Effects of floating wetlands on greenhouse gas emissions from wastewater lagoons

RMIT UNIVERSITY
Centre for Nature Positive Solutions

Authors

Lukas Schuster & Martino Malerba

Centre for Nature Positive Solutions,
School of Science, RMIT University,
Melbourne VIC 3000, Australia

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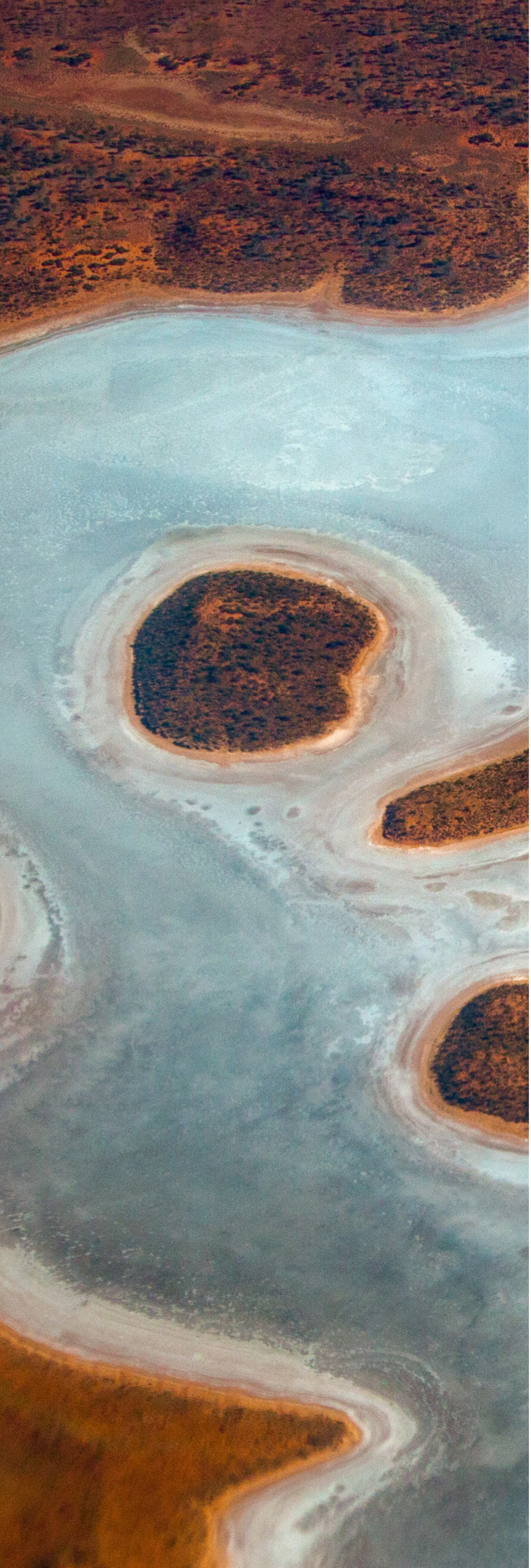

RMIT University acknowledges the people of the Woi wurrung and Boon wurrung language groups of the eastern Kulin Nation on whose unceded lands we conduct the business of the University.

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Executive summary

Wastewater treatment plants (WWTPs) are significant contributors of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) to global anthropogenic emissions. However, the Victorian water sector is committed to reducing its emissions and achieving net-zero targets by 2035.

Wastewater is typically characterised by high nutrient levels, particularly nitrogen and phosphorus, which can create the ideal conditions for microbial greenhouse gas production. Yet, simple management actions to reduce nutrient levels could significantly reduce such emissions.

We investigated the efficacy of using a constructed floating wetland (CFW) planted with Australian native wetland plant species (*Phragmites australis*, *Baumea articulata*, and *Bolboschoenus caldwellii*) as a nature-based solution for reducing nutrient levels and greenhouse gas emissions from a wastewater storage lagoon at the Westernport Water WWTP. To do so, we divided the lagoon into two channels using baffle curtains – a treatment channel with a CFW and a control channel (no CFW). Within each channel, we monitored greenhouse gas emissions continuously across two growing seasons between April 2023 and April 2025, along with monthly dissolved nutrient analyses (total Kjeldahl nitrogen, ammonium, nitrate, and total phosphorus) and regular monitoring of water quality parameters (temperature, dissolved oxygen concentrations, and pH).

We found that:

- The CFW had no significant effects on nutrient levels across the sampling period, with nutrient concentrations being comparable between the control and treatment channels. The absence of a net nutrient reduction in the treatment channel may be attributed to the early growth stage of the wetland plants or relatively high water turnover rates. However, more immediate results may be achieved by increasing the size of the CFW, as a greater water surface coverage is generally associated with improved nutrient reduction outcomes.
- Despite no reductions in nutrient levels, CO_2, CH_4, and N_2O fluxes were, on average, 17–63% lower from the treatment channel than from the control channel. These findings highlight the emission reduction potential of CFWs even when there are no net reductions in nutrient concentrations. With the wetland plant roots providing ample surface area for microbes, these emission reductions likely resulted from increased greenhouse gas consumption rates in the treatment channel.

However, more studies are needed to confirm this hypothesis.

Overall, these findings are promising as they suggest that installing a floating wetland can significantly reduce greenhouse gas emissions from wastewater lagoons, even when the wetland plants do not affect nutrient levels. Nevertheless, more long-term monitoring is required to determine the full potential of using CFWs to mitigate high nutrient concentrations and greenhouse gas emissions from wastewater.

Notably, CFWs have several other benefits, including providing habitat for native biodiversity and mitigating emerging contaminants (e.g., PFAS and pharmaceuticals). Thus, CFWs represent a comprehensive nature-based solution to achieving targets beyond the climate, including biodiversity conservation and increased water recycling in a circular economy framework.

Background

Westernport Water is working with RMIT's Centre for Nature Positive Solutions (CNPS) to mitigate and adapt to climate change. This research project investigated the use of floating wetlands to decrease nutrient concentrations and greenhouse gas emissions from a wastewater storage lagoon.

Wastewater treatment plants (WWTPs) can emit significant amounts of greenhouse gases, such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) [1]. Globally, greenhouse gas emissions from WWTPs account for 2.8% of total anthropogenic emissions [2]. Considering non-CO_2 greenhouse gases (such as CH_4 and N_2O), WWTPs are responsible for over 5% of anthropogenic emissions globally, and these emissions are predicted to increase by 20% by 2030 [3]. In Victoria alone, the water sector accounts for approximately one-quarter of total Victorian Government emissions, with approximately 1 million tonnes of greenhouse gases being released into the atmosphere every year [4]. CH_4 and N_2O emissions are particularly important as these gases have much higher global warming potentials (GWPs) than CO_2. For example, on a 100-year timescale, CH_4 has a GWP_{100} that is 32 times that of CO_2, whereas N_2O is 263 times more potent at warming the climate than CO_2 [5]. Consequently, WWTPs are important sources of anthropogenic greenhouse gas emissions and significant contributors to climate change.

