How methane emissions from mangroves matter for coastal blue carbon accounting

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1. What is coastal blue carbon and why is it important?

Coastal blue carbon (CBC) is carbon that is captured by coastal and marine organisms, and then stored in their coastal ecosystems. Up to 80% of the CBC captured in these shallow coastal ecosystems (SCE) is stored in the soil, which differentiates them from other carbon-storing ecosystems, such as tropical rainforests. Other carbon-storing ecosystems typically store most of their carbon in their biomass instead. Storing CBC in soil makes it much more stable, meaning it's stored longer because carbon fluxes in biomass are much higher than in soil. Thus the soil CBC reservoirs in these SCEs are essential in understanding the carbon storage potential of SCEs.

SCEs are important for both climate change mitigation and adaptation because on top of being important carbon sinks, they protect coastal communities from sea level rise and its associated effects. SCEs and their associated CBC have not been a significant part of the mitigation conversation until recently due to lack of peer-reviewed data on them and their carbon fluxes. This is also due to the amount of methane (CH_4) they produce naturally, which offsets some of the carbon dioxide (CO_2) stored as carbon in SCEs. There is still a lot of research to be done, but there is enough data to suggest that SCEs are important carbon sinks and are even better at storing carbon than their terrestrial counterparts.

A typical tropical mangrove near Tampa, Florida

Like most other ecosystems, mangroves are disappearing at an alarming rate due to human activity. The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services estimates that 87% of SCEs have been lost globally in the last 300 years. Around 35% of the world's SCEs have been lost between 1970-2015 and this rate has been accelerating annually since 2000. These losses have been driven by megatrends such as climate change, population increase, urbanization, particularly in coastal zones, and changing consumption patterns that have all fueled changes to land and water use and agriculture. The world's remaining SCEs are under threat due to water drainage, climate change, pollution, unsustainable use, invasive species, disrupted flows from dams and sediment dumping from deforestation and soil erosion upstream.

2. Mangroves and their importance in climate mitigation

For our purposes, the term SCE refers to three main types of coastal ecosystems: seagrass beds, salt marshes, and mangroves. Of the three, mangroves are by far the most common and have the most research, so we will focus on them in this analysis. Mangroves are intertidal forests, including more than 70 species of trees and shrubs, some ferns and palms. They are known for their iconic aerial roots that grow out of the water, which fulfill many important functions for the trees themselves, as well as the ecosystem as a whole. This highly specialized root structure allows them to directly absorb gasses from the atmosphere, instead of through soil or water like most other plants. Their roots also trap and hold nutrients, peat, and sediments, as well as help mute incoming tidal energy that could otherwise cause inland erosion.

An example of mangroves' submerged extensive above-ground root systems

Their ability to combat erosion from accumulating soil and diminishing wave energy make them important for ecosystem preservation, but they are also incredibly effective carbon sinks. They cover an estimated 139,170 square kilometers worldwide, but have a much larger historical range at more than 200,000 square kilometers. Their extent has shrunk steadily mainly due to coastal development. They are concentrated in tropical zones, with 95% of them found near the equator. In total, mangroves store around 10 GT of CBC, equivalent to 36.67 GT CO_2eq [1], worldwide. Mangrove forests account for 65% of all the carbon stored by SCEs worldwide [2], and 1.16% of all carbon stored by forests worldwide [3].

Outside of tundra and peatlands, mangroves store more carbon per unit area than any other ecosystem, storing three to four times the amount of carbon found in terrestrial forests. Globally, they sequester 0.015 GT of carbon annually [4], equal to 0.055 GT CO_2 [5]. On top of overall carbon stock, mangroves' carbon burial rates are also very high, with one study finding that they can sequester up to 40 times more carbon than similarly sized rainforests.

The reason mangroves are such efficient carbon sinks is because their submerged soils are largely anaerobic. The lack of oxygen causes decomposition to occur at slower rates than in aerobic, or terrestrial, ecosystems, meaning microbes break down organic matter and respire the CO_2 back into the atmosphere slower as well. This allows the organic matter to remain intact for longer periods of time, thus lowering the carbon flux of the ecosystem. Mangroves' terrestrial counterparts have higher carbon fluxes and thus return the CO_2 they sequester to the atmosphere at much faster rates.

