Salton Sea Long-Range Plan

Appendix F: Greenhouse Gas Emissions

March 2024

SALTON SEA MANAGEMENT PROGRAM

CALIFORNIA
NATURAL
RESOURCES
AGENCY

DEPARTMENT OF WATER RESOURCES
STATE OF CALIFORNIA

CALIFORNIA
DEPARTMENT OF
FISH &
WILDLIFE

Table of Contents

List of Figures

List of Tables

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Appendix F: Greenhouse Gas Emissions

1.1 Introduction

This memo describes a methodology that can be used to estimate the greenhouse gas (GHG) budget of the Salton Sea. GHG emission estimates are needed to compare current and future emissions for different proposed approaches for restoration of the Salton Sea. This work uses published literature sources and field observations to draw conclusions about carbon burial, cycling, and emissions while also factoring in expected changes in such processes in future years due to enhanced eutrophication, salinity increases, and general warming and drying of the lakebed and surface waters. The basic conceptual model used in this analysis is that the initial condition just before the flooding of the Colorado River created the modern Salton Sea in 1905 represents the background condition. Carbon accumulation and loss, as well as other GHG fluxes, from the system is estimated from this 1905 background.

Evidence in the literature suggests saline lakes are a source of carbon dioxide flux to the atmosphere (Duarte et al., 2008), and dry lake sediments are also a source of carbon dioxide (Keller et al. 2020). Other GHGs, notably methane and nitrous oxide, can also be potential sources from the lake and are estimated in this approach--although data on these GHGs are less abundant. Given the concern with GHG emissions, we generally use higher-end emission rates from literature values to develop conservative flux estimates. Actual measurements of the relevant GHG fluxes are limited in the Salton Sea ecosystem, and future data collection may refine these estimates. At a high level and for planning purposes, however, the quantity of carbon accumulated in the Salton Sea since 1905 is an important constraint on the potential emissions over time. Twentieth century carbon accumulation and GHG emission calculations are based on a ~2000 lake area and water quality, recognizing that this is an approximation with the lake having changed in area and water quality over the years in this period. However, water quality data from the early decades of the 20th century are virtually non-existent.

This methodology uses the rates of emission from the lake area and exposed lakebed area and can be applied to different restoration concepts presented in this Long-Range Plan. Each restoration concept has different surfaces areas of the Sea and of the exposed lakebed.

The memo is organized as follows:

Section 2: Description of Study Area

Section 3: Background Information and Assumptions

Section 4: Summary of Reference Values

Section 5: GHG Budget of the Salton Sea Per Year (until 2100) and To Date (from 1905)

Section 6: Conclusion

1.2 Description of Study Area

1.2.1 Inflows

The Salton Sea is located in the Sonoran Desert of southeastern California. The Sea itself was formed during a 17-month period from October 1905 to February 1907 by the breaching of a temporary diversion of the Colorado River. The background condition in this system represents the condition just before the breaching of the diversion that created the modern Salton Sea, and fluxes and storage are estimated from this starting point. Since then, the Salton Sea has been sustained by agricultural discharge, municipal and industrial effluent, and stormwater runoff from the Imperial, Coachella, and Mexicali Valleys. These flows are delivered to the Salton Sea via the New, Alamo, and Whitewater Rivers in addition to some ungauged local watershed discharge. Over time, evaporation and reduced inflows have caused the Salton Sea's elevation to gradually recede. Climate change-exacerbated increases in temperature and evaporation as well as decreases in water allocation and subsequent inflow are projected to further shrink the size of the Salton Sea and significantly warm the waters of the Sea.

For characterizing future volume, area, and salinity of the Salton Sea, we used a simple water and salt balance model termed the Salton Sea Accounting Model (SSAM). This is a spreadsheet model originally developed by the US Bureau of Reclamation (Reclamation) in the 1990s. Starting in 2014 Tetra Tech updated this model with the latest available data for sea inflows, elevations, and bathymetry data; recalibrated the model to be consistent with the latest elevation and salinity observations; and used the model to assist various Salton Sea conservation studies. SSAM is a conceptually simple "bucket"-type model guided by water and salt mass balance on an annual timestep. The recent historical elevation of the sea compared to the SSAM calculation is shown in Figure 1.

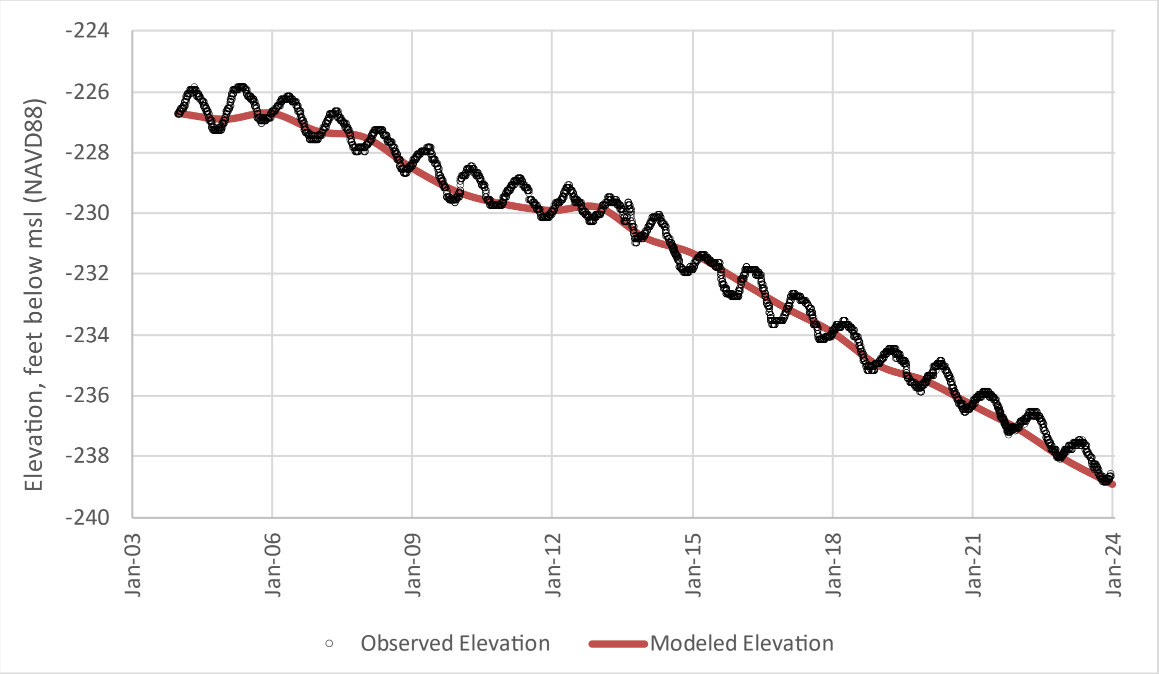

Figure 1. Plot of observed elevation (feet below mean sea level with a NAVD88 datum) and modeled elevation at the Salton Sea. Observed data are from the US Geological Survey and modeled elevations are calculated using the SSAM, given measured inflows over this period.

SSAM was used to establish the future state of the Salton Sea and exposed lakebed. The projected area of the Sea and the exposed lakebed over the 21st century were calculated using the SSAM and are shown in Figure 2. The discontinuity in modeled exposed lakebed area, particularly between 2020 to 2030, reflects the effective reduction in exposed lakebed area following the completion of habitat projects as part of the Phase 1: 10-yr plan. The ensuing GHG estimates are made based on the contributions of the modeled lake and exposed lakebed areas to carbon burial, cycling, and emissions. This appendix presents GHG calculations for the conditions shown in Figure 2; the main report contains calculations using similar rates for the areas of the Sea and exposed lakebed for different restoration concepts.

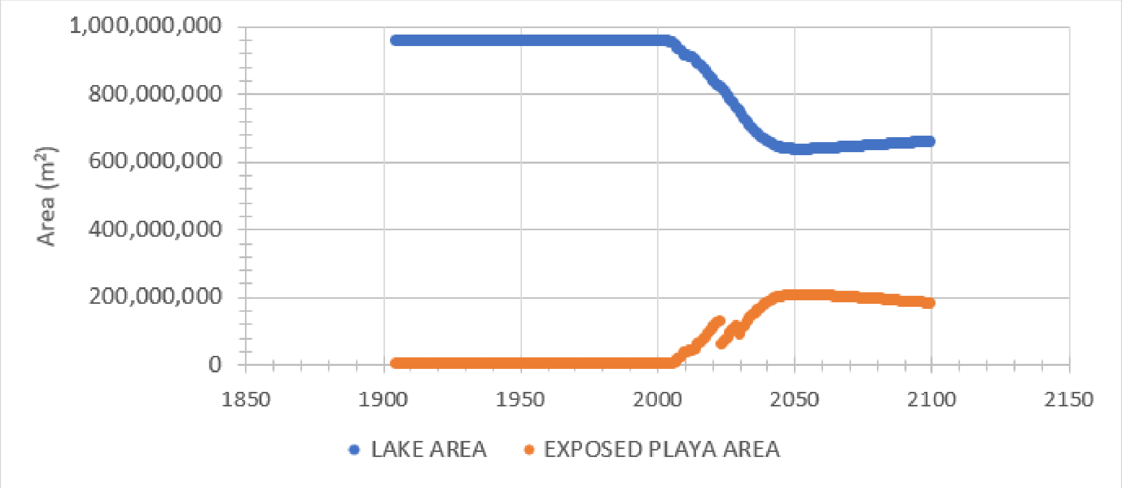

Figure 2. Results of a hydrologic model of the Salton Sea (SSAM) showing the decline in lake area during the first half of the 21st century and a corresponding increase in the exposed lakebed area. These model results will be used to scale estimates of carbon burial, cycling, and emissions over time. Note that the discontinuity in modeled exposed lakebed area, particularly between 2020 to 2030, reflects the expected completion of restoration projects that will effectively reduce exposed lakebed area. The sum of the exposed playa area and the lake area are constant (953.7 million m^2 or about 235,000 acres).

1.2.2 Salinity

The Salton Sea is a terminal water body. As there is no outflow, salts and nutrients from continual agricultural and municipal discharge have accumulated and increased the salinity of the Sea. Currently, the Salton Sea is more saline than ocean water (IID, 2022), and the concentration of salt in the Salton Sea increases by a rate of approximately 1% annually (UCANR, 2022). Pronounced evaporation and subsequent shrinking of the water volume will further increase the salinity over time. A plot of salinity over the recent historical period, and the modeled values using SSAM, is shown in Figure 3.

