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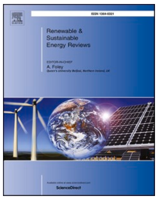

Potential ecological impacts of floating photovoltaics on lake biodiversity and ecosystem functioning

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ABSTRACT

The need to mitigate the effects of climate change is accelerating the development of novel technologies such as floating photovoltaics (FPV). Despite FPV being identified as an emerging issue of concern for biodiversity conservation, it is fast spreading globally and our understanding of their potential ecological impacts is limited. We present an overview of the current knowledge and provide an ecological perspective on FPV potential impacts on lake biodiversity and ecosystem functioning. To date, published works have highlighted reductions in light arrival, wind speed and water temperature with increased FPV cover but the subsequent cascading effects on biological and ecological processes remain unknown. We suggest that modifications in light and water temperature can alter individual regulatory processes affecting, primary production and energy transfer within lake food webs. Additionally, FPV can modify the thermal functioning and oxygenation of the water column while providing artificial habitats for organisms. These modifications can affect individual behavior and life-story but also alter the composition of plant and animal communities, trophic interactions and greenhouse gas balances. We suggest that FPV can also modify socioecological activities related to lake use (e.g., angling, leisure) and pressures at the meta-ecosystem level. Overall, we argue that FPV impacts will be highly context-dependent, varying across ranges of environmental conditions and industrial characteristics (e.g., FPV cover and location). Given the ecological and socio-economic implications of FPV, empirical quantifications based on robust designs are urgently needed and we provide here a unique guideline to help developing research programs to monitor these potential impacts.

1. Introduction

Climate change is driven by increasing greenhouse gas (GHG) emissions and is critically impacting biodiversity and ecosystems across the globe, with critical implications for humans [1,2]. The energy sector (electricity, heat, and transport) is responsible for 75 % of GHG emissions [3]. The increasing energy demand coupled with the urgent need to mitigate climate change is accelerating the renewable energy industry [4,5]. Contradictory, climate mitigation strategies such as renewable energies may have unexpected and counterproductive impacts on biodiversity and ecosystem functioning [6,7], and therefore pose a key challenge in their implementation. One such renewable energy strategy is the use of photovoltaic (PV) energy. The PV industry is evolving fast due to technological advances and cost reductions [8], allowing the exploration of innovative applications. A recent and promising advance of PV is the floating photovoltaic systems (FPV or floatovoltaic), which refers to arrays of PV modules attached to a floating structure and usually fixed on artificial water bodies (e.g., reservoirs, dams, gravel pit lakes, ponds) using a mooring system [8–12]. The FPV market is spreading over the globe with more than 545 FPV plants already in operation and many forthcoming projects [13], notably in Asia, Australia, and Europe [14]. These new installations are motivated because FPV presents several advantages compared to traditional terrestrial PV plants such as reduction in land use pressures for food production, and increased performance due to the cooling effects of water [15–17]. Yet, FPV might also induce negative impacts on freshwater ecosystems that might counterbalance their ecological benefits [18,19].

FPV is likely to affect a wide range of ecological parameters in

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Abbreviations

FPV	Floating photovoltaics
GHG	Greenhouse gas
Chl-a	Chlorophyll – a
PV	photovoltaic
NCP	Nature's contribution to people
DO	Dissolved oxygen
DOC	Dissolved organic carbon
MTE	Metabolic Theory of Ecology
GPP	Gross primary production
R	respiration
OC	Organic carbon
POC	Particulate organic carbon
Kl	Kilolitre

freshwater ecosystems, acting across levels of biological organization. It is therefore extremely challenging to predict the overall outputs of these interacting ecological effects, raising many questions about its potential (negative or positive) ecological consequences [20]. These uncertainties lead to an unclear regulation of FPV development [13], and stakeholders (industry, biodiversity managers or governmental services) are requesting the production of robust scientific knowledge to ensure knowledge-based management of this technology [13,21,22]. Freshwater systems support countless nature's contribution to people (NCP) and, in addition to their utilitarian value (e.g., drinking water), NCP also includes invaluable intrinsic and cultural values, such as climate regulation, biodiversity maintenance, and cultural aspects like well-being and scenic appreciation [23,24]. However, freshwater ecosystems are amongst the most threatened and degraded ecosystems due to multiple anthropogenic impacts such as habitat degradation and pollution [25]. This is particularly true for lakes that integrate human-induced effects on watersheds, airsheds and landscapes [26–28]. FPV has recently been recognized as one of the 15 emerging important issues of concern for global biodiversity conservation [29]. The deployment of FPV in water bodies can directly affect ecosystem functioning and associated services through abrupt changes in environmental conditions but, because its development is still very recent, assessments of their ecological impacts are still lacking [12,15,18,29].

In this study, we first provide a state-of-the-art of the current literature on the ecological impacts of FPV on freshwater ecosystems. Given the overall lack of knowledge in the literature, we then provide a novel ecological perspective exploring the potential impacts of FPV using well-established ecological theory and analogous studies. Based on the potential impacts identified with this approach, we finally provide a comprehensive guideline for monitoring FPV impacts on freshwater ecosystems. The integration of ecological theory to develop this monitoring guideline provides valuable insights into understanding the ecological consequences of FPV plants in freshwater ecosystems.

2. Current state-of-the art on the ecological effects of FPV

We first performed a search for published literature using the Web of Science (all databases and all years) on the ecological effects of FPV. The search terms included a combination of terms that refer to floating photovoltaic technology and potential ecological impacts on water quality, biodiversity and ecosystem functioning. Specifically, the search query was set as follow: "floating PV" OR "floating photovoltaics" OR "floating solar" OR "FPV" AND "impact" OR "water quality" OR "biodiversity" OR "primary production" OR "ecosystem service". The research outputs were then refined to include only research areas of interest, resulting in a first set of 58 studies. References cited in these studies were checked, and the list of references was completed by performing a similar search using Google Scholar. After screening the abstract of each study, a total of 25 studies that explicitly addressed the potential ecological impacts of FPV were considered as relevant. For each study, year of publication, research area, type of study, and main parameters considered were extracted.

We found that a large majority (68 %) of the selected studies were published within the last three years (2021–2023), highlighting the novelty of this topic. These studies were mainly published in the field of solar energy and renewables journals (48 %), and in the field of environmental sciences and ecological research (36%). In total, we identified 13 studies that performed empirical measurements (experimental mesocosm, laboratory and field studies) of potential ecological impacts (Table 1). Most of the empirical studies were conducted in Asia ($n = 7$), followed by Europe ($n = 4$), and focused nearly exclusively on the consequences on abiotic parameters.