Wastewater typically contains high nutrient concentrations, especially nitrogen and phosphorus [6]. In freshwater systems, high nutrient levels can create ideal conditions for microbes to produce greenhouse gases through respiration (CO_2) methanogenesis (CH_4), and nitrification and denitrification (N_2O) [7]. However, simple management interventions to reduce dissolved nutrient concentrations can significantly decrease such emissions. For example, Ollivier et al. [8] and Malerba et al. [9] showed that reducing dissolved nitrogen and phosphorus concentrations by 25% can decrease CH_4 emissions from man-made water bodies, on average, by 50%. However, it remains unclear whether similar nutrient reductions can mitigate greenhouse gas emissions from wastewater.

Constructed floating wetlands (CFWs) are promising for managing wastewater and reducing nutrient concentrations. These buoyant structures can support the growth of wetland plants, with plant roots growing directly into the water column. The plant roots provide ample surface area for microbial biofilms, which help trap suspended particles and facilitate the biological uptake of nutrients by the plants [10]. CFWs have been successfully used to treat wastewater, sewage discharges, and agricultural and stormwater runoffs, among other applications [11]. However, it is currently unclear to what extent CFWs can decrease greenhouse gas emissions by reducing nutrient concentrations.

This project aims to assess the effectiveness of a floating wetland in reducing nutrient concentrations and greenhouse gas emissions from the Westernport WWTP storage lagoon (Fig. 1). To do so, the lagoon was divided into two channels using baffle curtains – a treatment channel with a CFW and a control channel (no CFW) in April 2023 (Fig. 2). We created these two channels to be able to disentangle any CFW effects from environmental effects (e.g., seasonal variability in temperature) or typical fluctuations in nutrient concentrations in the wastewater, both of which can affect greenhouse gas emissions. The CFW was planted with three species of native wetland plants, *Phragmites australis*, *Baumea articulata*, and *Bolboschoenus caldwellii*, and was installed in May 2023. Within each channel, we deployed floating greenhouse gas sensors (called Pondi [12]; Fig. 3) to monitor CO_2, CH_4, and N_2O fluxes continuously before and after the floating wetland across two growing seasons (May 2023 – April 2025). We also monitored dissolved nutrient concentrations (total Kjeldahl nitrogen, ammonium, nitrate, and total phosphorus) and other water parameters (temperature, pH, and dissolved oxygen concentration) within each channel on a monthly basis.

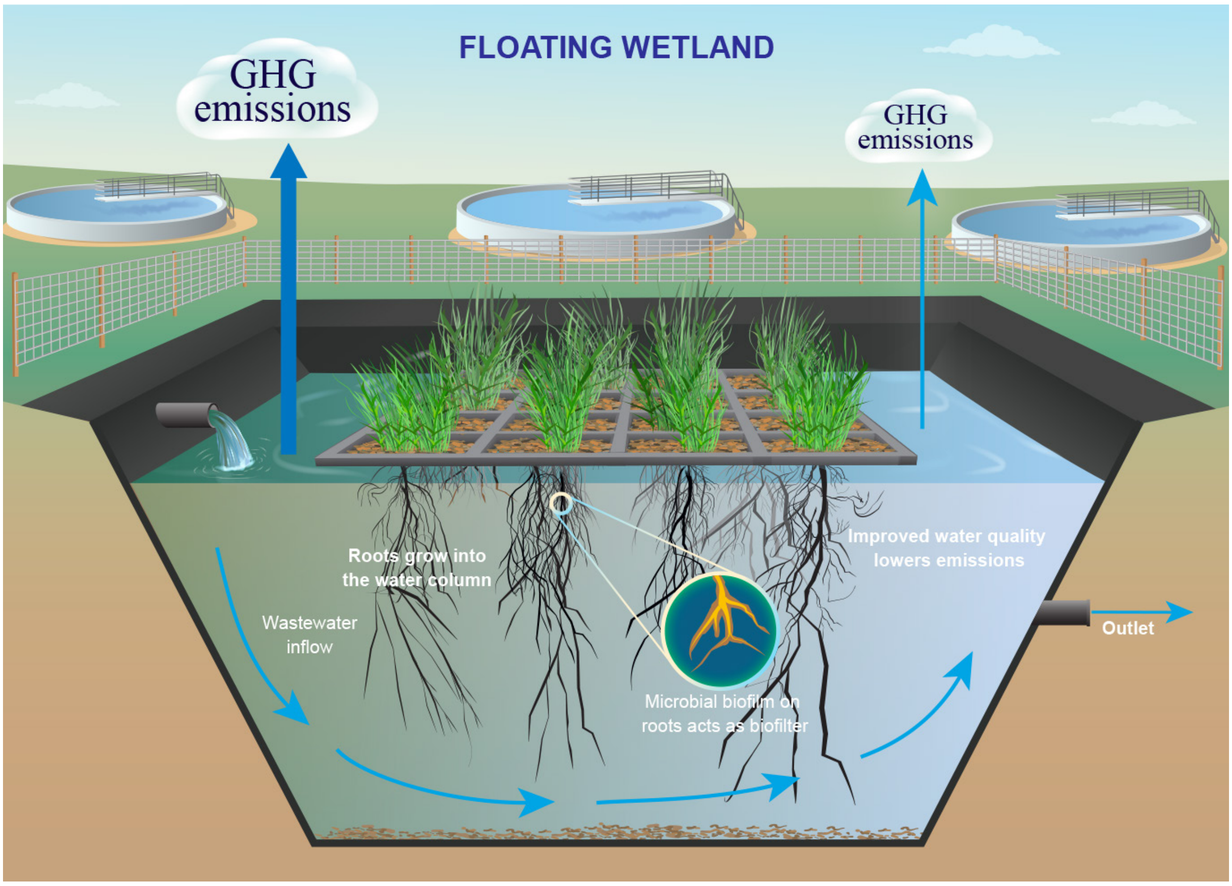


Fig. 1: Schematic of a constructed floating wetland (CFW) that was deployed at the Westernport WWTP storage lagoon. With roots growing into the water column, wetland plants can take up nutrients from the water, which is expected to result in a reduction in greenhouse gas emissions from the lagoon.

