Wetland Restoration in the San Joaquin Delta: Modeling the Impacts of Seasonality and Variation of Water Levels on the Greenhouse Gas Budget

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ABSTRACT

Wetlands are very sensitive ecosystems that can switch from a carbon sink to a carbon source depending on key variables. Management and efficient water use by wetlands should be examined to determine which water regimes optimize carbon sequestration. These management decisions must be informed by the potential greenhouse gas budget (GHG budget) of the wetland and the factors influencing this budget: light availability, air temperature, and season. My study determines the impact of seasonality and varying water regimes on the methane released from wetlands through the input of air temperature, GPP (Gross Primary Production), Reco (ecosystem respiration), PAR (Photosynthetically Active Radiation), EVI (Enhanced Vegetation Index), and three different water level regime data into the PEPRMT model (Peatland Ecosystem Photosynthesis Respiration and Methane Transport) to produce the output of the methane pulse of the wetland. The units are then converted to represent the methane flux in terms of carbon and then converted again to represent the GHG budget in terms of carbon dioxide. There is a positive relationship between light availability and methane emitted as well as an exponential relationship between air temperature and the methane pulse emitted from wetlands. Furthermore, the model results in contradicting outcomes to most scientific literature on this subject by suggesting the original water table height produces the most methane emissions compared to the expected high water table height. In conclusion, this study could provide the East End wetland managers with key information about water usage in order to improve the efficiency of such an invaluable resource.

KEYWORDS

PEPRMT model, carbon flux, light availability, air temperature, methanogenesis

INTRODUCTION

California has battled over the use of scarce and invaluable water for decades, exacerbated by drought and mass irrigation of agriculture (Swain, 2015). California's Sacramento - San Joaquin River Delta (the Delta from here on out) supplies water to more than 25 million people and irrigates 3 million acres of farmland ranging from the San Francisco Bay Area to Southern California (IPCC 2016). Droughts not only prevent water supplies from restocking, but they also release previously stored carbon into the atmosphere as carbon dioxide (Vahedifard et al. 2024). California wetlands introduce another aspect that requires strategic allocation of water resources which can be solved by determining the efficacy of current water usage.

Wetlands provide essential ecosystem services such as flood resilience and sequestering carbon (Were et al. 2019). However, due to the high fertility of the soil, wetlands have historically been drained and converted to agricultural land, not only removing a potential carbon sink, but also creating a carbon source (Drexler et al. 2009). The Delta is home to wetlands whose soils must be submerged in order to maintain carbon retention and thus requires enough water to flood the land (Eldardiry and Habib 2018). Now that the wetlands are restored, informed water management practices of wetlands are critical to keeping wetlands a healthy carbon sink while optimizing water usage (Pindilli et al. 2018).

There is a tradeoff between the amount of carbon sequestered and the amount of methane respired from wetlands under anaerobic conditions (Valach et al. 2022). Deciding how much water to add to a wetland and when to add this water is crucial to ensure the net balance of carbon released from wetlands is negative: under aerobic conditions (using less water), carbon dioxide is released into the atmosphere and there is very little carbon sequestered (Lal 2018). On the other hand, under anaerobic conditions (using more water) more methane (a more potent GHG) is released into the atmosphere (Bridgham et al. 2013). Using the PEPRMT model (Peatland Ecosystem Photosynthesis Respiration and Methane Transport), one can predict how a specific water quantity will affect how much carbon is exchanged between wetlands and the atmosphere and thus one can determine the greenhouse gas budget (Oikawa et al. 2017). This model can address the goal of restoration: to maximize carbon storage and minimize water use.

In order to balance conservation of water and carbon retained in the wetland ecosystem, I asked: How does the time of year affect the amount of water needed for wetlands without increasing the greenhouse gas budget? I further broke this question down into sub-questions: 1) What is the impact of light availability on methane emissions? 2) What is the impact of air temperature on methane emissions? 3) What is the impact of seasons on methane emissions? Light availability and air temperature are components of season and thus spring and summer will likely produce more methane emissions due to increased light and temperature promoting photosynthesis. However, this increased photosynthesis will reduce the carbon dioxide in the atmosphere creating an overall lower GHG budget.

METHODS

Study site

The wetland of focus in this study is the East End Wetland which is located on Twitchell Island, in the Delta, in Sacramento County, California (38°10N, 121°640W) (Figure 1) and is approximately 3.5 km^2 (Oikawa et al. 2017). East End was drained beginning in the 1850s, and was turned into corn fields due to the fertile soil. The restoration of the wetland began in 2013 and the restoration was planned to have a combination of open water and vegetated water channels and ponds. The surrounding tule and cattail plant material was spread to the restored wetland and gradual flooding began in January, 2014 to aid plant growth and stabilize the berms, thus preventing erosion.

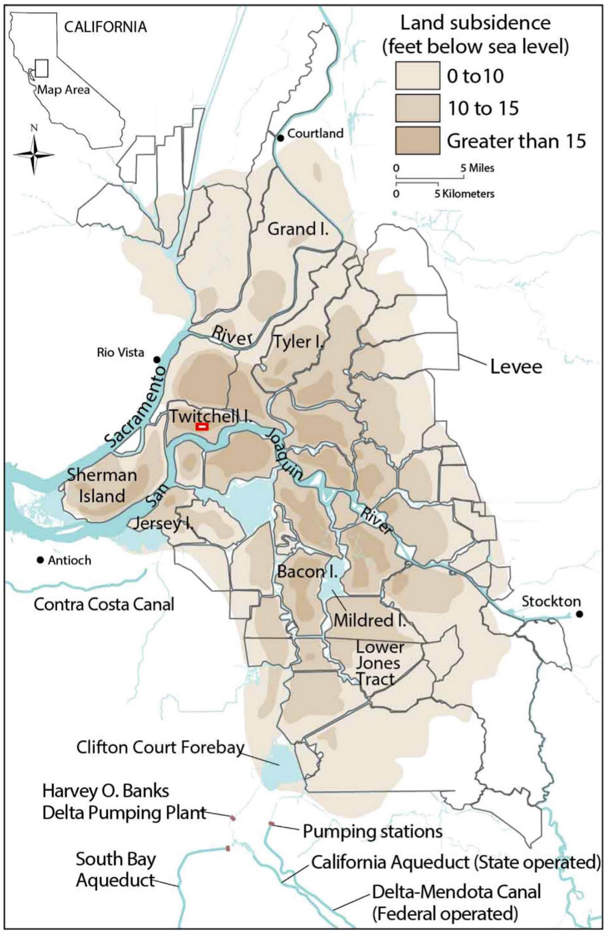

Figure 1. Map of the Sacramento-San Joaquin River Delta. The red box pinpoints the East End wetland site of Twitchell Island (Miller et al. 2008).

