Journal of Environmental Management 375 (2025) 124230

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Floating photovoltaics strongly reduce water temperature: A whole-lake experiment

Regina L.G. Nobre [a,*,1], Chloé Vagnon [a,1,**], Stéphanie Boulêtreau [a], Fanny Colas [b], Frédéric Azémar [a], Loïc Tudesque [a], Nathalie Parthuisot [a], Paul Millet [a], Julien Cucherousset [a]

[a] Centre de Recherche sur la Biodiversité et l'Environnement (CRBE), Université de Toulouse, CNRS, IRD, Toulouse INP, Université Toulouse 3 – Paul Sabatier (UT3), Toulouse, France

[b] Univ Lyon, Université Claude Bernard Lyon 1, CNRS, ENTPE, UMR 5023 LEHNA, F-69622, Villeurbanne, France

ARTICLE INFO

Handling editor: Lixiao Zhang

Keywords:
Floatovoltaics
Renewable energy
Climate change mitigation
Lakes

ABSTRACT

Floating photovoltaics (FPVs), solar panels installed on floating structures in freshwater ecosystems such as lakes, represent a growing renewable technology aimed at decarbonizing the energy sector. However, robust empirical assessments of its environmental effects are still lacking. We used a Before-After-Control-Impact design replicated at the ecosystem level (n = 6 lakes: three lakes with FPV compared to three non-FPV lakes) to determine the global effects of FPV on water temperature over three years and allowing to isolate FPV effects from natural variability. Overall, we found that the presence of FPV strongly decreased annual water temperature (1.2 °C on average). The reduction in water temperature induced by FPV increased significantly with air temperature and differed between seasons, with stronger reductions (up to 3 °C) observed during warmest days of the year in spring and summer. In addition, the reduction in water temperature also occurred in areas of the lakes that were not covered by FPV. In the context of climate warming, decreased water temperature in summer could benefit freshwater organisms but these benefits could be counterbalanced by other negative impacts such as decreases in dissolved oxygen and modifications in the C cycle, including greenhouse gas emissions. Therefore, the cascading effects of FPV on freshwater biodiversity and ecosystem functioning still need to be assessed.

1. Introduction

The Anthropocene marks a period of biodiversity, climatic, and energetic crises (Rehbein et al., 2020) that are caused by an escalating demand for resources and energy production, an intensification of landscape transformation, increased greenhouse gas emissions and an acceleration of global warming (Bonebrake et al., 2019; Brook et al., 2008; Rehbein et al., 2020). As a consequence, the frequency and the intensity of extreme weather events and natural hazards are increasing, leading to increased species extinction rates, jeopardizing biodiversity, ecosystem functioning and services (Barnosky et al., 2011; Grodsky, 2021). In response, governments worldwide have committed to transition toward renewable energy sources to limit climate change and human impacts on ecosystems (Olabi and Abdelkareem, 2022; Spillias et al., 2020). However, a global energy transition requires extensive infrastructure and technology development, which, if poorly planned, may result in unintended environmental impacts (Grodsky, 2021; Spillias et al., 2020). For instance, some hydropower projects, such as lowland dams in the Brazilian Amazon, can induce massive loss of pristine habitats and be more carbon-intensive (greenhouse gas emissions produced per unit of electricity generated) than fossil-fueled power plants (Almeida et al., 2019; Gibson et al., 2017). The effects of the deployment of renewable energy systems on biodiversity and ecosystem services may thus counterbalance the benefits of decarbonization (Gibson et al., 2017; Grodsky, 2021; Wu et al., 2023) and robust assessments of the environmental impacts of novel technologies used to produce renewable energy are needed.

One of the latest renewable technologies deployed worldwide is floating photovoltaic (FPV), i.e. photovoltaic panels installed on aquatic ecosystems (Cazzaniga and Rosa-Clot, 2021; Sahu et al., 2016). FPV has been identified as a promising technology due to its advantageous properties including land-sparing and higher efficiency compared to

* Corresponding author.
** Corresponding author.
E-mail address: regina-lucia.guimaraes-nobre@univ-tlse3.fr (R.L.G. Nobre).
[1] These two authors contributed equally to this study.

https://doi.org/10.1016/j.jenvman.2025.124230
Received 15 November 2024; Received in revised form 13 January 2025; Accepted 17 January 2025
Available online 29 January 2025

ground-mounted photovoltaics (Gadzanku et al., 2021; Sahu et al., 2016). It is estimated that covering 10% of the artificial reservoirs worldwide with FPV could be equivalent to the current global capacity of electricity generation by fossil-fuel plants (Almeida et al., 2022). Additionally, FPVs can decrease evaporative losses and these effects could be particularly relevant in drought-prone areas (Farrar et al., 2022; Padilha Campos Lopes et al., 2020). The deployment of FPV on freshwater ecosystems is following an exponential growth since the first commercial installation in an irrigation pond in California in 2008 (Farrar et al., 2022). To date, >600 FPV power plants have been installed in 28 countries worldwide, with a large majority of these power plants located in Asia (Nobre et al., 2024; Xia et al., 2023). Usually, FPV power plants are installed on artificial water bodies, such as gravel pits, aquaculture ponds, irrigation ponds, and reservoirs and cover an average of 34.2% (±22.0 SD) of the lake surface (Nobre et al., 2024). While FPV represents a novel opportunity for the energy sector, there is a very limited knowledge about its environmental consequences on freshwater ecosystems (Gadzanku et al., 2021; Nobre et al., 2023; Oliveira et al., 2024; Rocha et al., 2024) and FPV should be urgently studied due to its potential environmental effects (Sutherland et al., 2022).

The installation of FPV power plants on freshwater ecosystems can directly and indirectly affect multiple environmental parameters (Exley et al., 2021; Nobre et al., 2023). This can include reductions in light and wind intensity arriving at the lake surface and changes in dissolved oxygen concentration in the water column (de Lima et al., 2021; Ray et al., 2024). FPVs are also expected to impact ecosystem functioning by altering primary production and carbon cycling (Exley et al., 2022; Ray et al., 2024). In addition, FPVs are anticipated to affect water temperature in recipient ecosystems (Armstrong et al., 2020; Exley et al., 2021). Water temperature governs multiple ecological processes, ranging from individual metabolic rates (Brown et al., 2004) to broader ecosystem functions (Schallenberg et al., 2013). Therefore, understanding the impact of FPV power plants on water temperature is a prerequisite to fully apprehend its environmental consequences (Chateau et al., 2019; Nobre et al., 2023; Wang et al., 2022). In the context of global warming, which is increasing the frequency and severity of extreme weather events such as heatwaves and droughts (Woolway et al., 2021), FPVs have been identified as a potential mitigation strategy in freshwater ecosystems (Exley et al., 2021; Liu et al., 2023) as they can block shortwave radiation (Armstrong et al., 2020; Exley et al., 2021). While there is a growing number of modeling studies predicting that water temperature will decrease with increased FPV cover (Chateau et al., 2019; Exley et al., 2021; Ji et al., 2022), other studies have highlighted that FPVs might contribute to warming surface water due to reduced wind (Exley et al., 2021; Ilgen et al., 2023) or through heat emission from the FPV structure and reduced evaporative heat flux (Yang et al., 2022). Although the effects of FPVs on water temperature are among the most frequently studied impacts of this emerging technology (19 studies published in scientific journals; Rocha et al., 2024), analysis of existing literature revealed that most empirical research has primarily focused on small-scale pilot installations and short-term observations (Rocha et al., 2024), strongly limiting the robustness of our knowledge. FPV power plants are becoming a conspicuous part of the landscape (Bax et al., 2023) and, to date, long-term empirical assessments at the ecosystem scale of the global effects of FPVs on lake temperature, with robust experimental designs, are still lacking.

