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Integrating environmental understanding into freshwater floatovoltaic deployment using an effects hierarchy and decision trees

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Abstract

In an era of looming land scarcity and environmental degradation, the development of low carbon energy systems without adverse impacts on land and land-based resources is a global challenge. 'Floatovoltaic' energy systems—comprising floating photovoltaic (PV) panels over water—are an appealing source of low carbon energy as they spare land for other uses and attain greater electricity outputs compared to land-based systems. However, to date little is understood of the impacts of floatovoltaics on the hosting water body. Anticipating changes to water body processes, properties and services owing to floatovoltaic deployment represents a critical knowledge gap that may result in poor societal choices and water body governance. Here, we developed a theoretically-derived hierarchical effects framework for the assessment of floatovoltaic impacts on freshwater water bodies, emphasising ecological interactions. We describe how the presence of floatovoltaic systems may dramatically alter the air-water interface, with subsequent implications for surface meteorology, air-water fluxes and physical, chemical and biological properties of the recipient water body. We apply knowledge from this framework to delineate three response typologies—'*magnitude*', those for which the direction and magnitude of effect can be predicted; '*direction*', those for which only the direction of effect can be predicted; and '*uncertain*', those for which the response cannot be predicted—characterised by the relative importance of levels in the effects hierarchy. Illustrative decision trees are developed for an example water body response within each typology, specifically, evaporative water loss, cyanobacterial biomass, and phosphorus release from bed sediments, and implications for ecosystem services, including climate regulation, are discussed. Finally, the potential to use the new understanding of likely ecosystem perturbations to direct floatovoltaic design innovations and identify future research priorities is outlined, showcasing how inter-sectoral collaboration and environmental science can inform and optimise this low carbon, land-sparing renewable energy for ecosystem gains.

1. Introduction

Floating photovoltaic (PV) solar energy systems, floatovoltaics, are being deployed at accelerating rates despite limited understanding of the consequences for the hosting water body and ultimately implications for natural capital and ecosystem goods and services (World Bank Group, ESMAP & SERIS 2019) (table 1). Freshwater floatovoltaic designs are developing as the technology matures and predominantly comprise PV panels mounted on individual floats, on racking attached to floating

Table 1. Ecosystem services provided by water bodies. Source: (Aylward *et al* 2005). From Ecosystems and Human Well-being: Policy Responses by the Millennium Ecosystem Assessment. Copyright © 2005 Millennium Ecosystem Assessment. Reproduced by permission of Island Press, Washington, DC.

Provisioning	Water for consumptive use (drinking, domestic, industrial and agricultural use)
	Water for non-consumptive use (power generation, transport/navigation)
	Aquatic organisms for food and medicines
Regulatory	Maintenance of water quality
	Buffering of flood flows, erosion controls through water/land interactions and flood control infrastructure
Cultural	Recreation (river rafting, kayaking, hiking and fishing)
	Tourism (viewing)
	Existence values (personal satisfaction)
Supporting	Role in nutrient cycling Primary production
	Predator/prey relationships and ecosystem resilience