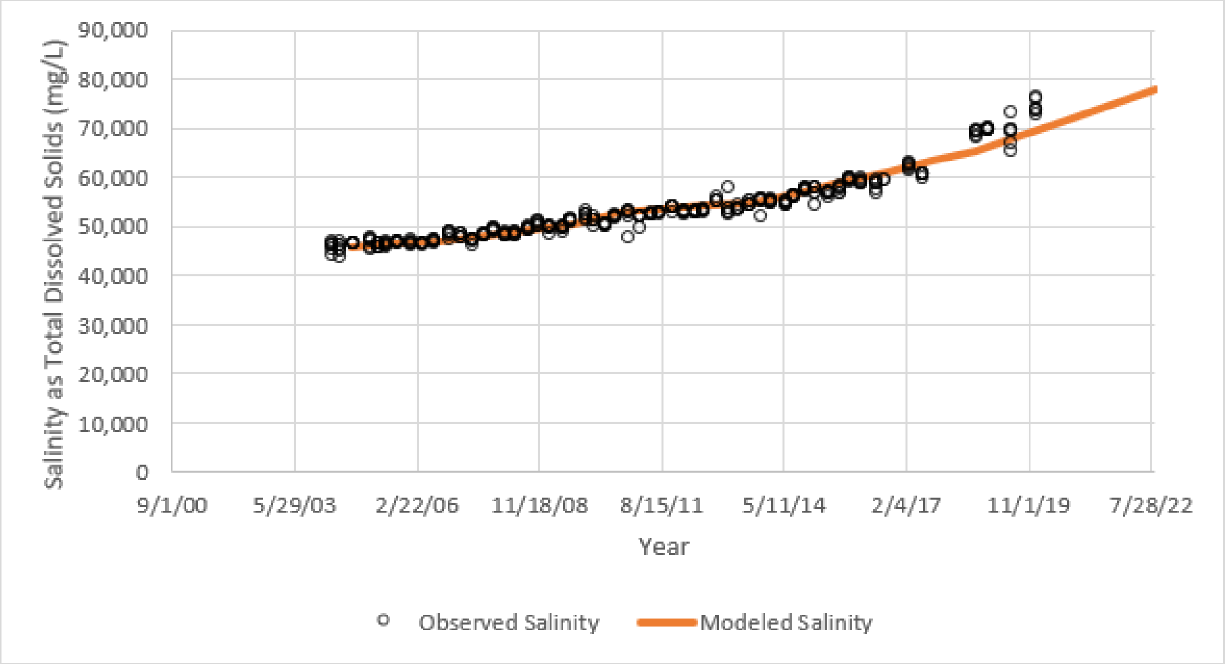

Figure 3. Plot of observed salinity and modeled salinity at the Salton Sea. Observed salinity data are from the US Bureau of Reclamation and modeled salinity were calculated using the SSAM, given measured inflows over this period.

1.2.3 Eutrophication

The continual loading of nutrients from agricultural drainage has also made the Salton Sea a productive saltwater ecosystem that is classified as a "eutrophic to hypereutrophic water body characterized by high nutrient concentrations, high algal biomass as demonstrated by high chlorophyll *a* concentration, high fish productivity, low clarity, frequent very low dissolved oxygen concentrations, massive fish kills, and noxious odors" (Setmire et al., 2000). Extensive oxygen depletion and the resultant creation of anoxic zones indicate that the biological productivity of the Salton Sea exceeds the capacity of the system to support it (Setmire et al., 2000). Representative data for phosphorus and nitrogen from 2002-2015 are shown in Figure 4 and Figure 5 (Tetra Tech, 2016).

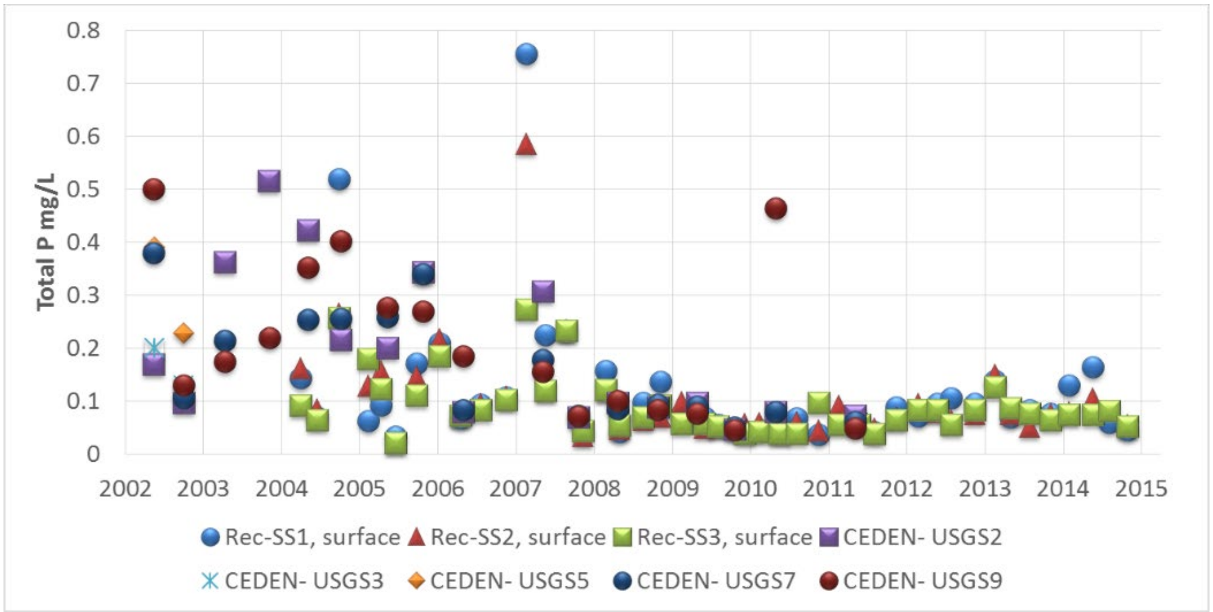

Figure 4. Observed data for total phosphorus at the Salton Sea. Summary of observed data sources reported in Tetra Tech (2016). The prefix Rec refers to Reclamation data. The prefix CEDEN refers to California Environmental Data Exchange Network data. The sampling location name appears after the dash.

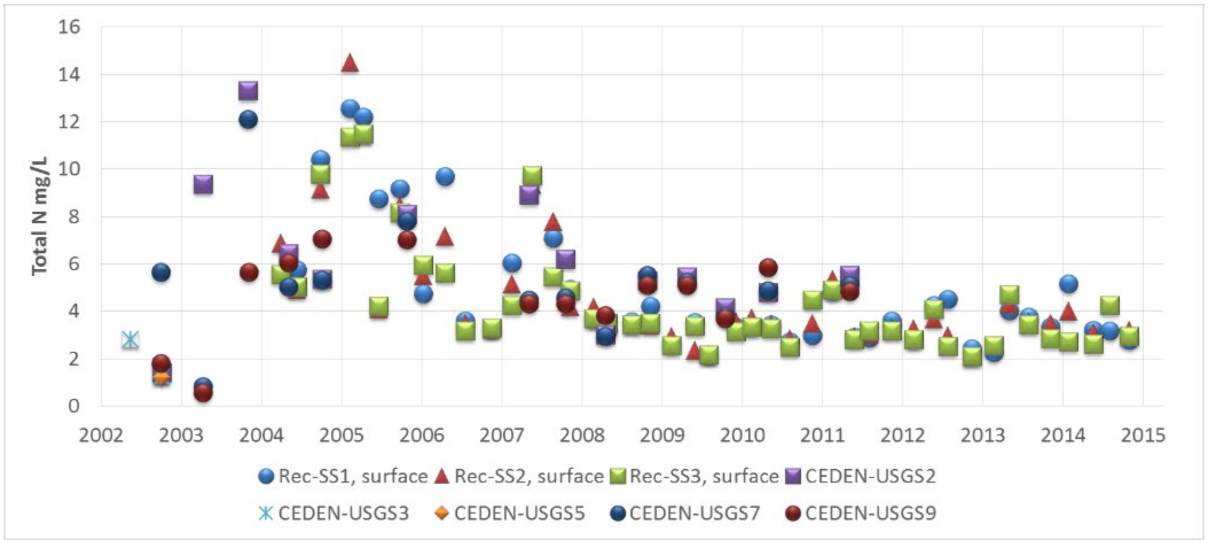

Figure 5. Observed data for total nitrogen at the Salton Sea. Summary of observed data sources reported in Tetra Tech (2016). The prefix Rec refers to Reclamation data. The prefix CEDEN refers to California Environmental Data Exchange Network data. The sampling location name appears after the dash.

The combination of warming, drying, salinity increases, and eutrophication is expected to influence biological, chemical, and physical processes that take place within the water column and in the lakebed. In turn, these conditions and processes will impact the GHG budget of the Salton Sea.

1.2.4 Carbon

Carbon concentrations in the Salton Sea and its inflows provide context for the potential emission levels. Measured organic and inorganic carbon concentrations in the inflow of Alamo, New, and Whitewater Rivers and in the Salton Sea are presented in Figures 6 and 7. Based on inflows of approximately 1.2 million acre-feet annually at 10 mg/l of total organic carbon, estimated organic carbon loads to the Salton Sea are 0.015 million tons per year. Similarly, at 4 mmol of carbon/l of inorganic carbon, the inorganic carbon loading is 0.072 million tons per year.

Inflowing carbon is only a part of the carbon in the Sea, with most of it derived from primary production in the waters of the Sea, as indicated by the considerably higher total organic carbon concentrations in Sea compared to the river inflows (Figure 7).

Duarte et al., (2008), for example, from a global study of saline lakes reported that these lakes have a median dissolved inorganic carbon concentration of 7.7 mmol/L, about 10 to 15 times greater than the concentration of a typical freshwater lake, and are a significant source of CO_2 flux. The values in this global study are comparable to the reported inorganic carbon concentrations in the Sea (Figure 7), and can be related to a part of the CO_2 fluxes from the Sea.

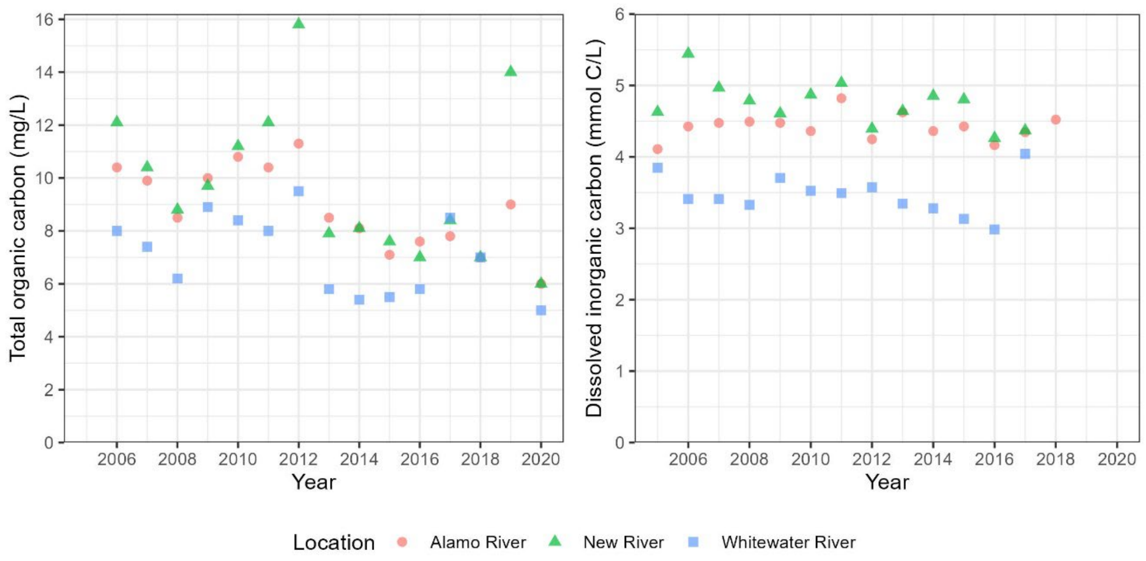

Figure 6. Inflow organic and inorganic carbon concentrations measured in Alamo, New, and Whitewater River.