The general objective of this study was to quantify the global effects of FPV power plants on lake water temperature. We used a replicated whole-lake experiment (Fig. 1) and a Before-After-Control-Impact (BACI) approach. BACI designs are highly appropriate for such investigations because they incorporate both temporal changes and control sites, effectively reducing the influence of unmeasured covariates on observed effects (Chevalier et al., 2019). We first measured the changes induced by FPV power plants on lake water temperature in three lakes with FPV compared to three non-FPV lakes over three years. Second, we quantified how the temperature effects induced by FPV power plants

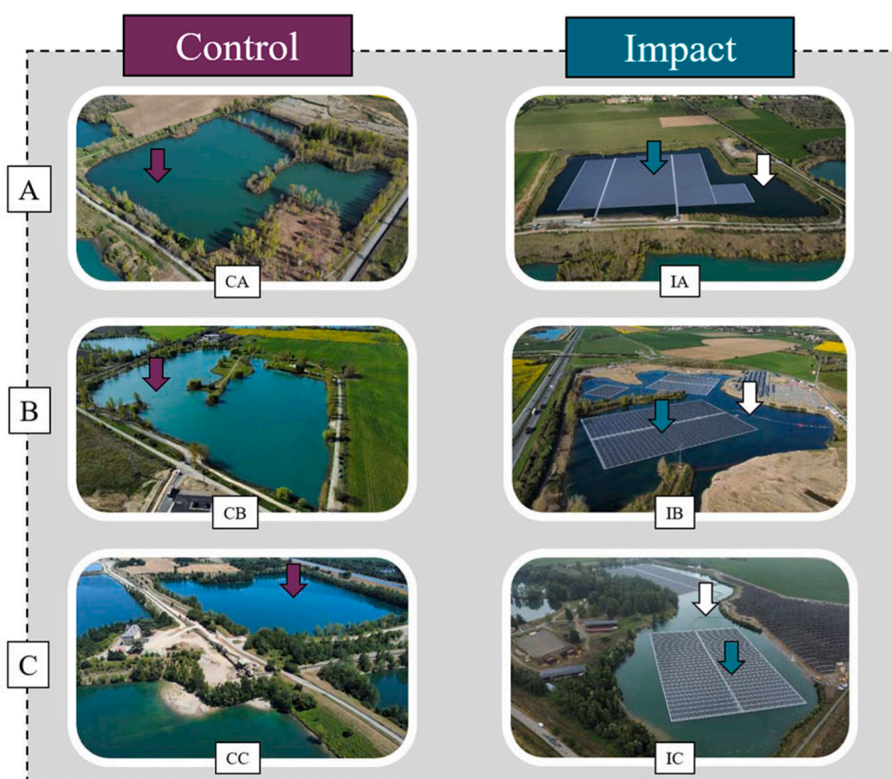

Fig. 1. The whole-lake experiment design employed in this study showing control (non-FPV: CA, CB, CC, *left*) and impact (FPV: IA, IB, IC, *right*) lakes. The locations of the temperature loggers are indicated by arrows. Dark cyan and white arrows indicate temperature loggers under FPV and in the uncovered area of the impact sites, respectively. Purple arrows indicate the location of the temperature loggers in control sites. FPV power plants were developed by Urbasolar.

vary across the year. Third, we assessed the spatial extent of the water temperature reduction induced by FPV power plants within the lakes by comparing water temperature in areas covered and uncovered by FPV.

2. Methods

2.1. Study area

This study was performed from December 2020 to December 2023 in six geographically close gravel pit lakes located in the Garonne River floodplain, southwestern France (43°16′N, 1°09′E, Fig. 2). These lakes display similar hydromorphological conditions (mean maximum depth = 4.97 m ± 0.72 SD, mean area = 0.13 km^2 ± 0.04 SD, mean perimeter = 2038.5 m ± 377 SD, mean surface to volume ratio = 0.48 ± 0.06, Table S1) and are hydrologically disconnected from each other and from the aerial hydrological network (Zhao et al., 2016). The lakes are all very close to each other (longest distance between two sites ~ 25 km) and they occupy a similar position in the landscape (mean elevation = 213.1 m ± 18 SD). They are surrounded by comparable vegetation, consisting of shrubs and a narrow layer of trees dominated by the genus *Populus* (Alp et al., 2016), embedded within an anthropized and agricultural landscape. The lakes experience a temperate oceanic climate (Cfb climate, Köppen classification). Based on their geographical proximity and high level of uniformity in landscape characteristics, these lakes are exposed to similar climatic conditions (e.g. air temperature, solar radiation). Among the six studied lakes, three lakes are not covered with FPV power plants (maximum depth = 4.70 m ± 0.61, mean surface to volume ratio = 0.50 ± 0.06 SD, mean area = 0.13 km^2 ± 0.07 SD, min = 0.09, max = 0.21, Table S1) while the three other lakes (maximum depth = 5.23 m ± 0.85 SD, mean surface to volume ratio = 0.45 ± 0.07, mean area = 0.13 km^2 ± 0.02 SD, min = 0.12, max = 0.15, Table S1) had FPV power plants installed during our study. The deployment of FPVs took place between November 2021 and March 2022. FPV power plants covered 40.3%, 51.5%, and 55.5% of the lakes area, respectively. This FPV coverage (49.1 % ± 7.9 SD) aligns with the typical coverage observed in FPV power plants across the globe (mean: 34.2 % ± 22 SD, Nobre et al., 2024); median: 37.5%, Xia et al. (2023).

2.2. Water temperature monitoring

Water temperature (°C) was monitored in the six studied lakes from December 2020 (approx. one year before FPV power plants installation) to December 2023 (approx. two years after FPV power plants installation). In each lake, a buoy was attached to a mooring using a stainless-steel cable and installed in the deepest part of the lake. Temperature loggers (n = 5 to 7 per lake depending upon lake depth) were attached to another stainless-steel cable attached to the buoy at 0.5 m and 1 m below the water surface, and then additional loggers were positioned every 1-m down to the lake bottom. In lakes with FPV power plants, buoy, mooring, and loggers were removed during FPV power plant installation and re-installed at the same location using a GPS. Following FPV power plant installation, the stainless-steel cables containing the loggers were directly attached to the floating structure. To compare water temperature in areas covered and uncovered by FPV power plants, an additional buoy with a mooring system and temperature loggers was installed approximately 50 m away from the FPV platform in the FPV lakes (Fig. 1). In uncovered areas, the average deepest point where the loggers were installed (5.0 m ± 0.7 SD) was similar to the depth of the monitoring point in the covered areas (5.9 m ± 1.0). All buoys were positioned in the open water zone of the lake (mean distance from the banks was 79.6 m ± 32 SD), with no direct shading from the riparian vegetation. Water temperature was recorded every 10 min throughout the monitoring period. Data from loggers were downloaded every 3 months. The monitoring started using loggers MX2201 (HOBO; Onset, USA) until August 2022 when these loggers were replaced in September 2022 by UA-001-64 (HOBO; Onset, USA) due to technical problems. Both loggers had similar accuracy (±0.5 °C) and resolution (0.14 °C and 0.04 °C at 25 °C for UA-001-64 and MX2201). These technical problems led to missing data (approximately 1% of the entire dataset). To estimate these missing values, we calculated the average temperature recorded by the nearest loggers positioned directly above and below the missing data point on the same vertical cable. To limit potential difference between lakes due to water level fluctuations and differences in maximal water depth, the analyses were conducted using the loggers deployed until 4 m deep. Daily water temperatures were calculated at each depth. The gravel pit lakes in this study are small (≤1 km^2, Downing, 2010) shallow (mean max depth = 5.5 m ± 0.8 SD, Padisák and Reynolds, 2003)) lakes with low potential for long-term stratification (Holgerson et al., 2022). While vertical variability in water temperature can occur throughout the year, we analyzed daily average temperatures from the integrated water column to represent the global thermal response of lakes to FPV installations and identify general response patterns. Therefore, all subsequent analyses were performed using averaged daily temperature across the water column.

