs of fertilizers, and other amendments (F_I) and management (F_{MG}) over a 20-year period, which is then converted to an annual SOC loss rate by dividing the estimated stock change by 20 (IPCC 2019). Further details are provided in Table S3.

Non-CO_2 Emissions from Restored Coastal Wetlands and Baseline Land Uses

We assembled CH_4 and N_2O emissions data from a range of coastal land uses and for Australian coastal wetlands from the literature and unpublished data. Methane (CH_4) and nitrous oxide (N_2O) from soil and water bodies were assigned global warming potentials of 25 and 298 times that of CO_2, respectively (Forster et al. 2007; consistent with values used in the Australian Greenhouse Gas Inventory). These data were used in BlueCAM to estimate emissions from baseline and coastal wetland tidal restoration project scenarios. Methane emissions from drains and ditches, aquaculture ponds (in production), cropland, forest land, and grazing land were not included in BlueCAM because these GHG emissions are not part of the mandatory inventory reporting categories under the IPCC and are not included in Australia's National Greenhouse Accounts. As the GHG emissions data used in BlueCAM typically have a log normal distribution, abatement in BlueCAM is calculated using the median values, which avoids overestimating emissions.

Uncertainty Analyses

We assessed the uncertainty using Monte-Carlo simulations (1,000 simulations) using the RISKAmp Excel add-in (Structured Data LLC, New York, NY, USA), where the mean,

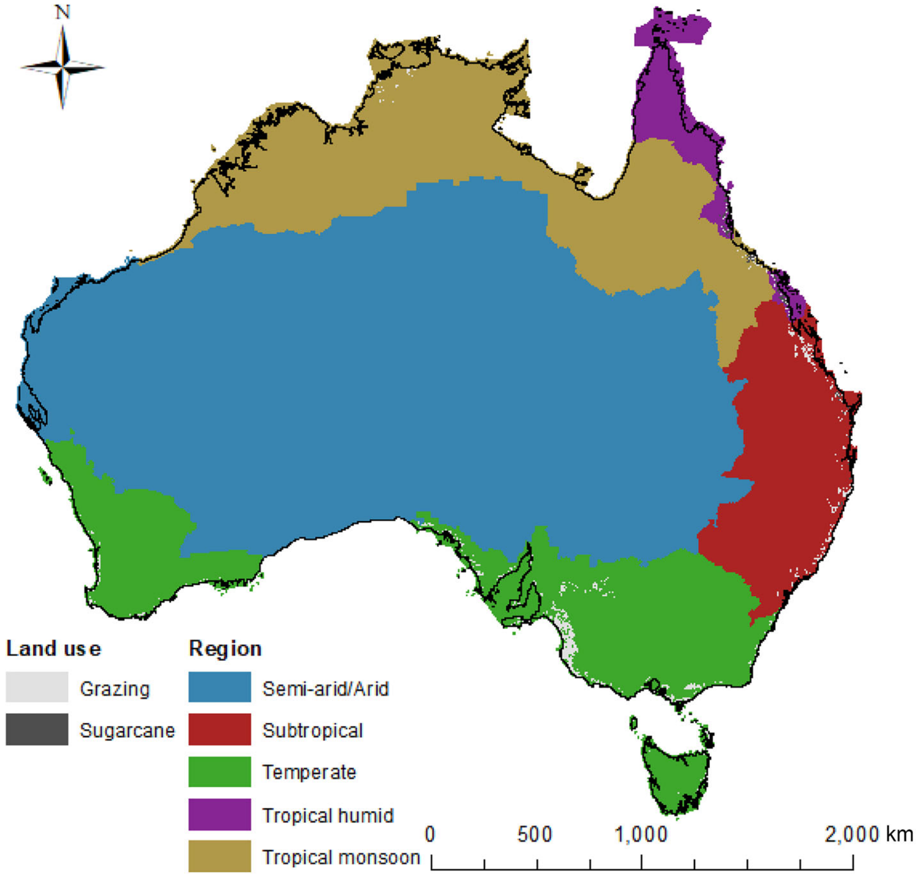


Figure 1. Map of the climatic regions used in the *Tidal Restoration of Blue Carbon Ecosystems Methodology Determination 2022*. Regions are modified from https://www.climatechangeinaustralia.gov.au/en/overview/methodology/nrm-regions/, Department of Environment, Australian Government. Areas of coastal grazing (gray) and sugarcane land (black) from which baseline soil organic carbon data extracted (from the Australian soil organic carbon map; Viscarra Rossel et al. 2014) are also indicated.

variation in the input parameters, and the form of the distribution of the data for each data input were included. These analyses were done for 225 different combinations of baseline land uses (nine land uses), restored coastal wetlands (five ecosystem types) for different climate regions (five regions) for abatement over 25 years.