3. SCEs and CBC in climate change literature

Despite their essential role in global climate regulation, SCEs remain undervalued by policy and decision-makers in national plans. However, in recent years the IPCC and other international organizations have begun to include SCEs in climate mitigation plans. In fact, CBC was included in the 2022 IPCC report and is being included as an important climate mitigation strategy. The IPCC states with high confidence that restoring SCEs will help sequester CO_2 effectively. Restoring SCEs can help provide clean water, bring job opportunities, increase biodiversity, and provide ecosystem restoration. SCEs also help reduce disaster risk, as they mitigate floods and protect coastlines. However, the lack of research has left significant gaps in our knowledge of the carbon and methane fluxes in SCEs, as well the potential of CBC in being a long-term, reliable carbon sink. Therefore, research, such as the main Australian offset study we're analyzing, on methane emissions and its impact on mangroves' overall climate mitigation potential is crucial.

4. Methane emissions in mangroves explained

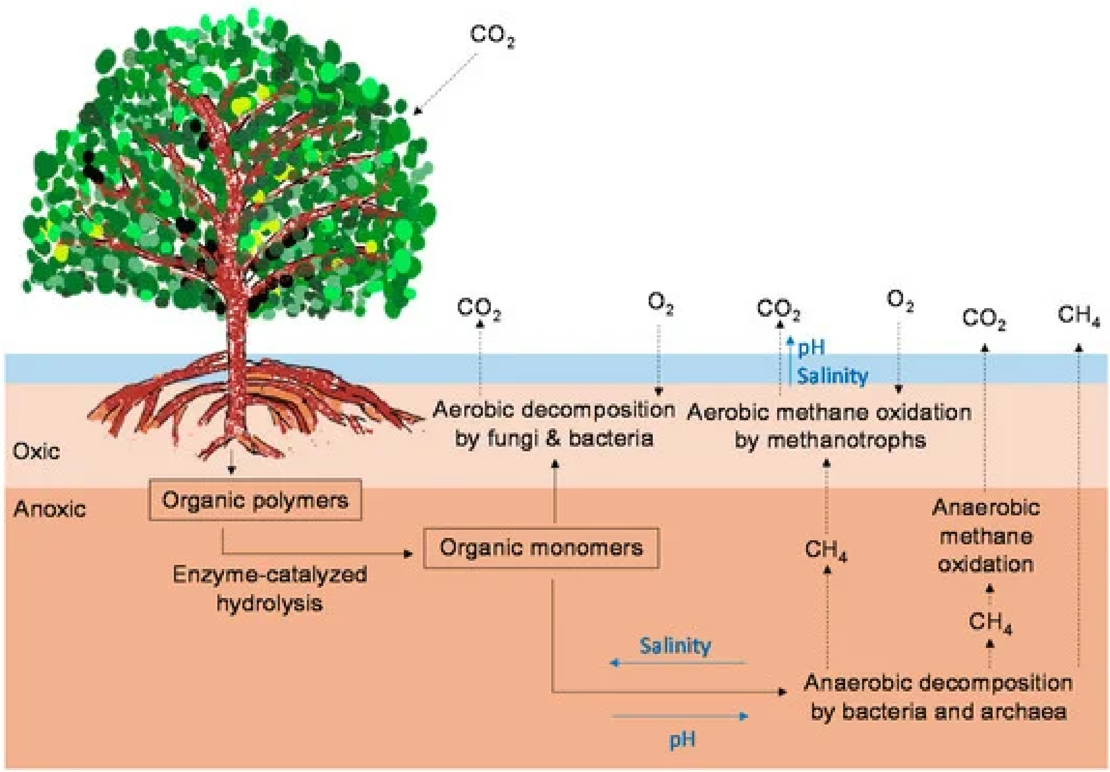
The associated methane emissions of mangroves is a huge contributing factor to assessing their viability as a climate mitigation strategy. These emissions have created uncertainty in the capacity that CBC systems can be relied upon for carbon sequestration. The production of methane in mangroves is a result of a class of archaea, called methanogens. Methanogens live in anoxic habitats, devoid of oxygen, like the water and sediment that make up mangroves' abiotic environment. They produce this methane by converting hydrogen and CO_2 to methane.

Chemical equation of this process:

$$\mathbf{CO_2 + 4\,H_2 \rightarrow CH_4 + 2\,H_2O}$$

This process is called methanogenesis, generating the methane as the final product of their metabolism. The methane produced in turn helps release ATP for their cellular processes. Even with their methane production, methanogens are vital parts of mangrove ecosystems. In fact, the very anoxic environment they require is the reason why decomposition is so slow in mangroves and allows for such high CO_2 burial rates. Methanogens are also the key to fixing nitrogen, which is a limiting resource in these environments, as nitrogen is commonly washed offshore by tides. They fix the nitrogen that mangrove trees require for regular plant function and amino acid production, making them essential to the trees' existence in saline habitats. They are the crux of a healthy mangrove ecosystem, making their methane emissions unavoidable. This anoxic environment is also the reason why mangroves have such high burial rates: the natural decomposition of biomass happens much slower in anoxic environments than in ones with oxygen. So, mangrove's anoxic environment is the reason why they have such high carbon stocks, but the tradeoff is that the slower anaerobic decomposition also emits methane.