Overall, these empirical studies highlighted that FPV can lead to a reduction in light penetration, with studies measuring irradiance reductions as high as 73 % and up to 100 % under panels [30,31]. Also, FPV can induce temperature reductions on the water column [32–36] (but see Ref. [37]), and the intensity of this effect is more pronounced during spring and summer. For instance, by comparing an area with FPV with an adjacent area without FPV, a reduction of water temperature of 0.2 °C during spring and 0.8 °C during summer under panels was observed, while no differences were observed in winter [36]. Reductions in DO [33–35,37,38] have also been reported, and can also vary accordingly to season. It was observed that DO in the water column was, on average, 1.1 mg/L and 1.7 mg/L lower under FPV during winter and summer, respectively [33]. Additionally, reductions of chlorophyll-a concentration [32,34,35,37,38] have been reported, and a reduction of 60 % on evaporation between a mesocosm with FPV cover compared to an uncovered one have been quantified [32]. Quantitative empirical studies on biotic parameters were particularly rare. In fact, only one recent study measured changes in zooplankton communities between coal mining subsidence wetlands with and without FPV and found that, while rotifers density was higher in wetlands without FPV, rotifer diversity and evenness were higher under FPV sites [39]. These were associated with changes in the relative distribution of dominant species due to modifications in light arrival affecting phytoplankton production [39], although this was not directly measured.

The rest of the literature used modelling approaches, and a large majority of them, were based on simulations in artificial reservoirs. Overall, these modelling studies have consistently predicted a decrease in evaporation rates with increased FPV cover [15,18,40–45]. While some models predicted that FPV covering 10 % of the recipient water body can lead to a reduction in evaporation ranging from 7 % to 19 % [41], other simulations predicted that 20 % cover can lead to a reduction of about 62 % on water evaporation. DO was also expected to decrease under FPV [34,37,46]. Additionally, FPV was predicted to induce changes in temperature and stratification patterns with the intensity of these changes being dependent on FPV cover [18,31,34,37,46–48]. Modelling approaches have also provided some first predictions on the effects of FPV plants on wind and solar radiation (and consequently water temperature), altering the air-water interface and surface meteorology [18,47], likely having consequences for biodiversity and ecosystem functioning. These predicted effects, however, are highly context-dependent, varying for instance with FPV cover on the simulated lake [47]. A global consensus that emerged from these studies indicates that the ecological impacts of FPV will be mainly driven by reductions of light and wind intensity at the water surface, which will affect the thermal properties of the lakes.

3. An ecological perspective on the potential impacts of FPV

Our state-of-the-art section confirms that current knowledge on the potential ecological impacts of FPV is still at its infancy, have primarily focused on abiotic parameters, and the subsequent effects on biological

Table 1
List of studies investigating the ecological impacts of FPV. References are grouped by study type (empirical, empirical/modelling and modelling).

Study type	Country	Approach	FPV ecological effects	References
Empirical	Jordan	Mesocosm	• Evaporation reduced by 60 % in FPV experimental ponds • 61 % reduction of chlorophyll-a for covered systems with groundwater source and 17.5 % for surface water source • Nitrate concentrations were 14 % lower with FPV	Abdelal et al., 2021
	Indonesia	Mesocosm	• Mesocosms with 100 % FPV cover had lower average temperature, lower DO, conductivity and Chlorophyll-a	Andini et al., 2022
	Netherlands	Artificial reservoir	• Pronounced effects of FPV on light intensity, with light reduction between 73 % and 100 % compared to a reference measurement • Limited evidences for FPV effects on water temperature and DO due to limited size of the pilot system	Bax et al., 2023
	Netherlands	Quarry/pit lake	• FPV lead to lower upper layer water temperature • DO in the water column was, on average, 1.1 mg/L and 1.7 mg/L lower with FPV during winter and summer, respectively • Floaters were covered by biofouling after 9 months	De lima et al., 2021
	South Korea	Artificial reservoir	• Water quality parameters did not differ before and after a FPV installation (0.04 % FPV cover) • Light intensity decreased by 50 % under FPV	Kim et al., 2019
	China	Mining subsidence wetlands	• Higher density of rotifers in wetlands without FPV • Higher diversity and evenness indices of rotifers in wetlands covered by FPV • Rotifers richness was not different between lakes with and without FPV	Li et al., 2023
	Taiwan	Aquaculture ponds	• Lower temperature, lower DO concentration, lower BOD, lower plankton biomass with FPV • Higher production and survival rates of cultured species with FPV	Wang et al., 2021
	Netherlands	Shallow pond	• water temperature was lower under FPV by 0.2 °C in spring and 0.8 °C in summer. No difference in winter • Frequency of hypoxia (DO < 6 mg/L) increased under FPV • There were no differences on other water quality parameters between FPV covered and uncovered areas • Plant growth was reduced under FPV areas	Ziar et al., 2020
	not applicable	Laboratory set-up	• PV cables did not release microplastics	Rebelo et al., 2021
	not applicable	Laboratory set-up	• FPV using semitransparent polymer solar cells can presented increased algal growth compared to opaque systems.	Zhang et al., 2020
Empirical & Modelling	Taiwan	Aquaculture pond	• 40 % FPV cover cold reduce chlorophyll-a concentration from 1.61 to 1.06 mg/L in winter and from 1.06 to 0.86 mg/L in summer • 40 % FPV could reduce in water temperature from 20.99 °C to 20.22 °C in winter and from 31.03 °C to 29.63 °C in summer • Reduction in DO concentration of 0.80 mg/L with a 40 % FPV cover	Château et al., 2019
	Germany	Dredge lake	• 73 % reduction in irradiance on the lake surface • Average reduction of 23 % in near-surface wind speed • No effect on water temperature when FPV cover <2 % • Nonlinear relationship between water temperature and FPV cover	Ilgen et al., 2023
	Singapore	Artificial reservoir	• FPV could increase water temperature by 0.3 °C and water column stability • FPV could reduce chlorophyll-a, TOC and DO by 30 %, 15 % and 50 %, respectively, and increase total nitrogen (10 %) and total phosphorus (30 %) • No effects on water temperature, water column stability or water quality in areas adjacent of the panels	Yang et al., 2022
Modelling	Egypt	Artificial reservoir	• Decreased water evaporation can save up to 61.7 % when FPV cover was 20 %	Abdelgaied et al., 2023
	United Kingdom	Artificial reservoir	• Increase in FPV cover can reduce water temperature, stratification period and mixing depths	Exley et al., 2021
	United Kingdom	Artificial reservoir	• Water temperature decreases with increasing FPV cover • Chl-a usually decreases with increasing FPV cover • Variations in FPV cover and sitting position affect the dominance of different functional groups of phytoplankton • FPV impacts on phytoplankton were dependent of FPV cover and location	Exley et al., 2022
	Chile	Artificial reservoir	• Lower FPV cover (<40 %) has little or no effect on algal growth. Higher FPV cover strongly reduce algal biomass	Haas et al., 2020
	China	Artificial reservoir	• FPV can reduce water temperature, water age, and relative water column stability of the reservoir. • The influence range of FPV on water temperature is spatially limited	Ji et al., 2022
	India	Artificial reservoir	• FPV covering 30 % of the reservoir could save 42,731.56 m^3 of water by reducing in evaporation loss	Nagananthini et al., 2021
	Romania	Artificial reservoir	• No effects on water quality after FPV implementation were predicted for a cover of 0.32%	Popa et al., 2021
	South Africa	Irrigation pond	• FPV could lead to 2961 Kilolitres (Kl) of water preserved by avoiding evaporation	Prinsloo et al., 2021
	Italy	Artificial reservoir	• FPV covering 30 % of a water body could lead to 49 % reduction in water evaporation • Positive relationship between evaporation reduction and FPV cover	Scavo et al., 2020
	Italy	Artificial reservoir	• FPV cover of 10.0 % could reduce evaporation (7–19 %)	Scavo et al., 2020
	India	Artificial reservoir	• For a 10 MW plant covering an area of 120,000 m^2, the estimated evaporation loss reduction was 210,000 kl/year	Goswami et al., 2019
	Egypt	Artificial reservoir	• FPV cover of 25 %, 50 %, 75 %, and 100 % could save about 2.1, 4.2, 6.3, 7.0, and 8.4 × 10^9 m^3/year	Abd-elhamid et al., 2021