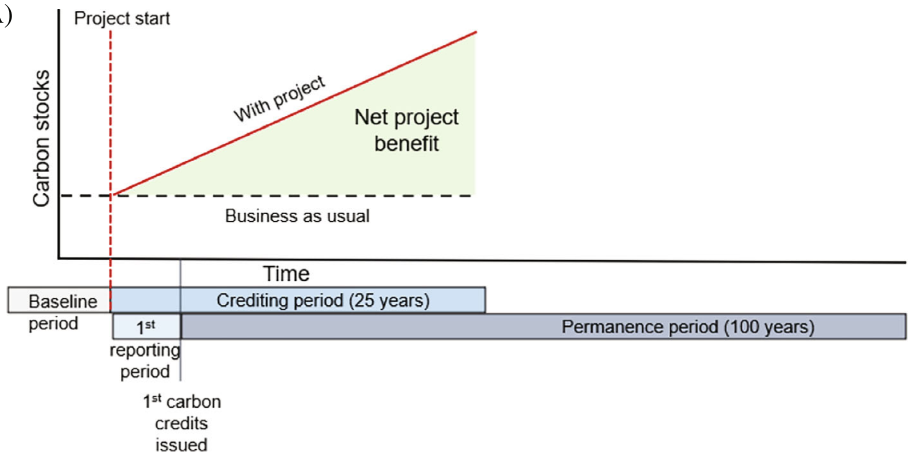
Results

The net abatement (Fig. 2A) in BlueCAM is estimated based on the difference in carbon stocks and GHG emissions between the existing land use (the business-as-usual baseline) compared to the carbon sequestered and stored in the vegetation (living aboveground and belowground biomass) and the soil, and GHG emissions that occur after tidal introduction. In BlueCAM, all carbon pools or GHG emission sources are estimated for baseline (i.e. existing land uses) and as a consequence of project activities using equations that are consistent with Intergovernmental Panel on Climate Change (IPCC) guidance (Kennedy et al. 2014). An advantage of the BlueCAM for project proponents is that no measurements of carbon pools or GHGs are required, beyond assessment of changes in extent of different vegetation types (Table S4 for links to the BlueCAM tool and supporting documentation; Fig. 2).

Stratification of Sites to Establish CEAs

CEAs are homogenous land units, which are delineated in BlueCAM by different land uses, vegetation types, and levels of land elevation (relative to the Australian height datum [AHD]—with zero AHD approximating mean sea level [MSL] in 1972 across 30 tide gauges). For example, within a project area that is grazing land behind a tidal barrier, CEA1 may occur at the level of mean high tide and likely to be restored to mangrove within the first reporting period; CEA2 may occur at highest astronomical tide and likely to be restored to saltmarsh within the first reporting period; CEA3 may be at land elevations predicted to be inundated by tides in 20 years, while the remaining grazing land on the highest elevation land within the project area, is unlikely to be inundated by the tide within the crediting period of the project (Fig. 3). If the project area land is a homogenous land use (e.g. grazing land) in the baseline, but different vegetation types develop as the project progresses, then for each reporting period different CEAs are established based on the coastal wetlands that

(A)



(B)

Equations and terms of BlueCAM	Explanations
$A_r = \Delta C_r \times (1 - B_{Seq}) + A_{r-1} + E_r - E_{fk,r} + RC$	Net abatement for a reporting period A_r
ΔC_r: organic carbon stock change, in t CO_2-e, for the project area for the reporting period, with $$\Delta C_r = \sum_i (CP_{i,r} - CP_{i,r-1})$$	$CP_{i,r}$ carbon stock (in t CO2-e) of soil and vegetation for the i[th] CEA in the project area at the end of the reporting period, multiplied by the area of each CEA in hectares (ha), less emissions from soil excavations. $CP_{i,r-1}$ carbon stock (in t CO_2-e) of soil and vegetation for the i[th] CEA in the project area at the end of the previous reporting period (or: baseline for first reporting period), multiplied by the area of each CEA in ha
B_{Seq}: sequestration buffer for the project which accounts for the risk that carbon sequestered as a result of the project does not remain permanently in the landscape. (http://www.cleanenergyregulator.gov.au/ERF/Choosing-a-project-type/Opportunities-for-the-land-sector/Risk-of-reversal-buffer).	a) 0.25 – if 25 year permanence period, b) 0.05 – if 100 year permanence period, which remains 0.05 if the project area includes 80-100% of impacted lands, and 0.25 if the project area includes less than 80% of impacted lands
A_{r-1}: carryover net abatement amount for the project area for the reporting period, in t CO_2-e	To account for possible negative abatement in the previous reporting period A_{r-1}. If A_{r-1} negative, the negative number is used; otherwise this term is zero.

Figure 2. (A) Blue carbon projects aim to achieve net abatement through increased carbon stocks and reducing GHG emissions for an area of land where the tide is restored (project start, red dashed line). Project abatement (green area) is estimated for a 25 year time period (blue) against a business-as-usual scenario (black dashed line) using BlueCAM. Abatement must be permanent for 25 or 100 years with the permanence period starting when the project first receives carbon credits, or when an area of land is added to the project (up to 7 years after project registration, or longer if no credits are issued after the first reporting period). (B) Description of the components of BlueCAM used to estimate net abatement in each carbon estimation area (CEA).

(Figure continues on next page.)

have developed in the project area following removal of the tidal barrier. For example, mangrove forests and/or saltmarshes may occupy the lower intertidal zone positions, depending on climatic region. Sparsely vegetated saltmarshes (salt flats), supratidal forests (e.g. *Melaleuca* and *Casuarina* spp.) or saltmarsh vegetation may occupy the upper intertidal and supratidal zones (climatic region dependent). Seagrass typically occupy sub-tidal and lower intertidal (lower half of the tidal range) positions.

In addition to land use and vegetation type, CEAs are also characterized by tidal range and elevation, which are components