Possible pathways for CO_2 and CH_4 emissions from mangrove forests

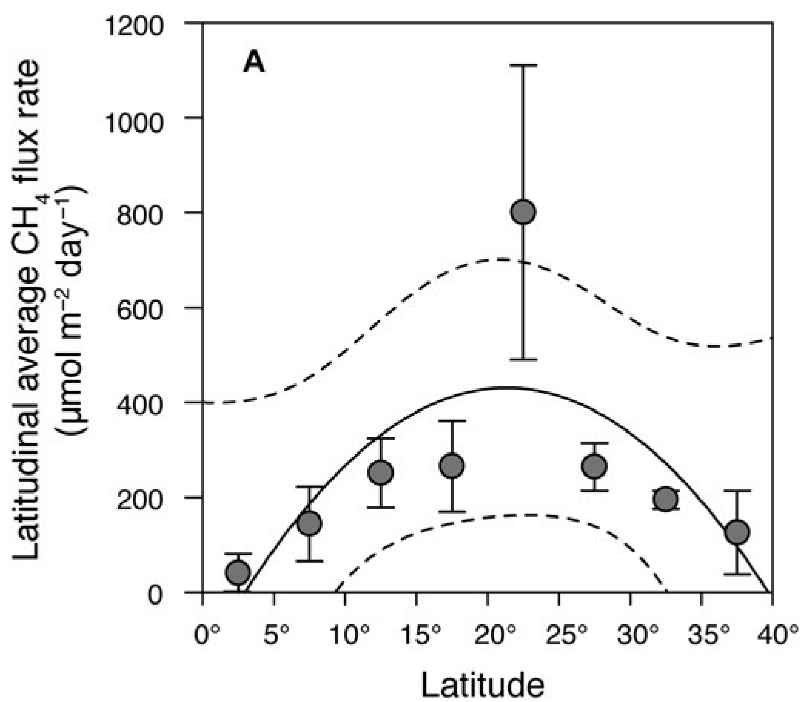


This image visualizes how different reactions throughout a mangrove ecosystem cycle gasses and nutrients. Methane originates from anaerobic decomposition in anoxic (oxygen-free) zones, which is why it is so prevalent in mangroves: their anoxic zones are crucial nitrogen-fixing parts of the ecosystem. Typically, in these systems there are other sources of methane, such as tree stems, but this is a simple representation. Methane in this system can be stopped before reaching the atmosphere by oxidation, either by aerobic oxidation or with anaerobic oxidation. When these occur, instead of methane being released, it is turned into carbon dioxide instead. When not oxidized, methane enters the atmosphere; this is the main methane emission pathway in mangroves.

5. Why mangrove methane emissions matter

Methane is the second most important greenhouse gas (GHG) behind carbon dioxide, and has caused approximately 20% of global warming since pre-industrial times. Because methane emissions are a natural part of mangrove function, these emissions inevitably offset some of the CO_2 sequestered. The offset study we're analyzing provides the first estimate of the global impact of this CO_2-methane offset. It found that these methane emissions dampen the positive climate impacts of the mangroves' CO_2 sequestration, as the released methane effectively negates the carbon removal benefits at an average of 20%, with high confidence that it's between 18-22%. In some latitudes, this number can be as high as 65%. The amount of methane released may be significantly lower than the amount of carbon dioxide stored, but methane is much more potent as a GHG.

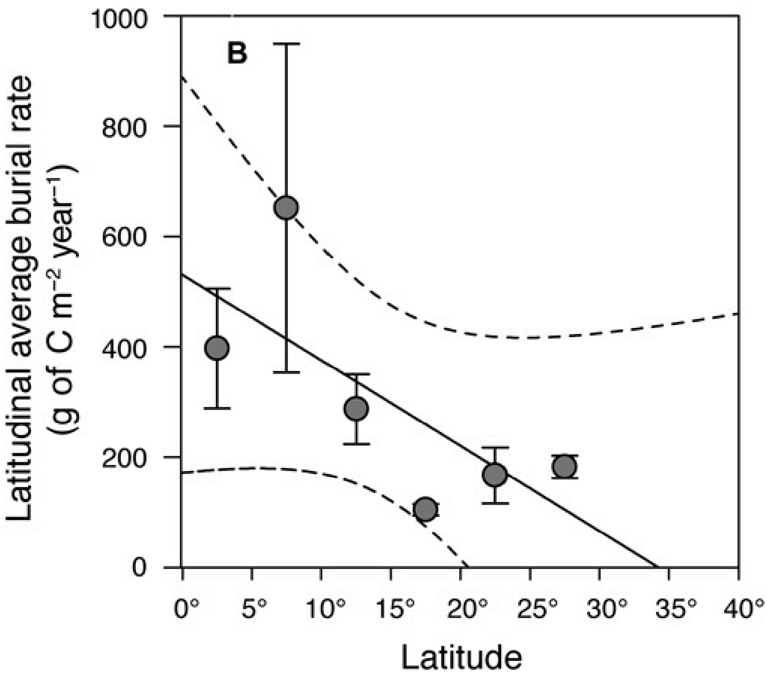
Latitudinal average mangrove CH_4 flux rates