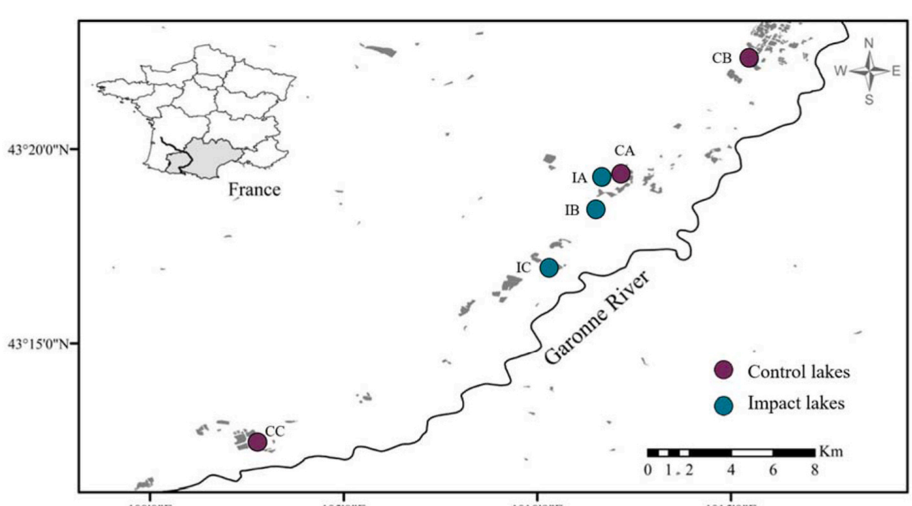

Fig. 2. Map of the study area located in the Garonne floodplain, southwest France. Dark cyan and purple symbols are lakes with (impact lakes IA, IB, IC, n = 3) and without (control lakes, CA, CB, CC, n = 3) FPV power plants, respectively.

2.3. Statistical analyses

We first assessed the effects of FPV power plants on lakes water temperature using a BACI approach (Chevalier et al., 2019; Smokorowski and Randall, 2017) in which control lakes were without FPV power plants and impact lakes were covered with FPV power plants, respectively. Control and impact lakes were paired based on their hydromorphological similarities established using a Principal Component Analysis (PCA) performed on environmental parameters (surface to volume ratio, maximal depth, perimeter and elevation). Euclidian distance between the lakes coordinates of the first two PCA axes (93.4% of the variability) was used to define the pairs (Fig. S4). The before and after periods correspond to the period before and after FPV power plant installations, respectively. For each pair of lakes, the middle date of the period between the start and the end of FPV power plant installation was considered as the transition date between the before and after periods in BACI analyses. We used a linear mixed effect model (LMM) to test the significance of the interaction between the period (i.e., before and after FPV power plant installation) and the treatment (i.e., with and without FPV power plants) on daily water temperature (Stewart-Oaten and Bence, 2001). Linear mixed effect model is a statistical model including fixed effects, which typically represent the relationship between the dependent variable and the explanatory variables (predictors) that are consistent across all groups or levels of the data, and random effects which allows tacking into account the variability that is not explained by the fixed effects (Zuur et al., 2009). In our model, the pair of lakes, the season, and the year were used as random effects. We included year and season as random effects to account for potential variability in the tested relationship arising from temporal fluctuations across different years and seasons. Lake identity and pairs were also used as random effects to account for the different FPV installation dates. This approach allows to better estimate the fixed effect of FPV installation by considering potential site-specific variations, separating the site-level variability from the overall trend. An autocorrelation structure of first-order, which includes the correlation coefficient between the residual observation of any given day *t* and the residual at day *t-1* (Mitchell et al., 2019), was also included in the model because, in high frequency data, the value measured at t+1 is directly affected by the value measured at t.

Second, we assessed the changes in water temperature induced by FPV power plants across the year and between different seasons by calculating the difference in water temperature between non-FPV and FPV lakes in each pair of lakes. Then, the average daily air temperature (°C) was calculated using hourly air temperature available from the closest weather station (43.4515° N, 1.262° E, Météo-France). Linear mixed effect models were used to test the effect of air temperature and seasons on the difference in water temperature induced by FPV power plants. The pair of lakes was included as a random effect in each model.

Third, to determine whether the effects of FPV power plants on water temperature are restricted to the water column located immediately under the FPV structures, or if this effect is homogeneous across the entire lake, we compared water temperature from loggers positioned under the FPV power plants with those installed in an uncovered area of the lakes. A linear mixed effect model was used to test the effect of the location (under FPV power plants and in the uncovered area within each FPV lake) on mean daily water temperature. In this model, the lake identity, season, and year were used as random effects, and an autocorrelation structure of first-order was included. All data analyses and visualization were performed with R software (v.4.2.2; R Core Team, 2022) using the packages nlme (Pinheiro and Bates, 2000) and ggplot2 (Wickham, 2016), respectively.

3. Results

During the three-year study period, daily water temperature displayed strong seasonal changes and averaged 16.6 °C (±6.9 SD), ranging from 4.0 °C in winter to 29.7 °C in summer (Fig. 3). This pattern was observed in the six studied lakes (Fig. S1). Water temperature was significantly lower in FPV lakes compared to lakes without FPV power plants after FPV installation (LMM, interaction period-treatment: $p < 0.001$; Fig. 4 and Table S2). Before FPV installation, water temperature

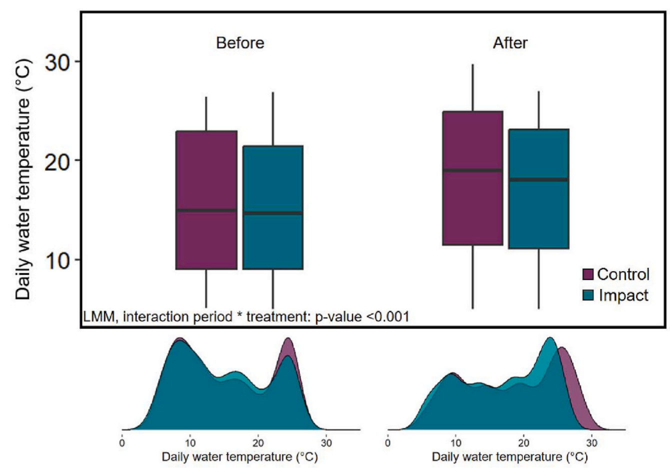

Fig. 4. Water temperature (daily average °C) and density distribution in lakes with (dark cyan) and without (purple) FPV power plants before (left) and after (right) installation.