and ecological processes remain unknown. Therefore, we aim here to provide a novel perspective on the ecological impacts of FPV on freshwater ecosystems using current and reference knowledge. This approach will allow to broaden the scope of previous studies and identify potential ecological implications that might have been overlooked in previous research due to the oversimplification of the ecological functioning of freshwater ecosystems. Based on ecological theory and analogue literature on effects of light, temperature, and wind on freshwater ecosystems, we investigated the potential ecological outcomes that FPV structures can trigger in lake ecosystems. Because freshwater ecosystems are extremely complex [49], we do not seek to conduct an exhaustive list of all possible ecological impacts of FPV on lake ecosystems, rather we aim to shed light on the main direct and indirect pathways through which FPV plants may influence biodiversity and ecosystem functioning by modifying key abiotic parameters, such as light, wind, and temperature (Fig. 1).

3.1. FPV effects mediated by light

To maximize energy production, FPV can cover a high proportion of water surface (up to 74 % [19]). The physical presence of FPV on the lake has the potential to strongly limit the arrival of light and photosynthetically active radiation [33,50,51]. Availability of light is amongst the main constraints for primary production, a crucial process driving the flow of energy within ecosystems [52,53]. Reduced light penetration will directly affect phytoplanktonic, macrophytic and benthic primary production, having the potential to modify biomass distribution in autotrophic communities [54] and organic matter dynamics [55,56] and to influence consumers diversity and nutrient cycling [57].

Previous studies have demonstrated that covering water surface (naturally and artificially) decrease light availability and primary production [52,58–60]. Models predicted that increases in FVP cover can result in lower algal growth and chlorophyll-*a* (chl-*a*) concentrations [20,34]. Château et al. [34] estimated that a 40 % FPV cover in a fish pond, would reduce average chl-*a* concentration from 1.61 to 1.06 mg/L during winter and from 1.06 to 0.86 mg/L over summer. However, the response of primary producers will depend on the percentage of surface covered [20]. Simulations suggested that significative reductions in algal biomass might happen when FPV cover is above 40 % [20]. A recent modelling approach predicted exponential decline in chlorophyll-a concentration as FPV cover increased. For instance, it was predicted that FPV cover exceeding 60 % or 70 %, depending on the array's location, could lead to extremely low chlorophyll-a concentrations (<1 μg L^{-1}) [48]. In fact, reductions in algal growth is perceived as a positive outcome of FPV because it could improve water quality in eutrophic lakes [15]. Paradoxically, low light can also lead to higher phytoplankton abundance due to interactions among species [61]. Competitive interactions between pelagic and benthic producers are driven by light (and nutrient context), and phytoplankton and periphyton are both better competitors for light (compared to macrophytes). Therefore, shifts in ecosystem functioning can be expected if drastic changes in light availability are made [61,62]. Light availability can also influence species composition [48,63,64] by acting as an environmental filter, favoring species with functional traits related to light utilization [65,66], as demonstrated for phytoplankton [59,67,68]. A compilation of growth-irradiance relationships of freshwater phytoplankton suggested that cyanobacteria are more adapted to low light environments [69] as they present adaptative strategies, such as the capacity of maintaining high rates of photosynthesis under low light [70,71]. Furthermore, mixotrophic species can alter their nutrition pathway from autotrophy to heterotrophy to compensate deficiency in light or nutrients [72]. Hence, the alterations induced by FPV on fundamental resources availability can trigger changes in processes regulating community assembly such as stabilizing mechanisms of coexistence regulated by intraspecific and interspecific competition.

Light drives the outcome of predator-prey encounters in lakes as phytoplankton, zooplankton and fish exhibit diel activity patterns associated with light intensity that will influence prey risk [73–75]. Many fish are visual predators and reducing light can affect prey detection and foraging success [76–78]. Low light conditions are known to affect visual detection of prey by i) reducing the reactive distance of planktivorous fish [77,79], ii) decreasing attack rates [80] and iii) decreasing the overall predation rate [78]. Ultimately, this can lead to evolutionary changes such as changes in phenotypes as observed when deteriorated visual conditions (high dissolved organic carbon, DOC) is associated to increased eye size in perch, a predatory fish [81].

Shading caused by FPV is also expected to reduce consumer biomass via lower trophic transfer efficiency [34,82]. Indeed, when light is a limiting resource (e.g., high DOC lakes), reduced benthic primary production can induce a decreased production and biomass at higher trophic levels such as benthic invertebrates and fish [52]. Light limitation can also have positive effects on consumers biomass when nutrient

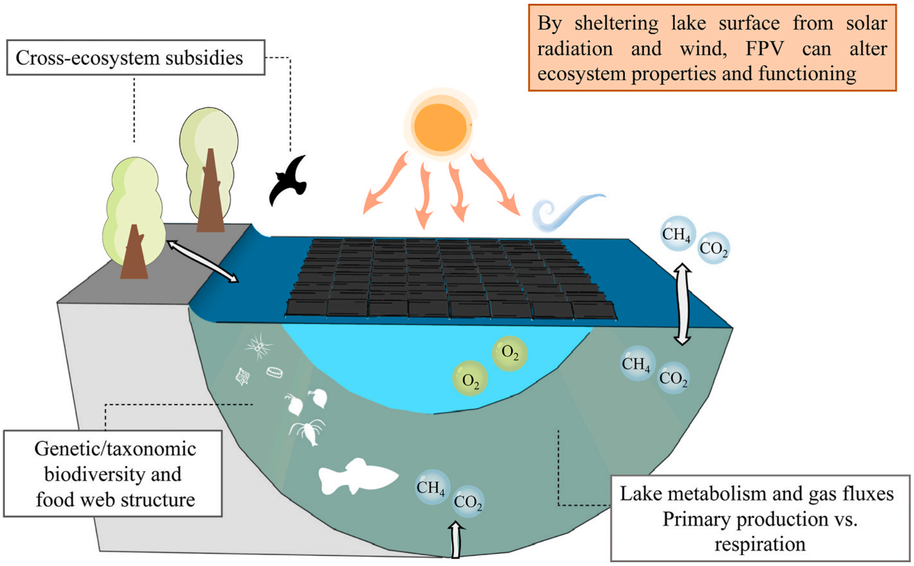

Fig. 1. Potential effects of FPV on lake ecology. FPV will partially block sunlight and wind, altering lake temperature. These modifications will induce ecological changes across levels of biological organization, from genotypes and phenotypes to communities, food webs and ecosystem functioning, including the fluxes of energy and organisms across ecosystems.

availability is limiting [83,84]. Indeed, in low light conditions, net photosynthetic rates are reduced, decreasing the Carbon to Nutrient ratio (better food quality) within primary producers, and reducing the elemental mismatch between primary producers and herbivores [84–86]. Consequently, the impacts of FPV on trophic transfer efficiency will likely depend on the interaction between multiple factors such as light levels and nutrient availability.