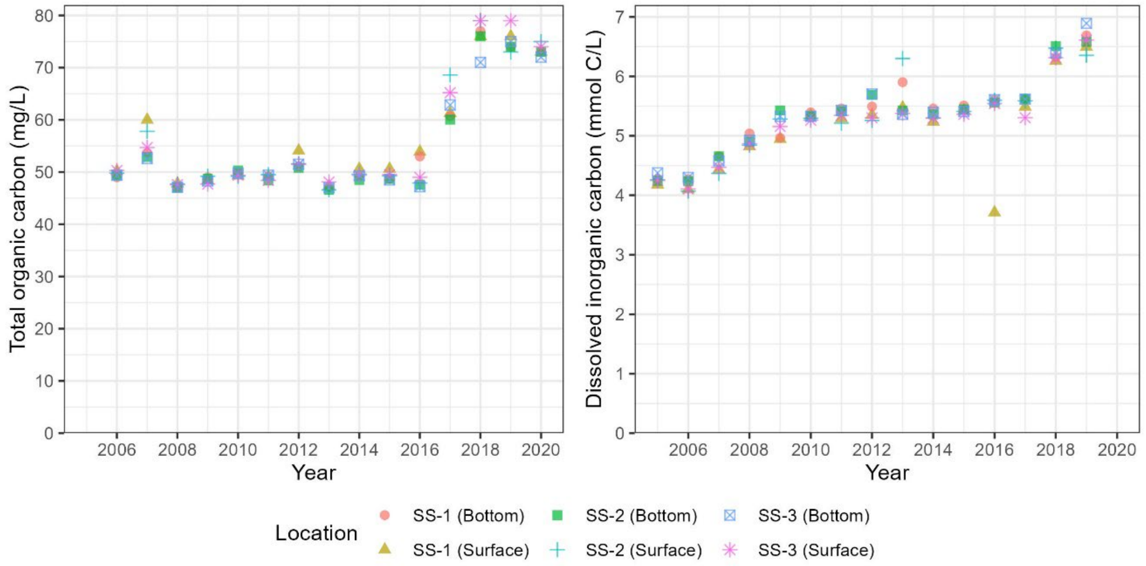

Figure 7.Organic and inorganic carbon concentrations measured in Salton Sea.

1.3 Background Information and Assumptions

Inland water bodies are an important component of the global carbon cycle. The quantification of net carbon emissions from lentic (still water bodies including lakes, ponds, and reservoirs), and lotic (flowing water bodies such as rivers and streams) has important implications for regional and global carbon budgets (Clow et al., 2015; Raymond et al., 2013).

Within a lacustrine environment, numerous processes involving carbon take place. Carbon enters lakes from upstream flow, groundwater inputs, atmospheric deposition, or fixation of atmospheric CO_2 by emergent macrophytes (Travnik et al., 2009). Primary production in the surface waters of lakes also sequesters CO_2 in the form of organic carbon. Carbon is lost through inorganic and organic carbon sedimentation, CO_2 efflux to the atmosphere, and downstream flows via streams and groundwater (Travnik et al., 2009). Within the water column, aquatic organisms perform aerobic and anaerobic respiration/oxidation, which release CO_2 and CH_4, respectively, and may even facilitate carbonate formation. At the water-sediment interface, burial of organic and inorganic carbon formed by these organisms occurs. Additionally, microbial decomposition and methanogenesis may occur, thereby releasing some of this sequestered carbon as CO_2 and CH_4. Thus, carbon is continually absorbed, cycled, buried, and emitted. The many carbon processes within a lacustrine environment are represented by input and output arrows shown in Figure 8. Lakes may also function as sources or sinks of nitrous oxide (N_2O), which is produced by nitrification and denitrification (Travnik et al., 2009).

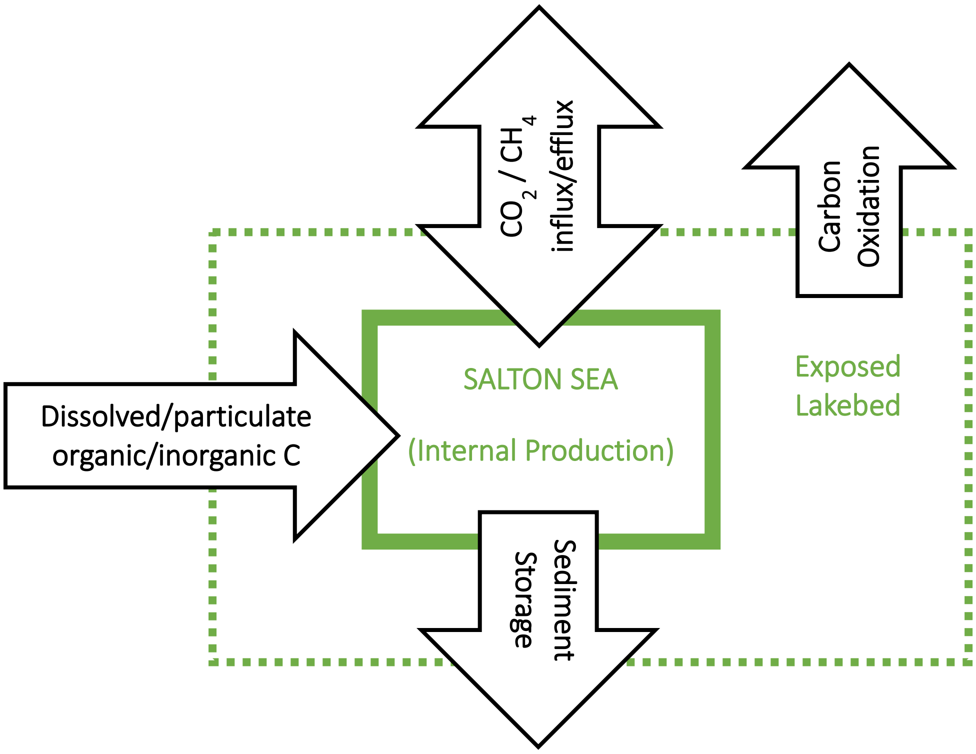

Figure 8. A flow diagram showing the major carbon-involving processes in the Salton Sea ecosystem. The goal of this memo is to estimate the magnitudes of each of these arrows.

To study net GHG emissions from lentic water bodies such as the Salton Sea, background information in this section was used to understand the consumption and production of carbon (in the form of CO_2 and CH_4) and N_2O by microorganisms in the lake system. All processes are mediated by geology, biology, and/or chemistry, and are affected by climate change and human activities in settlements surrounding the Sea, as discussed below.

The calculation of rates and quantities of individual processes for estimating net GHG emissions relied on the existing literature and was additionally based on the climatic and aquatic conditions in Salton Sea. Given with the limited data in the Salton Sea especially the measurements related to key variables of the involved processes (including atmospheric partial pressure of CO_2 and sediment organic carbon), rates in the Salton Sea were identified based on the results from similar studies and based on multiple factors such as climate, eutrophication, and salinity. The current estimation of net GHG emissions in Salton Sea is therefore subject to considerable uncertainty; additional local measurements are recommended and expected to increase the accuracy of estimation.

1.3.1 Carbon Inputs

Terrestrial carbon inputs into lake systems vary depending on climate, soil texture, geochemistry, and land use (Travnik et al., 2009). Carbon is transported from the water column to the sediments via flocculation of organic carbon, incorporation into biological material, and sedimentation of particulate organic matter (Travnik et al., 2009). Together, these processes represent a lake’s potential for carbon burial. Presently, lakes are rarely considered in regional terrestrial carbon budget calculations/estimations; however, carbon burial in lacustrine sediments is a significant global long-term carbon sink (Travnik et al., 2009). A national-level analysis of the organic carbon (OC) burial rates shows that water bodies of the conterminous U.S. (CONUS) sequester 20.8 trillion grams of C per year (Tg C/year) and that spatial patterns in OC burial are influenced by factors including water body type, size, and abundance, land use, and soil and vegetation characteristics (Clow et al., 2015).

Estimates of OC burial were developed from literature estimates. Although there are limited sediment data from the Salton Sea, these have not been previously evaluated for OC burial rates. Burial rates of organic and inorganic carbon are usually highest in small, eutrophic lakes where sediment collected from the watershed is retained for extended periods of time and can be mineralized or buried (von Wachenfeldt et al., 2008). OC burial in inland lentic water bodies is studied through field experiments that involve collecting sediment cores and calculating the proportion of organic carbon within the sample while also factoring in estimates of mass accumulation rates, burial efficiency, and other responses to geomorphic, climatic, and land-use/land-cover variables. OC concentrations in such sediment cores have shown high dependence on mean annual air temperature, due to its impact on ecosystem productivity, and on the k-factor of the soil (a measure of soil erodibility), due to how erosion introduces mineral matter to sediments (Clow et al., 2015). The eutrophic state of the Salton Sea system suggests that it has a high potential to bury OC, which will increase with projected increases in mean annual air temperatures. Additionally, reduced inflows over time have created a crusted, low-moisture layer, over 70% composed of sand and silt (Gao et al., 2021). This means that the soil has moderate to high k-factor indicating higher erodibility than fine textured soils composed primarily of clay, for instance (USDA, 2022). However, soil composition is heterogenous around the Salton Sea and may include more clay in some areas (Setmire et al., 1993). Statistical models were constructed in Mendonça et al., (2017) to study the modern OC burial rates of lakes and reservoirs at a global scale and the results suggest that the burial rate is positively correlated with annual average temperature and negatively correlated with lake/reservoir size and average slope.