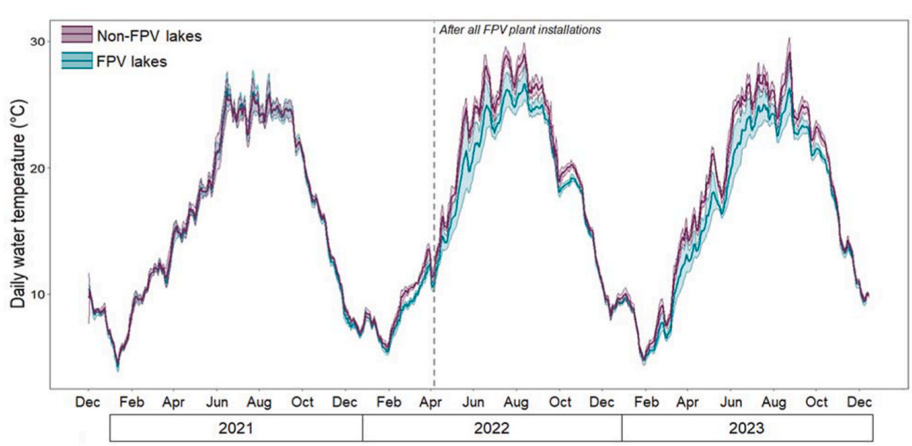

Fig. 3. Water temperature (daily average (°C) and standard deviation) in the lakes with (dark cyan) and without (purple) FPV power plants from December 2020 to December 2023. The dashed vertical line represents the date at which all FPV power plants were installed.

was, on average, 15.0 °C (±6.6 SD) and 15.3 °C (±6.8 SD) in the FPV and non-FPV lakes, respectively. After FPV power plant installation, water temperature was, on average, 16.9 °C (±6.5 SD) and 18.1 °C (±7.1 SD) in the FPV and non-FPV lakes, respectively (Fig. 4). Overall, the presence of FPV power plant decreased water temperature by 1.2 °C (±1.0 SD) compared to lakes without FPV power plant.

The reduction in water temperature induced by the presence of FPV power plants was significantly and positively associated with air temperature (LMM: $p < 0.001$; marginal $R^2 = 0.45$; Table S3). On average, a reduction of water temperature of 0.08 °C between FPV and non-FPV lakes was observed when air temperature increased by 1 °C (Fig. 5). When average daily air temperature was <10 °C (Fig. S2), the predicted reduction of water temperature was very limited (<0.5 °C). When the average daily air temperature was >30 °C (Fig. S2), the reduction of water temperature was >2 °C. The highest differences in water temperature reached >3 °C (Fig. 5)

The reduction in water temperature caused by FPVs was significantly different between seasons (LMM: $p < 0.001$; marginal $R^2 = 0.58$). A higher difference in daily water temperature between control and impact sites was observed in spring (mean daily difference 2.3 °C ± 0.9 SD), followed by summer (mean daily difference 1.9 °C ± 0.6) (post-hoc pairwise comparisons $p > 0.001$, Table S4, Fig. 6). These two seasons showed significantly larger differences compared to winter and autumn (mean daily differences of 0.6 °C ± 0.6 SD for winter and 0.6 °C ± 0.5 SD autumn) (Fig. 6, Table S4). Finally, in lakes containing FPV power plants, water temperature measured in the area covered with FPV (17.0 °C ± 6.5 SD) did not differ significantly (LMM, $p = 0.963$; Fig. S3; Table S5) from the water temperature measured in the uncovered area (16.8 °C ± 6.5 SD).

4. Discussion

As the global demand for renewable energy is increasing, robust knowledge on its potential environmental impacts is still lacking (Armstrong et al., 2020; Ramanan et al., 2024). This study provides the first replicated ecosystem-level assessment of the effects of FPV systems on water temperature in small and shallow lakes in a temperate climate. These ecosystems are highly representative of the freshwater ecosystems hosting FPV power plants globally, both in terms of lake

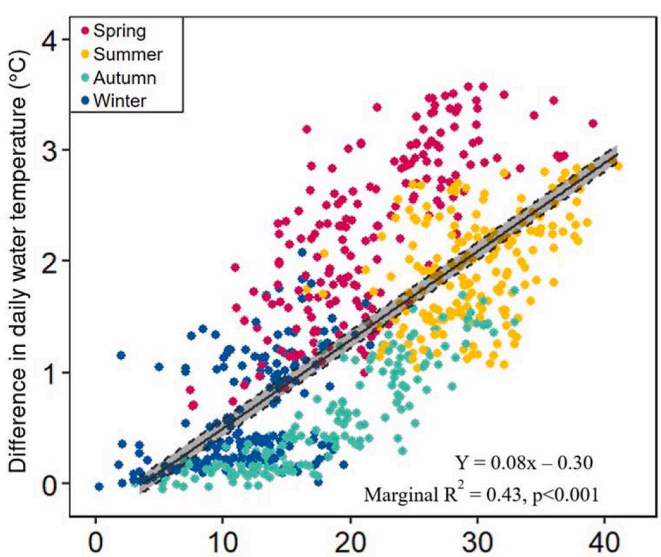

Fig. 5. Effect of air temperature on the difference in water temperature (daily average °C) between non-FPV lakes (control) and FPV lakes (impact). Points represent mean observed differences calculated from each pair of lakes. The line is the fitted model and the ribbons are the associated confidence intervals at 5% and 95%. Colors represent the different seasons.

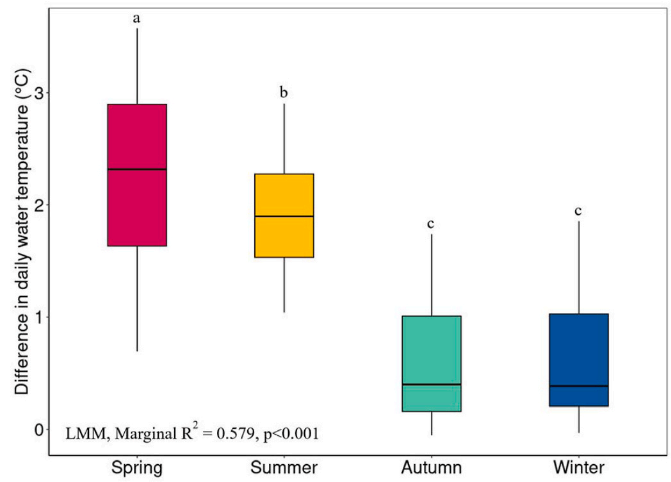

Fig. 6. Difference in water temperature (daily average °C) between non-FPV lakes (control) and FPV lakes (impact) for each season. Different letters indicate significant differences.

hydromorphology (89% of installed FPV power plants are in small (<0.5 km^2) and artificial shallow lakes) and FPV coverage (34.2 % ± 22 SD Nobre et al., 2024), thus offering robust insights into the environmental impacts of FPVs. Our results demonstrated that the presence of FPV strongly decreased annual water temperature (1.2 °C) and that this decrease in water temperature increased significantly with air temperature, with the strongest reductions (>2 °C) occurring during spring and summer, and reaching nearly 3 °C during the warmest days of the year. This effect was also consistently observed in an uncovered nearby zone, suggesting that the effect on water temperature extended beyond the FPV covered area. These findings are in accordance with modelling studies reporting an overall tendency of water temperature decrease under FPV presence (Chateau et al., 2019; Exley et al., 2021; Ji et al., 2022).