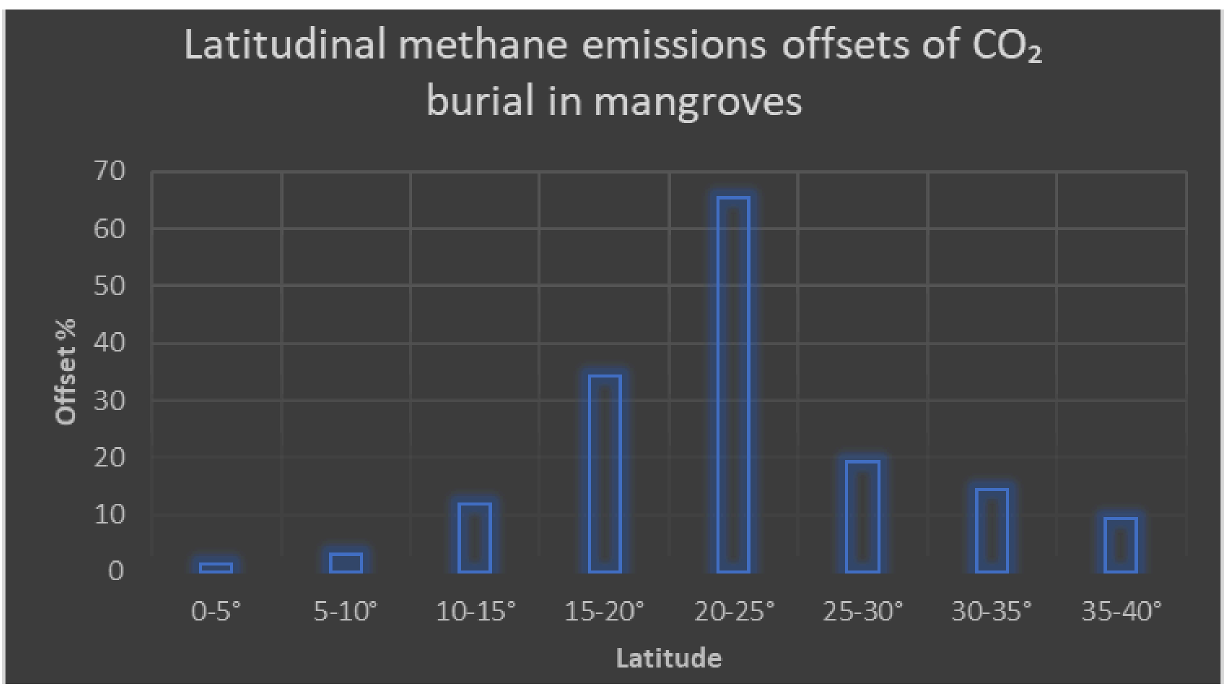
The latitude of where mangroves are located is loosely correlated with the amount of methane that is in flux at that site. Most latitudes have similar methane flux rates, between 25-225 micromoles per square meter per day, but the latitude of 20-25° has a significantly higher rate at more than 800 micromoles per square meter per day. This causes this latitude to have such a high offset between the CO_2 buried and methane emitted.

There is also evidence that there's a correlation between higher carbon burial rates and lower latitudes. This is likely due to the higher productivity of more tropical regions, allowing for more sequestration of carbon in the soil. Higher productivity causes higher burial rates because there are more plants to photosynthesize and sequester CO_2. Plants in ecosystems with higher productivity have access to more nutrients, allowing for faster performance of natural processes. These higher burial rates are important because the more CO_2 that is sequestered, the more methane emissions' effects are lessened. This is significant because it allows climate and conservation experts to focus more on lower latitudes to achieve higher carbon sequestration.