OC burial in lakes/ponds in CONUS has been shown to follow a log-normal distribution with median 31 g C/m^2/year and mean 46 g C/m^2/year (Clow et al., 2015). Recent increases in carbon sequestration by lakes have been driven by land-cover change, which has in general increased nutrient availability, aquatic productivity, and therefore OC burial in lakes (Anderson et al., 2013). Based on agricultural expansion in California and trends in nutrient loads in the Salton Sea, it is reasonable to conclude that the Salton Sea ecosystem has and will continue to experience similar productivity-boosted OC burial rates. Modern OC burial rates in lakes are estimated as 72 g C/m^2/year for U.S. Geological Survey hydrologic regions of Great Basin and California, with lake sediments containing approximately 6.2% carbon (Clow et al., 2015). Additionally, considering several factors including the temperature, size, slope of Salton Sea and the inflow and in-sea organic carbon concentrations, an OC burial rate of 72 g C/m^2/year was assumed and used.

Based on these estimates and changes in lake and exposed lakebed area as suggested in Figure 2, OC burial at the Sea was estimated at 0.25 million (M) metric tons of CO_2-eq/year from 1905 to 2004. Following 2004, decreases in lake area were assumed to have decreased OC burial mass but it was assumed that the *burial rate* of 72 g C/m^2/year remained constant. For this inflow scenario, after 2050, the lake area was modeled to have reached a steady size which will be able to bury approximately 0.17 M metric tons of CO_2-eq/year. Single-year and cumulative estimates of CO_2-eq burial are shown in Figure 9. These numbers may be compared to the approximate

0.015 tons of organic carbon in inflows (or 0.055 M tons of CO_2-eq). Thus, the majority of the CO_2-eq that is accumulated originates from in-Sea carbon production.

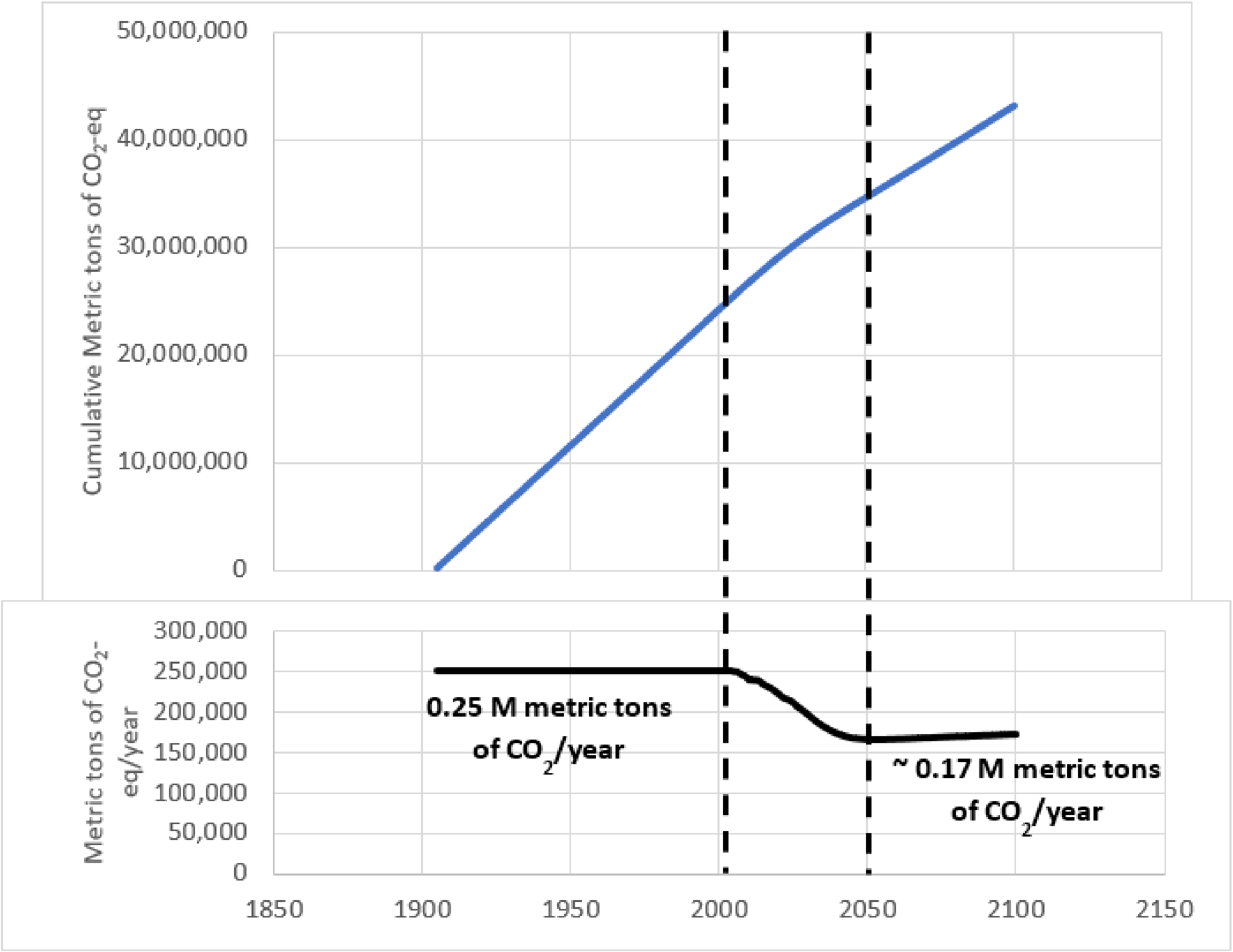

Figure 9. Top: Estimated cumulative metric tons of CO_2-eq of OC buried in lacustrine sediments of the Salton Sea. Bottom: Estimated metric tons of CO_2-eq of OC buried per year in lacustrine sediments of the Salton Sea. Both the top and bottom figures were computed using an estimated burial rate of 72 g C/m^2/year for lakes in western U.S. (Clow et al., 2015) and based on lake area assumptions and hydrology models used to support the development of Figure 2.

The estimated 72 g C/m^2/year burial rate is consistent with OC burial rate observations in eutrophic lakes in Europe, which themselves exhibit burial rates ranging from 60 to 100 g C/m^2/year (Anderson et al., 2014). However, a study of OC burial in eutrophic farm ponds in Iowa reveals greater and highly variable OC burial rates ranging from 148 to 17,000 g C/m^2/year (Downing et al., 2008). This latter study includes a multiple regression analysis that considers watershed to lake area ratio and sediment bulk density to estimate OC burial which could be used to refine the OC burial rate estimates for the Salton Sea. However, based on these additional studies, 72 g C/m^2/year is a conservative burial rate that can be used to estimate carbon sequestration by the Salton Sea ecosystem. As noted earlier, this estimate is based on a literature evaluation and future fieldwork in the Salton Sea may help develop refined estimates that capture its unique characteristics.

1.3.2 Carbon Outputs

1.3.2.1 Water-Atmosphere Interface

CH_4 is the most important GHG emitted from aquatic systems in terms of climate impacts because CH_4 is about 25 times more potent as a GHG than CO_2 on a 100-year time scale (Del Sontro et al., 2018; IPCC, 2013). Total CH_4 flux from a lake includes diffusive and ebullitive flux from the water column. Diffusive flux is the flux rate from water to the atmosphere and is driven by supersaturation in the water column. Ebullitive flux is the flux rate from the formation of bubbles that are transported to the surface. Ebullitive flux is directly related to biological activity in the water column while diffusive flux is mainly mediated by water temperature.

CH_4 emission rates are mostly influenced by the biological productivity of the surface water layer of lakes and reservoirs (ebullitive flux). It is estimated that a three-fold increase in phosphorus loading can cause a two-fold increase in CH_4 emissions rates (Beaulieu et al., 2019). Overall, two mechanisms are expected to increase aquatic productivity of lakes over the 21st Century:

1. Increases in fertilizer use and nutrient runoff from expanding crop-livestock ecosystems, which support increasing populations, and
2. Climate-driven increases in water temperature, which will enhance bacterial decomposition of algae and resultant emission of CH_4.

DelSontro et al. (2018) studied 8,233 aquatic systems (including lakes and impoundments) from 54 different countries to develop a global model to estimate total CH_4 emissions. Variables that were considered include lake size, chlorophyll *a* concentration (a proxy for biological productivity), and total concentrations of nitrogen and phosphorus (nutrients); however, it was found that the following relationship sufficiently predicted total CH_4 emissions rates from chlorophyll *a* concentration alone:

$$\log_{10}(\text{total } CH_4 \text{ emission rate} + 1) = 0.778 \times \log_{10}(\text{chlorophyll } a) + 0.940,$$

where emissions are in mg C/m^2/day and chlorophyll *a* is in µg/L.

The estimation of total CH_4 emissions assumes that chlorophyll *a* concentration has and will continue to remain steady at 33.4 µg/L, which is the annual average concentration level based on the measurements from 1997 to 1999 at the Salton Sea (Robertson et al., 2008; Tiffany et al., 2007). Thus, $\log_{10}(33.4) = 1.52$ and total CH_4 emission rate = $-1 + 10^{0.778 \times 1.52 + 0.940} = 131.61$ mg C/m^2/day. This estimated rate of 131.61 mg C/m^2/day is consistent with the estimates obtained by Yan et al., (2018) for 17 lakes (14 saline lakes) in the Tibetan Plateau, which showed a large range (0.1 to 551 mg C/m^2/day, with an average of 62.4 mg C/m^2/day) of CH_4 flux rates for the 17 lakes. Given with the conditions in Salton Sea and limited amount of measurements, 131.61 mg C/m2/day of CH_4 flux rate is within the range of observations of other saline lakes.

Using this estimate and changes in lake and exposed lakebed area as suggested in Figure 2, CH_4 emissions from the Salton Sea were estimated at 0.17 M metric tons of CO_2-eq/year from 1905 to 2004. Following 2004, decreases in lake area were assumed to have decreased CH_4 emissions but it was assumed that the burial rate of 131 mg C/m^2/year remained constant. After 2050, lake area was modeled to have reached a new equilibrium which will emit approximately 0.11 M metric tons of CO_2-eq/year (Figure 10).