FPV will affect other environmental parameters such as dissolved oxygen (DO) concentration, an essential water quality parameter [87]. DO can be directly affected by FPV through reduced air-water contact and gas exchanges with the atmosphere and indirectly through reduced light incidence. DO and primary productivity are strongly coupled, especially in bottom waters [88], with reductions in light limiting phototrophic activity (DO production). In fact, DO reductions under floating solar panels have been predicted by modelling studies [34] and *in-situ* measurements [33]. Château et al. [34] estimated a significative reduction in DO concentration of about 0.80 mg/L with a 40 % FPV cover. By comparing DO concentrations under a FPV structure and an open water reference point, de Lima et al. [33] found that DO concentrations were lower under the FPV (4.6 mg/L compared to 6.0 mg/L at the reference point). Low DO levels can alter organisms' distribution that will move from hypoxic to oxygenated water, or even be lethal to a variety of aquatic organisms when migration is not possible or anoxia in the entire ecosystem [89,90]. In fact, anoxia is recognized as one of the main possible negative outcomes of FPV deployment [19] (see section 4.3).

3.2. *FPV effects mediated by temperature*

FPV will physically block the incidence of shortwave radiation, reducing surface heating and likely leading to cooler surface water [18,31,34,47]. FPV can also alter dial variability in water temperature [31,37]. This is because FPV structure will warm during the day and release heat during the night potentially leading to lower dial variability in water surface. While, for a very low FPV cover (2 %), no effects on water temperature under a FPV plant and an adjacent area were measured [31]. It was estimated that FPV covering large proportions of lake surface (>~50 %) can result in significant water temperature reduction [47]. Château et al. [34] indicated that 40 % FPV cover can reduce, on average, water temperature from 20.99 °C to 20.22 °C in winter and from 31.03 °C to 29.63 °C in summer. Temperature regulates a variety of physical and chemical characteristics of water that have implications for ecological processes. For instance, temperature regulates oxygen solubility, decreasing with higher temperatures [91]. Water temperature also affect water viscosity and density that determine phytoplankton sinking rates regulating phytoplankton suspension and survival [92,93]. Water temperature modulates stratification patterns that can affect chemical and biological aspects within freshwater ecosystems (see section 4.1).

The Metabolic Theory of Ecology (MTE [94]) predicts that metabolic rate controls ecological processes, with fundamental processes rates increasing exponentially with temperature within the physiological range of organisms [94,95]. From plants to animals, increased physiological and metabolic rates (photosynthesis, respiration, growth, nutrient uptake) is commonly observed with increased temperature until a temperature optimum where rates start declining due to enzymatic system break down [93,94,96]. In fact, all organisms are characterized by a thermal niche and their species-specific thermal tolerances can thus define organisms' distribution and community composition. For instance, high temperatures can be lethal for some organisms, that under these circumstances may die or find a refugee in adjacent cool waters [97–99]. Over the long term, water temperature also play an important role on life history traits such as body size, life span, feeding mode and behavior [100]. Water temperature is a key driver of organism phenology by regulating, for instance, fish reproduction [101,102] and insect emergence [103,104]. A recent concern regarding climate change, is its effects on lake water surface warming and its consequences to lake ecology (e.g., phenological effects, lake biodiversity, biogeochemical processes). Lakes surface water temperature has increased at a global average rate of 0.34 °C per decade [105]. It has been suggested that FPV can thus be used as a management tool to buffer the effects of climate change on water surface warming [47].

From bacteria to fish, warmer temperatures promotes an increased proportion of small-sized organisms, among and within species [93,106–108]. Body-size is a central biological and ecological trait and a myriad of processes (from molecular to evolutionary dynamic) are linked to body size [109]. Body size is not only correlated to individual fitness and population growth, but it also affects size-dependent predation, having consequences to population and community dynamics. In mesocosms, Chironomids, which are usually abundant and with fast generation time, presented reduced body-size with increased temperature [110]. Because they represent an important food source for fish, birds and other invertebrates, reductions in body size can alter their nutritional value and modify attack rates and handling time of predators [110].

Temperature shapes the strength and stability of trophic relationships in aquatic food-webs through a variety of indirect pathways [111]. For instance, temperature can stimulate respiration in a greater extent than gross primary production because the temperature-dependence of respiration is higher than the temperature-dependence of photosynthesis, affecting the metabolic balance of the system [112,113]. Consumers will likely be more sensible to temperature changes than producers, leading to reinforced top-down control in linear food webs by increased grazing under higher temperatures [114,115]. In the scenario where FPV leads to lower temperature, it can be expected the opposite trend, with weaken top-down control and lower grazing pressure.

Furthermore, modifications in temperature leading to phenological alteration can also cause trophic mismatch between prey and predators affecting energy flow in aquatic food webs [114]. For example, it has been well documented that elevated temperatures cause earlier phytoplankton blooms in spring [116,117]. These asynchronies across different trophic levels can uncouple resource availability and consumer needs, and alter food webs [114,117]. Temperature changes can induce shifts in consumer diet, with increased herbivory observed in warmer conditions [118] and a higher consumption pressure on primary producers [118,119]. If FPV deployment cause a significative reduction in water temperature, it may favor ectothermic omnivores to consume more animal resources and less plants as they are easier to digest in lower temperatures and have higher nutrient content [120].

Water temperature strongly influences ecosystem-level processes which are mediated by biological activity. Higher temperature can increase physiological rates, such as fish excretion [121,122]. This is important because fish, via excretion, can significantly alter nutrient supply, supporting a high proportion of primary production [123]. Water temperature also modulates the decomposition rates of organic matter [76,124]. This is partially because C processing, sequestration, and mineralization rates in the water column and sediments are dependent on microbial activity that is directly associated to temperature [125]. Lower water temperature is usually related to decreased decomposition rate and thus, lower mineralization rates, likely because of reduced metabolic activity of decomposing bacteria and scavengers [76,126]. If FPV reduce water temperature and the mineralization of organic C, this will lead to higher organic C burial in sediments and alter C cycling [125].

Changes in water temperature induced by FPV have the potential to affect a variety of physiological and biological processes related to individual metabolism and even small temperature shifts could generate a cascade of impacts from the individual level to the whole food web [111]. The response of ecosystems to changes in temperature will therefore depend on the complexity of interaction networks and feedbacks between physical and biological processes [111].