Latitudinal average carbon burial rates



This figure visualizes the average burial rate of carbon by latitude. The higher the burial rate, the lower the CO_2-methane offset percentage because the more units of CO_2 sequestered for every unit of methane emitted, the lower the offset drops. Simply put, higher burial rates signify proportionally less impact from methane emissions. Because most latitudes produce similar amounts of methane (except 20-25°), carbon burial rates are an important indicator of the offset percentage. Higher productivity in lower latitudes is what causes higher burial there. The highest latitudes have no data as the study was unable to correctly identify the burial rates for these latitudes.



This figure visualizes the percent of mangroves' CO_2 sequestration that's offset by their methane emissions based on the latitude range they fall into. While the lowest latitudes between 0-10° essentially have no offset, the other latitudes of 10-15° and 25-40° also all have offsets lower than 20%, which is the average of all mangroves. The middle latitudes between 15-25° have the highest offsets, with 20-25° having the highest at 65.8%. This high number has the biggest implications for mangroves as a climate mitigation strategy, because it makes focusing on them seem less worthwhile.

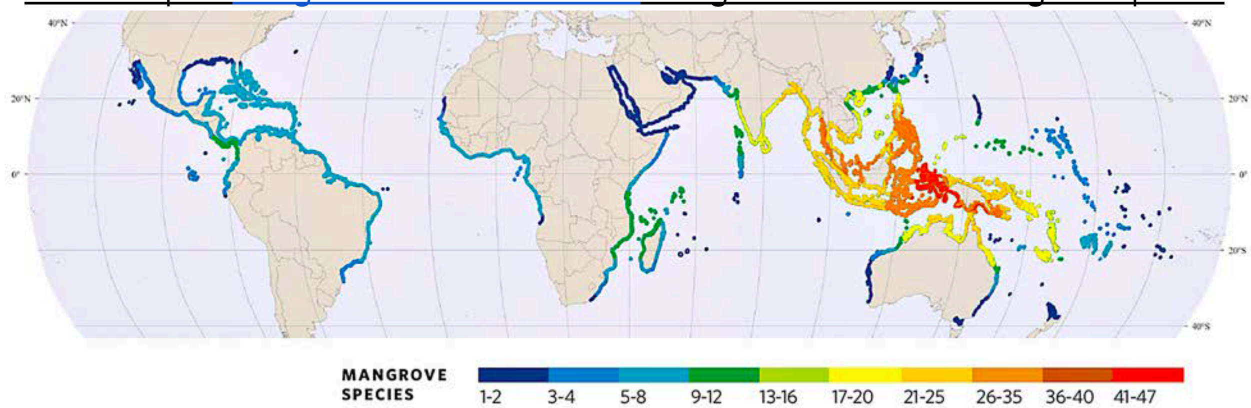
The lowest latitudes (0-15°) are the most tropical and thus have the highest productivity rate, which lends itself to higher CO_2 burial and thus a lower offset percentage. The higher latitudes (25-40°) have low offset percentage estimates because they have most likely been underestimated in previous literature, and don't have methane emissions data. This knowledge gap needs to be addressed in future studies, but overall mangroves in these latitudes do not have a large effect on total offsets because they represent such a small area of all mangroves, since 95% of mangroves fall outside of this latitude range.

The middle latitudes (15-25°) have the highest offset percentage due to lower burial rates coupled with high methane emissions. Furthermore, mangrove biomass per unit area is lower in midlatitudes, leading to lower burial rate and thus resulting in a higher offset percentage. Relatively high amounts of carbon are still stored in these locations, but the effectiveness of their storage is lowered by the amount of methane produced. Environmental factors also contribute to offset percentages. Specifically, climate and biodiversity play a key role in the percent offset mangroves in these areas have. Our analysis does not focus on this, but these factors are important in further understanding these offsets.

Weaving the data from the methane flux and carbon burial rate figures together, we can put our visualization of the percent offsets into context. The highest offset, between 20-25°, can be explained by the high methane fluxes in this latitude, since its carbon burial rate is comparable to similar latitudes (with the exception of the lowest latitudes). Conversely, the lowest offsets, between 0-15°, can be explained by high carbon burial rates, since their methane fluxes are comparable to most other latitudes (with the exception of 20-25°).

The other low offset, between 30-40°, is most likely due to the lack of methane flux data in these latitudes. Thus this low percentage should not be accepted as accurate, as reliable methane flux data still needs to be recorded to ascertain an accurate CO_2-methane offset percent for these latitudes. Overall, both carbon burial and methane flux rates are necessary to determine the offset for a certain latitude, making the results of this study a crucial benchmark for future estimates as well.

World map of mangrove distribution zones & regional number of mangrove species



This map represents the global locations and concentrations of mangroves across to help visualize the high concentration of them between 20°N and 20°S. The high concentration in lower latitudes shows that the majority of mangroves fall in the <20% CO_2-methane offset category, meaning most of them do not have the issue of high offset percentages associated with midlatitudes. In fact, the mangroves with highest species diversity and overall area are mostly concentrated in the lowest latitudes, which have negligible to very low (<10%) offset percentages.