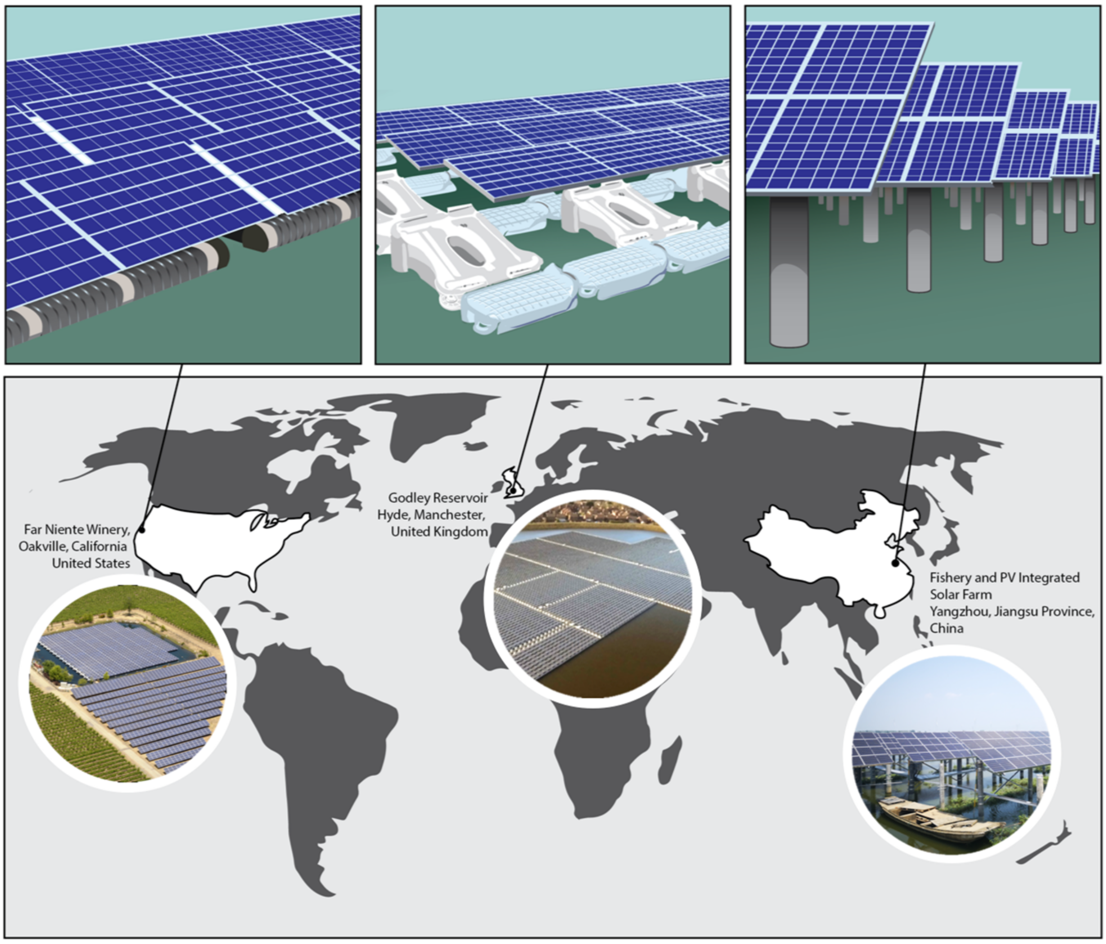

Figure 1. Design variants of freshwater floatovoltaic systems across the world, including a floating pontoon array at Far Niente Winery, California (SPG Solar [CC BY-SA 3.0]), continuous raft at Godley Reservoir, UK (© Forrest), and (c) a pole mounted system at Yangzhou, China (photo credit: Jinko Solar). First circle: this Floating PV system Far Niente Winery California 2018.jpg image has been obtained by the author(s) from the Wikimedia website where it was made available by Te750iv under a CC BY-SA 3.0 licence. It is included within this article on that basis. It is attributed to SPG Solar. Second circle: © Forrest. Third circle: photo credit: Jinko Solar.

pontoons, or poles fixed to the water body bed (Trapani and Redón Santafé 2015, Liu *et al* 2018) (figure 1). Without integrating environmental understanding into floatovoltaic system design and deployment, some sustainable development goals (SDGs), in particular 'life below water' and 'clean water and sanitation', could be adversely affected in pursuit of 'affordable and clean energy' (United Nations 2015).

Increased understanding of the ecosystem impacts and integration of environmental science into the design and deployment of freshwater floatovoltaic systems could cause a step-change in local ecosystem outcomes, minimising detrimental impacts and, appealingly, maximising ecosystem co-benefits (Hernandez *et al* 2019). This is especially pressing because floatovoltaic growth has been, and is expected to be, particularly rapid: capacity doubled from 2017 to 2018, the current capacity exceeds 1 GW, and individual installations of up to 150 MW are being deployed (World Bank Group, ESMAP & SERIS 2018). Further, there is significant potential for further growth as inland water bodies cover 5×10^6 km^2 of the Earth's surface (Verpoorter *et al* 2014) and deployments are occurring across the world, from arid areas (e.g. Far Niente Winery, California, figure 1) to temperate environments (e.g. Godley Reservoir, northern England, figure 1) (Trapani and Redón Santafé 2015). Growth is anticipated as floatovoltaics are an attractive alternative to building- and ground-mounted solar as they can be built at scale and mitigate increasing land use pressure, a growing concern globally (Lambin and Meyfroidt 2011, Spencer *et al* 2018). In some regions, such as Japan, land is too scarce to deploy ground-mounted solar parks. In other locations installation of floatovoltaic systems averts alternative land use revenue loss, for example an estimated $150 000 reduction in wine revenue annually at Far Niente winery (Smyth *et al* 2011). There are also system efficiency and security gains of locating solar arrays on water supply or hydroelectric power reservoirs due to the direct use of the electricity, existing grid connections and scope to improve power curves (Redón Santafé *et al* 2014, Sacramento *et al* 2015, Hoffacker *et al* 2017, Liu *et al* 2018). Finally, floatovoltaics also offer energy benefits, attributable to lower PV module temperatures when sited on water, with efficiency gains of up to 15% over ground-mounted systems reported in Brazil (Sacramento *et al* 2015), outputs of 1.3 times that of a ground-mounted system observed in South Korea (Lee *et al* 2014), and performance ratios approximately 10% higher than roof-mounted systems in Singapore (Liu *et al* 2018).

Whilst features of freshwater floatovoltaics make them very attractive compared to building- and ground-mounted systems, unknown water body impacts pose a key challenge to deployments (World Bank Group, ESMAP & SERIS 2019). Potential reductions in evaporation have been quantified for some locations (Redón Santafé *et al* 2014, Trapani and Redón Santafé 2015). However, other insights are predominantly limited to hypothesised effects, for example, the potential to manage aquatic properties through controlling nutrients, light and mixing; restoration of aquatic ecosystems through the infrastructure acting as artificial refugia; and comparison of a suite of potential environmental impacts with those imposed by ground-mounted PV systems (Redón Santafé *et al* 2014, Trapani and Redón Santafé 2015, Pringle *et al* 2017, Spencer *et al* 2018, Pimentel DA Silva and Branco 2018, World Bank Group, ESMAP & SERIS 2019). In addition, the lack of natural or anthropogenic analogues—ice and vegetation cover are seasonal and human-made platforms, such as jetties, are smaller scale and commonly within the littoral zone—limits the reliable inference of impacts from established knowledge of this pioneering water body use change. Moreover, it is likely that, for most deployments, there will be insufficient data (and resources) to be able to make detailed model predictions of water body-specific outcomes.

Implications for specific freshwater body processes, properties, ecosystem services and natural capital needs to be resolved, capturing the cascading corollaries, feedbacks and interactions throughout the aquatic system and the likely manifest impacts associated with floatovoltaic design. The lack of existing understanding, analogues and potential to model outcomes, alongside the exponential deployment rates, necessitates synthesising knowledge using theoretical understanding using an approach that incorporates uncertainties. Methodologies such as fuzzy decision trees or Bayesian belief networks offer a simple means to achieve this, framing understanding of floatovoltaic impacts, enabling insight into the likely direction and magnitude of change and, importantly, the associated confidence (Adriaenssens *et al* 2004, Uusitalo 2007). Additionally, fuzzy and Bayesian systems allow incorporation of both quantitative (e.g. observations and simulations) and qualitative (e.g. expert opinion) information to improve predictions as understanding progresses and identify priority areas for new knowledge (Adriaenssens *et al* 2004, Uusitalo 2007). Fuzzy and Bayesian approaches have been successfully applied to other environmental challenges, including watershed management decision support, developed collaboratively with the US Department of Agriculture Forest Service and Environmental Protection Agency (Jensen *et al* 2000); groundwater management that incorporated stakeholder concerns in addition to environmental factors (Alizadeh *et al* 2017); and the concurrent satisfaction of economic development, energy consumption, workforce, and GHG emission reduction goals (Jayaraman *et al* 2017).