An empirical monitoring conducted in small aquaculture ponds (800 m^2, 1 m deep) in Taiwan also reported that, when 40% of the surface area was shaded (simulation of FPV cover) the daily average surface water temperature was significantly lower by 0.7 °C and 1.4 °C in the two shaded ponds compared to the control ponds (Wang et al., 2022). We found that the temperature decrease induced by FPV power plants also occurred in a nearby uncovered zone of the lake, indicating that small and shallow ecosystems with high surface-to-volume ratios may be susceptible to rapid water temperature changes driven by FPV and uniform temperature distribution throughout the lake. It is important to consider that the effects of FPVs on water temperature can be highly context-dependent varying with industrial factors such as the proportion of the lake surface covered by FPVs, the spatial arrangement of the FPV plant and the material and technology of the plants (Exley et al., 2021). Overall, the reduction of water temperature is expected to be less pronounced under small-scale FPV power plants (e.g. pilot projects with FPV coverage <1%), because the thermal characteristics of the water will predominantly reflect the conditions of the surrounding uncovered areas due to the mixing of water (Bax et al., 2023). Indeed, studies reported no overall significant effects of FPVs on water temperature between covered and uncovered areas within the same system for projects covering less than 2% of lake surface (Bax et al., 2023; Ilgen et al., 2023). The environmental effects of FPV can also be contingent to site-specific hydromorphological characteristics (Nobre et al., 2023). Hydromorphological characteristics such as lake size (area, volume, depth) are key environmental attributes for determining hierarchical effects on several ecological processes, including internal processes such as sedimentation, mixing dynamics in the water column and extension of the euphotic zone (Lewis, 2011; Scheffer et al., 2006; Schindler and

Scheuerell, 2002). These hydromorphological characteristics can, therefore, interact with the proportion of FPV coverage and strongly influence the extent of FPV impacts on water temperature and quality, evaporation rates, biodiversity and functioning of aquatic ecosystems. Therefore, the intensity and extent of FPV effects on water temperature are also expected to vary when dealing with larger and deeper systems which have higher thermal inertia and that are submitted to stronger seasonal or annual patterns of stratification, such as hydroelectric reservoirs (Ji et al., 2022). This is because FPV effects will be dependent on the stability and temporality of hydrological dynamics (e.g. mixing vs. stratified periods), which may lead to depth-specific effects. Also, water temperature in these systems can be influenced by the inflow water temperature and inflow rates (Ji et al., 2022). Nevertheless, a model developed for lake Windermere, a deep lake in the United-Kingdom, predicted a decrease of 2.2 °C on mean annual surface water temperature for approximately a 50% FPV coverage (Exley et al., 2021). Our studied sites offer a highly representative scenario of current global installations contributing valuable insights into expected patterns in similar contexts. However, extrapolations to other types of ecosystems (e.g. large reservoirs) and other geographical locations facing different climatic conditions should remain cautious, and we highlight here the need to develop robust studies to address these effects in different conditions.

We also found that differences in water temperature between FPV and non-FPV lakes were positively correlated with air temperature and differed between seasons increasing in spring and summer. This is consistent with studies that reported more pronounced effects of FPVs on water temperature during warmer periods (Ilgen et al., 2023; Liu et al., 2023; Wang et al., 2022). The higher temperature differences between FPV and non-FPV lakes were observed in spring, likely resulting from seasonal variations in heat accumulation at the water column. In spring, increasing solar radiation begins to warm the water, but FPV coverage is probably reducing direct heat input and altering heat exchange with the atmosphere, thus retarding water warming in FPV lakes and amplifying the observed contrast between FPV and non-FPV lakes. This effect can have profound effect on the phenological dynamic of lake organisms (Alp et al., 2016). In summer, despite higher solar radiation, water temperature is already high and a potential equilibrium between heat gains and losses obtained over spring may have moderate the temperature contrast. The smaller differences observed in autumn and winter likely reflect the overall lower solar input, which diminish the influence of FPV coverage on thermal dynamics. These results empirically indicates that FPV may play a role in attenuating water temperature during periods of elevated air temperatures such as heatwaves. Climate change is a serious threat to freshwater ecosystems (Dudgeon, 2019; Reid et al., 2019; Woolway et al., 2022) leading to warmer surface waters, increased evaporation rates, and changes in mixing regimes (O'Reilly et al., 2015; Woolway et al., 2020). These changes can subsequently affect the physiological and metabolic rates of freshwater organisms (Brown et al., 2004; Cohen et al., 2018; Gillet and Dubois, 2007; Jeppesen et al., 2010). For instance, freshwater fish are ectotherm and particularly sensitive to fluctuations in water temperature, with warmer temperatures leading to shifts in the size structure of fish communities towards smaller-bodied individuals, and modifications in community composition due to variations in thermal and oxygen tolerances among species (Jeppesen et al., 2010). Moreover, water temperature also regulates multiple phenological processes within freshwaters such as fish spawning (Gillet and Dubois, 2007), onset of algal blooms (Winder and Sommer, 2012) and insect emergence (Ivković et al., 2013). Although this remains to be investigated, FPV might provide thermal refuges and limit the thermal impacts of climate warming on freshwater organisms. Survival rates and production of cultured species in FPV-covered aquaculture ponds were found to be higher than those in uncovered control ponds, likely due to the reduced fluctuations in water temperature (Wang et al., 2022).

However, FPV deployment can also represent an abrupt perturbation to recipient ecosystems (Nobre et al., 2023). For instance, shading from FPV structure can hinder primary production and the lower air-water interface may impede atmospheric reoxygenation, potentially leading to dissolved oxygen depletion (de Lima et al., 2021; Liu et al., 2023; Yang et al., 2022). A mesocosm experiment revealed that ponds with 70% FPV coverage experienced a rapid decline in water temperature and dissolved oxygen, resulting in near-anoxic conditions. These changes were accompanied by a 26.8% increase in whole-pond daily greenhouse gas emissions (Ray et al., 2024). Therefore, such environmental effects can hamper the benefits of reduced temperature by having complex, counterproductive impacts that remain to be fully quantified (Exley et al., 2021; Ilgen et al., 2023). Because the potential ecological effects of FPV on their host systems are contingent upon the proportion of water surface covered (Gillet and Dubois, 2007; Haas et al., 2020) and higher coverages are observed in small lakes (Nobre et al., 2024; Xia et al., 2023), we highlight that the potential pressure of FPV development may exert on these systems (Nobre et al., 2022). Small lakes and ponds (≤1 km^2) harbor greater richness of nearly all taxa per unit area compared to larger lakes, playing a crucial role in the maintenance of local and regional biodiversity (Downing, 2010).

5. Conclusion

In this study, we conducted an empirical assessment of the effects of FPVs systems on water temperature at the ecosystem scale over multiple years using a robust and replicated BACI design. To the best of our knowledge, our study represents a pioneering effort to employ such a robust method for evaluating temperature alterations resulting from FPV deployment in power plants exploited commercially (but see Ray et al., 2024 for experimentation). Our results demonstrated that FPV power plants can significantly reduce water temperature, with more pronounced effects observed in spring (mean reduction of 2.3 °C) and summer (mean reduction of 1.9 °C). The potential ecological pressures that FPV development may cause in small lakes, particularly changes in water temperature, can have cascading effects on broader ecological processes. Further studies are essential to deepen our understanding of how FPV installations can modulate not only the thermal dynamics but also the key ecological processes such as nutrient cycling, primary production, and greenhouse gas emissions. Future research should focus on empirically evaluating the cascading effects of FPVs on biodiversity and ecosystem functioning. Additionally, studies incorporating a broader range of ecosystem size (e.g. larger and deeper lakes, reservoirs) with different thermal dynamics and in different climatic zones will help improve our understanding of FPV-environment interactions. The development of FPVs can offer both opportunities and challenges, reinforcing the need for a balanced approach that considers not only the nexus between energy, water and food, but also ecosystem conservation. Effective collaboration between energy stakeholders, environmental managers and researchers is fundamental to allow optimal monitoring strategies such as a BACI design, so informed decisions that prevent the counterproductive effects related to FPV installations can be made.