6. How methane's global warming potential factors in

The discrepancy in potency between GHGs is expressed in global warming potential (GWP), which is a measure of how much energy the emissions of 1 ton of a GHG will absorb over a given period of time, relative to the emissions of 1 ton of CO_2. The IPCC quantifies the GWP of methane to be 27.2 times greater than that of CO_2 on a 100 year timescale, and 80.8 times greater than CO_2 on a 20 year timescale. The use of two different timescales is due to the fact that methane's atmospheric lifetime is far lower than CO_2, at around 12 years for CO_2 versus 300 to 1000 years for methane, respectively. So, when using 20 years, methane emissions are more potent than when using 100 years, since their effects will be far lower the longer the time period because methane's atmospheric lifetime is relatively short.

The study's 20% offset estimate uses methane's 20 year GWP, meaning mangroves' "real" CO_2 sequestration rates are only 80% of their face value for the near future. This means the adjusted CO_2 sequestration rate for mangroves is 0.044 GT CO_2 annually [6]. This represents around 0.076% of total annual global anthropogenic CO_2eq emissions [7]. While this number is small, in comparison mangroves account for only 0.027% of Earth's surface area [8], meaning they sequester almost three times as much CO_2 as the area they occupy.

However, this 20% offset drops significantly when using the 100 year timescale GWP. We calculated the new offset average as 6.7% [9], with a range of between 6-7.4% [10], when using methane's 100-year GWP. This is a huge drop in offset percentage, almost three times smaller in fact, meaning if we're thinking long term, mangroves' methane emissions become far less of an issue. While short term emissions are very important because the climate crisis has become so urgent, we must still plan long term because climate mitigation is not a quick-fix process.

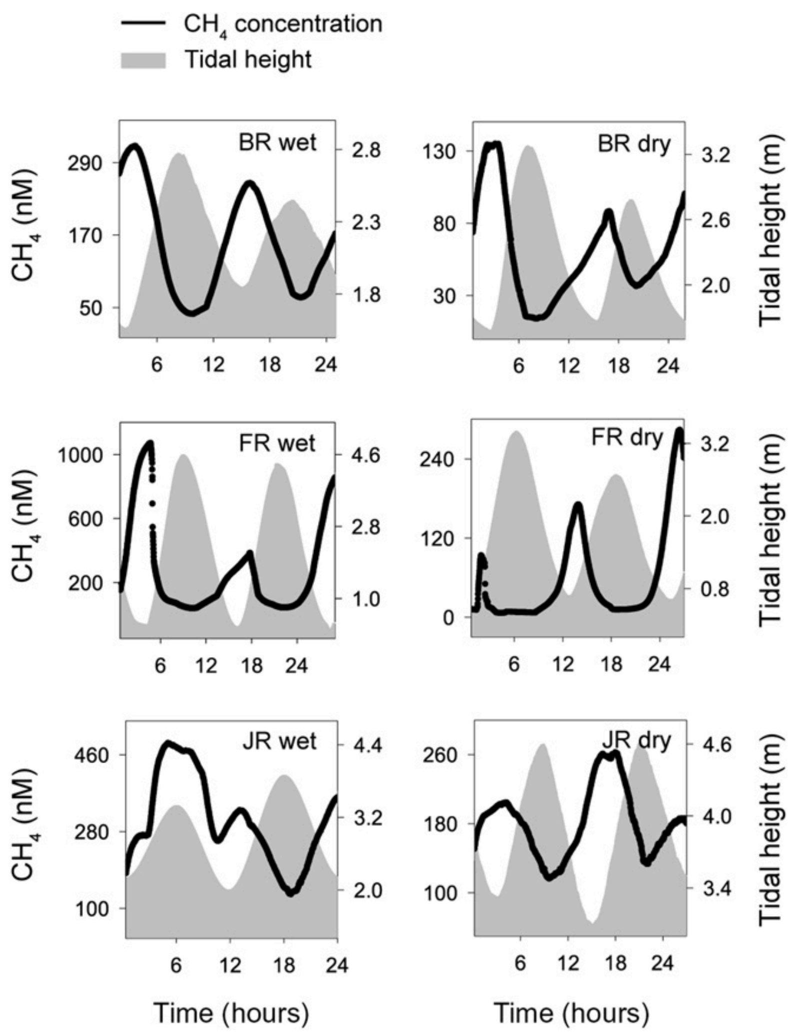
Many of the Paris Agreement's goals are anchored in 2050, while most of the IPCC's estimates and strategies are anchored in 2100. So depending on which organization's goals you look at, mangroves as a mitigation strategy can be more or less attractive based on the offset estimate used. Countries trying to fulfill their Nationally Determined Contributions (NDC) for the Paris Agreement may see the 20% offset as not as worthwhile, but the IPCC's yearly reports could take the much lower 6.7% offset into consideration and increase the role of mangroves in carbon dioxide removal strategies.