Biometeorology data

The eddy flux tower (Figure 2) -- which used the eddy covariance technique to measure methane, carbon dioxide, water, and energy fluxes to achieve an understanding of current and future carbon fluxes in the Delta -- was installed in November 2013 (Ameriflux 2013). The data collected by the tower can be found on AmeriFlux at site US-Tw4 Twitchell East End Wetland. This study used air temperature, water table height, GPP (Gross Primary Production), Reco (ecosystem respiration), and PAR (Photosynthetically Active Radiation) data. For the season data, I decided to split the year into quarters and assigned the first three months of the year (January-March) to winter, the next three months (April-June) to spring, the next three months (July-September) to summer, and the last three months (October-December) to fall.

Figure 2. Eddy flux tower at the East End wetland site. This tower measures methane fluxes, carbon dioxide fluxes, Photosynthetically Active Radiation (PAR) air temperature, and GPP.

Remote sensing data

EVI (Enhanced Vegetation Index) data was gathered from MODIS satellite sensors (NASA and USGS MOD09GA Version 6.1) and downloaded using Google Earth Engine. Global EVI data has been available since 2000 and is similar to the more widely used NDVI (Normalized Difference Vegetation Index) and is evaluated based on near-infrared and red bands and ranges from -1.0 to +1.0. However, EVI better accounts for variable atmospheric conditions (USGS 2023). The 500 meter surface reflectance on a daily time step uses reflectance layers from the MOD09GA, and is used as source data for MODIS land products.

The PEPRMT model

I decided to use the PEPRMT (Peatland Ecosystem Photosynthesis Respiration and Methane Transport) model created by Patty Oikawa that was developed to simulate methane and carbon dioxide exchange in the restored wetlands of the San Joaquin Delta (Oikawa et al. 2017).

In order to consider the impact of labile carbon on wetland methane emitted (the only difference between the DAMM and TP versions of the model), I decided to use the PEPRMT-DAMM version, comprised of PEPRMT-DAMM-GPP, PEPRMT-DAMM-Reco, and PEPRMT-DAMM-CH4 modules (Oikawa 2017). I was able to make slight modifications to the predetermined parameters in an attempt to better reflect the current East End wetland. While this succeeded in the Reco module, the GPP module did not mimic the trends of the collected GPP data from Ameriflux, which led me to simply use the collected GPP data rather than the modeled data. I averaged the Ameriflux 30 minute time step data for each day, collected the EVI data from MOD09GA version 6.1, and the data to use as inputs to produce outputs (Table 3). .

Table 3. The data collected and used as an input in each module of PEPRMT-DAMM to produce an output. Data was collected from AmeriFlux and Google Earth Engine.

Input	Module	Output
Day of Year Air Temperature PAR EVI	PEPRMT-DAMM-GPP	GPP
Day of Year Air Temperature Water Table Height Season Age of Wetland	PEPRMT-DAMM-Reco	NEE SOC Labile Carbon
Day of Year Air Temperature Water Table Height GPP (modeled or collected) SOC Labile Carbon Age of Wetland	PEPRMT-DAMM-CH4	Methane Pulse Emission

I repeated this control group process for the different water regimes to determine the impact of water on the greenhouse gas budget. I decided to form one control group (original, averaged daily data) and 2 treatment groups: a low water table height (subtracted 20 cm from the original, averaged daily data) and a high water table height (added 20 cm to the original, averaged daily data) (Appendix A).

Sub-question variables

In order to determine the impact of the sub-question variables on the methane emissions of wetlands, I used light availability, air temperature, and season as inputs for the PEPRMT model to produce the output of Methane Pulse Emissions (Table 3). The sub-question variables and the methane pulse emissions are not independent of each other, thus breaking the assumptions of most statistical models and rendering them invalid to use for my data. However, the mean and standard deviation of the input variables vs the output variable can provide insight to the effect seasonality has on methane emissions.

Carbon dioxide and methane flux

In order to determine the impact of the combined gas fluxes that comprise the GHG budget, I needed to convert these individual carbon dioxide and methane fluxes into the same units (carbon) and evaluate the net flux of the wetland. For the purpose of identifying the difference in methane emissions at different water regimes, it was important to keep the carbon dioxide contributions constant across all regimes. While the carbon dioxide flux is held constant, the methane flux (using the methane pulse emission output) can indicate the different contributions each water regime had on the combined GHG budget.

GHG budget

In order to make the carbon dioxide and methane fluxes comparable, I multiplied the fluxes by a Global Warming Potential (GWP) (IPCC 2023). Using GWP accounts for the different radiative forcing effects of the two gasses by putting the different fluxes into terms of carbon dioxide. I chose GWP100 to determine the energy absorbed by these different gasses – now in the same units – in 100 years (US EPA 2016). I selected the GWP value of 100 due to its prolific presence in scientific literature and to determine the longer term impacts of carbon gasses on the wetland GHG budget in relation to wetland restoration age.

RESULTS

Sub-question variables

I found that light availability (PAR) (*M*=444.7, *SD*=210.8) and methane pulse are positively related (Figure 4). Additionally, the air temperature (*M*=15.28, *SD*=5.782) and methane pulse follows an exponential trend at all water regimes (Figure 4). Furthermore, I learned that the largest methane pulse was at the original water table height (*M*=2.273×10^5, *SD*=1.570×10^5) (Figure 4a), the smallest methane pulse was at the low water table height (*M*=1.834×10^5, *SD*=1.751×10^5)(Figure 4b), and the methane pulse at the high water table height falls in between (*M*=1.982×10^5, *SD*=1.339×10^5)(Figure 4c). Lastly, there were varying impacts on the methane pulse from season to season and at each varying water regime (Figure 5). I also discovered the water regime with the smallest average across all years of methane emissions released was during winter at the low water table height (*M*=5.363×10^3, *SD*=3.809×10^3) and the largest average across all years of methane emissions released was during summer at the original water table height (*M*=3.915×10^4, *SD*=1.361×10^4).