CRediT authorship contribution statement

Regina L.G. Nobre: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Conceptualization. **Chloé Vagnon:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Stéphanie Boulêtreau:** Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Conceptualization. **Fanny Colas:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization. **Frédéric Azémar:** Writing – review & editing, Investigation, Conceptualization. **Loïc Tudesque:** Writing – review & editing, Investigation, Conceptualization. **Nathalie Parthuisot:** Writing – review & editing, Investigation, Conceptualization. **Paul Millet:** Methodology, Investigation, Conceptualization. **Julien Cucherousset:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Funding acquisition, Conceptualization.

Funding

This work was supported by the Office Français de la Biodiversité (OFB) and the French Agency for Ecological Transition (ADEME) as part of the SOLAKE and FLOATIX projects and by the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement n∘ 101065785 (ECLIPSE project). This study is part of the long-term Studies in Ecology and Evolution (SEE-Life) program of the CNRS.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We thank lake owners and managers for access to the lakes to perform our study. The FPV plants were developed by URBASOLAR. The authors are grateful to the *gravière* team for the help in field monitoring.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2025.124230.

Data availability

Data will be made available on request.

References

Almeida, R.M., Schmitt, R., Grodsky, S.M., Flecker, A.S., Gomes, C.P., Zhao, L., Liu, H., Barros, N., Kelman, R., McIntyre, P.B., 2022. Floating solar power could help fight climate change — let's get it right. Nature 606, 246–249. https://doi.org/10.1038/d41586-022-01525-1.

Almeida, R.M., Shi, Q., Gomes-Selman, J.M., Wu, X., Xue, Y., Angarita, H., Barros, N., Forsberg, B.R., García-Villacorta, R., Hamilton, S.K., Melack, J.M., Montoya, M., Perez, G., Sethi, S.A., Gomes, C.P., Flecker, A.S., 2019. Reducing greenhouse gas emissions of Amazon hydropower with strategic dam planning. Nat. Commun. 10, 4281. https://doi.org/10.1038/s41467-019-12179-5.

Alp, M., Cucherousset, J., Buoro, M., Lecerf, A., 2016. Phenological response of a key ecosystem function to biological invasion. Ecol. Lett. 19, 519–527. https://doi.org/10.1111/ele.12585.

Armstrong, A., Page, T., Thackeray, S.J., Hernandez, R.R., Jones, I.D., 2020. Integrating environmental understanding into freshwater floatovoltaic deployment using an effects hierarchy and decision trees. Environ. Res. Lett. 15, 114055. https://doi.org/10.1088/1748-9326/abbf7b.

Barnosky, A.D., Matzke, N., Tomiya, S., Wogan, G.O.U., Swartz, B., Quental, T.B., Marshall, C., McGuire, J.L., Lindsey, E.L., Maguire, K.C., Mersey, B., Ferrer, E.A., 2011. Has the Earth's sixth mass extinction already arrived? Nature 471, 51–57. https://doi.org/10.1038/nature09678.

Bax, V., van de Lageweg, W.I., Hoosemans, R., van den Berg, B., 2023. Floating photovoltaic pilot project at the Oostvoornse lake: assessment of the water quality effects of three different system designs. Energy Rep. 9, 1415–1425. https://doi.org/10.1016/j.egyr.2022.12.080.

Bonebrake, T.C., Guo, F., Dingle, C., Baker, D.M., Kitching, R.L., Ashton, L.A., 2019. Integrating proximal and horizon threats to biodiversity for conservation. Trends Ecol. Evol. 34, 781–788. https://doi.org/10.1016/j.tree.2019.04.001.

Brook, B., Sodhi, N., Bradshaw, C., 2008. Synergies among extinction drivers under global change. Trends Ecol. Evol. 23, 453–460. https://doi.org/10.1016/j.tree.2008.03.011.

Brown, J.H., Gillooly, J.F., Allen, A.P., Savage, V.M., West, G.B., 2004. Toward a metabolic theory of ecology. Ecology 85, 1771–1789. https://doi.org/10.1890/03-9000.

Cazzaniga, R., Rosa-Clot, M., 2021. The booming of floating PV. Sol. Energy 219, 3–10. https://doi.org/10.1016/j.solener.2020.09.057.

Chateau, P.-A., Wunderlich, R.F., Wang, T.-W., Lai, H.-T., Chen, C.-C., Chang, F.-J., 2019. Mathematical modeling suggests high potential for the deployment of floating photovoltaic on fish ponds. Sci. Total Environ. 687, 654–666. https://doi.org/10.1016/j.scitotenv.2019.05.420.

Chevalier, M., Russell, J.C., Knape, J., 2019. New measures for evaluation of environmental perturbations using Before-After-Control-Impact analyses. Ecol. Appl. 29. https://doi.org/10.1002/eap.1838.

Cohen, J.M., Lajeunesse, M.J., Rohr, J.R., 2018. A global synthesis of animal phenological responses to climate change. Nature Clim Change 8, 224–228. https://doi.org/10.1038/s41558-018-0067-3.

de Lima, R.L.P., Paxinou, K., Boogaard, F.C., Akkerman, O., Lin, F.-Y., 2021. In-situ water quality observations under a large-scale floating solar farm using sensors and underwater drones. Sustainability 13, 6421. https://doi.org/10.3390/su13116421.

Downing, J.A., 2010. Emerging global role of small lakes and ponds: little things mean a lot. Limnética 29, 9–24. https://doi.org/10.23818/limn.29.02.

Dudgeon, D., 2019. Multiple threats imperil freshwater biodiversity in the Anthropocene. Curr. Biol. 29, R960–R967. https://doi.org/10.1016/j.cub.2019.08.002.

Exley, Giles, Armstrong, A., Page, T., Jones, I.D., 2021. Floating photovoltaics could mitigate climate change impacts on water body temperature and stratification. Sol. Energy 219, 24–33. https://doi.org/10.1016/j.solener.2021.01.076.

Exley, G., Hernandez, R.R., Page, T., Chipps, M., Gambro, S., Hersey, M., Lake, R., Zoannou, K.-S., Armstrong, A., 2021. Scientific and stakeholder evidence-based assessment: ecosystem response to floating solar photovoltaics and implications for sustainability. Renew. Sustain. Energy Rev. 152. https://doi.org/10.1016/j.rser.2021.111639.

Exley, G., Page, T., Thackeray, S.J., Folkard, A.M., Couture, R.-M., Hernandez, R.R., Cagle, A.E., Salk, K.R., Clous, L., Whittaker, P., Chipps, M., Armstrong, A., 2022. Floating solar panels on reservoirs impact phytoplankton populations: a modelling experiment. J. Environ. Manag. 324. https://doi.org/10.1016/j.jenvman.2022.116410.

Farrar, L.W., Bahaj, A.S., James, P., Anwar, A., Amdar, N., 2022. Floating solar PV to reduce water evaporation in water stressed regions and powering water pumping: case study Jordan. Energy Convers. Manag. 260, 115598. https://doi.org/10.1016/j.enconman.2022.115598.