3.3. FPV effects mediated by wind

FPV create sheltered areas that decrease air-water contact and increase surface roughness, likely reducing wind speed at lake surface [18]. A recent study measured that FPV can lead to an average reduction of 23 % of near-surface wind speed [31]. The intensity of this effects is, however, hard to predict as it will depend on a combination of factors such as FPV surface cover, plant design, lake characteristics and surrounding landscape (e.g., morphometry and presence of littoral vegetation [18]). Nevertheless, even small changes in wind intensity can have significant effects on lake ecology [18,47]. Wind has a pivotal role on freshwater ecosystem function [127] as it directly influences water mixing, lake thermal dynamics [18,47], gas fluxes in the air-water surface [128], sediment resuspension, and nutrient distribution in the water column [129,130]. Reduction in wind speed can, for instance, decrease DO concentration because the rate of gas exchange at the air-water interface is a function of wind speed and gas concentration [131].

Decline in wind can also have indirect effects on eutrophication in shallow lakes due to wind-induced internal nutrient release. Indeed, reduction in wind speed and longer low speed duration can lead to longer stability periods and low DO in lake bottom (hypoxia), increasing phosphorus release from the sediments and algal production [127]. On the other hand, high wind is often related to nutrient release from the sediment due to resuspension, especially in shallow lakes [132]. Thus, while the deployment of FPV can inhibit sediment resuspension due to lower wind speed, it may also increase nutrient release from the sediments due to hypoxia in the water-sediment interface.

Additionally, reduction of wind intensity can modulate vertical displacement and horizontal drift passive dispersion processes, changing distribution patterns of aquatic organisms [133]. For phytoplankton, under low wind-speed, wind-generated turbulence is not strong enough to mix phytoplankton, neither to re-suspend planktonic species into the water column, favoring smaller and buoyant phytoplankton species to remain at water surface [134,135]. It has also been demonstrated that wind-induced water movements can affect zooplankton horizontal distribution, leading to downwind accumulation of larger zooplankton species [133,136]. Such effects on the fine-scale patterns of species distribution are likely to be induced by FPV.

4. Interactive effects of wind, temperature and light

4.1. FPV effects on stratification patterns and its implications

FPV shelters water surface from solar radiation and wind and alters water temperature, leading to modifications in lake thermal stratification patterns [18,47]. While temperature and wind are physical drivers of vertical mixing, they have different effects: reduction in wind tends to suppress mixing and stratify while decreased water temperature can enhance mixing [137]. Using a model, Exley et al. [47] predicted that significant FPV cover (>~50 %) can result in large temperature changes and extensive modification in stratification timing. The most common responses found were reduction in water temperature, shorter stratification period and shallower mixed depth, however, in low FPV cover scenarios, stratification was prolonged [47]. Understanding how FPV design will affect intensity and timing of lake stratification (stratification phenology) is therefore of utmost importance. Stratification determines many physical, chemical, and biological processes within lakes, including population dynamics and species interactions and it also influences the exchange of oxygen, nutrients, and carbon between lake surface and bottom [138]. Changes in the timing of stratification onset can cause shifts in phytoplankton bloom, leading to trophic mismatches at the basis of food web [139]. In addition, longer stratifications are usually related to hypolimnetic anoxia due to restrictions in the vertical mixing of oxygen from the surface [91]. In turn, anoxic conditions at the lake bottom can lead to nutrient remineralization (e.g., phosphorus release) and promote higher methane (CH_4) emission through methanogenesis [138]. CH_4 is a highly potent greenhouse gas compared to CO_2 [140] and, if FPV causes longer periods of stratification and lake bottom anoxia, it may generate counterproductive results by increasing lake contribution to global warming through increased CH_4 emission.

4.2. FPV effects on evaporation and seasonal dynamics

Water evaporation is an essential physical control of lakes, regulating for instance surface water temperature, stratification, gas fluxes in the air-water interface and water levels [105,141,142]. Evaporation rates are highly dependent on temperature. Climatic change is expected to lead to an increase of 16 % of global annual mean lake evaporation rates by 2100 [105]. Higher temperatures have been correlated with changes in water level seasonal cycles, due to early summer evaporation rates, leading to lower lake water levels [143]. Changes in water level can not only compromise water quantity [144] but also water quality by inducing regime shifts in lake ecosystems [145].

FPV are predicted to reduce evaporative losses due to the combined effect of decreased wind speed and water temperature [40,146,147]. A study using floating covers demonstrated that water evaporation can be suppressed up to 96.8 % with high FPV cover fractions as the floating cover reduces solar radiation input, the ventilation at water–air interface and blocks water vapor [144]. In a pilot scale test (2 m × 2 m x 1 m tank), FPV lead to a 60 % reduction in evaporation [32]. Although empirical studies specifically with FPV as floating covers are limited, models predicted an evaporation reduction potential of FPV ranging from 50 % to 90 % [15,41–45]. Because climate change will limit water availability and more prolonged and frequent droughts are expected [148,149], FPV could provide water savings. However, this claimed benefit may be highly context dependent, as it will depend on FPV cover and local meteorological conditions such as relative humidity, wind speed and temperature [150].

By affecting fundamental properties of lakes such as temperature, light availability and mixing, FPV can potentially impact lake spatial and seasonal dynamics (e.g., water level seasonal dynamics). These dynamics defines the match-mismatch of food web interactions, impacting food web structure and energetics at lake ecosystems, which can lead to severe consequences such as regime shifts [151].

4.3. FPV influence on lake metabolism and gas fluxes

Lake metabolism is the balance between respiration (R) and gross primary production (GPP), two of the most fundamental processes in ecosystems [152]. GPP is the assimilation of inorganic carbon into organic plant material and O_2 release through photosynthesis (dependent on light), while respiration is related to biochemical transformations of lake organic carbon (OC) resulting in the uptake of O_2 and release of CO_2 and CH_4 [153]. On a global-scale the GPP:R rate defines the role of the ecosystem as sources or sinks of C [153], with lake productivity also being an important driver of lakes' emission rates [154]. GPP and R have a high sensitivity to light availability and temperature and FPV can affect lake metabolism and gas emissions in multiple and interactive ways (e.g., light and primary production, temperature and respiration rates, wind and nutrient loading). For instance, if FPV reduce primary production due to reduced light, and to lower metabolic rates caused by lower temperature, the ecosystem might increase its potential as a CO2 source. Following FPV installation, a high mortality of primary producers (e.g., phytoplankton and macrophytes) from light limitation is expected. This might induce an input of organic matter to the sediment that has the potential to fuel methanogenesis, and hence the CH4 emissions to the atmosphere [155,156].

The role of lake as a source of GHGs might also be enhanced by FPV if wind reductions decrease DO concentration or induce longer stratifications to promote hypoxia. Generally, low oxygen concentrations and anoxic conditions favor the use of alternative electron acceptors such as carbon (for methanogenesis) and nitrate (denitrification), having N_2O and CH_4 as final products which are gases with greater potential as GHG than CO_2 [157]. Over a longer time period, lakes may undergo a process of oligotrophication caused by the reduced biomass of primary producers. This will decrease OM availability and GHG production and emission are expected to decrease. This dynamic will be dependent of temperature, oxygen conditions and nutrients availability. While the effects of FPV on ecosystem metabolism are hard to predict [18], their understanding is of utmost importance to ensure that FPV is not triggering counterproductive impacts regarding GHG emissions.