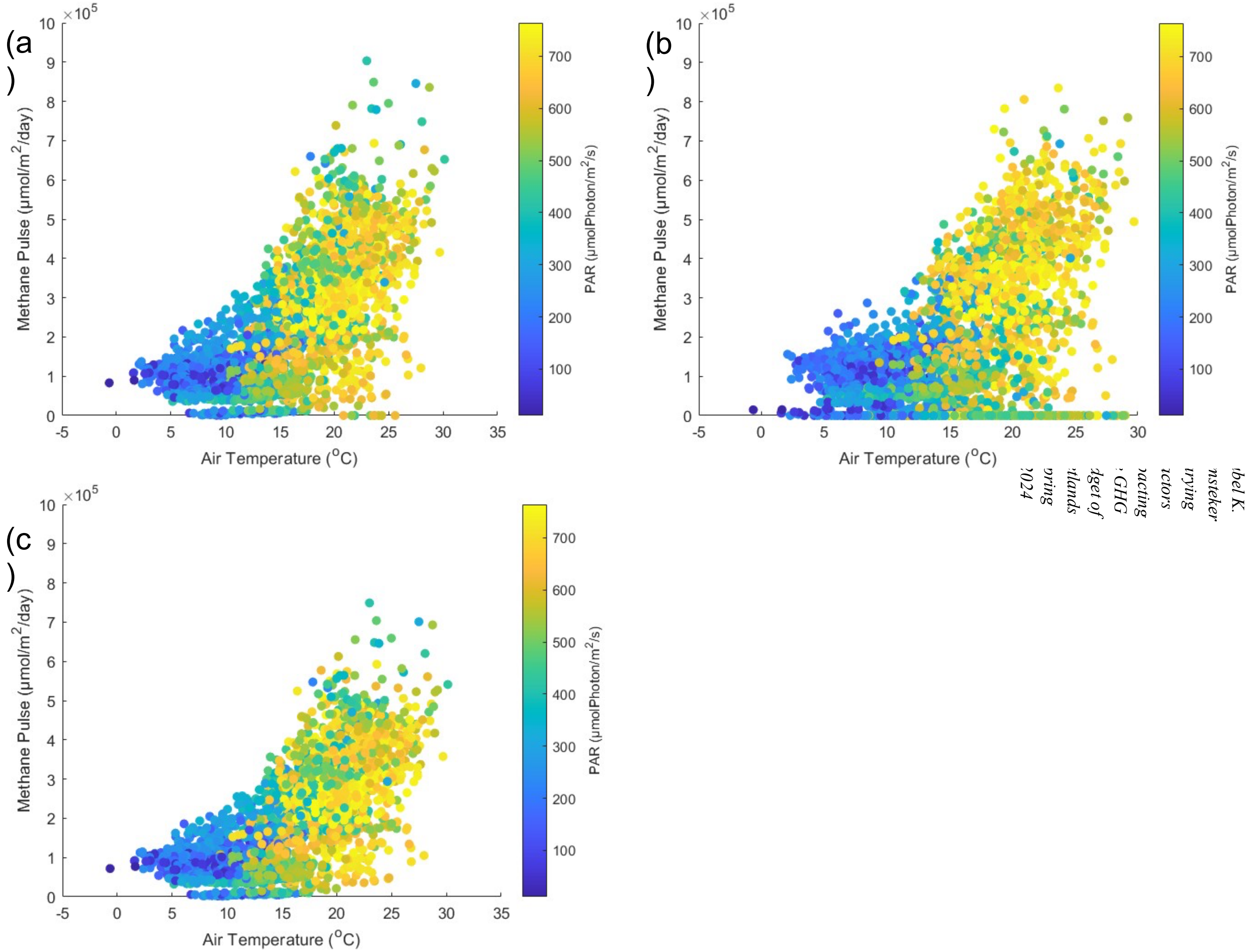

Figure 4. Scatter plots of the impact of air temperature and light availability (PAR) on methane emissions across the three water regimes. (a) methane emissions at the original water table height, (b) methane emissions at the low water table height, and (c) methane emissions at the high water table height.

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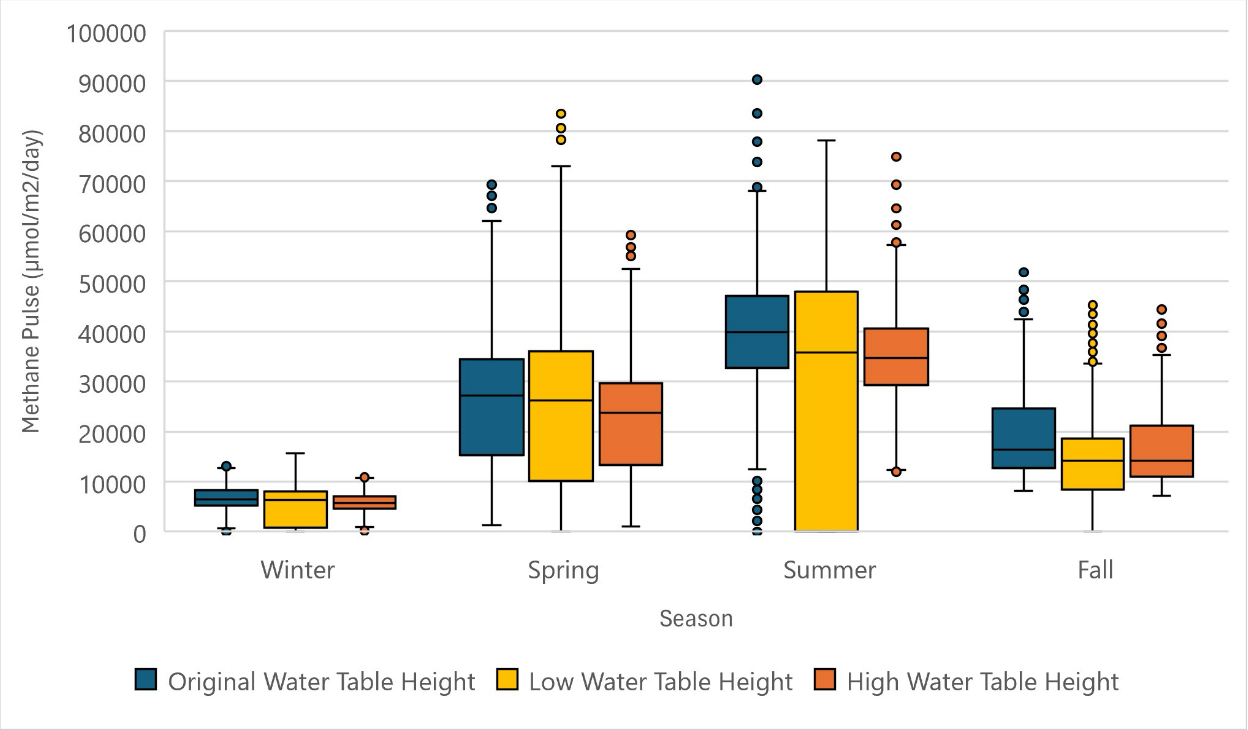