Given the rapid deployment trajectory of freshwater floatovoltaics, the complexity of water body function and the need to manage our globally important water bodies, a means to delineate potential floatovoltaic impacts, incorporating cascades and interactions, is urgently required. Consequently, in this article we develop an effects hierarchy of floatovoltaic impacts on water bodies grounded in theoretical understanding of water body function (objective 1). We then illustrate the use of this hierarchy with examples of ecosystem process, property and service response using illustrative decision trees that are categorised into one of three typologies dependent on the certainty of outcome (objective 2). We do not attempt to exhaustively catalogue all possible ecosystem impacts of floatovoltaic deployment here, but instead to provide a conceptual framework that can be adopted to guide future studies of an increasing range of impacts. We present the effects hierarchy, decision trees and response typologies as a means to promote dialogue between environmental scientists and floatovoltaic practitioners, acting as a primer for the co-design of innovative environmentally-beneficial future deployments and identification of future research priorities to ensure the astute deployment of this emerging means of low carbon electricity generation.

2. Methods

To develop understanding of the effects of floatovoltaics on freshwater bodies (objective one), we drew on established understanding of water body physical, chemical and biological functioning (Oke 1987, Wetzel *et al* 2001, Kalff 2002). From this, we developed an effects hierarchy to provide a theoretical framework to determine the likely cascading and interactive influences of floatovoltaics on freshwater bodies. We determined some of the principal perturbations with implications for ecosystem processes, properties and services within each level in the effects hierarchy, identifying primary interactions within and between levels. Given that the causal reasoning within the effects hierarchy is underpinned by decades of global fundamental research and understanding of water body function, our framework is intended to be applicable across climate zones. We recognise that there is a context-dependency of freshwater ecosystem function, and that ecological responses are likely to vary among water bodies. However, it is our intention that the hierarchy is used as a logical construct to identify these system-specific behaviours.

By selecting specific water body processes, properties and services of concern or interest, and using the effects hierarchy, we then developed illustrative decision trees to delineate the magnitude and certainty of freshwater body process, property and ecosystem service responses (objective 2). These were categorised to represent three response typologies—*magnitude, direction*, and *uncertain*—in descending order of our confidence in predicted response, informed by the dependencies within the effects hierarchy. For the *magnitude* typology fundamental understanding of water bodies enables inference of the both the direction and magnitude of change. For the *direction* typology there is greater uncertainty, and thus whilst the direction of change could be inferred the magnitude could not. Finally, for the *uncertain* typology, it was not possible to infer direction nor magnitude given uncertainty in response, often due to feedbacks and interactions. Specifically, we selected evaporation, cyanobacterial biomass, and phosphorus release from sediment. We select these non-exhaustive examples of physical, chemical and biological changes in response to floatovoltaics, to illustrate the use of the hierarchy. Given the plethora of potential, cascading freshwater ecosystem responses to floatovoltaic deployment it is not possible to delineate every possible outcome here. However it is our intention that, by presenting illustrative examples, we will enable the wider community to apply this approach to an increasingly diverse array of potential effects. Each level in the effect hierarchy was represented in the decision trees, with the likely perturbation depicted by the shading of an arbitrary number of symbols ranging from a strong decrease to a strong increase (figure 4). To delineate the level of certainty in outcome, shading was extended across a varying number of symbols, grounded in the expertise of the authors, with higher intensity shading indicating greater confidence. Interconnections between factors, including direct and indirect effects and feedbacks, are illustrated by arrows, with the width indicating the relative importance. Other factors known to be important in determining the response, which were not central or were uncertain, are connected by dashed arrows. Given that the hierarchies explicitly depict certainty of prediction (shading), they are able to display relative certainties of effects when compared across climate zones and system types.

3. Results

3.1. Effects hierarchy of floatovoltaic on water bodies

As a primer for future research and to inform decisions using existing knowledge, we propose a freshwater floatovoltaic effects hierarchy grounded in theoretical understanding of water body function (figures 2 & 3). Specifically, we identified changes to the air-water interface (level 1) caused by the physical presence of floatovoltaics as the first order effect, with subsequent effects on surface meteorology (level 2), changes in air-water fluxes (level 3) and implications for water body physical, chemical and biological properties (level 4) (figures 2 & 3). Consequently, floatovoltaic design is pivotal, specifically all characteristics that may influence the effect of their physical presence including extent, spacing of panels, materials used, albedo and mounting system. Air-water interface variables primarily comprise air-water connectivity and surface roughness but will also encapsulate factors such as isolation of air between the water surface and PV array (figure 2). Surface meteorology effects will be dominated by shortwave radiation and wind speed and turbulence but also include any changes to other meteorological variables including air temperature and relative humidity (figure 2). Wind mixing and surface heating will commonly dominate the air-water fluxes although the exchange of gases and water vapour may also be influential (figure 2). Finally, water body properties, which may also be impacted by perturbations to processes within the bed sediment, include variables such as temperature and oxygen at various depths, light attenuation (physical); phosphorus, nitrogen and carbon dioxide concentrations, pH, contaminant bioavailability (chemical); phytoplankton, fish, invertebrate, macrophyte community composition and biomass (biological) (figure 2). Whilst the effects stem from the changes to the air-water interface and cascade down to the water body properties, interactions within and between levels are pivotal in determining ecosystem response (figure 3). In particular, the impact on the water body mixing regime is important in predicting various other water body properties, with the potential for the floatovoltaic system to reduce, increase or have no impact. Below we discuss each level in turn, highlighting the principal impacts in light of the influences on ecosystem function, reflecting on floatovoltaic design implications and linkages to other levels in the system.