Gadzanku, S., Mirletz, H., Lee, N., Daw, J., Warren, A., 2021. Benefits and critical knowledge gaps in determining the role of floating photovoltaics in the energy-water-food nexus. Sustainability 13, 4317. https://doi.org/10.3390/su13084317.

Gibson, L., Wilman, E.N., Laurance, W.F., 2017. How green is 'green' energy? Trends Ecol. Evol. 32, 922–935. https://doi.org/10.1016/j.tree.2017.09.007.

Gillet, C., Dubois, J.P., 2007. Effect of water temperature and size of females on the timing of spawning of perch Perca fluviatilis L. in Lake Geneva from 1984 to 2003. J. Fish. Biol. 70, 1001–1014. https://doi.org/10.1111/j.1095-8649.2007.01359.x.

Grodsky, S.M., 2021. Matching renewable energy and conservation targets for a sustainable future. One Earth 4, 924–926. https://doi.org/10.1016/j.oneear.2021.07.001.

Haas, J., Khalighi, J., de la Fuente, A., Gerbersdorf, S.U., Nowak, W., Chen, P.-J., 2020. Floating photovoltaic plants: ecological impacts versus hydropower operation flexibility. Energy Convers. Manag. 206, 112414. https://doi.org/10.1016/j.enconman.2019.112414.

Holgerson, M.A., Richardson, D.C., Roith, J., Bortolotti, L.E., Finlay, K., Hornbach, D.J., Gurung, K., Ness, A., Andersen, M.R., Bansal, S., Finlay, J.C., Cianci-Gaskill, J.A., Hahn, S., Janke, B.D., McDonald, C., Mesman, J.P., North, R.L., Roberts, C.O., Sweetman, J.N., Webb, J.R., 2022. Classifying mixing regimes in ponds and shallow lakes. Water Resour. Res. 58, e2022WR032522. https://doi.org/10.1029/2022WR032522.

Ilgen, K., Schindler, D., Wieland, S., Lange, J., 2023. The impact of floating photovoltaic power plants on lake water temperature and stratification. Sci. Rep. 13. https://doi.org/10.1038/s41598-023-34751-2.

Ivković, M., Miliša, M., Previšić, A., Popijač, A., Mihaljević, Z., 2013. Environmental control of emergence patterns: case study of changes in hourly and daily emergence of aquatic insects at constant and variable water temperatures: changes in daily emergence of aquatic insects. Int. Rev. Hydrobiol. 98, 104–115. https://doi.org/10.1002/iroh.201301483.

Jeppesen, E., Meerhoff, M., Holmgren, K., González-Bergonzoni, I., Teixeira-de Mello, F., Declerck, S.A.J., De Meester, L., Søndergaard, M., Lauridsen, T.L., Bjerring, R., Conde-Porcuna, J.M., Mazzeo, N., Iglesias, C., Reizenstein, M., Malmquist, H.J., Liu, Z., Balayla, D., Lazzaro, X., 2010. Impacts of climate warming on lake fish community structure and potential effects on ecosystem function. Hydrobiologia 646, 73–90. https://doi.org/10.1007/s10750-010-0171-5.

Ji, Q., Li, K., Wang, Y., Feng, J., Li, R., Liang, R., 2022. Effect of floating photovoltaic system on water temperature of deep reservoir and assessment of its potential benefits, a case on Xiangjiaba Reservoir with hydropower station. Renew. Energy 195, 946–956. https://doi.org/10.1016/j.renene.2022.06.096.

Lewis, W., 2011. Global primary production of lakes: 19th baldi memorial lecture. IW, 1, 1–28. https://doi.org/10.5268/IW-1.1.384.

Liu, Z., Ma, C., Li, X., Deng, Z., Tian, Z., 2023. Aquatic environment impacts of floating photovoltaic and implications for climate change challenges. J. Environ. Manag. 346, 118851. https://doi.org/10.1016/j.jenvman.2023.118851.

Mitchell, D.J., Dujon, A.M., Beckmann, C., Biro, P.A., 2019. Temporal autocorrelation: a neglected factor in the study of behavioral repeatability and plasticity. Behavioral Ecology arz180. https://doi.org/10.1093/beheco/arz180.

Nobre, R., Boulêtreau, S., Colas, F., Azemar, F., Tudesque, L., Parthuisot, N., Favriou, P., Cucherousset, J., 2023. Potential ecological impacts of floating photovoltaics on lake biodiversity and ecosystem functioning. Renew. Sustain. Energy Rev. 188, 113852. https://doi.org/10.1016/j.rser.2023.113852.

Nobre, R., Boulêtreau, S., Cucherousset, J., 2022. Small lakes at risk from extensive solar-panel coverage. Nature 607. https://doi.org/10.1038/d41586-022-01891-w, 239–239.