5. FPV acting from genes to the meta-socio-ecosystem scale

Regarding the individual and genetic level, organisms can respond to modifications in their environment by genetic adaptation (e.g., selection of intraspecific variation in light limitation), phenotypic plasticity (e.g., alteration of photosynthetic traits under low light) and species sorting (e.g., sorting due to interspecific variation in light limitation) [158]. For instance, phytoplankton species from different functional groups, when exposed to low light conditions, increased their phenotypic variability to reduce interspecific competition and maximize individual success [159]. Fish can also display rapid responses (within a few generations) to environmental pressures such as changes in temperature [160]. Using models, Château et al. [34] predicted that the cooling effect of 60 % of FPV cover could reduce fish appetite and subsequently fish production. Species generation time will affect the temporal dynamics of their responses to FPV, with faster and more intense responses likely occurring for short-generation time species [161]. This is especially true for phytoplankton, because they are abundant, have fast generation time and high genotypic diversity, providing the ground for fast trait evolution induced by strong selective pressures [158]. Rapid changes induced by FPV (e.g., temperature, light) are therefore expected to induce rapid response for such organisms and time-lagged effects at higher trophic levels, such as long-lived fish [161].

FPV can also interfere on processes happening at the land-water interface. Fluxes of matter, organisms and energy across ecosystems is ubiquitous, with ecosystems being connected by reciprocal subsidies [162–164]. Hence, perturbations in one habitat can cascade in unexpected consequences in the adjacent ecosystem [165]. Terrestrial allochthonous organic matter is an important resource for aquatic food webs and affects the lake C budget. Carbon budgets in aquatic ecosystems can be highly dependent on inputs of dissolved and particulate organic carbon from land (DOC and POC, respectively), with tree leaves being a major input of terrestrial POC [166,167]. FPV can affect the arrival of terrestrially derived organic matter in different ways: 1) by partial removal of the surrounding vegetation during the construction, reducing terrestrial POC production (e.g., leaves); 2) FPV may impede leaves to enter the lake, and finally 3) spatial disposition of FPV arrays will determine the fate of suspended leaf and its sedimentation within lakes as FPV will limit their drifting. FPV will modulate the availability and modify spatial distribution of POC, with potentially important consequences on biochemistry and ecosystem functioning [167].

Emerging insects link freshwater and the adjacent terrestrial ecosystems [168] and, in some areas adjacent to large lakes, insect emergence can exceed terrestrial secondary production by a factor of 100 or more [169]. Therefore, aquatic insects represent a significant input of resources supporting terrestrial consumers such as birds, reptiles, and spiders [170]. Light and temperature trigger insect emergence, with earlier emergence in warmer water temperatures and longer photoperiod [104,171]. Thus FPV may alter the timing of aquatic insect emergence and nutrient subsidization across ecosystems, potentially inducing trophic mismatch with terrestrial consumers.

Mobile organisms, such as birds, have an important role in driving the flow of nutrients across ecosystems through the spatial interactions between nutrient recycling and feeding and affect ecosystem functioning across spatial scales [172] (Fig. 2). FPV may alter the habitat use

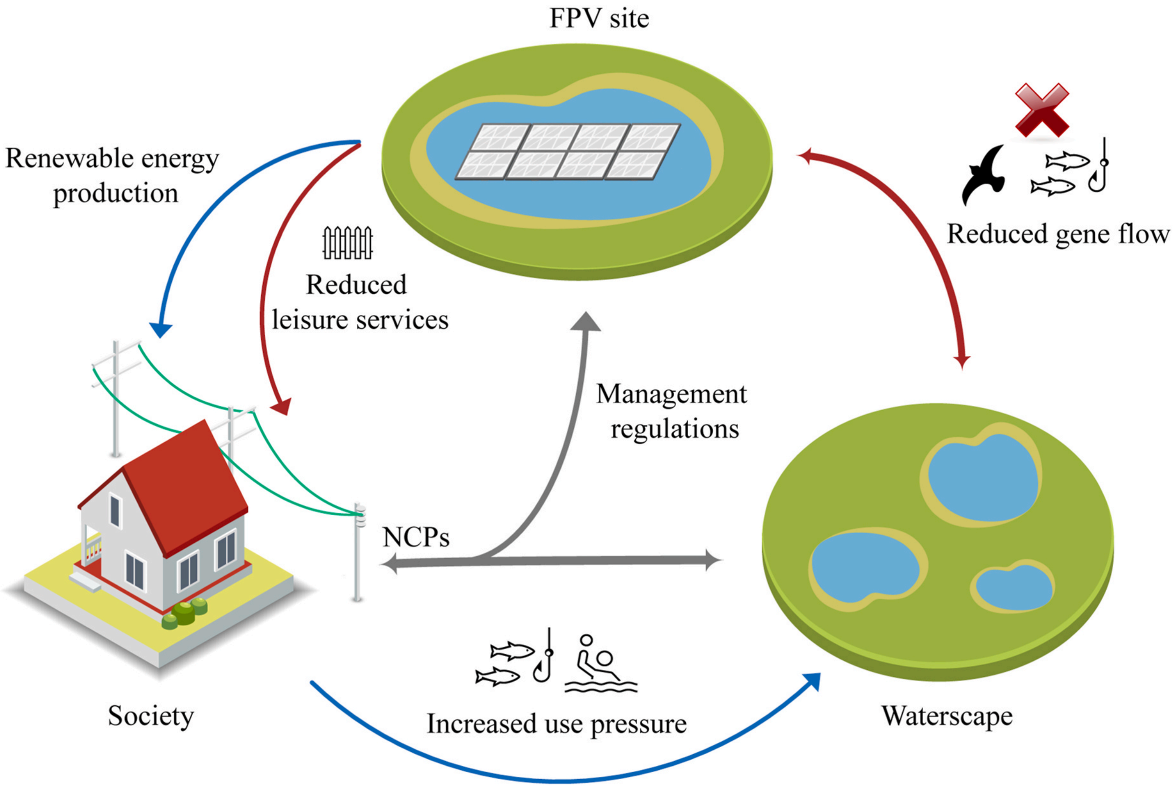

Fig. 2. Potential changes in socio-meta-ecosystem dynamics induced by FPV. The schema also highlights the role of society to apply management regulations in FPV sites and at the waterscape level to guarantee the maintenance and provisioning of material and non-material Nature's Contributions to people. Red arrows represent reduced fluxes and blue arrows increased fluxes.

and behavior of piscivorous birds, changing the flux of nutrients across ecosystems. While FPV may attract some birdlife [173], their presence, however, may be unwanted. While bird dropping is a natural input of nutrients from adjacent ecosystems into lakes [174,175], when they are accumulated above the panels and then flushed into the water during discrete cleaning or rainfall events, they may represent a pulsed input of nutrients and affect water quality [33].