3.1.1. Level 1—air-water interface

The unique impacts of floatovoltaics on the hosting water body stem from their physical presence altering the air-water interface. In light of perturbations to ecosystem function these will likely be dominated by reduced air-water connectivity which will change the surface meteorology and actively inhibit air-water fluxes. The extent of air-water connectivity reduction can be quantified with relative certainty as it will be determined by floatovoltaic extent and design, with larger arrays and those with larger footprints, such as systems mounted on continuous floats (figure 1), reducing connectivity most. Another important consideration will be changes in surface roughness, which will also modify the surface meteorology with implications for air-water fluxes. As for air-water connectivity, surface roughness changes will be dependent on floatovoltaic extent and design, although the relative change in surface roughness, and implications for processes impacted by it, will be modulated by the surface roughness of the surrounding land.

3.1.2. Level 2—surface meteorology

The implications for surface meteorological conditions will largely be driven by the reduced air-water connectivity with implications for shortwave radiation pivotal for ecosystem response given its role in warming the water, photosynthesis and photodegrading compounds (Schmid and Köster 2016, Madsen-østerbye *et al* 2018, Deng *et al* 2018). Reductions in shortwave radiation are predictable with relative confidence, as they will be proportional to the decrease in air-water connectivity. Wind will also be affected with notable implications for ecosystem processes, in particular mixing and consequent impacts on water body properties (Wang *et al* 2015, Woolway *et al* 2017, Cyr 2017). The magnitude of effect on wind will be related to the extent and design of the floatovoltaic system, but modulated by water body size and the roughness of surrounding terrain, making estimates of change less certain (Markfort *et al* 2010). Other surface meteorological variables may also be altered with less significant impacts on ecosystem processes. For example, humidity profiles could be modified and the properties of the PV panels may change the spectral distribution of the solar radiation reaching the water surface (Woolway *et al* 2015).

3.1.3. Level 3—air-water fluxes

Changes in the surface meteorological conditions will regulate heat, momentum and gas fluxes between the water and air (Woolway *et al* 2015). Resolving the perturbations to fluxes of heat and wind mixing energy, especially for those water bodies that stratify or could stratify (Woolway and Merchant 2019), is critical as together they drive the thermal dynamics of water bodies with subsequent implications for a multitude of ecosystem processes (Woolway *et al* 2017). Surface heating will be reduced by floatovoltaics in response to the reductions in shortwave radiation, leading to cooler surface water. However, insulating effects of the solar arrays could reduce outgoing fluxes (i.e. net longwave radiation and sensible and latent heat fluxes) resulting in warmer surface water compared to the situation where no array is present (as observed for soil temperatures at ground-mounted solar parks at night and during the winter (Armstrong *et al* 2016)). The change in surface heating could be estimated reasonably well for a given floatovoltaic extent and design, although the consequent changes in net longwave, sensible and latent heat fluxes will add uncertainty. Wind mixing of the water body is also likely to decline given the reduction in air-water connectivity along with lowering of the wind speed over and downwind of the floatovoltaic array in response to the increased roughness. Confidence in wind mixing predictions is somewhat lower than for surface heating given uncertainties propagated from changes in surface wind conditions, however, as mixing energy varies with the cube of the wind speed, relatively small reductions in the wind speed could have notable impacts (Wüest *et al* 2000).

3.1.4. Level 4—physical, chemical and biological properties

The next layer in the hierarchy encompasses a plethora of highly interactive physical, chemical and biological water body properties. The water body properties may be impacted by processes solely within the water body or involve interactions with the atmosphere or bed sediments. Whilst the relative importance and likely perturbations to these properties will vary with water body, the impact on the thermal regime, unless other characteristics of the water body prevent stratification, will be central in controlling the ecosystem effects. Together, changes in surface heating and wind mixing regulate the water body thermal regime by governing the occurrence, length and strength of stratification and hence mixed layer

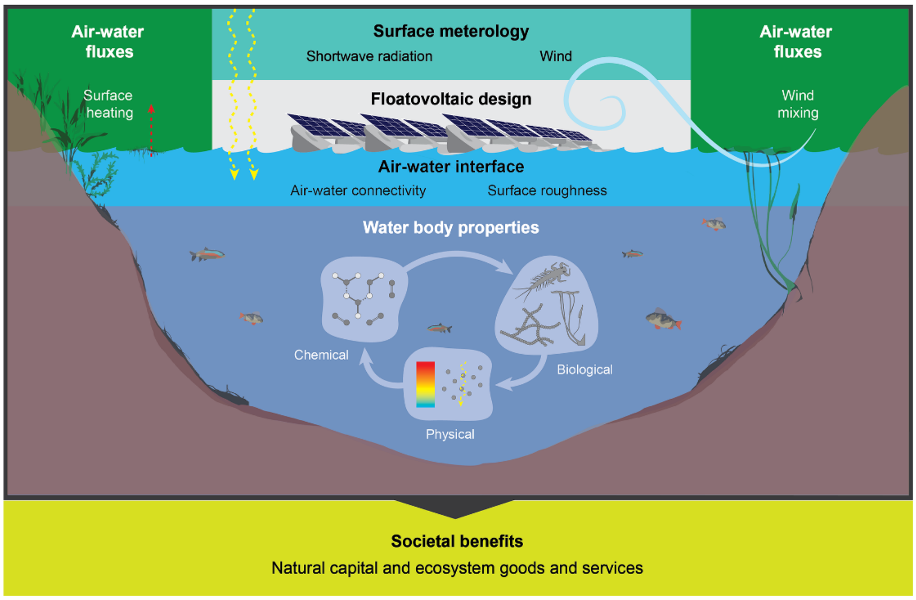

Figure 2. Graphical representation of the freshwater floatovoltaic effects hierarchy illustrating the key variables affected in each level of the effects hierarchy. A three-dimensional representation of the effects hierarchy is provided in figure 3.