$\boldsymbol{E_r}$: sum of emitted and avoided CH_4, N_2O and CO_2 emissions, in t CO_2-e, for the project area for the reporting period $\boldsymbol{E_r} = \sum_i\left(\left(\boldsymbol{E_{B,CH_4,i}} + \boldsymbol{E_{B,N_2O,i}} + \boldsymbol{E_{B,CO_2,i}}\right) - \left(\boldsymbol{E_{r,CW,CH_4,i}} + \boldsymbol{E_{r,CW,N_2O,i}} + \boldsymbol{E_{r,CO_2,i}} + \boldsymbol{E_{r,TR,CO_2,i}}\right)\right)$	$\boldsymbol{E_{B,CH_4,i}}$, $\boldsymbol{E_{B,N_2O,i}}$, and $\boldsymbol{E_{B,CO_2,i}}$ are baseline emissions of CH_4, N_2O and CO_2 for the ith CEA in the project area, calculated by multiplying their respective global warming potential with their mass (in t/ha) and the area of the CEA (in ha). $\boldsymbol{E_{r,CW,CH_4,i}}$ and $\boldsymbol{E_{r,CW,N_2O,i}}$ are the emissions of CH_4 and N_2O for the ith CEA in the project area, calculated as above but for the reporting period. $\boldsymbol{E_{r,CO_2,i}}$ emissions of CO_2 (in t CO_2-e) for the ith CEA in the project area in the reporting period if land type has not changed (i.e. = $\boldsymbol{E_{B,CO_2,i}}$); otherwise this term is zero. $\boldsymbol{E_{r,TR,CO_2,i}}$ transition emissions of CO_2 (in t CO_2-e) from changes in live vegetation biomass following tidal restoration, or disturbance events calculated from the mass of CO_2, (t/ha) emitted from the ith CEA in the project area for the reporting period, multiplied by the area of each CEA in ha
$\boldsymbol{E_{fk,r}}$: total fuel emissions for the project area for the reporting period, with $\mathbf{E_{fk,r}} = \sum_{\mathbf{f}}\sum_{\mathbf{k}}\frac{\mathbf{Q_f} \times \mathbf{e_f} \times \mathbf{F_{fk}}}{\mathbf{1000}}$	$\boldsymbol{f}$ fuel type $\boldsymbol{k}$ greenhouse gas type $\boldsymbol{Q_f}$ quantity of fuel type f combusted in the reporting period for the project area, in kilolitres $\boldsymbol{e_f}$ energy content factor for fuel type f, as per NGER, in gigajoules per kilolitre $\boldsymbol{F_{fk}}$ emission factor for gas type k for fuel type f, in kilograms per CO_2-e per gigajoule.
RC	The total number of Australian carbon credit units relinquished in relation to each CEA in the project area under sections 88, 90 or 91 of the Act (https://www.legislation.gov.au/Details/C2020C00281) during the reporting period.

Figure 2 (Continued)

included within the hydrological assessment, and other broader contextual information that proponents must provide when registering a project with the ERF and prior to the start of any tidal restoration activity (see Carbon Farming Initiative 2022, Supplement to the Carbon Credits [Carbon Farming Initiative—Tidal Restoration of Blue Carbon Ecosystems] Methodology Determination 2022). Tidal range and type of tidal cycle (semi-diurnal, diurnal, or mixed) vary around the Australian coast with tidal range varying from 1 to 10 m. Therefore, elevation of CEAs are standardized within BlueCAM, using a standardized tidal position index (STPI; adapted from Lal et al. 2020) to accommodate regional variations in tidal range. Using the STPI, tidal range is standardized between −1 for lowest astronomical tide and 1 for highest astronomical tide, with mean tide level being zero.

$$\mathrm{STPI} = (\mathrm{En} - \mathrm{MTL})/(\mathrm{HAT} - \mathrm{MTL})$$

where En is the upper or lower elevation boundary of the CEA (meters above AHD, the local geodetic datum); MTL is the mean tide level (AHD, approximately MSL); and HAT is

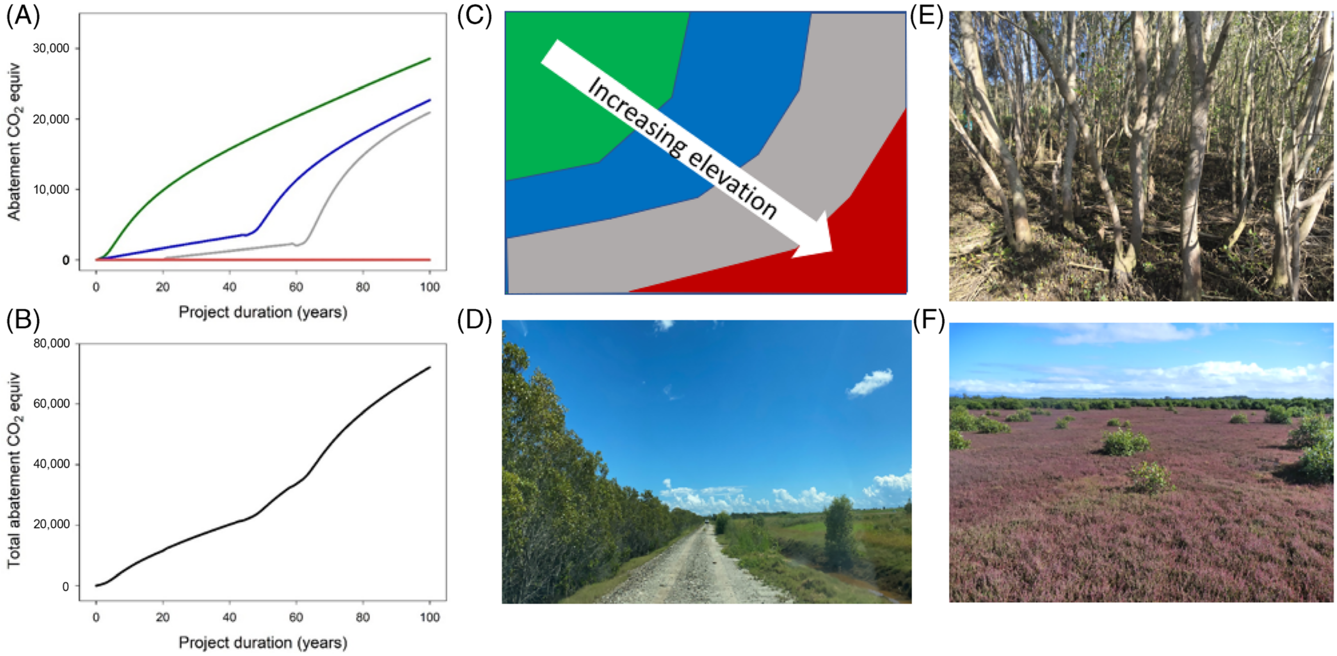


Figure 3. A hypothetical example of estimated carbon abatement in subtropical coastal wetlands restored from a baseline of grassland (A and B) for three carbon estimation areas (CEAs) at different elevations (C) over 100 years with sea-level rise (using the median Representative Concentration Pathway 8.5 sea-level rise scenario; IPCC 2013). The total abatement for the site (summed abatement for all CEAs, 101 ha) is shown for the 100-year reporting/permanence period (B). CEA1 (green) is lowest elevation where mangrove vegetation is restored (e.g. on the left of panel D and in panel E); CEA2 (blue) is high elevation where saltmarsh vegetation is restored but transitions to mangrove at ~45 years (F); CEA3 (gray) is where the baseline transitions to saltmarsh at 20 years and to mangroves at ~60 years; the remaining land (red) is where the baseline land use is high elevation grassland that is never inundated (right of panel D). Inflections in the blue and gray lines indicate when elevation thresholds for ecosystems are crossed (e.g. saltmarsh transitions to mangrove, F) due to increasing inundation with sea-level rise, where living saltmarsh biomass is decomposed and emitted as CO_2 in 1 year, and carbon accumulation subsequently changes to that of the new vegetation type.