Figure 5. Boxplots of season vs daily mean methane pulse at varying water table heights.

Carbon dioxide and methane flux

I found that the constant carbon dioxide flux (*M*=-350.5, *SD*=285.6) was negative across all years except for 2014 (Figure 6) and the varying methane flux was positive across all years (Figure 7). The original water table height across all years produced the most methane emissions on average (*M*=27.15, *SD*=6.597) and the low water table height across all years produced the least methane emissions on average (*M*=21.93, *SD*=8.071), with the methane emissions produced at a high water table height falling in the middle (*M*=23.67, *SD*=5.440).

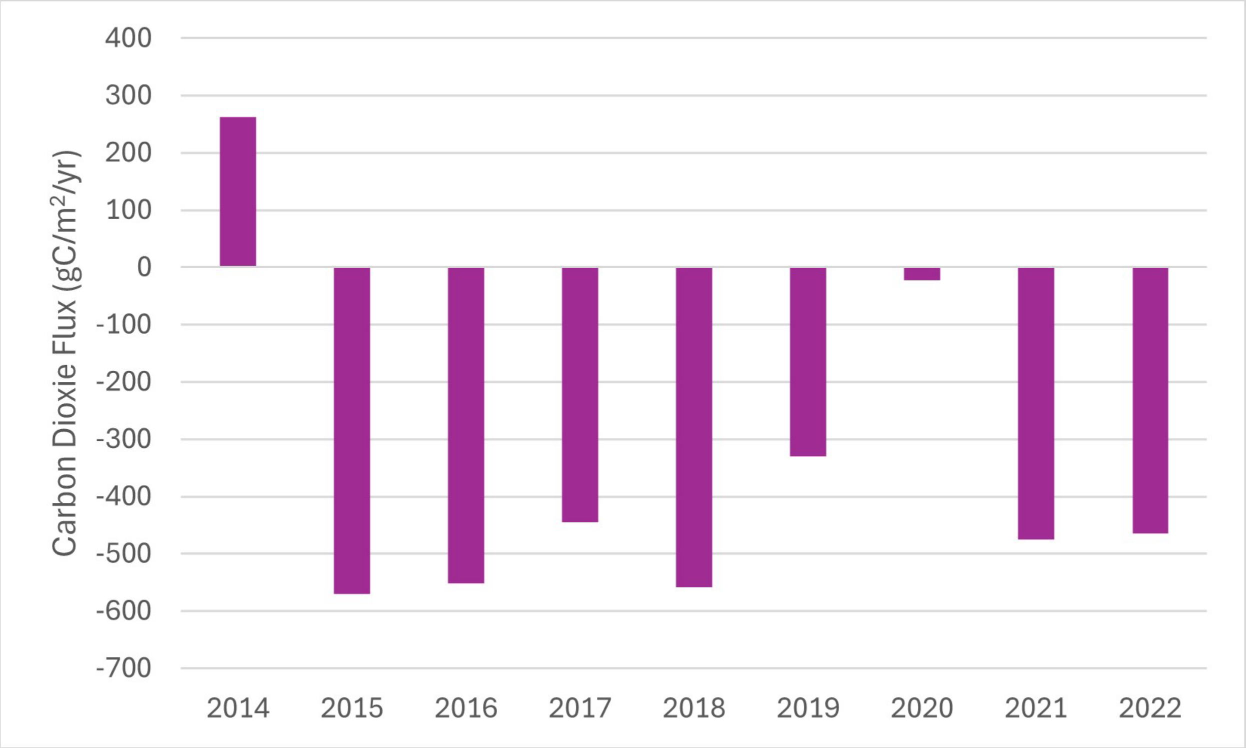

Figure 6. Bar graph showing the carbon dioxide flux of the East End wetland (2014-2022). This is used for all water regimes to predict the GHG budget of the East End wetland.