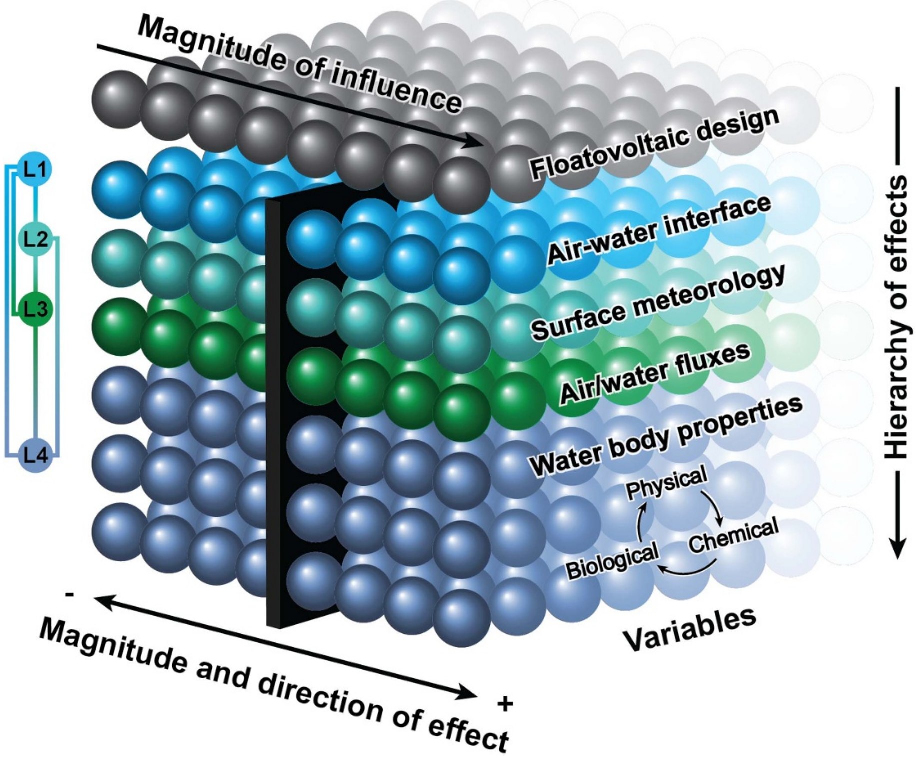

Figure 3. Conceptual three-dimensional representation of the freshwater floatovoltaic effects encapsulating each level within the effects hierarchy, depicting the cascade of effects, interactions and feedbacks stemming from the physical presence of floatovoltaics on the water body. Specifically, the x-axis represents the direction and magnitude of effect for each variable, the y-axis the level in the hierarchy and the z-axis the variables in each layer in the hierarchy. Two-dimensional expressions of the three-dimensional conceptual representation can be developed to produce decision trees for specific ecosystem processes, properties and services (figure 4).

depth dynamics (Woolway *et al* 2017). As the likely reduction in both surface heating and wind mixing leads to opposing impacts on stratification and mixed layer depth, predicting the magnitude, or even direction, of the change is difficult: decreased surface heating tends to reduce stratification strength, allowing easier mixing, whilst decreased wind mixing increases stratification (Woolway *et al* 2017). This is