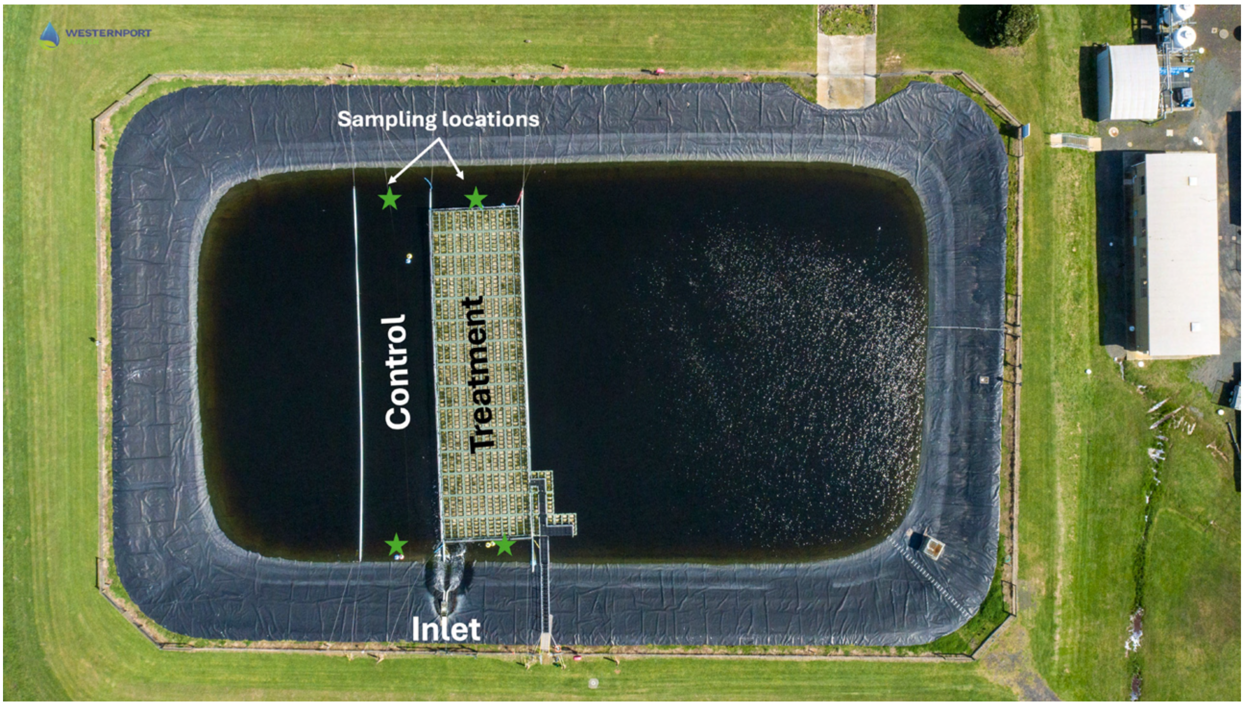


Fig. 2: Storage lagoon with the control and treatment (floating wetland) channels. The inlet to the lagoon is connected to a splitter box that allows for equal water inflow into the two channels. Stars indicate the four sampling locations (i.e., start and end of the control channel, start and end of the treatment channel) for greenhouse gas fluxes, dissolved nutrient levels, and water quality parameters.

Fig. 3: Photo of a Pondi – one of CNPS' floating greenhouse gas sensors equipped with CO_2, CH_4, and N_2O sensors to continuously measure gas concentrations within the chamber. All data is sent to a cloud via 4G, allowing for the real-time monitor of greenhouse gas fluxes. Each Pondi is equipped with a solar panel for continuous battery charging and a robotic pump (white U-shaped structure) for periodic venting to prevent gas saturation within the chamber.

Baseline monitoring

To ensure that there were no systematic differences in nutrient levels, water parameters, and greenhouse gas fluxes between the control and treatment channels, we conducted baseline monitoring in April 2023 before the floating wetland was installed. Specifically, we collected water samples for nutrient analyses (total Kjeldahl nitrogen, ammonium, nitrate, and phosphorus) and took water quality measurements (temperature, dissolved oxygen concentration, and pH) at all four sampling locations within the channels. We also deployed eight Pondi (two at each sampling location) and monitored greenhouse gas fluxes for one week (Fig. 4).

Overall, nutrient levels and water quality parameters were comparable between channels during baseline monitoring (Table 1). Similarly, we could not detect any significant differences in CO_2 ($F_{1,7}$ = 0.45, P = 0.52), CH_4 ($F_{1,7}$ = 0.03, P = 0.86), or N_2O fluxes ($F_{1,7}$ = 0.09, P = 0.77) between channels (Fig. 5). However, we found that CH_4 fluxes were, on average, 636% higher at the end (0.09 g CH_4 m^{-2} day^{-1}) compared to the start of the channels (0.01 g CH_4 m^{-2} day^{-1}; $F_{1,7}$ = 36.24, P < 0.001). With water running through the channels, these higher CH_4 emissions were likely a result of increased accumulation rates of nutrient-rich sludge at the end of the channels. Such sludge deposits provide the ideal conditions for anaerobic CH_4 production [13].

Table 1: Summary of the (a) nutrient levels and (b) water quality parameters collected during baseline monitoring at the different sampling locations (start or end of channel) in the control and treatment channels.

	Start of channel		End of channel	
	Control	Treatment	Control	Treatment
a) Nutrient levels				
Total Kjeldahl nitrogen (TKN) (mg L^{-1})	10	9.8	9.3	8.7
Ammonium (mg L^{-1})	<1	<1	<1	<1
Nitrate (mg L^{-1})	6.6	6.6	6.7	6.7
Total phosphorus (mg L^{-1})	8.2	8.1	8.3	8.1
b) Water quality parameters				
Temperature (°C)	16	16	15.9	15.9
Dissolved oxygen (%)	50.3	50.9	57	59.2
pH	7.42	7.65	7.42	7.61