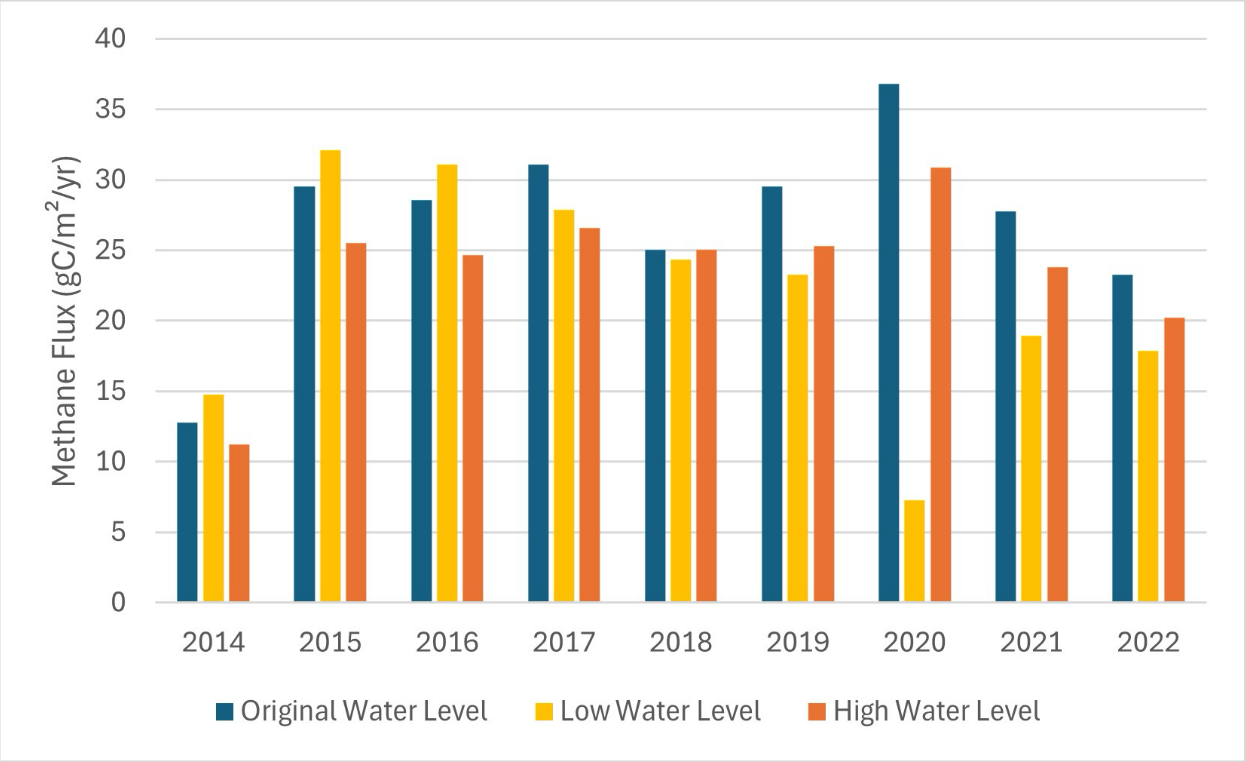

Figure 7. Stacked bar graph showing the methane flux of the East End wetland (2014-2022).

GHG budget

I found that all years except for 2014 and 2020, the GHG budget was negative for all water regimes (Figure 8). I also determined that across all years, the average GHG budget produced at the original water table height (*M*=-307.9, *SD*= 977.6) was the largest GHG budget and across all years the average GHG budget produced at a low water table height (*M*=-495.9, *SD*= 858.29) was the smallest GHG budget, with the budget produced at a high water table height (*M*=-432.9, *SD*= 967.4) falls in between.

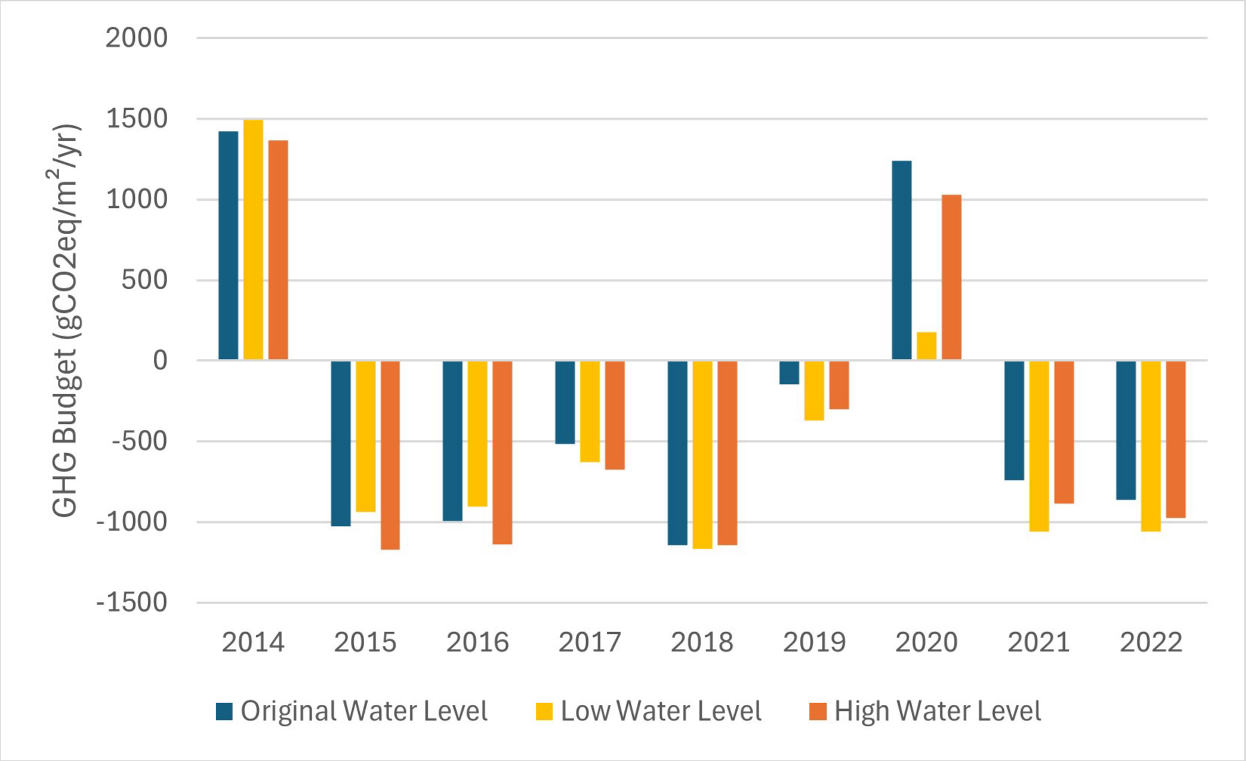

Figure 8. Stacked bar graph of GHG budget across the three water table heights.

DISCUSSION

The methane emissions of the original water table height compared to the low and high water table heights did not support my hypothesis. I hypothesized that the order of water level regimes, from the least to most methane emitted, would be the low, original, and then high.

However, as previously stated, the original water table height produced most methane emissions and had the highest average GHG budget of the three regimes. On the other hand, the low water table heights produced the least methane emissions and had the smallest average GHG budget, as determined by my study, which supported my hypothesis. This suggests that the model may not be the most proficient at reflecting the measured carbon fluxes and GHG budget.