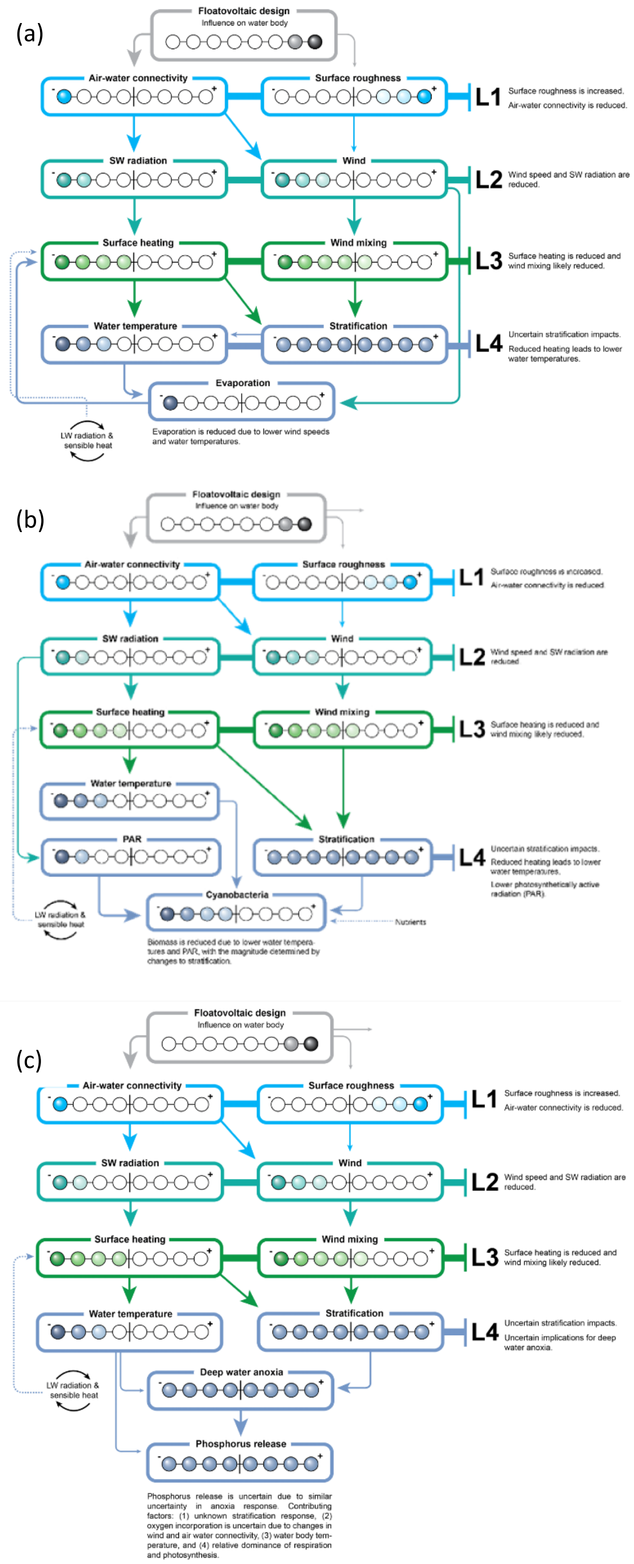

Figure 4. Illustrative fuzzy decision trees of the primary pathways of cascading and interacting effects for (a) evaporation (magnitude), (b) cyanobacterial biomass (direction), and (c) phosphorus release from bed sediments (uncertain) for a high influence freshwater floatovoltaic system. Higher shading intensity indicates a more likely effect, the extent of shading represents the certainty in response and the arrow thickness the relative importance of each of the variables. These are illustrative two-dimensional representations of the conceptual effects hierarchy (figure 2) grounded in existing knowledge of water body function responses to floatovoltaic deployment.

a major source of uncertainty when predicting the impacts of floatovoltaics given the pervasive impact of the thermal regime on most aspects of the ecosystem (O'reilly *et al* 2003, Adrian *et al* 2009, Shimoda *et al* 2011, North *et al* 2014), precluding the accurate prediction of the magnitude and direction of change in a myriad of interdependent physical, chemical and biological properties which exhibit strong depth gradients (e.g. temperature, oxygen, nutrients) with implications for habitat quality.

3.1.5. Interactions and feedbacks within and between levels

Aquatic ecosystems are renowned for their complexity, underpinned by their response to external drivers and internal interactions (Maberly and Elliott 2012). Consequently, accurate prediction of changes to water body processes, properties and implications for ecosystem services in response to floatovoltaic deployment is significantly hampered due to the interactions both within and between levels in the effects hierarchy (figure 3). For example, whilst primary productivity should decrease with cooler water, given the relationship between temperature and metabolic rates (Kremer *et al* 2017), primary production may be more strongly influenced by the reduction in photosynthetically active radiation (PAR; the solar radiation wavelengths used for photosynthesis). Moreover, the responses will vary with water body characteristics, for example implications for thermal dynamics (i.e. stratification) could be a key determinant for water body response for natural water bodies but unimportant for reservoirs with short residence times or that are mechanically mixed. Consequently, incorporation of interactions within and between levels in the effects hierarchy will be central to reliable response predictions.

3.2. Floatovoltaic effects on freshwater ecosystem processes, properties and services

Here we demonstrate how the effects hierarchy can be used to identify likely causal relationships between floatovoltaic deployment and freshwater ecosystem response, enabling predictions of potential impacts on the water body given the current state of knowledge. We classify the responses into one of three typologies—*magnitude, direction* and *uncertain*—in light of the confidence in the prediction dictated by dependencies within the effects hierarchy. Below, we provide illustrative decision trees for an example of each typology, extending across physical, chemical and biological responses, and consider the implications for ecosystem services. These are examples amongst many potential responses; producing an exhaustive outline of potential outcomes is beyond the scope of this article. It is our intention that developers, in conjunction with water body scientists, will be able to use this approach to identify further potential impacts of specific floatovoltaic deployments.

3.2.1. Magnitude response typology: evaporation

Magnitude typology responses are those that are qualitatively and quantitatively well-understood, and primarily involve perturbations to variables within the first three layers in the effects hierarchy—the air-water interface, near surface meteorology and air-water fluxes (figure 2). Impacts on the key regulating variables for water body function in these layers (i.e. air-water connectivity, surface roughness, shortwave radiation, wind, surface heating and wind mixing) can be resolved for a given water body and floatovoltaic design with high confidence, in terms of both the direction and likely magnitude of change.

A pertinent example is the reduction in evaporative water loss, which could be a driver for floatovoltaic deployments in areas of water scarcity (Medellín-azuara *et al* 2015). Evaporative water loss will be reduced given the anticipated decrease in the dominant drivers (wind speed and water temperature) largely resulting from a reduction in air-water connectivity (figure 4(a)). The accuracy with which the reduced air-water connectivity can be quantified allows relatively high confidence in the prediction that: 1) surface water temperatures will be lower as shortwave radiation receipts, and hence surface heating, will be reduced; and 2) decreased wind speeds at the water's surface will lead to reductions in evaporation (figure 4(a)). However, estimating the magnitude of effect of these primary controls is made less certain because of other confounding phenomena which are harder to estimate, thus preventing the prediction of exact evaporation rates. For example, if the water body stratifies, surface water temperature could be affected and thereby evaporation rates (Woolway *et al* 2014, 2016). Stratification is affected by both the reduction in surface wind speed and the reduction in surface heating and controls the depth to which a water body is mixed. The depth of mixing affects how heat is vertically distributed within a water body and hence surface water temperature. However, even if effects on the stratification regime are large, subsequent effects on surface water temperature and hence evaporation will likely be much smaller than those driven by the reduction in short wave radiation (figure 4(a)).

3.2.2. Direction response typology: cyanobacterial biomass

Ecosystem processes, properties and services that fall within the *direction typology* are those affected by stratification but also strongly influenced by the air-water interface, near surface meteorology, and air-water fluxes, enabling postulation of the direction of effect but precluding robust estimation of the magnitude. For example, we anticipate that cyanobacterial blooms will decline in response to floatovoltaics, even if the magnitude of this effect is highly uncertain. This is likely to be of interest given the increase of blooms with climate change and effects on water resources, recreation and health (Smith 2003, Metcalf and Codd 2009). For example, 500 000 people living near Lake Erie were advised not to drink their tap water in 2014 due to cyanobacterial blooms (Michalak 2016), and damage costs were estimated to be up to £75–114 M per year for cyanobacterial blooms in England and Wales (Pretty *et al* 2003).