approximated by the high high-water solstice spring tides. The denominator of the STPI defines the upper half of the intertidal zone and is expressed by the difference between HAT and MTL. The STPI range of vegetation types varies with climatic region (Table 2) because of influences of climate on the range of elevation over which coastal vegetation occur (e.g. Duke et al. 2019). The STPI range for each vegetation type in each region was established from case studies in each climatic region (Lovelock et al. 2022).

The STPI position of different CEAs is used to delineate high elevation zones where biomass and SOC accumulation of mangroves is reduced because of limited tidal inundation (Table 2; Lovelock et al. 2022). In some regions, high intertidal areas with limited tidal inundation often have mangrove scrub (Feller et al. 2010; Rogers et al. 2017; Lovelock et al. 2022) and reduced sediment and SOC accumulation (e.g. McKee et al. 2007; Adame et al. 2010; Lovelock et al. 2014; Kelleway et al. 2017) reflecting the limited vertical accommodation space for accumulating soil organic carbon (Kirwan & Megonigal 2013; Woodroffe et al. 2016; Rogers et al. 2019*a*, 2019*b*). Although in some cases elevation may not reflect hydroperiods, because of tidal amplification or attenuation, we assume that levels of tidal inundation of the intertidal zone broadly follow elevation contours (e.g. Glamore et al. 2021). Thus, BlueCAM moderates the level of carbon abatement estimated for each mangrove CEA using the STPI, providing lower abatement than the regional value in high intertidal positions by using a multiplier (Table 2). The application of multipliers reduces the total abatement that is credited (compared to use of a single regional value) and provides more accurate estimates of carbon abatement compared to the use of single regional value (Lovelock et al. 2022).

Sea-Level Rise and Carbon Estimation Areas

Projects that use the ERF blue carbon method must consider the impacts of sea-level rise on the project over the permanence period selected by the project (25 or 100 years; Fig. 2). As sea-level rise progresses, coastal vegetation that is unimpeded by barriers can colonize land further inland (sometimes called landward retreat or landward migration) as the tide reaches further inland and the supratidal land become more frequently inundated (Schuerch et al. 2018). Projects that have 100-year permanence periods that include less than 80% of all land that is expected to be affected by tidal restoration, including the influence of sea-level rise within the 100-year permanence period are subject to a 25% discount through the use of a carbon sequestration buffer, $\boldsymbol{B}_{\mathbf{Seq}}$ (Fig. 2). Project lands can be used for some other purposes until they become inundated; following inundation they will be allocated to a CEA and

Table 2. The standardized tidal position index (STPI) elevation ranges of CEAs for each climate region and vegetation type used to estimate aboveground biomass in BlueCAM, and the multiplier to estimate the proportion of biomass accumulation and soil organic carbon sequestration in higher elevation CEAs. In subtropical and tropical monsoon regions, the high intertidal zone may be occupied by mangroves or saltmarshes, depending on local conditions. Mangroves are present in some temperate regions but not others.

Vegetation Type	*STPI Range of Carbon Estimation Area (CEA)*	*BlueCAM Value Used*	*Multiplier—Aboveground Biomass*	*Multiplier—Soil Organic Carbon*
Arid—semiarid				
Seagrass	<0	Seagrass	1	1
Tall mangrove	0–0.40	Mangrove	1	1
Scrub mangrove	0.40–0.47	Mangrove	0.5	0.5
Sparsely vegetated saltmarsh (salt flat)	0.47–1.0	Sparsely vegetated saltmarsh (salt flat)	0	1
Saltmarsh	0.47–1.0	Saltmarsh	1	1
Supratidal vegetation	>1	Supratidal (nonforested)	No data	No data
Subtropical				
Seagrass	<0	Seagrass	1	1
Tall mangrove	0–0.37	Mangrove	1	1
Scrub mangrove	0.37–0.73	Mangrove	0.75	0.5
Tall hinterland mangrove (if present)	0.73–1.0	Mangrove	0.9	0.35
Saltmarsh (if present)	0.73–1.0	Saltmarsh	1	1
Supratidal vegetation	>1	Supratidal forest	1	1
Tropical—monsoon				
Seagrass	<0.1	Seagrass	1	1
Tall mangrove	0–0.49	Mangrove	1	1
Scrub mangrove	0.49–0.68	Mangrove	0.35	0.50
Salt flat	0.68–0.81	Sparsely vegetated saltmarsh (salt flat)	0	1
Tall hinterland mangrove (if present)	0.81–1.0	Mangrove	0.35	0.35
Saltmarsh (if present)	0.81–1.0	Saltmarsh	1	1
Supratidal vegetation	>1	Supratidal forest	1	1
Tropical—humid				
Seagrass	<0	Seagrass	1	1
Tall mangrove	0–0.32	Mangrove	1	1
Scrub mangrove	0.32–1.0	Mangrove	0.7	0.7
Supratidal vegetation	>1	Supratidal forest	1	1
Temperate—with mangroves				
Seagrass	<0	Seagrass	1	1
Mangrove	0–0.45	Mangrove	1	1
Saltmarsh	0.45–1	Saltmarsh	1	1
Supratidal vegetation	>1	Supratidal forest	1	1
Temperate—no mangroves				
Seagrass	<0	Seagrass	1	1
Saltmarsh	0–1	Saltmarsh	1	1
Supratidal vegetation	>1	Supratidal forest	1	1

designated as a coastal wetland where management activities are further restricted (see Tidal restoration of blue carbon ecosystems method [http://cleanenergyregulator.gov.au/] for details of activities that may occur within CEAs under the method).