Sub-question variables

When looking at the light availability (PAR) and air temperature versus methane emissions, there is very little difference in the distribution of data across the three water regimes (Figure 4). However, as stated previously, the original water table height, on average, produces more methane emissions than the two treatment groups. This doesn't reflect the results of previous studies that would hypothesize the high water table group to produce the most methane (Martel et al. 2020).

There is a noticeable trend in the low water table graph where data at all air temperatures and PAR values produce around zero methane emissions (Figure 4b). There are signs of this trend in the other regime graphs, but not to the same extent as the low water table height (Regina et al. 2015). Despite the increased light availability contributing to increased air temperatures and thus increased microbial activity (Ngwabie et al. 2011), there is still very little methane being produced (reduced methanogenesis). This is likely due to the reduction in the anaerobic status of the environment (less water means greater access to oxygen) which reduces microbial activity that produces methane (Batson et al. 2015).

Again, there is very little difference in distribution of data across the three water regimes when analyzing the season graphs (Figure 5). The most obvious difference is in the summer months where the low water table height (*IQR*= $4.789\text{x}10^4$) varies far more than that of the original water table height (*IQR*= $1.435\text{x}10^4$) and the high water table height (*IQR*=$1.1\ 36\text{x}10^4$). This is likely due to the varying levels of anaerobic status of the wetland (Martel and Qaderi 2017): the more water available, the more methane produced and the less water available, the less methane produced via methanogenesis (Zhao et al. 2020). This is because there is rarely very little water to cause a highly aerobic environment at the original water table height (due to the controlled water levels of the impacted East End wetland) and the high water table height is an additional 20 cm to the original water table height, which would prevent it from having very little water unlike the low water table heights (Yuan et al. 2021).

The trend of low water regime showing the most variation in season can also be seen in the winter months (Martel and Qaderi 2017). In the winter months, the wetland produces the least amount of methane emissions (as mentioned earlier), likely due to the reduction in light availability and air temperature, slowing microbial activity and hence producing less methane gas (Yang et al. 2020). There is also the smallest difference in means across the original, low, and high water regimes in the winter months (*Mdn*=$6.417\text{x}10^3$, *Mdn*=6245, *Mdn*=$5.537\text{x}10^3$ respectively), likely due to the fact that light availability and air temperature are so reduced that water level is a secondary factor impacting the amount of methane released (Martel et al. 2020).

Carbon dioxide and methane flux

Due to the fact that the restoration of the East End wetland included the planting of seedlings, the already photosynthesizing plants were able to remove carbon dioxide from the atmosphere thus producing negative carbon dioxide flux in only the second year after restoration (Figure 6). The spike in 2014 means the wetland was a carbon dioxide source, due to the seedlings not being fully developed and thus not photosynthesizing at the optimal rate (Dinsmore et al. 2009). Photosynthesis contributes to the GPP of an ecosystem, which is then compared to the carbon dioxide respired to determine the carbon dioxide flux (Salimi et al. 2021). Because I am comparing the impact of seasonality and water levels on the methane flux and GHG budget, I decided to keep the carbon dioxide flux constant to better evaluate the role of methane on the GHG budget. However, it is important to note that water is needed to promote plant growth that then sequesters carbon, so the low water table height may experience more carbon dioxide emissions (Dinsmore et al. 2009). For this reason, the less negative carbon flux in 2020 is likely due to the reduced water level in the East End wetland (Pugh et al. 2018). This carbon dioxide flux reduces the GHG budget of the wetland (Zhuang et al. 2007).

There was a positive methane flux across all years and water regimes due to methane being stored in wetlands for a short period of time before returning to the atmosphere (DeLaune et al. 2018). Due to the reduction in water level of the wetland in 2020, there was a reduction in the methane flux because there was less water to create an anaerobic environment where microbial activity prospers and undergoes methanogenesis to produce methane (Evans et al. 2021). However, there was still a carbon dioxide contribution via aerobic respiration by microbes (Batson et al. 2015). There was also a large difference in methane flux at a low water table height (7.27 gC/m2/yr) compared to the original water table height (36.81 gC/m2/yr) and high water table height (30.86 gC/m2/yr). This is likely due to the low water table heights hitting a threshold in water level that produces vastly reduced methane emissions (Rocher-Ros et al. 2023) This increased methane flux increases the GHG budget of the wetland (Zhuang et al. 2007).

GHG budget

There was a negative GHG budget across all water regimes and in all years except for 2014 and 2020 (Figure 8). This means there was more carbon being sequestered in the wetland than released into the atmosphere. The positive GHG budget in 2014 means the wetland was a carbon source, likely due to the methane push that emanates from newly restored wetlands and when water regimes change, like flooding the old corn field that was once the East End wetland (Dinsmore et al. 2009). In 2020, the wetland was also likely a carbon source due to the reduced water levels, diminishing the carbon dioxide photosynthesized by plants requiring the limited availability of water and not sequestering carbon at optimal rates (Regina et al. 2015). Due to carbon dioxide making up most of the GHG budget, this reduction in photosynthesis and thus carbon retention led to wetland becoming a carbon source rather than a sink as seen in other years (Berger et al. 2019). There is also a large disparity between the different water regimes in 2020, with the low water regime (178.39 gC/m^2/yr) having a far smaller GHG budget than the original water table height (1241.61 gC/m^2/yr) and the high water table height (1027.57 gC/m^2/yr). This is likely due to the reduced water level creating a more aerobic environment and reducing microbial activity and thus reducing the methane emitted contributing to the GHG budget (Rocher-Ros et al. 2023). So while plants at all water regimes were struggling to store carbon dioxide via photosynthesis, the low water level produces less methane, ultimately causing a lower GHG budget.

Limitations and future directions

There are several limitations of this study ranging from data availability to the use of the model to the evaluation of carbon dioxide on each individual water regime's GHG budget. First, there was no data, provided by Ameriflux, for the first 10 days of 2014 which could have skewed some of my results. In the future, this gap should be filled to reduce any potential bias. Second, I was unable to optimally parameterize the PEPRMT-DAMM-GPP module and thus I was unable to use the modeled GPP for the PEPRMT-DAMM-CH4 module. Instead I used the measured GPP provided by Ameriflux. This could alter the effectiveness of the model and means my results are not a true representation of the model. Third, using any model to attempt to forecast a system as complicated as the biogeochemical properties of wetlands is difficult and may not be the most adept at predicting wetland fluxes (Bechtold et al. 2014), and thus the original water table height produces the most methane emissions and largest yearly average GHG budget, rather than following the expected high water table producing the most methane emissions and having the largest GHG budget. Lastly, this model was created for current environmental conditions, but as conditions change due to climate change, the biometeorology of wetlands will change as well, and thus models can be further adapted to reflect future fluxes of wetlands.