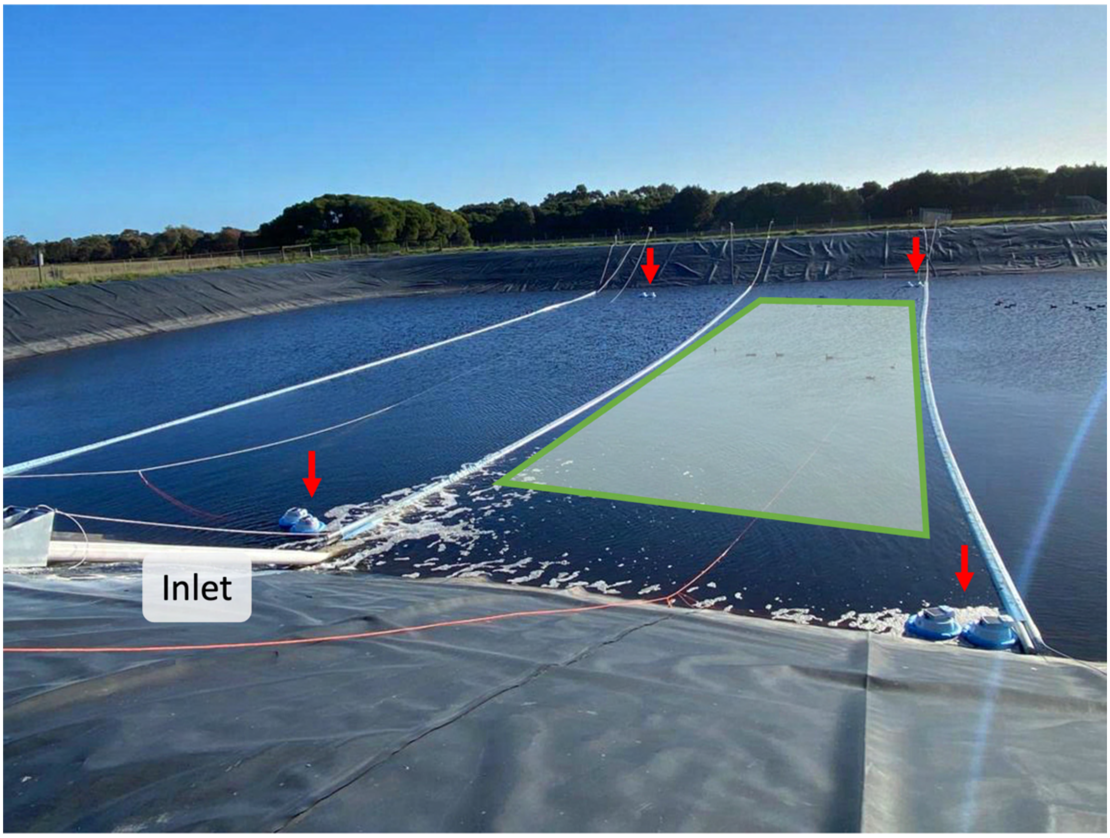


Fig. 4: Baseline monitoring using Pondi (marked by red arrows) deployed within the treatment (on the right-hand side of the lagoon inlet) and control (on the left) channels. The shaded green area indicates the deployment location of the CFW.

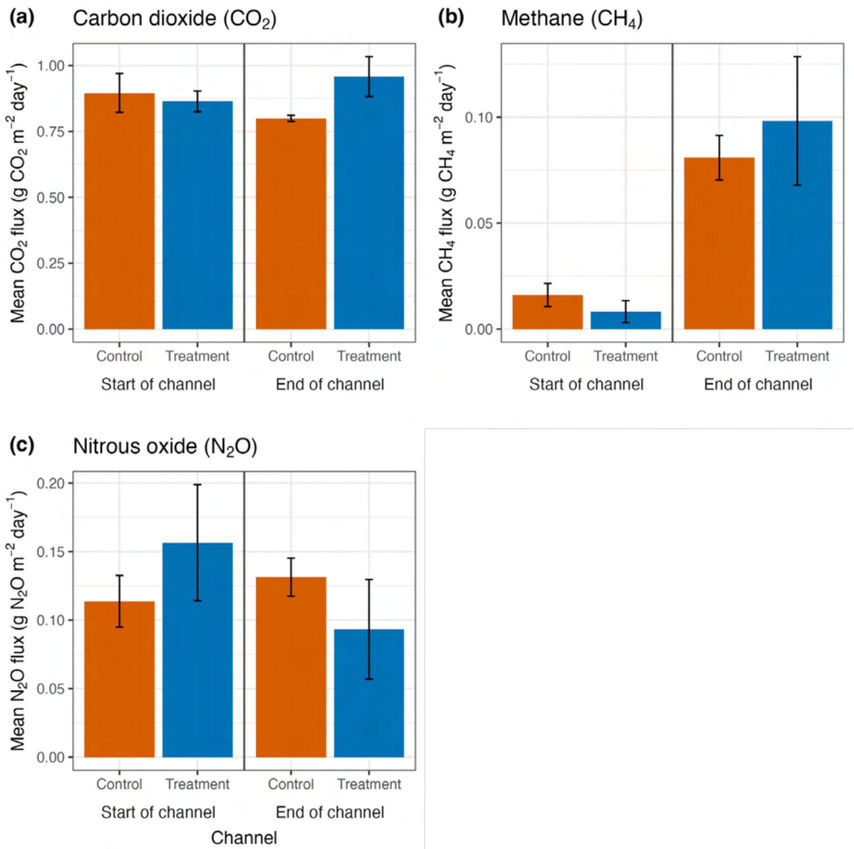


Fig. 5: Average (a) carbon dioxide (CO_2; in g CO_2 m^{-2} day^{-1}), (b) methane (CH_4; in g CH_4 m^{-2} day^{-1}), and (c) nitrous oxide (N_2O; in g N_2O m^{-2} day^{-1}) fluxes at the different sampling locations (start or end of channel) in the control (orange) and treatment (blue) channels. Error bars indicate standard errors.

Floating wetland: effects on nutrients and greenhouse gas fluxes

Nutrient levels

Following baseline monitoring, the CFW was installed in the treatment channel in May 2023, and we continued our monthly monitoring for two years (May 2023–April 2025).

Across the sampling period, we found that dissolved nutrient levels varied over time, but we could not detect any persistent differences in nutrient concentrations between the control and treatment channels (Fig. 6). Similarly, when considering the overall nutrient levels across the whole sampling period, we could not detect any significant differences in TKN ($F_{1,55}$ = 0.12, P = 0.73), nitrate ($F_{1,55}$ = 0.01, P = 0.94), or total phosphorus levels ($F_{1,55}$ = 0.08, P = 0.78) between the control and treatment channels (Fig. 7). Ammonium levels in the wastewater were consistently undetectable in the wastewater across our sampling period (<1 mg L^{-1}).