Cyanobacterial growth rates increase with water temperature, up to an optimum (Reynolds 2006), and so one might argue that reductions in water temperature beneath floating solar arrays would reduce growth rates. In addition, reductions in underwater PAR availability are also likely to limit growth and production (Reynolds 2006). Since we can be relatively confident of the reduction in water temperature and PAR we hypothesise a reduction in total cyanobacterial biomass (figure 4(b)). However, there exists great uncertainty in the magnitude of this change in absolute biomass and, crucially, in the relative dominance of cyanobacteria within the wider phytoplankton community. Assertions regarding the relatively high temperature optima of cyanobacteria (Paerl and Huisman 2008) may be invoked in suggesting that these taxa would lose their competitive edge and dominance at lower temperature. However, cyanobacteria taxa vary greatly in their traits, tolerances and sensitivities (Carey *et al* 2012, Mantzouki *et al* 2016). There is much among-species variability in optimum temperatures and in the extent to which growth rate scales with temperature, such that cyanobacteria cannot be claimed to be competitively inferior at lower temperatures in any universal sense (Lürling *et al* 2013, Visser *et al* 2016). In addition, some cyanobacteria are shade tolerant by virtue of their efficiency in harvesting light and their ability to regulate buoyancy; abilities that will interact with the strength of thermal stratification (Mantzouki *et al* 2016). Therefore, whilst we hypothesise that total cyanobacterial biomass reduction is possible, compositional changes in the cyanobacterial community will introduce great uncertainty into this aggregate response. Specifically, it is possible that floatovoltaic deployment will give low temperature- and shade-adapted cyanobacteria a performance advantage, such that they could outcompete less well adapted taxa and bloom (Scheffer *et al* 1997, Soares *et al* 2013). It is clear that we need to resolve these uncertainties by monitoring cyanobacterial community dynamics in waterbodies with floating solar deployments, and conducting appropriately-scaled experiments.

3.2.3. Uncertain response typology: phosphorus release

Uncertain typology responses are generally those for which the effect of stratification is central to the response or those that culminate as a result of perturbation to several driving interactive variables and feedbacks. An example of this is the release of phosphorus (and indeed other nutrients and contaminants) from bed sediments due to the development of deep water anoxia (Mortimer 1941). Understanding the response of phosphorus concentrations, especially bioavailable phosphorus, to floatovoltaic deployment is critical as it is frequently the most growth-limiting nutrient for phytoplankton, has implications for the aquatic food web and is regulated in water supply (Vollenweider 1968).

Floatovoltaics could impact the occurrence of deep water anoxia, and thus the release of phosphorus from bed sediments, in a number of ways. The deoxygenation of bottom waters is strongly linked to prolonged stratification which separates deep waters from the surface layer where oxygen exchange with the atmosphere takes place (Foley *et al* 2012). Consequently, since the response of stratification to floatovoltaics is highly uncertain given the reduction in both wind mixing and surface heating, the direction of change in deep water anoxia, and therefore phosphorus release cannot be resolved (figure 4(c)). Moreover, uncertainty in phosphorus release is increased as although lower water temperature would enable a higher oxygen concentration, the reduction in air-water connectivity and wind speed over the water body will likely result in a decrease in oxygen flux into the water (figure 4(c)). The conditions at the sediment-water interface may also impact biological activity in the sediment with implications for water chemistry (Celo *et al* 2006). Finally, any impact on phytoplankton will affect both oxygen production via photosynthesis and deoxygenation via respiration (Xu and Xu 2016), rendering the net effect on ecosystem metabolism difficult to predict (figure 4(c)).

3.2.4. Freshwater ecosystem service response

We advocate that those considering deployment should consider and trade-off the consequences for the full range of ecosystem processes, properties and implications for ecosystem services water bodies provide (table 1). Without a considered approach one problem may simply be swapped for another and opportunities for positive impacts missed. For example, within the UK, water companies wish to reduce the occurrence of cyanobacterial blooms, especially in reservoirs used for recreation. However, they are also aware that phytoplankton responses will be species-specific and have concerns that filamentous diatoms, which perform well under cooler and darker conditions and block filters, may proliferate with implications for water treatment processes and costs (Reynolds *et al* 2002, Hoeger *et al* 2005). Moreover, while reduced evaporation, as in the *magnitude* typology example, could increase water quantity, the potential for phosphorus release from bed sediments, as in the *uncertain* typology example, to be increased prevents confident determination of the effect of floatovoltaics on water for consumptive use.

Expanding our considerations to higher trophic levels, there are potential impacts of floatovoltaics on fish communities, and thus services related to food provisioning and recreational opportunities. For example, cooler waters beneath the deployments may provide a thermal refuge for cool-water fish species, mitigating climate warming impacts (Edwards *et al* 2016). In addition, reduced solar radiation receipts may hamper visual predation (Figueiredo *et al* 2016, Ekvall *et al* 2019). Such food web effects are complex, since visual predation by planktivorous fish (on zooplankton) and on planktivorous fish (by piscivores) could be affected. Further, these impacts, if they occur, could interact with other responses such as lower oxygen contents (Zhu *et al* 2008) and reductions in primary productivity (Downing *et al* 1990).

Furthering understanding of the implications for climate regulation, a critical ecosystem service, is an important knowledge gap as water bodies are globally important processors of carbon (Butman *et al* 2016) and the ecosystem carbon impact informs the true carbon intensity (i.e. g C kWh) of the electricity and thus the decarbonising attraction of the technology. However, resolving perturbations to water body carbon cycling requires a considerable research effort. Carbon enters a water body from the catchment, or in some circumstances is drawn into the water from the atmosphere as carbon dioxide. Carbon may either be lost in the outflow, buried in the bed sediment, or be outgassed as methane or carbon dioxide. Thus, floatovoltaic deployment will alter a myriad of relevant within-water body carbon processes, ultimately making assessment of water body climate regulation challenging. For example, the net release of greenhouse gases to the atmosphere will be affected by changes to air-water connectivity, heat fluxes and wind mixing (Mammarella *et al* 2015), by changes to stratification and deoxygenation at depth (Vachon *et al* 2019), by changes to productivity and decomposition within the water body (Delsontro *et al* 2018), and by changes to ultraviolet light receipts and thus photodegradation of dissolved organic carbon (Madsen-østerbye *et al* 2018). Further, carbon cycling differs significantly between water bodies, for example the magnitude of greenhouse gas release varies by several orders of magnitude (Bastviken *et al* 2011). Consequently, to resolve the impact on climate regulation, several decision trees developed for individual ecosystem processes and properties would need to be integrated.