FPV impacts are also anticipated at the waterscape level [176]. FPV deployment can affect the movements of organisms and matter in the network of lakes within the landscape [177], (Fig. 2). Wind blowing in the lake surface can release vegetative cells from water collecting and transporting phytoplankton by wind [178]. Anemochory has also been demonstrated to be a relevant route of dispersion between freshwater ecosystems for zooplankton [179–181]. Reduction of dispersal capacity, combined with the selective pressures induced by resource limitation (e.g., light reduction) caused by FPV deployment can lead to declines in interspecific and intraspecific diversity due to genetic bottleneck and inbreeding processes. In that sense, FPV deployment might interfere with patterns of local but also regional species diversity.

The flux of matter and energy between ecosystems is also greatly affected by human actions [182]. Lakes are ecosystems known for their multiple uses such as drinking water, recreational and cultural activities (e.g., angling, lake shore running, dog walk, scenic appreciation). When FPV are deployed, exploitation, maintenance or security reasons will decrease or totally limit other activities. For instance, angling will be affected by FPV because access to sites can be prohibited, or when co-use of site is allowed, angling area will be diminished to guarantee the integrity of FPV structure. Recreational angling can also be affected by change in fish behavior that may hide under FPV, in areas where angling may not be allowed. These changes must therefore be modulated and associated with fishery management practices such as stocking. If public access is prohibited, this will considerably limit the movement of humans in the waterscape and reduce important vector of nonnative species introduction [176]. The reduction (or total disappearance) of angling will strongly alter fishing-induced selective pressure and might lead to new evolutionary trajectories in unfished lakes.

FPV also cause a visual change in the landscape due to modifications on the water bodies, but also on its adjacent terrestrial habitat (e.g., vegetation removal during construction or to avoid shading on the panels). These changes have the potential to generate conflicts with the local population [50,183] and compromising the non-material psychological benefits provided by freshwaters such as aesthetic value [183]. In that sense, FPV deployment must be thought in the meta-socio-ecosystem context [182] as it can impose changes also in human activities related to freshwater ecosystems (Figs. 2 and 3).

Using theoretical ecology and current FPV studies, we argue that i) FPV plant can have the potential to trigger numerous ecological impacts in both aquatic and adjacent terrestrial ecosystems, affecting different levels of biological organizations (Fig. 3), and that ii) these effects have been largely overlooked despite this representing a pre-requisite to limit the negative ecological impacts of FPV and ensure that the full environmental benefits of FPV are obtained without sacrificing freshwater biodiversity or the functioning of lake ecosystems.

6. The role of FPV physical structure

FPV arrays will enhance the structural complexity of a lake by providing new habitat in the pelagic zone. The floating pontoons that

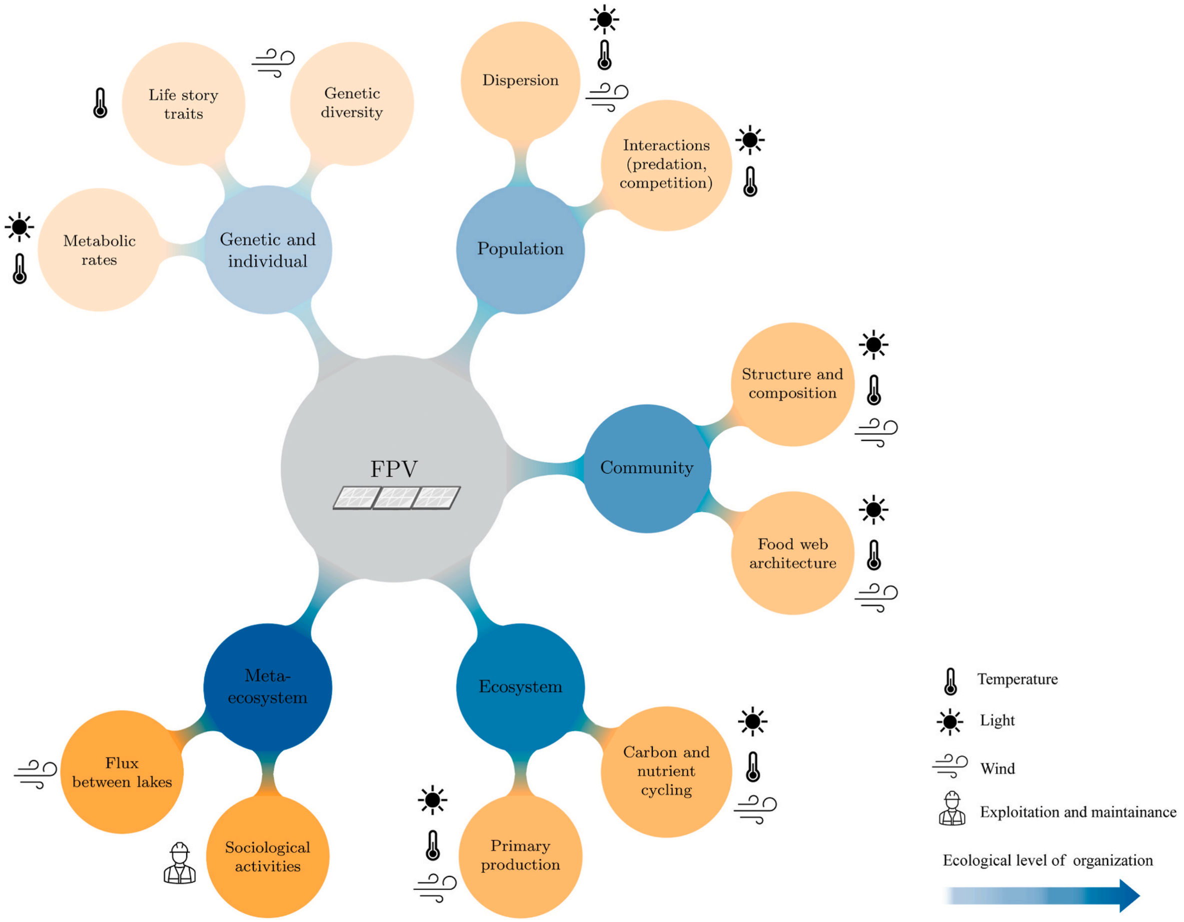

Fig. 3. Expected ecological effects of FPV across different levels of ecological organization. These effects are caused by alterations in light, wind, temperature, and restrictions in lake access caused by FPV exploitation and maintenance.

Table 2
List of suggested parameters to be monitored when assessing the ecological impacts of FPV on freshwater biodiversity and ecosystem functioning.