To ensure that the lack of an effect of the CFW on nutrient levels was not a result of potential water mixing and nutrient exchange between channels, we compared nutrient levels at the lagoon inlet to the nutrient levels at the end of the control and treatment channels. However, we could not detect any differences in nutrient levels between the inlet and the channels (Fig. 8), confirming that the CFW did not affect overall nutrient levels in the lagoon.

The lack of an effect of the CFW on nutrient levels may be due to various factors. First, the wetland plants may have been at an early growth stage, limiting their capacity to influence dissolved nutrient concentrations. More immediate results may be achieved by increasing the surface area of the floating wetland, as nutrient reduction efficacy is positively correlated with wetland size [11]. Second, nutrient removal is likely influenced by water residence times; if turnover rates in the lagoon are too high, reductions in nutrient concentrations may not be detectable. Consequently, CFWs may be more effective for nutrient mitigation in lagoons with low water turnover and longer residence times [11].

Fig. 6: (a) Total Kjeldahl nitrogen, (b) nitrate, and (c) total phosphorus (in mg L^{-1}) at the different sampling locations (start or end of channel) within the control (orange) and treatment (blue) channels across the sampling period.

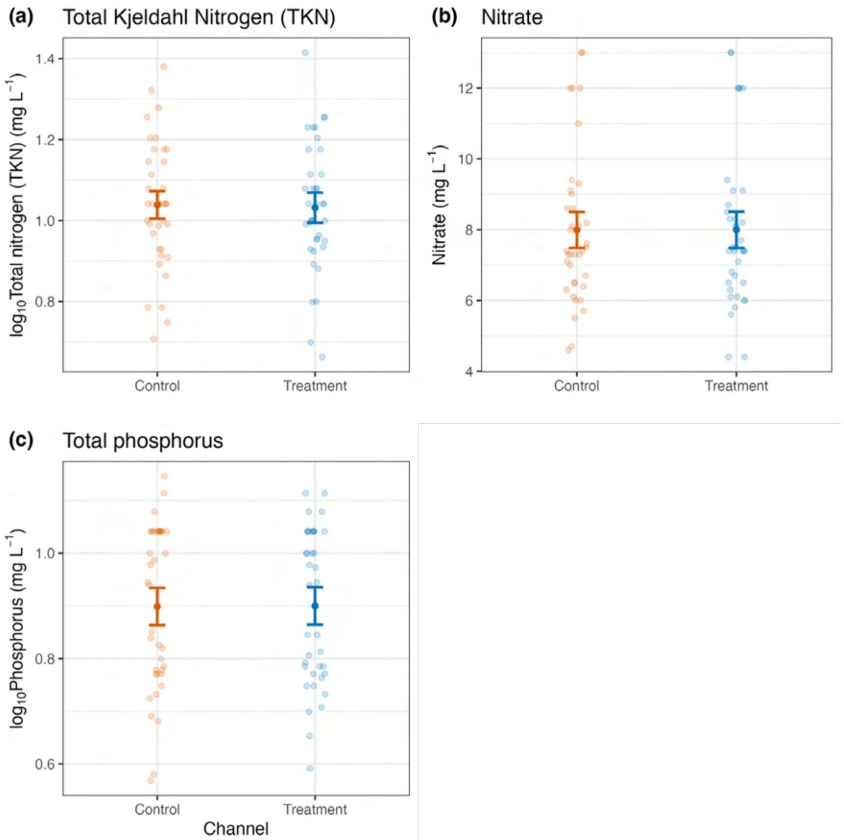


Fig. 7: Average (a) total Kjeldahl nitrogen, (b) nitrate, and (c) total phosphorus levels (in mg L^{-1}) in the control (orange) and treatment (blue) channels across the sampling period. Opaque points are the predicted means ± 95% confidence intervals from the statistically significant linear mixed effects model; semi-transparent points are the raw data.

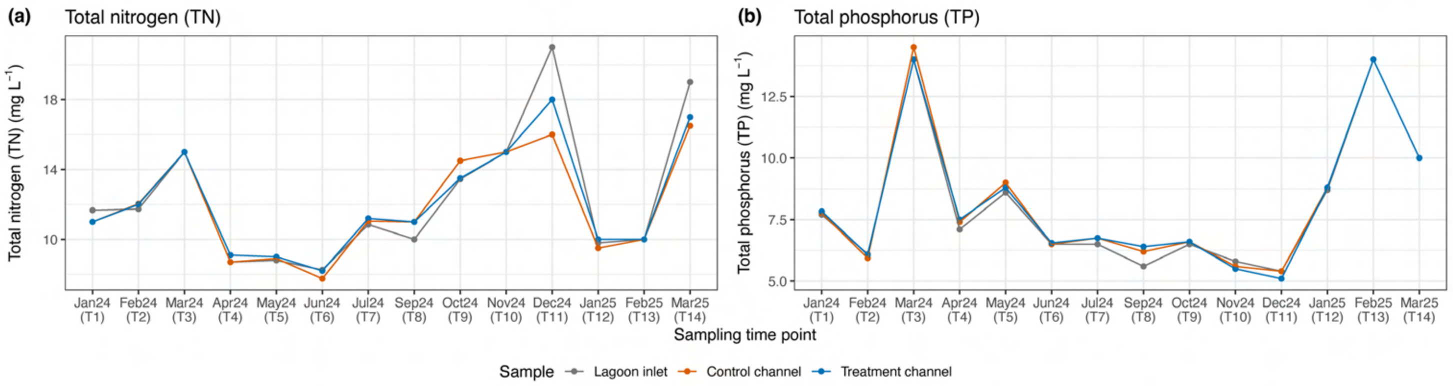


Fig. 8: (a) Total nitrogen and (b) total phosphorus (in mg $^{L-1}$) at the lagoon inlet (grey) and at the end of the control (orange) and treatment (blue) channels.

Greenhouse gas fluxes

CO_2, CH_4, and N_2O fluxes fluctuated across the sampling period, with greenhouse gas fluxes sometimes being higher from the control channel than the treatment channel and vice versa (Fig. 9). Notably, we found that the two harvesting events of the wetland plants in September 2024 and March 2025 significantly affected CH_4 fluxes from the treatment channel, with CH_4 emissions sharply increasing after both harvests (Fig. 9). This spike in CH_4 emissions following plant harvesting may be due to trapped CH_4 being released from the plant root systems. Specifically, floating vegetation often traps CH_4, which is then consumed by CH_4-oxidising microbes [14]. However, the trimming and harvesting of plant shoots may act as a disturbance, resulting in the release of trapped CH_4.