Regional Approach to Modeling Abatement

Because of regional variation in climate and its effects on coastal wetland carbon stocks and fluxes, BlueCAM uses different values of the parameters described in Figure 2 for each climatic region, thereby estimating regionally specific abatement when implementing coastal wetland restoration. Coastal wetlands in different climatic regions achieve different levels of abatement. Additionally, baseline land uses, carbon stocks, and GHG fluxes also vary regionally. Therefore, BlueCAM uses climatic region-specific rates of abatement (carbon sequestration and GHG emissions) by differing coastal wetland vegetation types and land uses.

Carbon Accumulation in Biomass and Soils in Restored Coastal Wetlands

In BlueCAM, accumulation of carbon in biomass and soils are summed for each reporting period after tidal restoration has occurred (CP_r; Figure 2). The curve for estimating woody biomass accumulated in BlueCAM is of the form:

$$\text{Biomass} = a \times \exp\left(-\frac{k}{\text{age}}\right)$$

where a is the mean mature biomass (± SEs) observed in the region, k is a slope constant determined from the median value from a range of chronosequence studies (29.6; Lovelock et al. 2022), and age is the stand age in years. The asymptote of the curve (a) is set by the mature aboveground biomass carbon based on the mean of field observations for each climatic region (Table S5; Serrano et al. 2019; Adame et al. 2020). Belowground biomass was modeled as a fixed proportion of aboveground biomass. We used a root:shoot ratio of 0.32 (median; mean 0.47 ± 0.07 (± SE, 95% of 0.17–0.47) for mangroves (Adame et al. 2020) and 0.27 for supratidal forests, based on values reported for tropical trees (Mokany et al. 2006). For saltmarsh and seagrass, fine roots (<2 mm) biomass that is concentrated in the upper layers of the substrate is included within the SOC accumulation estimates and therefore belowground biomass values were set to zero. Where no data were available for a particular ecosystem in a climatic region (e.g. arid/semiarid saltmarsh), we applied values from another climate region based on expert knowledge of the similarity among coastal wetland communities from different climatic regions.

Saltmarshes and seagrasses have lower aboveground biomass compared to mangroves and supratidal forests. After restoration, BlueCAM calculates that the biomass of these herbaceous communities is accumulated within 1 year. Accumulation of biomass of mature saltmarsh and seagrass stands may take longer than 1 year in temperate and arid/semiarid regions with woody saltmarsh species (e.g. *Tecticornia* sp.), although there were insufficient data to establish growth curve models for them. Sparsely vegetated saltmarsh (also referred to as salt flats or sabkha) occur in high intertidal elevations and can covered with cyanobacterial mats (Lovelock et al. 2010). In these settings, biomass carbon was conservatively set to zero.

Soil Organic Carbon Accumulation

Values of soil organic CARs were similar between restored and natural coastal wetlands and thus using CAR values from natural ecosystems was deemed appropriate for projects that restore tidal flows and establish coastal wetlands (Lovelock et al. 2022). For each ecosystem type CAR did not differ significantly among climatic zones ($p > 0.05$) (see Fig. S1). CAR values were also similar in saltmarshes with herbaceous structure (succulents, grasses; typically occupying lower saltmarsh elevations) compared to rush-dominated saltmarshes (typically occupying higher intertidal elevations), and therefore a median value of CAR for all saltmarsh types was used in BlueCAM. SOC sequestration in sparsely vegetated saltmarsh (salt flats) was lower than that for saltmarshes (Table 3). Similar to biomass, ecosystem specific rates of CAR were adjusted by multipliers for CEAs that are at higher elevation in the intertidal zone (with higher STPIs) in order to reflect lower productivity (Lamont et al. 2020), lower sediment trapping (Adame et al. 2010), and conditions that favor decomposition of organic matter over preservation (Lovelock et al. 2017; Spivak et al. 2019). Overall, the BlueCAM values for carbon accumulation in soils and biomass were lower than those provided at tier 1 defaults in IPCC guidance (Table S6).

Emissions Associated with Transitions among Coastal Wetland Types with Tidal Restoration and Sea-Level Rise

The method recognizes that following tidal restoration processes contributing to vertical growth of substrates (e.g. mineral sediment and organic matter addition) may be sufficient to balance or exceed rates of sea-level rise. In these cases, ecosystems adapt to sea-level rise and may also extend their distribution laterally (Krauss et al. 2014; Schuerch et al. 2018) as indicated in Figure 3, where mangroves spread into high-elevation land areas over time. Where rates of vertical accretion are lower than the rate of sea-level rise and the project land is low in the intertidal zone and/or barriers are present that prevent landward expansion of ecosystems, then the saltmarsh or mangrove community that establishes after tidal restoration may not persist and will be eventually replaced by other ecosystems, including seagrass, unvegetated mud flats, channels, or other macrophytes (e.g. seaweeds or other aquatic plants) if submergence and erosion occurs. These ecosystem transitions influence the abatement achieved as emissions occur when vegetation dies and different ecosystems have differing rates of carbon accumulation in biomass and soils.

For ecosystem transitions involving coastal vegetation die off (e.g. a transition from saltmarsh to mangrove; or supratidal forest to saltmarsh), BlueCAM calculates emissions that occur when the biomass carbon is converted to CO_2 (emissions associated with ecosystem transitions $\boldsymbol{E_{r,\mathrm{TR}}}$; Fig. 2) and the new coastal wetland type will begin to accumulate biomass and SOC at the rate specified for the new wetland type in that climatic region (Fig. 3). For mangroves transitioning from scrub forms to taller forms as frequency of inundation increases, CO_2 emissions are estimated as zero as trees persist through the transition, increasing their growth rates (Feller et al. 2003). On death of herbaceous vegetation 100% of the aboveground biomass is estimated to be released as CO_2. For mangrove forests, supratidal forests and other woody vegetation (e.g. those that may occur in the baseline), CO_2 emissions are calculated as 40% of the total aboveground biomass (leaves, branches, fine wood), assuming that the woody parts of the trees (the bole) and belowground biomass remains in place or decomposes very slowly (IPCC 2019).