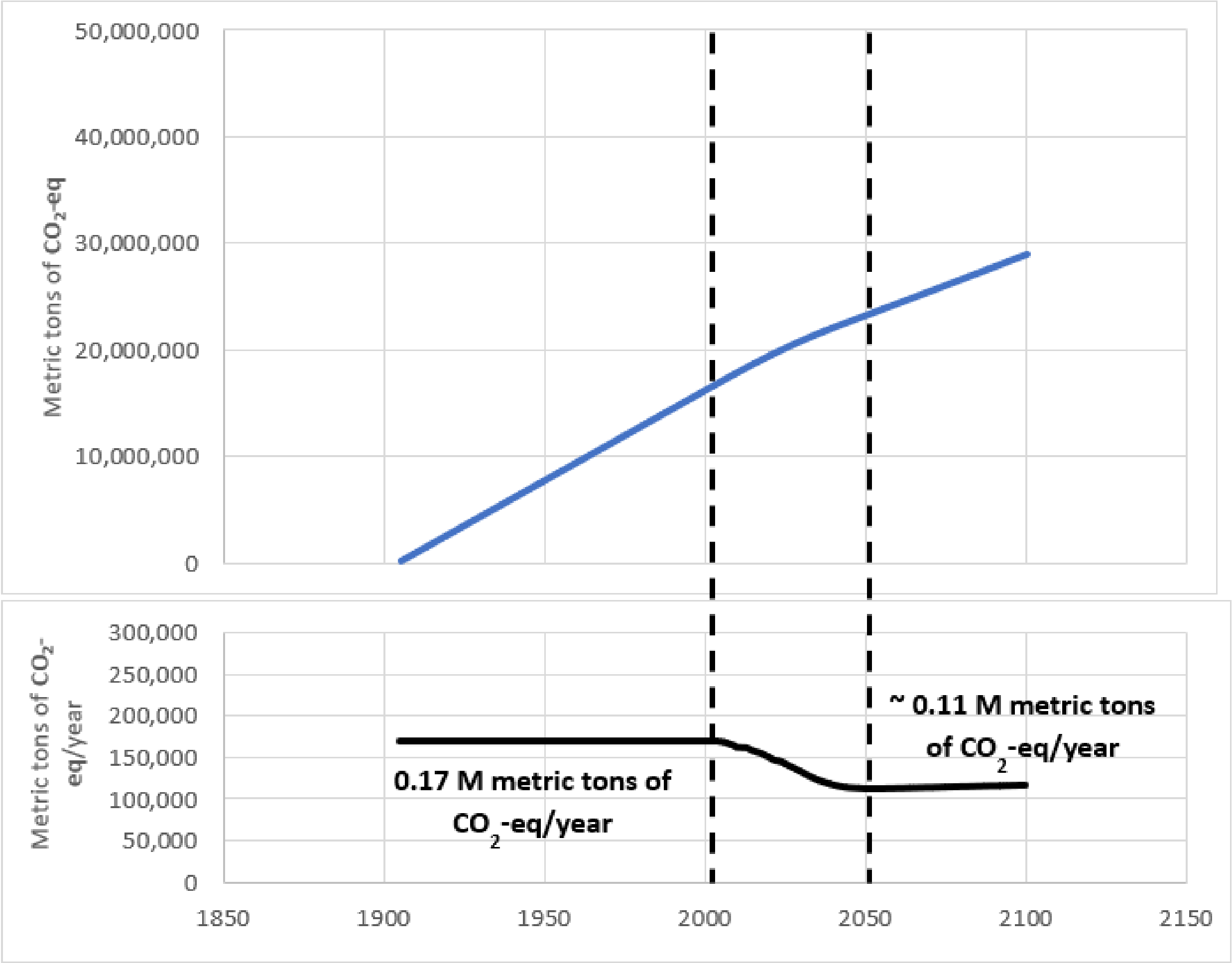

Figure 10. Top: estimated cumulative metric tons of CO$_2$-eq of CH$_4$ emissions from the lake area of the Salton Sea. Bottom: estimated metric tons of CO$_2$-eq of CH$_4$ emissions per year from the lake area of the Salton Sea. Both the top and bottom figures are computed using an estimated emission rate of 131.61 mg CH$_4$-C/m^2/year assuming chlorophyll *a* concentration is constant at 33.4 µg/L (DelSontro et al., 2018; Beaulieu et al., 2019; Robertson et al., 2008) and based on lake area assumptions and hydrology models used to support the development of Figure 2.

A more refined approach for computing CH$_4$ emissions from the Salton Sea since its formation in 1905 would consider the extent to which the Sea's eutrophic status, biological productivity, and temperature-driven microbial degradation have evolved over time. Estimates of CH$_4$ emission rates at other lakes can be applied to the Salton Sea by comparing key ecosystem indicators such as change in % agriculture in catchment (indicating land-use change), total phosphorous and nitrogen (indicating runoff), and chlorophyll *a* concentration (indicating biological productivity). Furthermore, predictions of global land-use change, disruptions of nutrient cycles, and warming climate scenarios can affect burial rate assumptions for future planning.

Chlorophyll *a* data, indicative of planktonic algae and algal blooms, can be variable over time. Data collected by Reclamation from 2004 to 2015 shows that the chlorophyll *a* concentration often exceeded 150 µg/L from 2005 to 2007; however, from 2009 to 2015, it was around 30 µg/L, suggesting that a concentration of 33.4 µg/L is a valid assumption for at least the last decade (Reclamation, 2007). The cause of this decline is not known, because the overall nutrient status of the Sea still indicates an excess of nutrients.

The diffusive flux of CO_2 from the lake surface can also be estimated. Solubility of GHGs in water changes with temperature. Additionally, surface water turbidity (represented by wind fetch) may stimulate more rapid influx or efflux. In saline lakes, chemical processes, such as carbonate precipitation/dissolution reactions and the chemical enhancement of CO_2 exchange rates due to hydration of atmospheric CO_2 directly to bicarbonates, are more prevalent (Duarte et al., 2008). Thus, saline lakes support higher CO_2 exchange rates with the atmosphere due to the chemistry of the environment. Flux of CO_2 is dependent on surface water pCO_2 (partial pressure of CO_2), surface water temperature, and chemical enhancement of the rate of gas exchange (detailed above). Chemical enhancement alone was shown to increase average CO_2 fluxes by a factor of 2.3 (Duarte et al., 2008). Furthermore, eutrophication may amplify or reverse some of these chemical enhancements due to its effect on the cycling of carbon (Morales-Williams et al., 2021).

The previously established OC burial rate was estimated at 72 g C/m^2/year or 16.4 mmol C/m^2/day (Clow et al., 2015). Clow et al. (2015) also states that 72% of the estimate for total OC burial in CONUS water bodies (including lakes and reservoirs), is emitted as CO_2 (Clow et al., 2015). 72% of 16.4 mmol C/m^2/day is approximately 11.8 mmol C/m^2/day.

Additional estimates of CO_2 flux can be found in the literature for comparison. CO_2 flux computed for 15 shallow, eutrophic lakes in Iowa ranged from –0.01 to 0.05 mol C/m^2/day (-10 to 50 mmol C/m^2/day) (Morales-Williams et al., 2021). A study of 196 globally distributed saline lakes shows that CO_2 flux averaged 81 mmol C/m^2/day (Duarte et al., 2008). CO_2 emissions are correlated with lake size and total phosphorus as discussed in DelSontro et al. (2018); and a rate of 18.0 mmol C/m^2/day can be estimated using the empirical equation derived in DelSontro et al. (2018) based on the current size of Salton Sea and limited total phosphorus concentrations. Yan et al., (2018) studied 17 lakes in the Tibetan Plateau (14 of them are saline lakes) and the estimated CO_2 flux rate was 73.7 mmol C/m^2/day as an average of the 17 lakes. As mentioned in the previous section, the results of Yan et al., (2018) also indicate that CO_2 flux is greater for lakes with higher dissolved organic carbon concentrations, salinity, water temperature, and as well as dissolved inorganic carbon concentrations. McDonald et al. (2013) studied mean CO_2 flux across different ecoregions in the U.S. and suggests an estimate of 0.29 g C/m^2/day or 24.2 mmol C/m^2/day with a 95% confidence interval of 5.8 to 58 mmol C/m^2/day for the ecoregion Salton Sea is located in.

These studies suggest that the Salton Sea, a eutrophic, saline, and warm inland water body with high organic and inorganic carbon concentrations, is most likely a CO_2 net emitter and with a relatively high CO_2 emission rate. A flux rate of 58 mmol C/m^2/day is used, which is the upper rate of the study by McDonald et al. (2013). Note that this is much higher than the 11.8 mmol C/m^2/day suggested by Clow et al. (2015); however, we assume that the effect of eutrophication and salinity on the diffusive flux of CO_2 are masked in such a global study and would be represented by the upper bound of the region-specific study in McDonald et al. (2013).

Using this estimate and changes in lake and exposed lakebed area as suggested in Figure 2, CO_2 flux from the Salton Sea was estimated at 888,000 metric tons of CO_2/year from 1905 to 2004. This is higher end estimate of the GHG impact of the Salton Sea, assuming that the water quality was approximately the same over the first century of its existence. In other words, this estimate is based on the area of the Sea, and not its changing water quality, for which limited long-term data exist besides salinity. Following 2004, decreases in lake area are assumed to have decreased CO_2 flux but it was assumed that the flux rate of 58 mmol C/m^2/day remains constant. After 2050, lake area was modeled to have reached a new equilibrium which will emit approximately 610,000 metric tons of CO_2/year (Figure 11).