When comparing the greenhouse gas fluxes between the control and treatment channel across the whole sampling period, we found that overall CO_2 fluxes were, on average, 30% lower from the treatment (1.34 g CO_2 m^{-2} day^{-1}) compared to the control channel (1.91 g CO_2 m^{-2} day^{-1}; $F_{1,137} = 63.02$, $P < 0.0001$; Fig. 10).

Contrastingly, reductions of CH_4 and N_2O emissions in the treatment channel differed between sampling locations (start or end of channel; CH_4: $F_{1,137} = 3.27$, $P = 0.07$; N_2O: $F_{1,137} = 3.97$, $P = 0.04$). Specifically, CH_4 fluxes at the start of the treatment channel (0.005 g CH_4 m^{-2} day^{-1}) were, on average, 63% lower than from the start of the control channel (0.01 g CH_4 m^{-2} day^{-1}), whereas CH_4 fluxes at the end of the treatment channel (0.02 g CH_4 m^{-2} day^{-1}) were, on average, 39% lower than from the end of the control channel (0.03 g CH_4 m^{-2} day^{-1}; Fig. 11a). Similarly, N_2O fluxes at the end of the treatment channel (0.07 g N_2O m^{-2} day^{-1}) were, on average, 17% lower than from the end of the control channel (0.09 g N_2O m^{-2} day^{-1}), whereas N_2O fluxes did not significantly differ at the start of the channels (Fig. 11b).

Given that we did not find any persistent differences in nutrient levels between the control and treatment channels, the significant reductions in greenhouse gas emissions from the treatment channel were likely driven by other factors. For example, the roots of the wetland plants likely provide ample surface area for greenhouse gas-consuming organisms to settle and establish, which can drive significant reductions in net emissions [7,14,15]. Specifically, algae may take up CO_2, whereas CH_4 is oxidised to CO_2 by methanotrophic microbes, and N_2O is reduced to nitrogen gas by nitrogen-cycling bacteria. However, further studies are needed to uncover the exact mechanisms that drove the observed reductions in greenhouse gas emissions in the treatment channel.

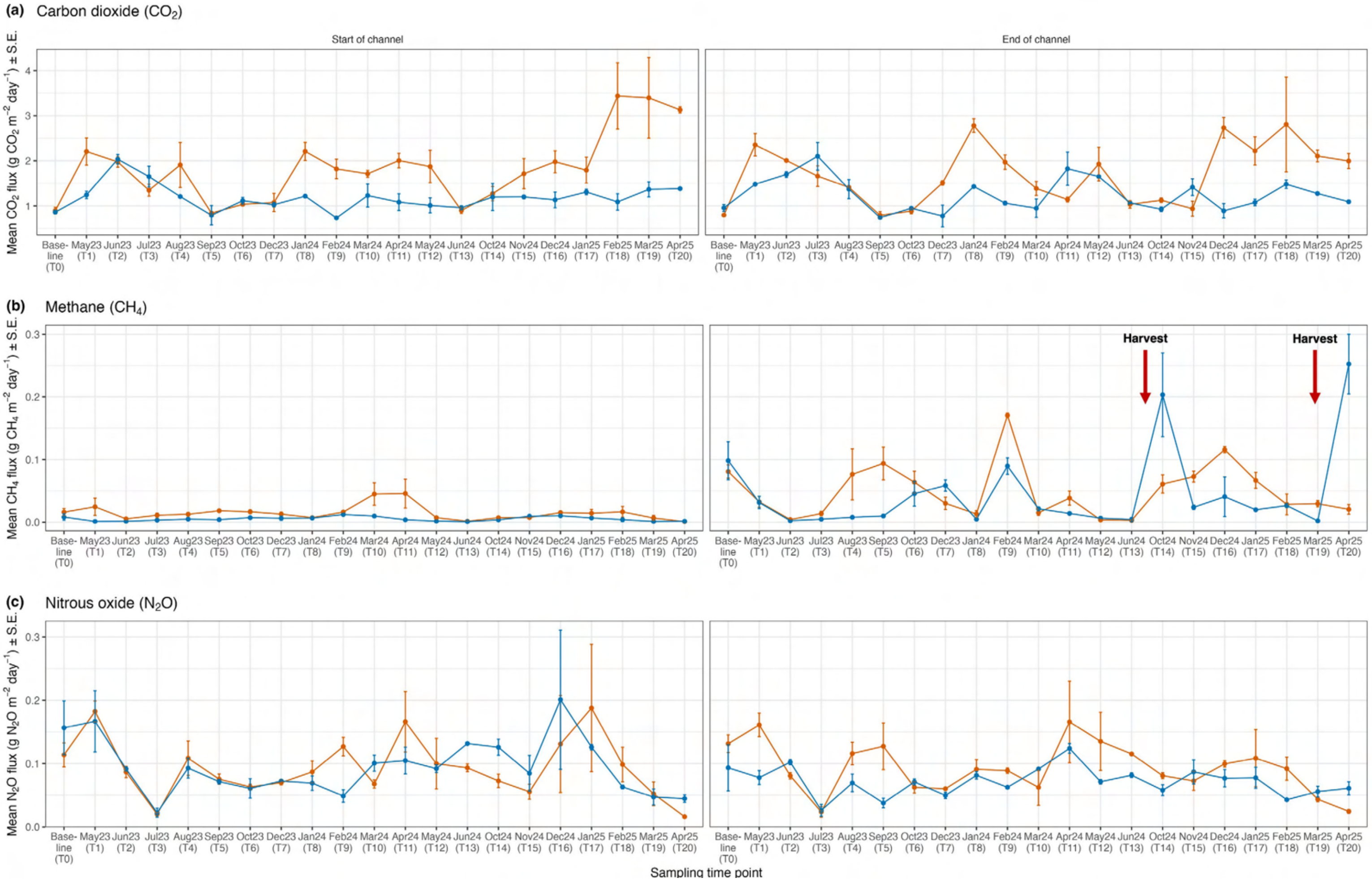


Fig. 9: Average (a) carbon dioxide (CO_2; in g CO_2 m^{-2} day^{-1}), (b) methane (CH_4; in g CH_4 m^{-2} day^{-1}), and (c) nitrous oxide (N_2O; in g N_2O m^{-2} day^{-1}) fluxes at the different sampling locations (start or end of channel) within the control (orange) and treatment (blue) channels across the sampling period. Error bars indicate standard errors. Red arrows indicate plant harvesting events.