CO_2 Emissions from Baseline Land Uses

In the baseline woody biomass that is present (either unmanaged forests or supratidal forest) may die with restored tidal flows resulting in CO_2 emissions (Fig. 2; $\boldsymbol{E_{B,CO_2}}$). In BlueCAM these woody biomass pools were assumed to be sparse, grown recently on land initially cleared and managed for agriculture (cropping or grazing). Biomass of this sparse woody vegetation was assumed to be similar to mixed species plantings that are 10–15 years old, or 60 Mg dry matter/ha (Paul et al. 2015; Preece et al. 2017). Vegetation may be younger than 15–20 years,

Table 3. Values of soil organic carbon accumulation rate (CAR) estimated by ecosystem in Australia. Data are means and standard errors, medians and upper and lower 95% confidence intervals and are derived from data from Serrano et al. (2019) with additional published and unpublished data (Table S1).

		CAR (Mg C ha^{-1} yr^{-1})			
Ecosystem	*Number of Estimates (n)*	*Mean ± 1 SE*	*Median*	*95% CI Lower*	*95% CI Upper*
Seagrass	43	0.32 ± 0.05	0.21	0.23	0.42
Mangrove	48	1.40 ± 0.16	0.95	1.07	1.73
Saltmarsh	28	0.77 ± 0.22	0.48	0.32	1.21
Supratidal forests	8	0.62 ± 0.05	0.61	0.51	0.74
Sparsely vegetated saltmarsh (salt flat)	3	0.23 ± 0.06	0.25	0	0.49

as woody vegetation on agricultural land is regularly managed by landholders to maintain pasture for grazing or other agricultural land uses. Therefore, emissions arising from a loss of woody vegetation caused by tidal restoration activities may be overestimated in some instances, leading to conservative estimates of abatement. The biomass of any herbaceous vegetation in the baseline was assumed to be 4.2 Mg dry matter/ha (Australian Government Department of Industry, Science, Energy and Resources 2018).

Soil Organic Carbon in the Baseline

SOC dynamics vary depending on the baseline land uses (Lasco et al. 2006). Soil organic CAR in the baseline scenario may be negative (i.e. a net emission of CO_2) or positive (i.e. a net sink of CO_2). A shift in land use from baseline conditions where soil organic matter is oxidized due to drainage, disturbance or excavation of soils, to conditions where soils accumulate mineral and organic material can stimulate significant CO_2 abatement for some restoration projects (Kennedy et al. 2014; Needelman et al. 2018). Rates of organic matter decomposition control the direction and magnitude of GHG fluxes and are influenced by changes in inundation/moisture, salinity, temperature regimes, and the degree of soil disturbance in the baseline land use activities (e.g. Iram et al. 2021).

In the case of tidally restricted wetlands, CAR in Australia was estimated as 0.47 Mg C ha^{-1} yr^{-1}. These values were derived from estimates of soil CAR in hydrologically modified mangrove forests, saltmarshes, and other herbaceous communities from three Australian sites and are therefore applicable to a range of baseline tidally restricted wetlands (Table S2). Soil CAR within salt evaporation ponds that are in production have demonstrated no SOC accumulation (Gulliver et al. 2020). Coastal wetlands may also occur in the baseline, and in this case CAR values from natural coastal wetlands (Table 3) were used to calculate carbon sequestration in the baseline.

Soil Organic Carbon Loss with Agriculture

Agricultural land uses in the baseline can result in CO_2 emissions as tillage and other practices disturb soils resulting in decomposition of soil organic matter (IPCC 2019). Soil CO_2 emissions from baseline land uses were linked to SOC stocks in the baseline land uses (Table 4) following the approach of Hagger et al. (2022). Annual SOC stock change factors (Table S3) were applied to SOC estimates for different land uses for the different climatic regions that were extracted from the Australian national SOC map (Table 4).

Non-CO_2 Emissions from Baseline Land Uses and Restored Coastal Wetlands

The restoration of tides and changes in land use resulting from an ERF project activity can also influence the emissions of methane (CH_4) and nitrous oxide (N_2O) from soil and water (Fig. 2; $\boldsymbol{E_{B,CH_4}}$, $\boldsymbol{E_{B,N_2O}}$). The production of CH_4 and N_2O arises from microbial activity that is influenced by anoxic soil conditions (which enhance GHG emissions), temperature (with higher emissions in warmer/tropical regions and lower emissions in colder/temperate regions), salinity (where high salinity may lower CH_4 emissions), the intensity of eutrophication (nutrient enrichment from fertilizers enhances N_2O emissions), and SOC and vegetation type and structure (Poffenbarger et al. 2011; Al-Haj & Fulweiler 2020; Iram et al. 2021). GHG emissions for baseline land uses were available for most land uses but were not available for each climatic region (Table 5).

For coastal wetland GHG emissions (Fig. 2; $\boldsymbol{E_{CW,CH_4}}$, $\boldsymbol{E_{CW,N_2O}}$) the data were divided into two climatic regions, one with relatively low emissions (arid/semiarid, temperate, and tropical humid) reflecting saline, cool, and oligotrophic environments, and the other with higher emissions (monsoonal tropics and subtropical) that are warm and with higher nutrient levels and/or lower salinity (Table 6). Because GHG emissions vary with levels of inundation, plant productivity, and salinity (Poffenbarger et al. 2011; Iram et al. 2021), GHG emissions from mangroves were adjusted over the intertidal zone using the same multiplier used for biomass (Table 2). There were no GHG data for sparsely vegetated saltmarshes (salt flats) which were allocated emission factors of zero given theoretical expectations that high salinity, limited inundation, and low SOC density in this coastal wetland type would result in low levels of GHG emissions (Poffenbarger et al. 2011; Al-Haj & Fulweiler 2020). The overall approach resulted in GHG emission values in BlueCAM that are lower than global values of GHG emissions from coastal wetlands (Kennedy et al. 2014) (Tables S6 & S7). Lower GHG emissions in Australian coastal wetlands likely reflect conditions arising from the stable sea levels over many thousands of years (Rogers et al. 2019*a*, 2019*b*), high salinity (due to aridity), low carbon and nutrient levels in

Australian wetlands compared with many other global locations where freshwater flows, nutrient enrichment, and productivity are higher (Al-Haj & Fulweiler 2020; Iram et al. 2021).