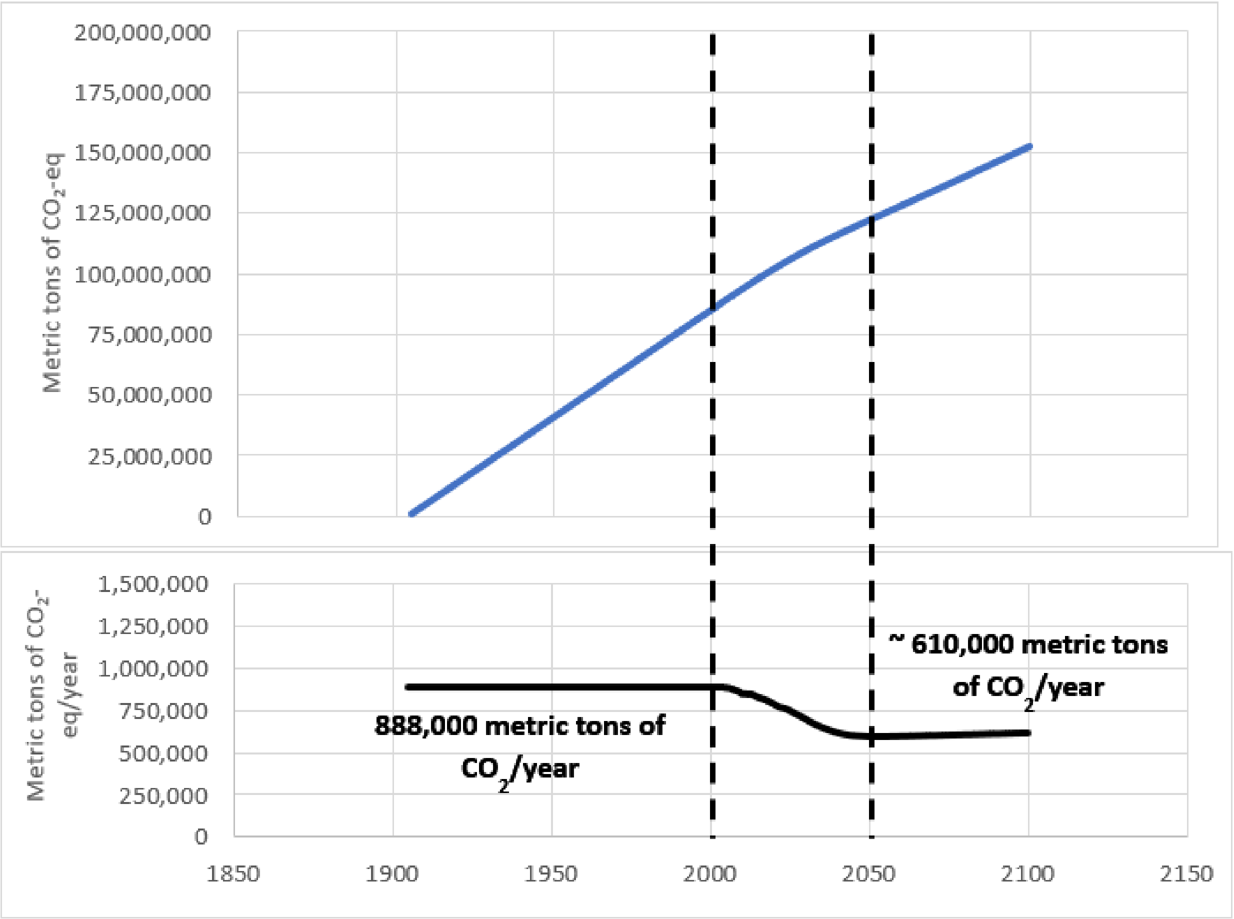

Figure 11. Top: Estimated cumulative metric tons of CO_2 emissions from the lake area of the Salton Sea. Bottom: Estimated metric tons of CO_2 emissions per year from the lake area of the Salton Sea. Both the top and bottom figures are computed using an estimated emission rate of 58 mmol C/m^2/day (McDonald et al., 2013) and based on lake area assumptions and hydrology models used to support the development of Figure 2.

1.3.2.2 Sediment-Atmosphere Interface

The intermittent or permanent, partial, or complete desiccation of inland waters due to climate change, diversion and/or consumptive use of water resources, and other modifications of the water bodies and hydrologic cycle expose previously submerged sediments to the atmosphere (Keller et al., 2020; Marce et al., 2019). Such drying of inland waters allows the oxidation of organic carbon in sediments, thereby releasing carbon into the atmosphere. This carbon flux is due to enzymatic activity and microbial growth, which results in the CO_2 emissions from dry sediments (Keller et al., 2020; Fromin et al., 2010). The onset of drying stimulates the breakdown of OC and release of CO_2 by sediment-dwelling microbes while short re-wetting episodes can trigger microbial respiration and remobilization of OC and nutrients, which releases more CO_2 (Marce et al., 2019). Thus, some variables that impact CO_2 emissions from dry sediments include moisture, organic matter, and air temperature (Keller et al., 2020).

A global estimate of 320 mmol C/m^2/day (minimum of 216 to maximum of 515 mmol/m^2/day) can be used for CO_2 emissions from the dry sediments of lakes with a permanent or seasonally dry area that exceeds 900 m^2 (Marce et al., 2019). This estimate is based on gas chamber sampling of desiccated sediments of lakes and reservoirs in Germany and Spain, representing a total of 187,542 km^2 of permanently and seasonally dry area. Alternatively, Keller et al. (2020) studies the CO_2 emissions from dry sediments of lakes based on Köppen-Geiger climate zone – tropical, arid, temperate, continental, and polar. The Salton Sea is in an arid climate zone. Based on the 196 inland water ecosystems studied in Keller et al. (2020), CO_2 flux from dry sediment in arid lakes averaged 623 mmol C/m^2/day (minimum of 187 to maximum of 1907 mmol C/m^2/day). This contrasts with the global estimate of 320 mmol C/m^2/day cited above.

The lake associated with the maximum flux in the arid zone is located at 5 m elevation and experiences annual mean air temperatures of 42°C and 37.7% moisture content. As the Salton Sea is located at low elevation and experiences peak summer air temperatures that are similarly high, we can use 1907 mmol C/m^2/day as a peak CO_2 flux rate from dry sediment, but this value is adjusted downward to allow for the emissions from accumulated carbon to occur over a defined period of 5 or 20 years. At the highest rate of reported, the entire carbon accumulation from 1905 to the present would be emitted in a single year. This value was thus divided by 5 or 20, to use emission rates that would be allow the sediment carbon to be lost to the atmosphere over a reasonable and longer period of time.

Based on this estimate and changes in lake and exposed lakebed area as suggested in Figure 2, CO_2 emissions from the exposed lakebed surrounding the Salton Sea can be estimated from 2006 onwards, when exposed lakebed area was non-zero. Annual effective exposed lakebed area - as additionally exposed lakebed area of each year and further adjusted considering possible short periods of rewetting of dried sediment - was calculated and used. The available carbon content from annual effective exposed lakebed area was estimated as the historically accumulated carbon from the carbon burial calculated in Section 1.3.1 and the oxidation of exposed sediment was assumed to take place for a 5-year or a 20-year period. Once the accumulated carbon is oxidized, sediment will not contribute to CO_2 flux. Thus, if the highest possible rate of 1907 mmol C/m^2/day were used, the same total quantity of carbon would be emitted, although this would occur over a much shorter time (the cumulative quantity of carbon emitted would stay the same).

CO_2 emissions from the exposed lakebed surrounding the Salton Sea under a 5-year oxidation period assumption and under a 20-year oxidation period assumption are shown in Figure 12 and Figure 13, respectively.

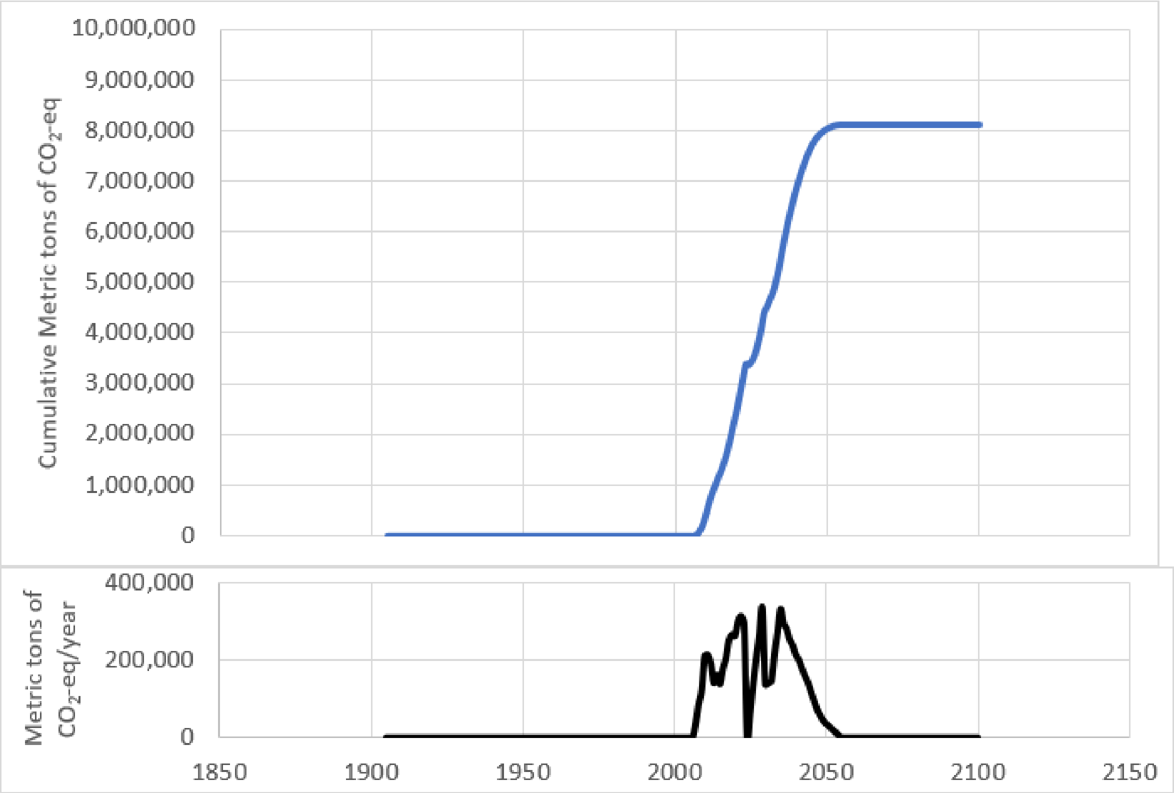

Figure 12. Top: Estimated cumulative metric tons of CO_2-eq of CO_2 emissions from dried lacustrine sediments surrounding the Salton Sea under an assumed 5-year oxidation period. Bottom: Estimated metric tons of CO_2-eq of CO_2 emissions from dried lacustrine sediments surrounding the Salton Sea. Both the top and bottom figures were computed using an estimated emission rate of 1907 mmol $C/m^2/day$ (Keller et al., 2020) and based on lake area assumptions and hydrology models used to support the development of Figure 2.