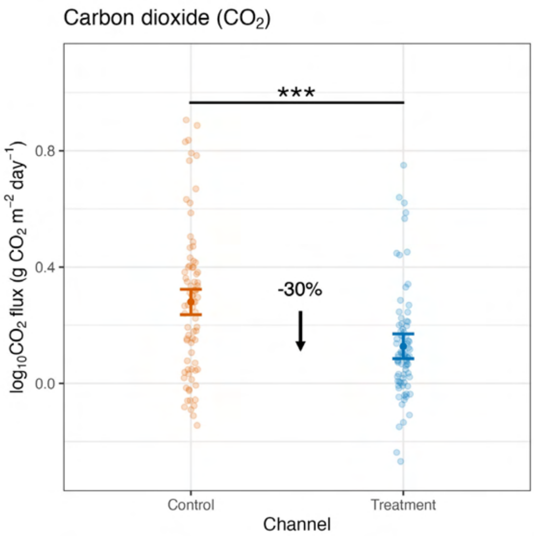


Fig. 10: Average carbon dioxide (CO_2; in g CO_2 m^{-2} day^{-1}) fluxes in the control (orange) and treatment (blue) channels across the sampling period. Opaque points are the predicted means ± 95% confidence intervals from the statistically significant linear mixed effects model; semi-transparent points are the raw data; asterisks indicate significant differences.

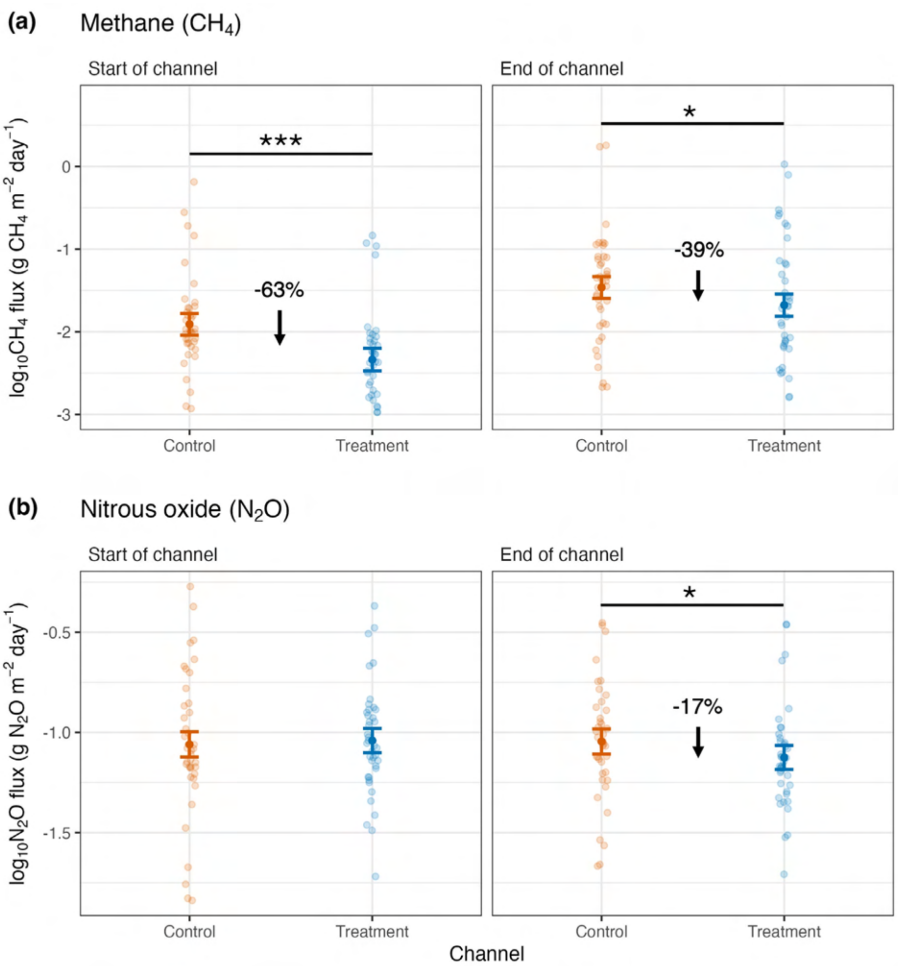


Fig. 11: Average (a) methane (CH_4; in g CH_4 m^{-2} day^{-1}) and (b) nitrous oxide (N_2O; in g N_2O m^{-2} day^{-1}) fluxes at the different sampling locations (start or end of channel) in the control (orange) and treatment (blue) channels across the sampling period. Opaque points are the predicted means ± 95% confidence intervals from the statistically significant linear mixed effects model; semi-transparent points are the raw data; asterisks indicate significant differences.

Water quality

Across the sampling period, water temperature and pH did not significantly differ between the control and treatment channels (temperature: $F_{1,55} = 0.25$, $P = 0.62$; pH: $F_{1,58} = 2.48$, $P = 0.12$; Fig. 12a,b). Contrastingly, we found that dissolved oxygen levels differed between channels, but the effect depended on the sampling location ($F_{1,45} = 4.01$, $P = 0.05$). Specifically, dissolved oxygen concentrations were, on average, 15% higher at the end of the treatment (92.8%) than at the end of the control channel (80.7%), whereas dissolved oxygen concentrations were comparable at the start of the channels (Fig. 12c).

The overall higher dissolved oxygen concentrations at the end of the treatment channel may be a result of increased photosynthetic rates of algae. Importantly, higher dissolved oxygen concentrations are conducive to increased aerobic CH_4 oxidation rates [16]. Hence, these findings may support our hypothesis that increased CH_4 consumption associated with increased algal photosynthesis may have driven the reduced CO_2 and CH_4 emissions from the treatment channel. Nevertheless, molecular analyses to uncover the compositions and metabolic capabilities of microorganisms found on the plant roots are needed to confirm this hypothesis.