CO_2 Emissions from Excavation of Soils and Fuel Consumption

During tidal restoration projects, excavation of soils may be needed to alter the hydrology of sites, and the construction of tidal barriers (e.g. bund or levee walls) may be required to prevent flooding of adjacent areas. In BlueCAM emissions associated with soil excavations (included within the term CP_{ir}; Fig. 2) were assumed to be 50% of the SOC stock of the excavation area (Atwood et al. 2017; Lovelock et al. 2017). SOC stocks for baseline land uses were extracted from the Australian national SOC map (Viscarra Rossel et al. 2014, estimated to 30 cm) (Table 4) and for coastal wetlands from Serrano et al. (2019; estimated to 1 m).

Emissions from fuel consumption (E_{fk}; Fig. 2) associated with the project are calculated separately to the land-based components of BlueCAM using parameters provided by the National Greenhouse and Energy Reporting Regulations (http://www.cleanenergyregulator.gov.au/ERF/). Fuel emissions associated with the project are subtracted from the net abatement after calculation of the land-based emissions and removals (Fig. 2).

Table 4. Mean values of soil organic carbon (SOC) stocks to 30 cm for grazing and sugarcane (cropping) land for Australia. Values are derived from the Australian soil organic carbon map (Viscarra Rossel et al. 2014) for land on the coast (delineated using the Smartline Coasts Sediment Compartment and Realms data, available online). NA indicates where data is not available.

Climatic Region	*Mean Grazing SOC (Mg C/ha)*	*Mean Sugarcane SOC (Mg C/ha)*
Tropical monsoon	40.2	42.0
Tropical humid	63.7	67.8
Subtropical	65.3	64.0
Semiarid/Arid	30.4	NA
Temperate	62.2	NA

Uncertainty Analyses and Limitations of BlueCAM

BlueCAM is a model with multiple inputs (Fig. 2) that are cumulative but have differing levels of uncertainty. To understand the likely distribution of values from blue carbon projects and facilitate comparison to the BlueCAM deterministic outputs (based on the use of mean and median values for inputs), we assessed the uncertainty using Monte-Carlo simulations (1,000 simulations). These analyses found that BlueCAM outputs were similar to the 40th percentile of the simulated outputs (Figs. S2 & S3) and therefore are conservative estimates of abatement. The distribution of the potential abatement for six scenarios from the Tropical monsoon climate region are shown in Figure S2.

Discussion

BlueCAM has limitations that may be improved in the future. These include the use of a regional approach, based on climate regions, that does not include finer scale landscape variations due to geomorphic setting and other environmental factors that may influence the level of abatement achieved with tidal restoration of coastal wetlands (Rogers et al. 2019*a*, 2019*b*; de Paula Costa et al. 2021). For example, the use of STPI boundaries to apply multipliers for reducing abatement at high elevations may vary among landscapes with different geomorphological and hydrological characteristics (Glamore et al. 2021). BlueCAM could be improved with further refinement of input parameters that are uncertain because of limited data availability or because they are based on other models (e.g. SOC in the baseline land uses).

Table 5. Greenhouse gas emissions, median values (range in parentheses), of methane and nitrous oxide from baseline land uses in Australian coastal land from published and unpublished data. *Includes natural and constructed ponds and tidally restricted fresh and brackish wetlands. Shaded cells are values not included in BlueCAM because they are not implemented in Australia's Greenhouse Gas Inventory.

Baseline Land Uses	*Emissions of CH_4 (kg ha yr^{-1})*	*n*	*Emissions of N_2O (kg ha yr^{-1})*	*n*
Wetlands				
Flooded agricultural land, managed wet meadow or pasture	325.0 (3.3 to 1,594.3)	6	14.0 (2.7 to 25.3)	2
Ponds and other constructed water bodies*	226.3 (4.4 to 420.5)	2	NA	
Aquaculture (in production)	NA		Linked to product yield (Kennedy et al. 2014)	
Aquaculture (not in production) saline (if not saline, use value for ponds)	−0.1	1	0.6 (0.2 to 0.6)	3
Forest land				
Melaleuca forest	1.2 (−2.2 to 4.7)	2	0.2 (0.2 to 0.3)	2
Unmanaged forest	−1.4 (−2.2 to −0.7)	5	0.7 (0.6 to 1.8)	12
Crop land				
Sugarcane	0.0 (0.0 to 44.2)	3	12.2 (0.0 to 37.8)	11
Cropping	0.0 (0.0 to 0.4)	2	0.7 (0.6 to 1.8)	6
Drainage channels or ditches in cropland	62.4	1	NA	
Grassland				
Managed (grazing)	3.2 (−11.3 to 1,019.2)	7	0.3 (0.0 to 1.0)	4

Table 6. Greenhouse gas emissions, median values (range in parentheses), of CH_4 and N_2O from different climatic regions in Australian coastal wetlands from published and unpublished data. Negative values indicate a net sink (uptake).