Nobre, R., Rocha, S.M., Healing, S., Ji, Q., Boulêtreau, S., Armstrong, A., Cucherousset, J., 2024. A global study of freshwater coverage by floating photovoltaics. Sol. Energy 267, 112244. https://doi.org/10.1016/j.solener.2023.112244.
Olabi, A.G., Abdelkareem, M.A., 2022. Renewable energy and climate change. Renew. Sustain. Energy Rev. 158, 112111. https://doi.org/10.1016/j.rser.2022.112111.
Oliveira, P.M.B., Almeida, R.M., Cardoso, S.J., 2024. Effects of floating photovoltaics on aquatic organisms: a review. Hydrobiologia. https://doi.org/10.1007/s10750-024-05686-0.
O'Reilly, C.M., Sharma, S., Gray, D.K., Hampton, S.E., Read, J.S., Rowley, R.J., Schneider, P., Lenters, J.D., McIntyre, P.B., Kraemer, B.M., Weyhenmeyer, G.A., Straile, D., Dong, B., Adrian, R., Allan, M.G., Anneville, O., Arvola, L., Austin, J., Bailey, J.L., Baron, J.S., Brookes, J.D., De Eyto, E., Dokulil, M.T., Hamilton, D.P., Havens, K., Hetherington, A.L., Higgins, S.N., Hook, S., Izmest'eva, L.R., Joehnk, K.D., Kangur, K., Kasprzak, P., Kumagai, M., Kuusisto, E., Leshkevich, G., Livingstone, D.M., MacIntyre, S., May, L., Melack, J.M., Mueller-Navarra, D.C., Naumenko, M., Noges, P., Noges, T., North, R.P., Plisnier, P., Rigosi, A., Rimmer, A., Rogora, M., Rudstam, L.G., Rusak, J.A., Salmaso, N., Samal, N.R., Schindler, D.E., Schladow, S.G., Schmid, M., Schmidt, S.R., Silow, E., Soylu, M.E., Teubner, K., Verburg, P., Voutilainen, A., Watkinson, A., Williamson, C.E., Zhang, G., 2015. Rapid and highly variable warming of lake surface waters around the globe. Geophys. Res. Lett. 42. https://doi.org/10.1002/2015GL066235.
Padilha Campos Lopes, M., De Andrade Neto, S., Alves Castelo Branco, D., Vasconcelos De Freitas, M.A., Da Silva Fidelis, N., 2020. Water-energy nexus: floating photovoltaic systems promoting water security and energy generation in the semiarid region of Brazil. J. Clean. Prod. 273, 122010. https://doi.org/10.1016/j.jclepro.2020.122010.
Padisák, J., Reynolds, C.S., 2003. Shallow lakes: the absolute, the relative, the functional and the pragmatic. Hydrobiologia 506–509, 1–11. https://doi.org/10.1023/B:HYDR.0000008630.49527.29.
Pinheiro, J., Bates, D., 2000. Mixed-Effects Models in S and S-PLUS_. Springer, New York. https://doi.org/10.1007/b98882, 10.1007/b98882>. Springer.
Ramanan, C.J., Lim, K.H., Kurnia, J.C., Roy, S., Bora, B.J., Medhi, B.J., 2024. Towards sustainable power generation: recent advancements in floating photovoltaic technologies. Renew. Sustain. Energy Rev. 194, 114322. https://doi.org/10.1016/j.rser.2024.114322.
Ray, N.E., Holgerson, M.A., Grodsky, S.M., 2024. Immediate effect of floating solar energy deployment on greenhouse gas dynamics in ponds. Environ. Sci. Technol. 58, 22104–22113. https://doi.org/10.1021/acs.est.4c06363.
Rehbein, J.A., Watson, J.E.M., Lane, J.L., Sonter, L.J., Venter, O., Atkinson, S.C., Allan, J.R., 2020. Renewable energy development threatens many globally important biodiversity areas. Global Change Biol. 26, 3040–3051. https://doi.org/10.1111/gcb.15067.
Reid, A.J., Carlson, A.K., Creed, I.F., Eliason, E.J., Gell, P.A., Johnson, P.T.J., Kidd, K.A., MacCormack, T.J., Olden, J.D., Ormerod, S.J., Smol, J.P., Taylor, W.W., Tockner, K., Vermaire, J.C., Dudgeon, D., Cooke, S.J., 2019. Emerging threats and persistent conservation challenges for freshwater biodiversity. Biol. Rev. 94, 849–873. https://doi.org/10.1111/brv.12480.
Rocha, S.M.G., Armstrong, A., Thackeray, S.J., Hernandez, R.R., M Folkard, A., 2024. Environmental impacts of floating solar panels on freshwater systems and their techno-ecological synergies. Environ. Res.: Infrastruct. Sustain. 4, 042002. https://doi.org/10.1088/2634-4505/ad8e81.
Sahu, A., Yadav, N., Sudhakar, K., 2016. Floating photovoltaic power plant: a review. Renew. Sustain. Energy Rev. 66, 815–824. https://doi.org/10.1016/j.rser.2016.08.051.
Schallenberg, M., de Winton, M.D., Verburg, P., Kelly, D.J., Hamill, K.D., Hamilton, D.P., 2013. Ecosystem services of lakes. In: Ecosystem Services in New Zealand – Conditions and Trends. Manaaki Whenua Press, Lincoln, New Zealand, p. 24.
Scheffer, M., Van Geest, G.J., Zimmer, K., Jeppesen, E., Søndergaard, M., Butler, M.G., Hanson, M.A., Declerck, S., De Meester, L., 2006. Small habitat size and isolation can promote species richness: second-order effects on biodiversity in shallow lakes and ponds. Oikos 112, 227–231. https://doi.org/10.1111/j.0030-1299.2006.14145.x.
Schindler, D.E., Scheuerell, M.D., 2002. Habitat coupling in lake ecosystems. Oikos 98, 177–189. https://doi.org/10.1034/j.1600-0706.2002.980201.x.
Smokorowski, K.E., Randall, R.G., 2017. Cautions on using the Before-After-Control-Impact design in environmental effects monitoring programs. FACETS 2, 212–232. https://doi.org/10.1139/facets-2016-0058.
Spillias, S., Kareiva, P., Ruckelshaus, M., McDonald-Madden, E., 2020. Renewable energy targets may undermine their sustainability. Nat. Clim. Chang. 10, 974–976. https://doi.org/10.1038/s41558-020-00939-x.
Stewart-Oaten, A., Bence, J.R., 2001. Temporal and spatial variation in environmental impact assessment. Ecol. Monogr. 71, 305–339. https://doi.org/10.1890/0012-9615(2001)071[0305:TASVIE]2.0.CO;2.
Sutherland, W.J., Atkinson, P.W., Butchart, S.H.M., Capaja, M., Dicks, L.V., Fleishman, E., Gaston, K.J., Hails, R.S., Hughes, A.C., Le Anstey, B., Le Roux, X., Lickorish, F.A., Maggs, L., Noor, N., Oldfield, T.E.E., Palardy, J.E., Peck, L.S., Pettorelli, N., Pretty, J., Spalding, M.D., Tonneijck, F.H., Truelove, G., Watson, J.E.M., Wentworth, J., Wilson, J.D., Thornton, A., 2022. A horizon scan of global biological conservation issues for 2022. Trends Ecol. Evol. 37, 95–104. https://doi.org/10.1016/j.tree.2021.10.014.
Wang, T., Chang, P., Huang, Y., Lin, T., Yang, S., Yeh, S., Tung, C., Kuo, S., Lai, H., Chen, C., 2022. Effects of floating photovoltaic systems on water quality of aquaculture ponds. Aquacult. Res. 53, 1304–1315. https://doi.org/10.1111/are.15665.
Wickham, H., 2016. ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag.
Winder, M., Sommer, U., 2012. Phytoplankton response to a changing climate. Hydrobiologia 698, 5–16. https://doi.org/10.1007/s10750-012-1149-2.
Woolway, R.I., Jennings, E., Shatwell, T., Golub, M., Pierson, D.C., Maberly, S.C., 2021. Lake heatwaves under climate change. Nature 589, 402–407. https://doi.org/10.1038/s41586-020-03119-1.
Woolway, R.I., Kraemer, B.M., Lenters, J.D., Merchant, C.J., O'Reilly, C.M., Sharma, S., 2020. Global lake responses to climate change. Nat. Rev. Earth Environ. 1, 388–403. https://doi.org/10.1038/s43017-020-0067-5.
Woolway, R.I., Sharma, S., Smol, J.P., 2022. Lakes in hot water: the impacts of a changing climate on aquatic ecosystems. Bioscience 72, 1050–1061. https://doi.org/10.1093/biosci/biac052.
Wu, D., Grodsky, S.M., Xu, W., Liu, N., Almeida, R.M., Zhou, L., Miller, L.M., Roy, S.B., Xia, G., Agrawal, A.A., Houlton, B.Z., Flecker, A.S., Xu, X., 2023. Observed impacts of large wind farms on grassland carbon cycling. Sci. Bull. 68, 2889–2892. https://doi.org/10.1016/j.scib.2023.10.016.
Xia, Z., Li, Y., Guo, S., Chen, R., Zhang, W., Zhang, P., Du, P., 2023. Mapping global water-surface photovoltaics with satellite images. Renew. Sustain. Energy Rev. 187, 113760. https://doi.org/10.1016/j.rser.2023.113760.
Yang, P., Chua, L.H.C., Irvine, K.N., Nguyen, M.T., Low, E.-W., 2022. Impacts of a floating photovoltaic system on temperature and water quality in a shallow tropical reservoir. Limnology 23, 441–454. https://doi.org/10.1007/s10201-022-00698-y.
Zhao, T., Grenouillet, G., Pool, T., Tudesque, L., Cucherousset, J., 2016. Environmental determinants of fish community structure in gravel pit lakes. Ecol. Freshw. Fish 25, 412–421. https://doi.org/10.1111/eff.12222.
Zuur, A.F., Ieno, E.N., Walker, N., Savel'ev, A.A., Smith, G.M., 2009. Mixed Effects Models and Extensions in Ecology with R, Statistics for Biology and Health. Springer, New York, New York, NY. https://doi.org/10.1007/978-0-387-87458-6.