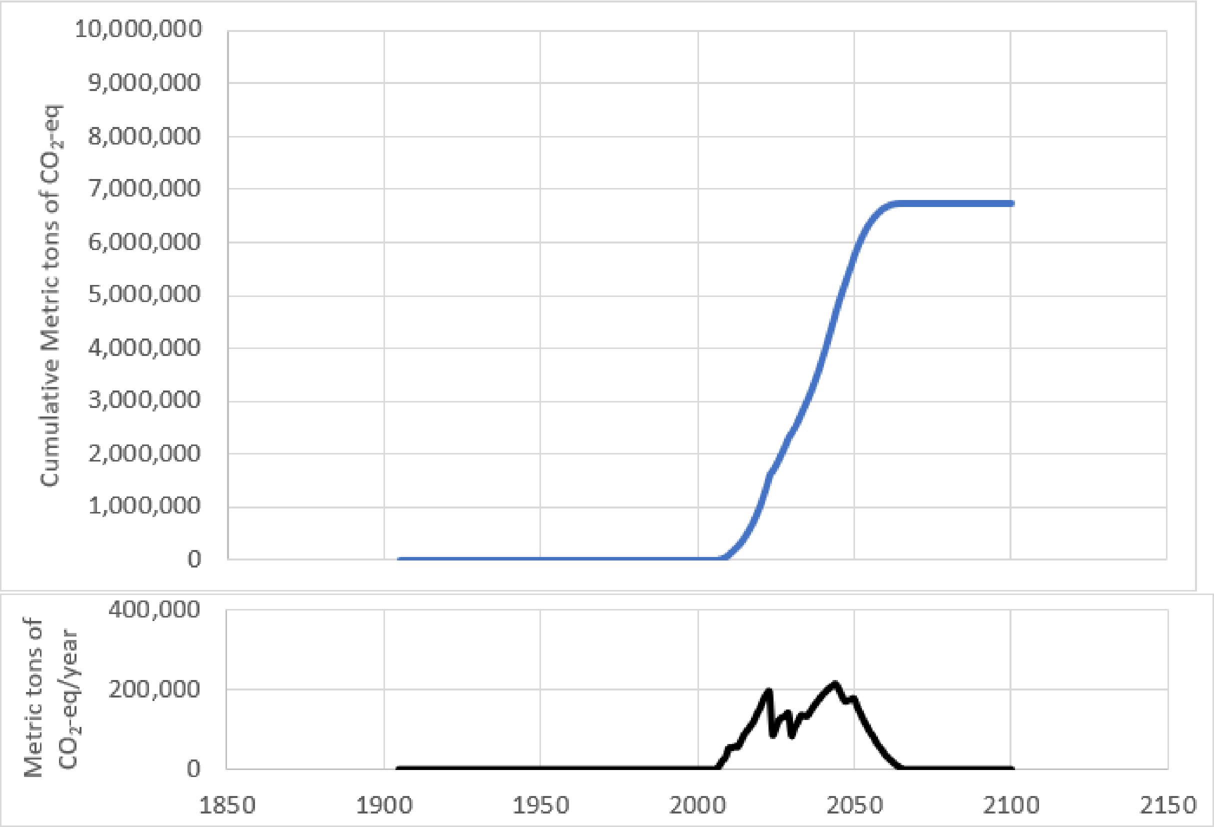

Figure 13. Top: estimated cumulative metric tons of CO_2-eq of CO_2 emissions from dried lacustrine sediments surrounding the Salton Sea under an assumed 20-year oxidation period. Bottom: estimated metric tons of CO_2-eq of CO_2 emissions from dried lacustrine sediments surrounding the Salton Sea. Both the top and bottom figures were computed using an estimated emission rate of 1907 mmol C/m^2/day (Keller et al., 2020) and based on lake area assumptions and hydrology models used to support the development of Figure 2.

The CO_2 flux estimates for the drying lakebed surrounding the Salton Sea can be refined by using a model based on a global study of lakes. A closed chamber gas analysis of samples of desiccated sediment from 196 drying water bodies shows that CO_2 emissions rates from dry inland lakes or reservoirs is around 207 mmol/m^2/day with a global standard deviation of 405 mmol/m^2/day (Keller et al., 2020). This means that while most dry sediments are net emitters of CO_2, some sediments may still be net absorbers of CO_2 from the atmosphere. Supporting *in situ* measurements of moisture, conductivity, and air temperature, local elevation and latitude can be used to refine the CO_2 flux estimate for the Salton Sea using the following linear mixed effects model developed by Keller et al., 2020:

$F(CO_2)$ = -0.22 x Elevation + 0.25 x Latitude + -0.14 x Conductivity + 0.3 x Temperature + 0.4 x Moisture + 0.3 x Organic Matter + 0.23 x (Moisture : Organic Matter) + 0.12 x (Moisture : Temperature) + 0.04,

where variables are $\log_{10}$- and z-transformed.

Not considered in this analysis are CH_4 emissions from shallow, oxygenated sediments due to methanogenic bacterial respiration. This is because we assume that the Salton Sea is anoxic owing to its eutrophic to hypereutrophic status. However, some findings indicate that surficial sediments are key to understanding CH_4 dynamics and fluxes of whole lake CH_4 budgets (Bastviken et al., 2008). At the same time, algal productivity provides a source of labile carbon to stimulate CH_4 emission under anoxic conditions via methanogenesis (Beaulieu et al., 2018). Thus, an assessment of such CH_4 emissions could further affect the future GHG budget of the shrinking and drying Salton Sea, especially since CH_4 has a higher global warming potential than CO_2 and since methane production rates are enhanced by temperature, which itself is projected to increase due to climate change. The data to do this evaluation at present are not available at the Sea, but future study is recommended if a more refined GHG estimate is desired.

1.3.3 Nitrous Oxide Emissions

N_2O is a product of denitrification (reduction of NO_3^- to N_2) and by-product of nitrification (oxidation of NH_4^+ to NO_3^-) (Woszczyk and Schubert, 2021). Thus, flux of N_2O is correlated with availability of oxygen and nitrates, and with temperature of the water column. N_2O flux from lakes is not well studied and the estimates here are from a small number of lakes where these values have been reported. A study of lakes in the Colorado Rocky Mountains shows that N_2O flux from high-deposition lakes (i.e., receiving 5 – 8 kg N/ha/year) varied from 0.8 to 6.4 µmol N/m^2/hour (0.308 to 2.47 g N_2O/m^2/year) (McCrackin and Elser, 2011). Therefore, for a eutrophic lake such as the Salton Sea that is influenced by agricultural drainage, the upper limit of 2.47 g N_2O/m^2/year can be used. For comparison, in the south Baltic coastal lakes, N_2O flux is estimated at 0.269 g N_2O/m^2/year (Woszczyk and Schubert, 2021), smaller than the lower bound cited above. Results from DelSontro et al. (2018) suggest that the rate of N_2O flux is positively correlated with lake size and Chlorophyll *a* concentration; and a 0.345 g N_2O/m2/year can be estimated using the derived equation in DelSontro et al. (2018) based on the current size of Salton Sea and reported Chlorophyll *a* concentration. N_2O emission rates for 17 lakes including 14 saline lakes in the Tibetan Plateau (Yan et al., 2018) were estimated as 0.104 g N_2O/m2/year averaged across all lakes. As studies on the N_2O flux in warmer lakes are limited, the reported upper bound of 2.47 g N_2O/m^2/year in McCrackin and Elser, (2011) was used for Salton Sea given with warm water temperature and substantial eutrophication. Figure 14 shows the cumulative and annual emission of N_2O from the lake surface.

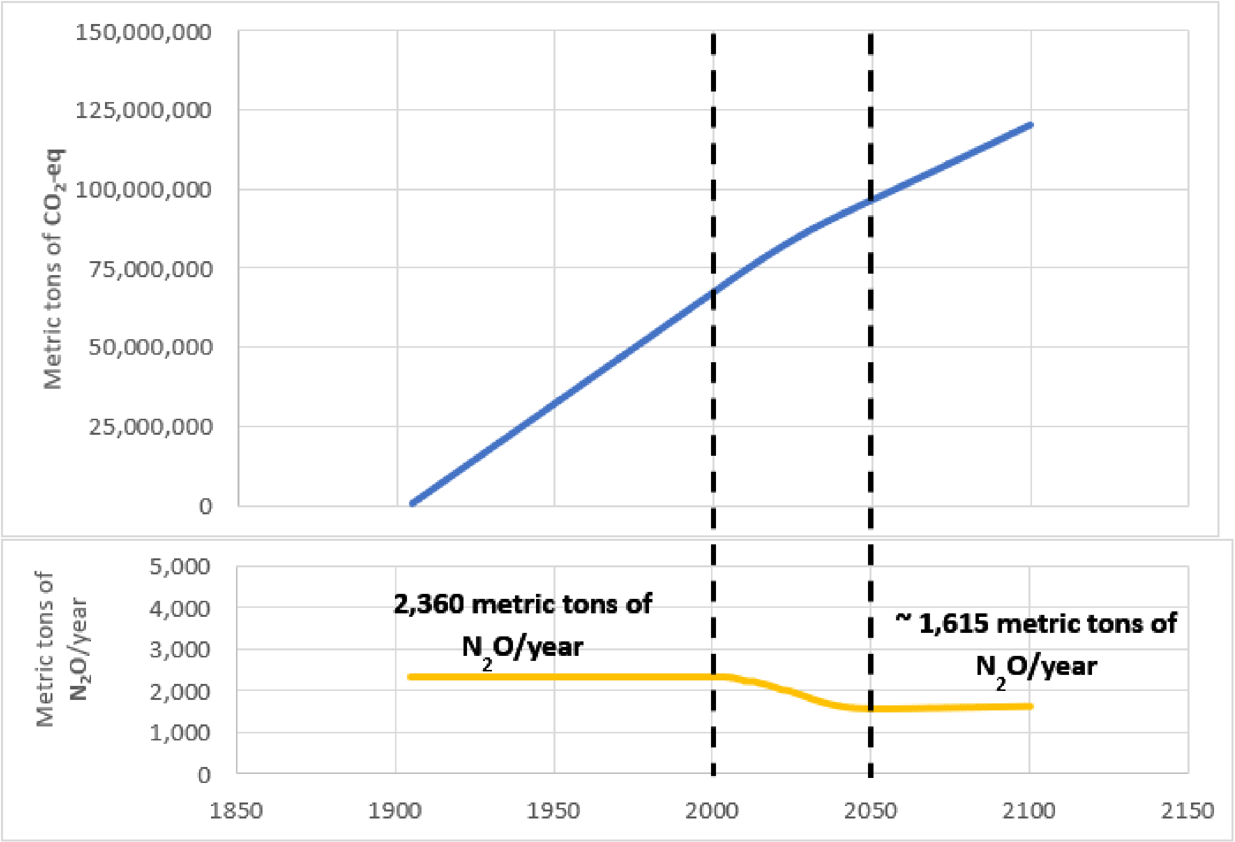

Figure 14. Top: Estimated cumulative metric tons of CO_2-eq of N_2O flux from the lake area of the Salton Sea. Bottom: Estimated metric tons N_2O flux per year from the lake area of the Salton Sea. Both the top and bottom figures were computed using an estimated emission rate of 2.47 g N_2O/m^2/year (McCrackin and Elser, 2011) and based on lake area assumptions and hydrology models used to support the development of Figure 2.

1.4 Summary of Reference Values

Tables 1 and 2 summarize the sources of reference values that were used to understand the GHG budget of the Salton Sea.

Table 1. COLUMN 1: Sources of background information that were used to compute the GHG budget of the Salton Sea; COLUMN 2, 3, 4: The GHG process that can be estimated based on information gathered from the source and its contribution (either + or -) to the GHG budget; COLUMN 5, 6, 7: Estimated rates of input or output from the system based on the information gathered, converted to a variety of units to allow for comparison across studies.

		GHG	**Process**	**mmol C/m^2/day**	**g C/m^2/year**	**g CO_2-eq/m^2/year**
Clow, et al. (2015)	**+**	**Carbon Burial**				
DelSontro, et al. (2019)	-	**CH_4 Emissions**	**Eutrophication**			
Keller, et al. (2020)	-	**CO_2 Emissions**	**Drying**			
McDonald, et al. (2013)	-	**CO_2 Emissions**	**Open Water Diffusive Flux**			
McCrackin and Elser (2011)	-	**N_2O Emissions**		mmol N_2O/m^2/day	g N_2O/m^2/year	

x 365 x 12 / 1000 **x (44 / 12)**

x 365 x 44 / 1000 **x 298***

factor for global warming potential

Table 2. The same information as in Table 1 but with the values from the sources converted into different units and filled out in COLUMN 5, 6, 7. NOTE: for CO_2 emissions from open water diffusive flux, a range of values suggested by McDonald et al., 2013 is provided along with a mean value that is suitable for California. This is to illustrate the high uncertainty in emission rates associated with this process.