Climate Regions	*Emissions CH_4 (kg ha yr^{-1})*	*n*	*Emissions N_2O (kg ha yr^{-1})*	*n*
Arid/semiarid, temperate, tropical humid				
Mangroves	2.19 (0.91 to 3.31)	3	0.24 (0.17 to 2.75)	3
Saltmarsh	0.11 (−0.21 to 0.44)	2	0.13 (0.02 to 0.23)	2
Seagrass	0	1	0	1
Supratidal forest	−2.19	1	0.25	1
Sparsely vegetated saltmarsh (salt flats)	NA		NA	
Tropical monsoon, subtropical				
Mangroves	13.33 (5.01 to 15.51)	3	2.3 (−0.05 to 10.10)	5
Saltmarsh	6.42 (−0.17 to 17.19)	4	2.43 (2.19 to 2.66)	2
Seagrass	0	1	0	1
Supratidal forest	4.64	1	0.18	1
Sparsely vegetated saltmarsh (salt flats)	NA		NA	

Emissions associated with building structures (e.g. concrete associated with tidal gates) were not included because they were estimated to be a minor component of total emissions; however, as data becomes available in the future, these types of emissions could also be included in calculations of total emissions.

One of the key differences between the *Tidal Restoration of Blue Carbon Ecosystems Methodology Determination 2022* and the blue carbon restoration methods developed within Verra (Verra VM0033; Needelman et al. 2018) is that BlueCAM does not include discounts for allochthonous carbon that is trapped in coastal wetlands and incorporated within soils. While allochthonous carbon has been detected in coastal wetland soils in Australia, contributions of allochthonous carbon were typically small compared to autochthonous sources in saltmarshes and mangroves (Saintilan et al. 2013), but large in some sites for seagrass (Samper-Villarreal et al. 2016). In Australia's existing accounting framework, organic carbon that is eroded from landscapes and transported to the coast is assumed emitted as CO_2, and therefore any portion of this organic carbon trapped in coastal wetlands could be considered an avoided emission (Kelleway et al. 2020). Under the Australian carbon accounting framework excluding this avoided emission, which is uncertain in magnitude, is a conservative approach consistent with the ERF standards (Kelleway et al. 2020). Future development of BlueCAM could revisit the importance of allochthonous carbon sources and sinks.

Despite the limitations of BlueCAM it is an approach based on robust, empirical observations that will reduce the costs of implementing blue carbon tidal restoration projects, because onground field measurements of abatement are not required (although evidence of coastal wetland restoration is required). Field measurements are costly, may not always be logistically feasible and also have uncertainties (e.g. in allometric relationships) (Adame et al. 2017). Assessments of trade-offs between precision and cost for monitoring and verification of forest carbon projects have shown that costs of monitoring and verification can exceed the revenue from carbon credits and that cost is a critical component in development of forest carbon methods that provide incentives (Köhl et al. 2020). The tidal restoration activities for which BlueCAM was developed has costs associated with hydrological assessments and reducing project risks to adjacent land holders and therefore the use of BlueCAM may reduce the risks of limited financial incentives to participate in blue carbon projects. As the *Tidal Restoration of Blue Carbon* method is tried and tested, detailed assessments of financial return on investment may become available, helping to advance knowledge needed to support coastal wetland restoration (Bayraktarov et al. 2016). Additionally, as projects are developed and more data become available, BlueCAM can be revised to improve the accuracy of model projections, a process that has occurred with the terrestrial Australian full carbon accounting model (FullCAM; Richards & Evans 2004; Roxburgh et al. 2019).

Estimations of blue carbon from tidal restoration of coastal wetlands can provide incentives for restoration, which, if implemented, will provide multiple ecosystem services that benefit coastal communities (Barbier et al. 2011; Duarte et al. 2013). Development of methodologies that are simple and inexpensive to implement is an important element in promoting uptake of restoration projects. Here we have developed a model for abatement with tidal restoration of Australian coastal wetlands which uses the large body of research available within Australia. BlueCAM could be extended to cover activities in addition to tidal restoration (e.g. seagrass restoration or avoided clearing or disturbance activities). Given the similarities of Australian coastal wetlands to others in the Indo-Pacific region (in similar climatic and biogeographic regions), BlueCAM may be widely applicable, although verification and development of appropriate parameters for sites outside Australia would be needed before it could be used with high levels of confidence.

The uncertainty in BlueCAM outputs reflects limited data for some input parameters, which may be improved with further field measurements and incorporated in future models of component processes. BlueCAM may be updated over time to include new information from tidal restoration projects, that can further improve the accuracy of estimates of abatement and which may be available at finer spatial scales (e.g. Lymburner et al. 2020). BlueCAM enables the implementation of new blue carbon restoration projects using tidal restoration activities, thereby enhancing carbon capture, and facilitating reductions in GHGs to the atmosphere as well as restoration of the multitude of ecosystem service benefits provided by coastal wetlands.

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Supporting Information

The following information may be found in the online version of this article:

Figure S1. Box and whisker plot of Australian soil carbon accumulation rates by ecosystem type and climatic region.

Figure S2. Simulated frequency of abatement estimates over 25 years for 1 ha with transitions from a range of baseline land uses to mangroves in the topical monsoon climate region.

Figure S3. Relationship between abatement estimated by BlueCAM for 1 ha at 25 years (in CO_2e) and the value of the 40th percentile of 1,000 Monte Carlo simulations of carbon abatement.

Table S1. Published and unpublished estimates of soil organic carbon accumulation used in calculation of project scenario ecosystem soil organic carbon accumulation.

Table S2. Published and unpublished estimates of soil organic carbon accumulation used in calculation of baseline land use soil organic carbon accumulation.

Table S3. Summary of stock change parameters for a subset of baseline land uses in tropical Queensland.

Table S4. Links to documents supporting the Tidal Restoration of Blue Carbon Ecosystems Methodology Determination 2022.

Table S5. Mature aboveground biomass carbon (mean and standard error, Mg C ha^{-1}) in coastal wetlands of Australia.

Table S6. Comparison of carbon stocks and fluxes in the Tidal Introduction BlueCAM and those provided by the Kennedy et al. 2014 (Tier 1 default values).

Table S7. Comparison of greenhouse gas fluxes in the Tidal Introduction BlueCAM and those provided by the IPCC 2013, 2019 (Tier 1 default values).

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