7. Disturbances and their effects on mangrove methane emissions

While healthy mangroves' methane emissions are a concern that should be part of the overall carbon accounting when evaluating them as mitigation measures, degraded and destroyed mangroves produce far more emissions than healthy ones do. As mentioned, significant portions of mangroves have already disappeared and coastal human development has accelerated this. The most common anthropogenic disturbances are due to conversion for agriculture and aquaculture. Aquaculture especially has substantial negative impacts on mangrove carbon stocks, leading to an average of 83% reduction in biomass and a 52% reduction in soil carbon.

The draining of mangroves for agriculture also leads to higher methane emissions. This is because drainage upends the balance of the ecosystem by removing the water which provides nutrients, houses microorganisms, and building blocks of mangroves. This leads to less productivity and thus less carbon burial, as well as increased methane emissions due to faster decomposition of organic matter. Drainage essentially makes mangroves' burial process and rate more similar to their terrestrial counterparts' process and rate, removing the high CO_2 burial rates which make mangroves so valuable for sequestration. Furthermore, the Australian offset study found that the highest methane emissions occurred at low tide (exposed sediments) and the lowest methane emissions occurred at high tide (full submersion of mangrove roots). This provides further evidence that exposing mangrove soil to the air increases overall emissions, on top of the other negative effects of drainage on ecosystem health.

CH_4 concentrations over two tidal cycles



This figure visualizes the offset study's findings that methane emissions increase with lower tides: methane concentrations are compared to time of day, which directly corresponds to tidal height. It shows the three different sites (BR, FR, JR) studied during the wet and dry seasons in Queensland, Australia. Methane concentrations are typically higher when the tide is low, and typically lower when the tide is high. There are two reasons for this. One is that at high tide, methane oxidizing bacteria are able to oxidize methane before it's released to the atmosphere. The other is that during high tide, the increase in hydrostatic pressure helps keep methane emissions low. The hydrostatic pressure during low tide is not as high, which enables more methane emissions to occur.

Another study has shown that mangrove death causes surplus methane emissions compared to healthy mangroves' emissions. Dead mangroves remain an active part of the carbon cycle, and their methane emissions are eight times or more higher than the living mangroves. This accounts for approximately 26% of total mangrove methane emissions, meaning increasingly disturbed mangroves will only increase methane emissions in the future.

8. Disturbances and their effects on mangrove CO_2 burial rates

Projecting current mangrove deforestation rates into the future, they could result in an additional 0.6785 GT CO_2eq emitted by 2095 [11]. This loss of soil carbon from the destruction of mangroves and other SCEs contributes to at least 3-19%, or 0.15-1.02 GT CO_2 [12], of global annual deforestation-caused CO_2 emissions. In total, all deforestation activities account for 9% of global GHG emissions [13]. This means that 0.27-1.71% of global GHG emissions are caused just by mangrove and other SCE deforestation [14]. In contrast, one study estimates that if left undisturbed, mangroves' carbon sequestration could expand their carbon stock by around 0.016 GT annually [15], or 0.0587 GT CO_2eq [16].

Another source of indirect anthropogenic disturbances is climate change. Sea level rise (SLR) and intensifying tropical storms, both caused by global warming, are the main culprits. SLR leads to release of soil carbon in mangroves due to flooding that kills trees. These dead trees in turn emit carbon from the decomposition of their decaying biomass, as well as emitting methane from their dead stems.

Intensifying tropical storms, like cyclones, have devastating effects on mangroves as well. After a series of these storms, the disturbed environment begins to select for short-saturated forests, which have dense, closed canopies of short, stunted trees that grow in waterlogged soils. They have shallow root systems, whereas mangroves have much deeper root systems, which causes them to have much smaller carbon stocks than mangroves. Additionally, their shallow roots make them more susceptible to toppling over in high winds, making for a much less stable ecosystem and thus carbon stock as well. Consequently, these storms indirectly decrease and destabilize mangrove carbon stocks. If deforestation and climate change related disturbances continue, mangroves will release more GHGs.