In order to determine the optimal water level for wetlands to optimize carbon sequestration while using the least amount of water possible, there would need to be an expanded analysis to more water level regimes to determine thresholds of carbon fluxes (Su et al. 2009). Furthermore, to explore the larger impact of carbon fluxes on the GHG budget, there would need to be an implementation of another model to estimate the carbon dioxide fluxes of wetlands rather than using collected carbon dioxide data to determine the GHG budget. Additionally, to make this model more efficient, the PEPPERMINT-DAMM-GPP module would need to be improved via alterations of the predetermined parameters to better fit each individual wetland and thus better reflect real-world, measured data.

Broader implications

Given the battle over water in California, it is essential to use water as efficiently as possible (Drexler et al. 2009). This is particularly true when it comes to the restoration of wetlands, because they can easily turn from a carbon sink to a carbon source due to poor water management (Yang et al. 2020). This study can provide insight into how wetlands can be best managed to optimize carbon sequestration while using as little water as possible and possibly inform the managers of the East End wetland (Zhuang et al. 2007).

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REFERENCES

Batson, J., G. B. Noe, C. R. Hupp, K. W. Krauss, N. B. Rybicki, and E. R. Schenk. 2015. Soil greenhouse gas emissions and carbon budgeting in a short-hydroperiod floodplain wetland. Journal of Geophysical Research: Biogeosciences 120:77–95.

Bechtold, M., B. Tiemeyer, A. Laggner, T. Leppelt, E. Frahm, and S. Belting. 2014. Large-scale regionalization of water table depth in peatlands optimized for greenhouse gas emission upscaling. Hydrology and Earth System Sciences 18:3319–3339.

Berger, S., E. Braeckevelt, C. Blodau, M. Burger, M. Goebel, O. Klemm, K.-H. Knorr, and C. Wagner-Riddle. 2019. A 1-year greenhouse gas budget of a peatland exposed to long-term nutrient infiltration and altered hydrology: high carbon uptake and methane emission. Environmental Monitoring and Assessment 191:1–16.

DeLaune, R. D., J. R. White, T. Elsey-Quirk, H. H. Roberts, and D. Q. Wang. 2018. Differences in long-term vs short-term carbon and nitrogen sequestration in a coastal river delta wetland: Implications for global budgets. Organic Geochemistry 123:67–73.

Dinsmore, K. J., U. M. Skiba, M. F. Billett, and R. M. Rees. 2009. Effect of water table on greenhouse gas emissions from peatland mesocosms. Plant and Soil 318:229–242.

Drexler, J. Z., C. S. Fontaine, and S. J. Deverel. 2009. The legacy of wetland drainage on the remaining peat in the Sacramento — San Joaquin Delta, California, USA. Wetlands 29:372–386.

Eldardiry, H., and E. Habib. 2018. Carbon capture and sequestration in power generation: review of impacts and opportunities for water sustainability. Energy, Sustainability and Society 8:1–15.

Evans, C. D., M. Peacock, A. J. Baird, R. R. E. Artz, A. Burden, N. Callaghan, P. J. Chapman, H. M. Cooper, M. Coyle, E. Craig, A. Cumming, S. Dixon, V. Gauci, R. P. Grayson, C. Helfter, C. M. Heppell, J. Holden, D. L. Jones, J. Kaduk, P. Levy, R. Matthews, N. P. McNamara, T. Misselbrook, S. Oakley, S. E. Page, M. Rayment, L. M. Ridley, K. M. Stanley, J. L. Williamson, F. Worrall, and R. Morrison. 2021. Overriding water table control on managed peatland greenhouse gas emissions. Nature 593:548–552.

Intergovernmental Panel On Climate Change (IPCC). 2023. Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. First edition. Cambridge University Press.

Lal, R. 2018. Digging deeper: A holistic perspective of factors affecting soil organic carbon sequestration in agroecosystems. Global Change Biology 24:3285–3301.

Martel, A. B., and M. M. Qaderi. 2017. Light quality and quantity regulate aerobic methane emissions from plants. Physiologia Plantarum 159:313–328.

Martel, A. B., A. E. Taylor, and M. M. Qaderi. 2020. Individual and interactive effects of temperature and light intensity on canola growth, physiological characteristics and methane emissions. Plant Physiology and Biochemistry 157:160–168.

Miller, R., M. Fram, R. Fujii, and G. Wheeler. 2008. Subsidence Reversal in a Re-Established Wetland in the Sacramento-San Joaquin Delta, California, USA. San Francisco Estuary and Watershed Science 6.

Ngwabie, N. M., K.-H. Jeppsson, G. Gustafsson, and S. Nimmermark. 2011. Effects of animal activity and air temperature on methane and ammonia emissions from a naturally ventilated building for dairy cows. Atmospheric Environment 45:6760–6768.

Oikawa, P. Y., G. D. Jenerette, S. H. Knox, C. Sturtevant, J. Verfaillie, I. Dronova, C. M. Poindexter, E. Eichelmann, and D. D. Baldocchi. 2017. Evaluation of a hierarchy of models reveals importance of substrate limitation for predicting carbon dioxide and methane exchange in restored wetlands. Journal of Geophysical Research: Biogeosciences 122:145–167.

Pugh, C. A., D. E. Reed, A. R. Desai, and B. N. Sulman. 2018. Wetland flux controls: how does interacting water table levels and temperature influence carbon dioxide and methane fluxes in northern Wisconsin? Biogeochemistry 137:15–25.

Regina, K., J. Sheehy, and M. Myllys. 2015. Mitigating greenhouse gas fluxes from cultivated organic soils with raised water table. Mitigation and Adaptation Strategies for Global Change 20:1529–1544.

Rocher-Ros, G., E. H. Stanley, L. C. Loken, N. J. Casson, P. A. Raymond, S. Liu, G. Amatulli, and R. A. Sponseller. 2023. Global methane emissions from rivers and streams. Nature 621:530–535.