		GHG	**Process**	**mmol C/m^2/day**	**g C/m^2/year**	**g CO_2-eq/m^2/year**
Clow, et al. (2015)	**+**	**Carbon Burial**		16.4	72	**264**
DelSontro, et al. (2019)	-	**CH_4 Emissions**	**Eutrophication**	11	48	**177**
Keller, et al. (2020)	-	**CO_2 Emissions**	**Drying**	1,907	8,353	**30,626**
McDonald, et al. (2013)	-	**CO_2 Emissions**	**Open Water Diffusive Flux**	58	256	**939**
McCrackin and Elser (2011)	-	**N_2O Emissions**		0.15 mmol N_2O/m^2/day	2.47 g N_2O/m^2/year	**2.47 x 298* = 736**

**factor for global warming potential*

1.5 GHG Budget of the Salton Sea Per Year (until 2100) and To Date (from 1905)

Plotting cumulative emissions for the Phase 1: 10-Yr Plan concept in CO_2-eq from CO_2, N_2O, and CH_4 open water flux shows that CO_2 and N_2O are similarly important contributors to the Salton Sea's GHG budget (Figure 15).

GHG emissions from open water are calculated from the sum of the wetted surface of the Sea and 10-year plan projects. The wetted surface area calculations incorporate 10-Yr Plan projects coming online over varying timelines and reflect the shrinking surface area of the Sea over time, as predicted by SSAM (further described in Appendix D of the LRP).

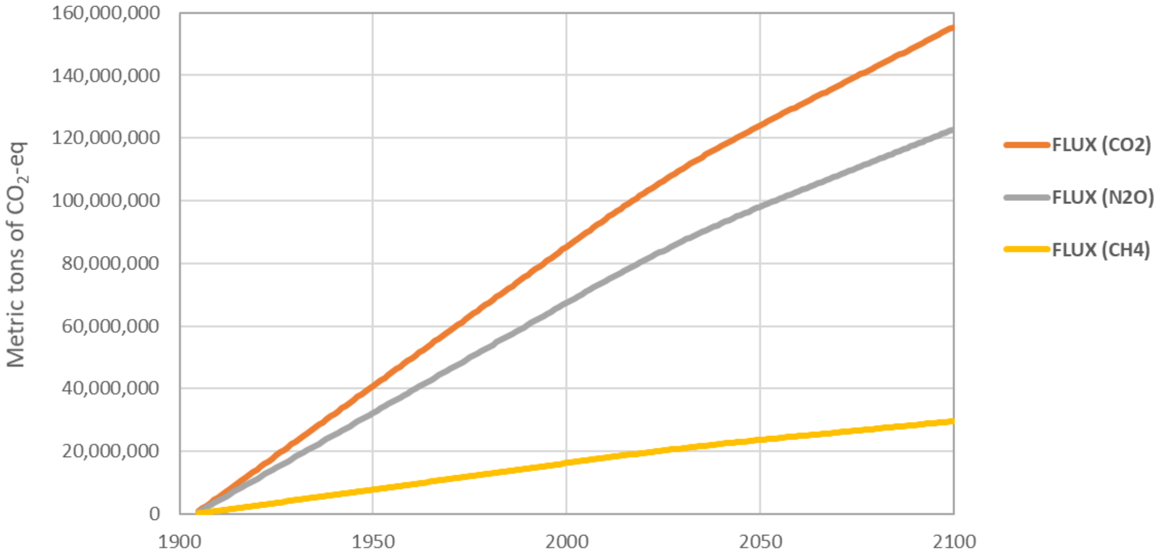

Figure 15. Cumulative emissions of CO_2, CH_4, and N_2O for the Phase 1: 10-Yr Plan concept in units of metric tons of CO_2-eq. Note that CH_4 has a global warming potential that is 25x that of CO_2, and N_2O has a global warming potential that is 298x that of CO_2 on a 100-year time scale (IPCC, 2013). For comparison across global warming potentials, y-axis units are in metric tons of CO_2-eq.

For a per annum understanding of the Salton Sea GHG for the Phase 1: 10-Yr Plan concept, see Table 3 to compare estimates of OC burial, CO_2 emissions from the oxidation of the exposed lakebed, CH_4 emissions, and diffusive flux of CO_2 and N_2O from the wetted surface. For cumulative estimates since the formation of the Salton Sea since 1905, see Table 4.

Table 3. For the Phase 1: 10-Yr Plan concept, annual estimates of OC burial, CO_2 emissions from the oxidation of the exposed lakebed, CH_4 emissions, and diffusive flux of CO_2 and N_2O from the lake water surface in 2000, 2018, 2020, 2028, 2030, 2050, and 2100. The years 2018 and 2028 are the beginning and ending dates of the 10-Yr Plan. Units are in metric tons of CO_2-eq per year unless otherwise stated.

		Drying from Exposed Lakebed		Eutrophication (diffusive + ebullitive)	Diffusive Flux from Lake Water Surface	
YEAR	**Carbon Burial**	**CO_2 (assuming 5-year Oxidation)**	**CO_2 (assuming 20-year Oxidation)**	**CH_4 (assuming no change in *Chl a* or TP)**	**CO_2**	**N_2O *metric tons of N_2O per year**
	Metric tons of CO_2-eq *per year*					
2000	0.25 M	0	0	0.17 M	0.89 M	0.70 M 2,360*
2018	0.23 M	0.22 M	0.10 M	0.16 M	0.82 M	0.65 M 2,170*
2020	0.23 M	0.27 M	0.14 M	0.15 M	0.80 M	0.63 M 2,120*
2028	0.22 M	0.01 M	0.14 M	0.15 M	0.78 M	0.62 M 2,070*
2030	0.21 M	0.19 M	0.15 M	0.14 M	0.75 M	0.59 M 2,000*
2050	0.18 M	0	0.17 M	0.12 M	0.65 M	0.51 M 1,730*
2100	0.19 M	0	0	0.13 M	0.68 M	0.54 M 1,800*

Table 4. For the Phase 1: 10-Yr Plan concept, cumulative estimates of OC burial, CO_2 emissions from the oxidation of the exposed lakebed, CH_4 emissions, and diffusive flux of CO_2 and N_2O from the lake water surface by 2000, 2010, 2020, 2030, 2050, and 2100. Units are in metric tons of CO_2-eq to date (i.e., since 1905).

		Drying		**Eutrophication (diffusive + ebullitive)**	**Diffusive Flux from Lake Water Surface**	
YEAR	**Carbon Burial**	**CO_2 (assuming 5-year Oxidation)**	**CO_2 (assuming 20-year Oxidation)**	**CH_4 (assuming no change in *Chl a* or TP)**	**CO_2**	**N_2O**
	Metric tons of CO_2-eq *to date (since 1905)*					
2000	24.2 M	0	0	16.2 M	85.3 M	67.4 M
2010	26.7 M	0.29 M	0.073 M	17.9 M	94.1 M	74.4 M
2020	29.0 M	2.2 M	0.89 M	19.5 M	102 M	80.9 M
2030	31.2 M	4.0 M	2.5 M	21.0 M	110 M	87.0 M
2050	35.0 M	7.9 M	6.6 M	23.5 M	124 M	97.7 M
2100	44.5 M	7.9 M	7.3 M	29.9 M	157 M	124 M

1.6 Conclusions

Based on the assumptions made and references consulted in Sections 3 and 4, we can estimate that by 2000, the Salton Sea sequestered 24.2 M metric tons of CO_2-eq of carbon, while emitting 85.3 M metric tons as CO_2, 16.2 M metric tons as CH_4, and an additional 67.4 M metric tons CO_2-eq of N_2O from open water flux. As noted in the Introduction, these estimates are based ~2000 water quality levels and lake area, because data from the early decades of the 20th century are not available. These values may be considered conservative from the standpoint of GHG impact, in that higher-end estimates of fluxes were typically used from the literature for developing the total GHG emissions for the Salton Sea.

The calculations in this Appendix indicate that that the Salton Sea may have increased the global warming potential of the atmosphere, when measured in terms of CO_2-eq. This is consistent with global findings as an estimated 90% of aquatic ecosystems studied emit CO_2 to the atmosphere, showing that lakes, including saline lakes, are significant global and regional CO_2 emitters (Kling et al., 1992; Cole et al., 1994; Cole et al., 2007; Duarte et al., 2008). Warmer lakes also emit more CO_2 than comparable cooler lakes (Kosten et al., 2010).

Furthermore, estimated CH_4 emissions from the Salton Sea are amplified due to eutrophication. Methane is a major product of carbon metabolism in lakes (Bastviken et al., 2008). Studies show that CH_4 emissions from lakes account for 6-16% of global non-anthropogenic emissions and that reservoirs account for 18% of global anthropogenic emissions (Bastviken et al., 2004; St. Louis et al., 2000). Currently, GHG emissions from lakes are equivalent to ~20% of global fossil fuel emissions, and even moderate levels of enhanced eutrophication could increase the atmospheric effect of GHG emitted from lakes (measured as CO_2-eq) by 5, 26, or 42% based on increases in chlorophyll *a* concentration by 1, 5, or 10 µg/L (DelSontro et al., 2019). Due to the magnitude of such changes, a refined estimate of CH_4 emissions to date and in the future would benefit from higher resolution observations of chlorophyll *a* concentration at the Salton Sea.

We estimate that by 2020, an additional 0.89 to 2.2 M metric tons CO_2-eq of CO_2 had been emitted following the slow oxidation of an increasing exposed lakebed area, depending on the oxidation timeline (i.e., a 20- to 5-year process timeline). From 2050 to 2100 for the Phase 1: 10-Yr Plan concept, assuming that the Salton Sea's lake and exposed lakebed areas stabilize, carbon burial rates will plateau at 0.19 M metric tons of CO_2-eq/year while emissions of N_2O and CO_2 will be at least 0.54 and 0.68 M metric tons of CO_2-eq/year, respectively. CH_4 emissions from the lake are less significant than emissions of N_2O and CO_2 but would equal at least 0.13 M metric tons of CO_2-eq/year.

Total emissions from the lake surface would therefore be at least 1.29 M metric tons of CO_2-eq/year by 2050, by which time oxidation of the exposed sediment would have contributed an additional 6.6 to 7.9 M metric tons CO_2-eq of CO_2.

While the above GHG fluxes are all estimates, at a high level they may be compared to the annual loads of carbon based on measured concentrations and inflows (0.087 M tons per year of organic and inorganic C, or 0.31 M tons of CO_2-eq per year). Assuming roughly equal levels of inflows into the Sea over its recent period of existence (~120 years), the total emissions exceed the inflows but are of the same order of magnitude (see Table 3). The excess emissions may be explained by in-Sea carbon production and the role of other GHGs (N_2O and CH_4) that have a much higher global warming potential in the CO_2-eq calculation.

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