Properties	Parameters	Rationale
Water physical and chemical properties	Light intensity	Light intensity and photosynthetically active radiations in the water column will be modified due to FPV shading effect.
	Temperature	Solar radiation and wind mixing will be modified, likely altering water temperature profiles and stratification patterns.
	Nutrients	By reducing wind, FPV can inhibit sediment resuspension and affect the internal loading of nutrients (C, N and P). FPV can also increase nutrient release by sediments if it is associated to hypoxia at the water-sediment interface. Change in biodiversity will also modify nutrient cycling.
	Dissolved oxygen (DO)	Reduced wind and contact at the water-atmosphere interface can lead to lower water column oxygenation and change in (DO) profiles. Reduced light penetration can limit phototrophic activity and DO production by primary producers.
	Micropollutants	Leaching and UV degradation from FPV panels and flotation devices may induce the released of a variety of micropollutants (e.g. heavy metal and organic compounds).
Biodiversity	Phytoplankton, periphyton and macrophytes	Alterations in light arrival induced by FPV can lead to a reduction in algal growth, mainly in the area covered by FPV, and a shift in community structure favoring taxa adapted to low light conditions.
	Zooplankton and macroinvertebrates	Changes in light distribution and wind can influence patterns of zooplankton diel vertical migration and horizontal distribution. Additionally, biomass and community structure of zooplankton and macroinvertebrates may change following changes in the structure of primary producer and aquatic vertebrates consuming them. Emergence of macroinvertebrates will likely change.
	Fish and amphibians	FPV will reduce predation pressure by providing refuge from piscivorous birds, will increase habitat complexity, provide shaded areas and reduce water temperature which can influence spatial distribution of fish, fish behavior, food availability as well as fish metabolism and consequently community biomass. Amphibians inhabiting littoral habitats are likely to be less affected by FPV than fish.
	Birds and bats	FPV can alter bird and bats behavior and habitat use as they can be attracted by FPV platforms for nesting but they may also avoid the area due to the use of repellent technologies or reduced availability of predation areas. Changes in fish habitat use and insect emergence will also change food availability.
Ecosystem Functioning	Pelagic and benthic primary production	Light is the main source of energy for primary producers and changes in primary production will energy flow within the ecosystem. Additionally, floaters can represent a novel growing area (i.e. biofouling) leading to a new source of organic matter for consumers and providing habitat for sessile organisms.
	Greenhouse gases emission (GHGs)	FPV may change the role of the water bodies as a source or sink of GHGs. If FPV leads to longer stratification periods or bottom anoxia due to lower oxygenation of the water column, it can favor process such as methanogenesis. On the other hand, water bodies can become a sink of CO_2 if FPV leads to lower organic matter production.
	Lake metabolism	Because FPV may affect oxygenation of water column through i) changes in gas exchanges at the air-water interface, ii) changes in oxygen solubility due to modification in water temperature and iii) changes in metabolic rates of primary producer and consumer, FPV can alter lake metabolism.

are the base structure of the floatovoltaic arrays create a novel surface area located at the euphotic zone, providing conditions for the development of biofouling [33] and habitat for sessile species in the pelagic zone of lakes. de Lima et al. [184] found that, 9 months after FPV installation, a high proportion of the floating structure was covered by small bivalves and biofouling. Although there is still a lack of empirical evidence regarding the ecological effects of FPV physical structure, studies on habitat complexity provided by artificial structures have shown that habitat heterogeneity provided by the presence of artificial structures can been correlated with increased abundance and diversity of macroinvertebrates [185]. Fish can also be attracted to artificial structures because the enhanced habitat complexity can provide cover, increasing juvenile fish survival by creating refuges from predation and also by providing spawning and nesting substrate [186–188]. Indeed, it has been observed that the underneath portion of the FPV may be used as a resting and nesting area for birds and fish [33,173]. Rosa-Clot (2020) observed that, in a lake where FPV plants were installed, carps tended to spend time under the FPV platforms due to sun shading and to the presence of attached algae. FPV structure can also reduce predation pressure by piscivorous birds because i) water accessibility (or predation area) is reduced due to FPV cover; ii) FPV can serve as a refuge for fish hiding from bird predation [189]; and due to iii) the use of repellent technologies. Additionally, FPV structure can be a source of chemical pollution to water bodies due to release of chemicals and microplastics originated from degradation of FPV components over time [190].

7. A guideline for monitoring the potential ecological impacts of FPV

Recently, FPV has been identified as one of the main emerging issues of concern for biodiversity conservation [29], and there is still an important knowledge gap regarding their potential ecological impacts. Based on our investigations and existing knowledge, we provide here a comprehensive set of parameters related to i) the physical and chemical characteristics of the water, ii) the structure of biodiversity and iii) the functioning of ecosystems that we recommend to monitor when aiming to assess the ecological impacts of FPV (Table 2). This set of parameters is based on previous recommendations from existing literature [18,30], and from our investigations. These guidelines offer a unified, multidisciplinary framework for assessing the potential effects FPV on aquatic ecosystems and should provide knowledge that could help to understand their context-dependency.

Ideally, we recommend to performed these monitoring surveys using a BACI (Before - After - Control – Impact) design that allows to take into consideration potential confounding factors and natural variability in ecosystems [191,192]. This means that water bodies that are meant to receive FPV should be monitored several years before FPV installation to obtain a robust reference. Control sites with similar geomorphological, physico-chemical and biological characteristics should also be included in the monitoring program to provide a baseline of biodiversity and ecosystem dynamics. Monitoring should be performed at least once per season to take into account the main changes occurring in lake ecosystems. It is expected that the complex ecological impacts of FPV will take several years – decades-to eventually reach an equilibrium.

8. Conclusion

FPV may induce a myriad of ecological impacts in aquatic and their adjacent terrestrial ecosystems across levels of biological organization. While it is difficult to predict the general outcome of these multiple, sometimes opposing, effects, some alterations can compromise the conservation of multiple NCPs derived from freshwater ecosystems such as water provisioning and climate regulation. Based on existing literature of the ecological effects of FPV as well as on ecological theory regarding the ecological effects of the physical parameters most likely impacted by FPV (light, temperature, wind), we expect that these ecological effects will be highly context-dependent, varying across ranges of environmental (e.g., lake trophic status, community assemblage, local climate) and industrial (e.g., FPV % cover, array design), resulting in a large variability in responses between ecosystems. While water temperature, chlorophyll-a and DO concentrations and evaporation rates have been the main parameters studied so far, the development of the ecological perspective on the potential effects of FPV suggested in this study should improve our ability to identify the potential ecological implications that have been overlooked in previous research, such as species behavior and migration patterns, freshwater communities structure (but see Refs. [39,48]), ecosystem functioning (e.g. nutrient cycling, lake metabolism and GHGs emission). Quantifying the impacts (positive or negative) of such an environmental change and how lake ecosystems will respond to it is extremely challenging. It will require continuous and long-term monitoring before and after FPV installation and the use in conjunction of methods to quantify aquatic biodiversity, food webs and ecosystem functions (e.g., C Cycle and lake metabolism) within context-dependent scenarios. We hope that the guideline for monitoring FPV plants provided in this study should serve as a practical tool for researchers, policymakers, and industry stakeholders to assess and manage the potential ecological impacts of FPV installations. Again, we argue that empirical studies such as *in situ* monitoring and experiments based on robust and replicated designs are essential to quantify the possible ecological impacts of FPV, assuring that it is reaching its goals as a sustainable technology, but also providing fundamental knowledge on ecosystem responses to abrupt environmental changes.

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.

Data availability

No data was used for the research described in the article.

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