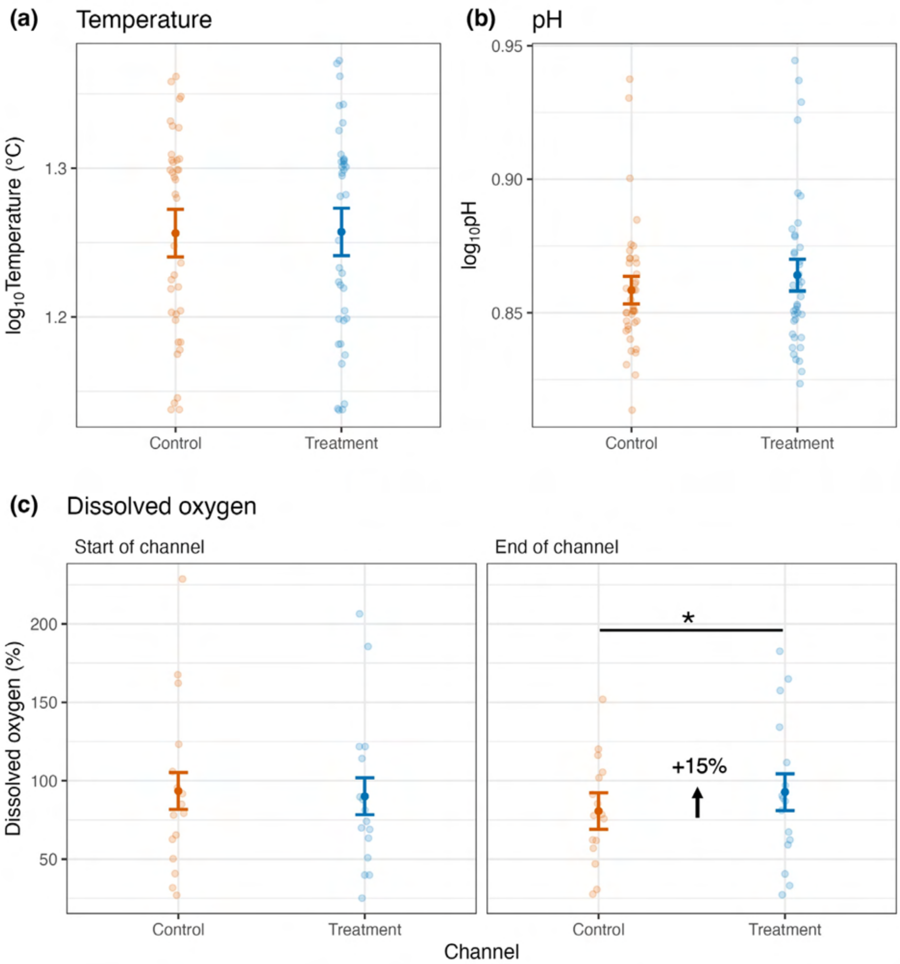
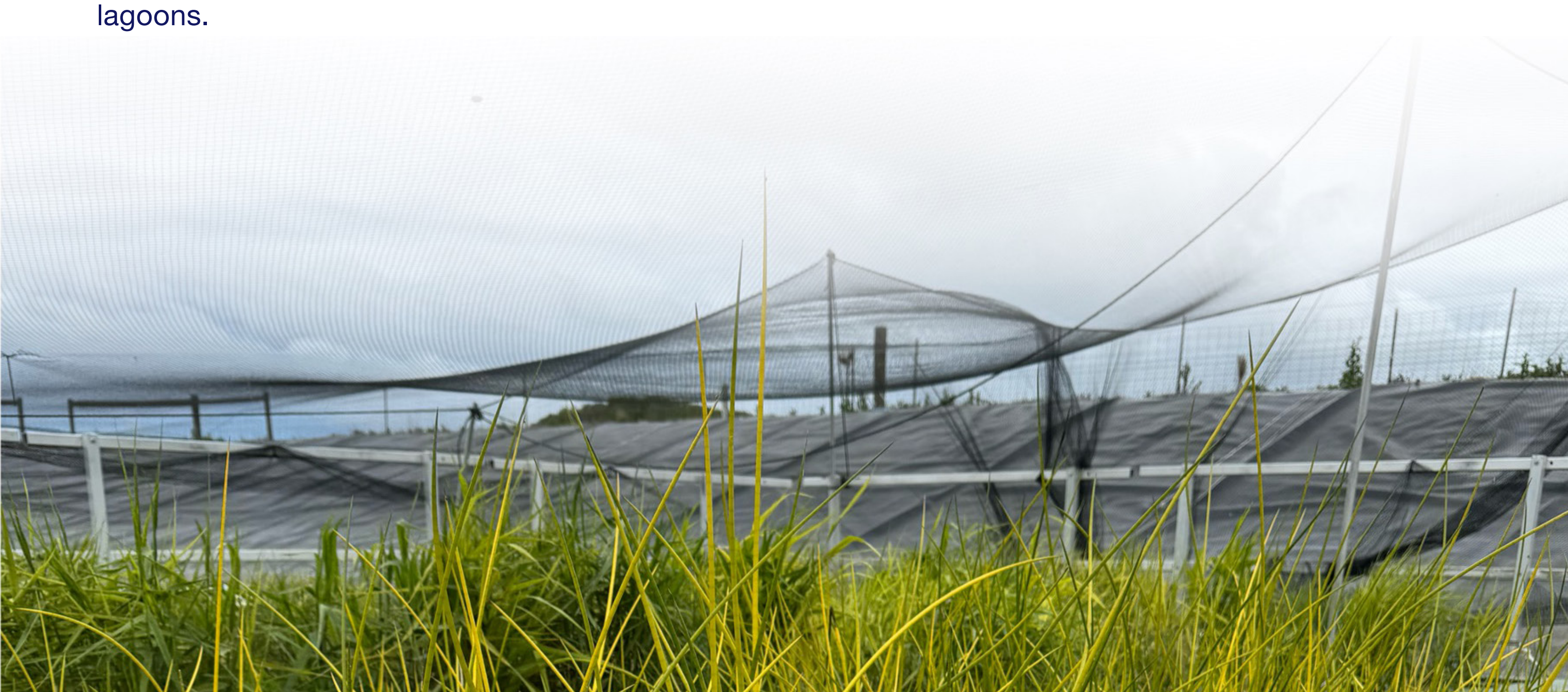


Fig. 12: Average (a) temperature (in °C), (b) dissolved oxygen concentrations (in %), and (c) pH in the control (orange) and treatment (blue) channels across the sampling period. Error bars indicate standard errors.

Conclusions

The CFW did not have any effects on dissolved nutrient concentrations in the wastewater lagoon across our sampling period. Yet, greenhouse gas emissions from the treatment channel that contained the CFW were significantly lower than from the control channel. Specifically, average CO_2 emissions decreased by 30%, whereas CH_4 and N_2O emissions decreased by 17–63%, depending on the sampling location (start or end of channel) within the channels.

These findings highlight the efficacy of CFWs in reducing greenhouse gas emissions from wastewater lagoons, even when the CFW does not affect nutrient levels. Nevertheless, more long-term studies are needed to uncover the full potential of such CFWs to reduce nutrient levels and greenhouse gas emissions from wastewater lagoons.



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Project contacts:

Dr Lukas Schuster
lukas.schuster@rmit.edu.au

Dr Martino Malerba
martino.malerba@rmit.edu.au

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