Salimi, S., S. A. A. A. N. Almuktar, and M. Scholz. 2021. Impact of climate change on wetland ecosystems: A critical review of experimental wetlands. Journal of Environmental Management 286:112160.

Swain, D. L. 2015. A tale of two California droughts: Lessons amidst record warmth and dryness in a region of complex physical and human geography. Geophysical Research Letters 42:9999–10,003.

Su, T.-M., S.-C. Yang, S.-S. Shih, and H.-Y. Lee. 2009. Optimal design for hydraulic efficiency performance of free-water-surface constructed wetlands. Ecological Engineering 35:1200–1207.

US EPA, O. 2016, January 12. Understanding Global Warming Potentials. Overviews and Factsheets. District of Columbia, USA.

US Geological Survey. 27 September 2021. Landsat Enhanced Vegetation Index version Landsat 9. Ball Aerospace & Technologies Corpora-tion, NASA Goddard Space Flight Center, and Northrop Grumman. Boulder, Colorado, USA and Greenbelt, Maryland, USA.

Vahedifard, F., C. C. Goodman, V. Paul, and A. AghaKouchak. 2024. Amplifying feedback loop between drought, soil desiccation cracking, and greenhouse gas emissions. Environmental Research Letters 19:031005.

Were, D., F. Kansiime, T. Fetahi, A. Cooper, and C. Jjuuko. 2019. Carbon Sequestration by Wetlands: A Critical Review of Enhancement Measures for Climate Change Mitigation. Earth Systems and Environment 3:327–340.

Yang, H., J. Tang, C. Zhang, Y. Dai, C. Zhou, P. Xu, D. C. Perry, and X. Chen. 2020. Enhanced Carbon Uptake and Reduced Methane Emissions in a Newly Restored Wetland. Journal of Geophysical Research: Biogeosciences 125:e2019JG005222.

Yuan, X., Q. Liu, B. Cui, X. Xu, L. Liang, T. Sun, S. Yan, X. Wang, C. Li, S. Li, and M. Li. 2021. Effect of water-level fluctuations on methane and carbon dioxide dynamics in a shallow lake of Northern China: Implications for wetland restoration. Journal of Hydrology 597:126169.

Zhao, M., G. Han, J. Li, W. Song, W. Qu, F. Eller, J. Wang, and C. Jiang. 2020. Responses of soil CO2 and CH4 emissions to changing water table level in a coastal wetland. Journal of Cleaner Production 269:122316.

Zhuang, Q., J. M. Melillo, A. D. McGuire, D. W. Kicklighter, R. G. Prinn, P. A. Steudler, B. S. Felzer, and S. Hu. 2007. Net Emissions of Ch4 and Co2 in Alaska: Implications for the Region’s Greenhouse Gas Budget. Ecological Applications 17:203–212.

APPENDIX A: Water Level Regimes over Time

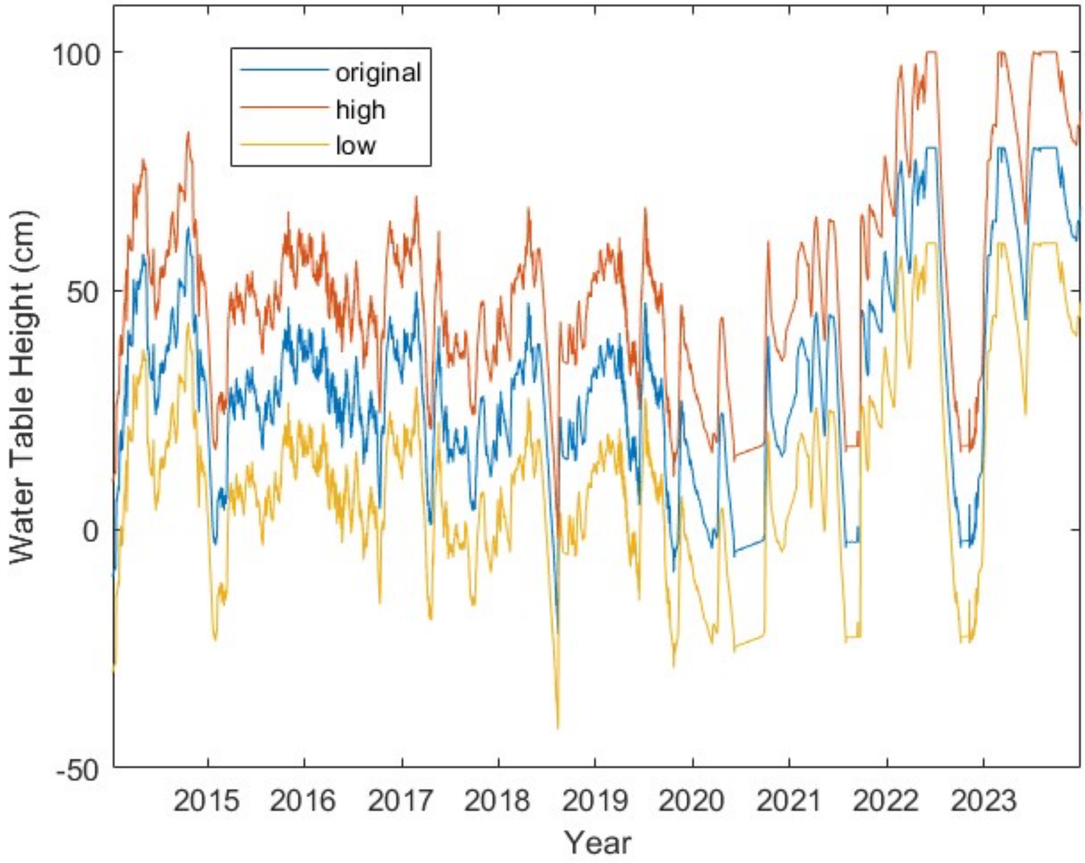

Figure A1. The three different water level regimes used in my study to determine the impact of water variation on methane emissions and the GHG budget. The original water table height (blue) is the measured data provided by AmeriFlux, the low water table height (yellow) is 20 cm less than the original, and the high water table height (orange) is 20 cm greater than the original.