9. Conclusions and recommendations moving forward

Based on our analysis of the Australian offset study and supporting literature, we conclude that protecting and restoring mangroves is the best course of action regarding the role they should play in climate mitigation. While the average 20% offset needs to be accounted for in CBC assessments, it does not negate the overall carbon burial benefits of mangroves. In fact, the study's latitudinal data findings are a key resource to help inform mangrove restoration efforts. It provides us with the first estimate of the global magnitude of these offsets, giving us the ability to identify where to focus efforts on sequestration of CO_2 within CBC sites.

Because latitude plays a major role both in the amount of methane produced and the CO_2 sequestered, it should be considered an important factor in determining where to invest resources. Based on this data, we recommend that restoration efforts focus on latitudes that have the lowest offset percentage, mainly between 0-15°, especially because these latitudes have the highest density of mangroves as well. These lower latitudes have methane offset rates of only 1.4-3%, and constitute the majority of land mass for mangroves. The latitudes between 0-15° house a mangrove area of 97,500 square kilometers, representing 70% of all mangroves worldwide [17]. This means that focusing on these latitudes should provide plenty of restoration opportunities. Additionally, since a majority of mangroves are found in these latitudes, the benefits of restored and conserved mangroves' low offset percentages will maximize net CO_2 sequestered by mangroves.

These latitudes are predominantly in developing countries, meaning restoration would also help these coastal communities glean the other ecosystem services mangroves have to offer, such as flood control and fishing-based economies. Therefore, focusing restoration efforts in these areas would not only give restoration and conservation efforts the most bang for their buck, but also provide co-benefits for coastal communities. Respectful cooperation with local communities would be crucial in ensuring that restoration and conservation actually positively impact these communities.

Furthermore, the fact that disturbed, degraded and destroyed mangroves contribute far higher methane emissions is another motivating factor for encouraging restoration efforts. The bottom line is that mangroves will continue to produce methane regardless, but getting and keeping them healthy will minimize these emissions, as well as maximize their CO_2 sequestration capabilities.

Calculations:
(Numbers correspond to footnotes)

1. $10 \text{ GT C} * 44 \text{ mol } CO_2 / 12 \text{ mol C} = 36.67 \text{ GT } CO_2$
2. 10 GT C (mangroves) / 15.4 GT C (all SCEs) = 65%
3. 10 GT C (mangroves) / 861 GT C (all forests) = 1.16%
4. $15 \text{ Tg} * 1 \text{ GT}/10^3 \text{ Tg} = 0.015 \text{ GT}$
5. $0.015 \text{ GT C} * 44 \text{ mol } CO_2 / 12 \text{ mol C} = 0.055 \text{ GT } CO_2$
6. $0.055 \text{ GT } CO_2 * 0.8 = 0.044 \text{ GT } CO_2$
7. $0.044 \text{ GT } CO_2 / 58 \text{ GT } CO_2 = 0.076\%$
8. $139{,}170 \text{ km}^2 / 509{,}600{,}000 \text{ km}^2 = 0.027\%$
9. CH_4 $GWP_{20} = 80.8$, CH_4 $GWP_{100} = 27.2$

   0.2/80.8 = x/27.2

   5.44 = 80.8x

   X = 6.7
10. Using offset range:

0.18/80.8 = x/27.2	0.22/80.8 = x/27.2
4.896 = 80.8x	5.984 = 80.8x
X = 6	X = 7.4

11. $678.5 \text{ Tg } CO_2\text{eq } (10^9 \text{ kg} / 1 \text{ Tg}) (1 \text{ GT} / 10^{12} \text{ kg}) = 0.6785 \text{ GT } CO_2\text{eq}$
12. $0.15 \text{ Pg } CO_2\text{eq } (10^{12} \text{ kg} / 1 \text{ Pg}) (1 \text{ GT} / 10^{12} \text{ kg}) = 0.15 \text{ GT } CO_2\text{eq}$

    $1.02 \text{ Pg } CO_2\text{eq } (10^{12} \text{ kg} / 1 \text{ Pg}) (1 \text{ Gt} / 10^{12} \text{ kg}) = 1.02 \text{ GT } CO_2\text{eq}$
13. $5.3 \text{ Gt } CO_2\text{eq} / 58 \text{ Gt } CO_2\text{eq} = (0.09) \times (100) = 9\%$
14. (0.03) (0.09) = (0.0027) x (100) = 0.27%

    (0.19) (0.09) = (0.0171) x (100) = 1.71%
15. $16 \text{ MT C} * 1 \text{ GT}/ 10^3 \text{ MT} = 0.016 \text{ GT C}$
16. $0.016 \text{ GT C} * 44 \text{ g } CO_2/12 \text{ g C} = 0.0587 \text{ GT } CO_2$
17. $97{,}500 \text{ km}^2 / 139{,}170 \text{ km}^2 = 70\%$

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- Explain the analysis question
- Make it look more like an article