4. Discussion

Delineating the likely impacts of floatovoltaics for specific freshwater bodies and floatovoltaic designs is crucial to ensure that any positive ecosystem impacts are enhanced and any detrimental effects mitigated against or, at least, taken into account in the decision-making process. Our theoretically-derived effects hierarchy provides the first step towards this, providing a means to query the impact of the rapidly accelerating deployments of floatovoltaics on freshwater body function. Identification of the four levels in the effects hierarchy—air-water connectivity, surface meteorology, air-water fluxes and finally water body physical, chemical and biological properties—provides an overarching framework to interrogate the potential implications for ecosystem processes, properties and services. The illustrative decision trees for evaporation, cyanobacterial biomass and phosphorous release demonstrate a means by which floatovoltaic developers and operators, in collaboration with environmental scientists, can step-through the effects hierarchy to develop understanding of the likely outcome for specific ecosystem processes, properties or services. Ultimately their development could inform floatovoltaic deployments that safeguard critical ecosystem functions, assuring appropriate water body governance alongside the generation of much needed low carbon electricity. Moreover, the decision trees identify attributes of floatovoltaic system design and deployment that could be innovated to influence ecosystem effects. Finally, identification of the three response typologies identified knowledge 'bottle-necks', in particular effects on stratification, that prohibit confident predictions of ecological responses, and thus can guide future research efforts.

Our effects hierarchy and resulting decision trees provide an approach for understanding the consequences of floatovoltaics on freshwater ecosystems. Given the infancy of scientific inquiry into this novel use of water surfaces, there is currently insufficient knowledge to determine which water bodies are most suitable for deployment, what floatovoltaic designs are optimal, or which ecosystems properties are likely to be affected. Consequently, further collaborative research and innovation is required and the understanding developed should be embedded in floatovoltaic design and deployment. Given the interdependence between the floatovoltaic system and the ecosystem, ideally the portfolio of research and innovation should be co-developed between engineering and environmental researchers, the floatovoltaic industry and other relevant stakeholders such as water companies and environmental organisations using methods proven successful for water body management (Bell *et al* 2013, BRE 2014a, 2014b, SolarPower Europ 2019, World Bank Group, ESMAP & SERIS 2019). Below we present collaborative research priorities and design and deployment innovations that may maximise positive impacts of this emerging source of low carbon electricity.

4.1. Research priorities

Given the uncertainty revealed through the effects hierarchy and illustrative decision trees, further research is urgently required to ensure other SDGs, ecosystem services and natural capital are not foregone in the pursuit of low carbon energy. Collaborative research intensity is required to develop the required understanding, using environmental science expertise to better resolve the magnitude and direction of likely ecosystem effects and incorporating floatovoltaic developer and operator expertise to optimise design and deployment decisions. Consequently, we recommend four themes of collaborative research priorities: field research, modelling, floatovoltaic innovations and informing best practice. In addition, the holistic environmental, economic and energy security implications of floatovoltaics should be contextualised with alternative means of electricity generation both now and under climate change scenarios.

4.1.1. Field research

There are currently very few data sets that quantify the impacts of floatovoltaics. Embedding targeted water body monitoring systems and strategies into the design and operation of floatovoltaic systems would generate invaluable data to better resolve impacts across water body types and floatovoltaic designs, as well as alerting operators and water body managers to any potential impacts (e.g. anoxia of bottom waters) (Crawford *et al* 2015). Moreover, the close-working required will promote codeveloped research that is both scientifically robust and valuable to industry practices. In particular, known key drivers of water body function should be monitored, including PAR receipts, temperature, dissolved oxygen, nutrient concentrations and chlorophyll-a throughout the water profile both under and away from the floating solar array using logging devices. In addition, campaign sampling of phytoplankton composition, zooplankton and fish would be valuable. Ideally pre-deployment data collection should be undertaken, although the practicalities of deployment may inhibit this.

4.1.2. Modelling

The development of modelling capabilities to explore the impacts of floatovoltaics across water body types and floatovoltaic designs is pivotal given the financial and time costs of field research. This modelling should incorporate a range of approaches from detailed two and three-dimensional mechanistic models (e.g. Delft3D (Dissanayake *et al* 2019)) to explore impacts on water body processes in detail to more simplified one-dimensional process-based models (e.g. MyLake (Saloranta and Andersen 2007)) that are computationally more efficient thus enable exploration of model sensitivities and uncertainties along with multiple modelling scenarios and, finally, fuzzy classification approaches outlined here given the rapid insight they provide (Saloranta and Andersen 2007, Bocaniov and Scavia 2016). Data collection from a wide range of water bodies with floatovoltaic systems as suggested above, as well as data routinely collected before and after floatovoltaic instalment for some water bodies (i.e. UK water supply reservoirs), will be invaluable for constraining the models.

4.1.3. Floatovoltaic innovations

Given the potential for flexibility in the design and deployment of floatovoltaics, there may be considerable opportunity to innovate floatovoltaics to enhance critical ecosystem services and SDGs beyond outcomes related to affordable and clean energy. Our effects hierarchy highlights that the impacts primarily stem from the effect of floatovoltaics on air-water connectivity, with some potential effects from perturbations to water surface roughness. Consequently, collaborative research on the means by which floatovoltaic design could be manipulated to promote positive ecosystem impacts is required. For example, floatovoltaics could be designed to meet a desirable level of air-water connectivity and the percentage cover of the water body, spacing between PV panel rows, and pattern of PV panels (i.e. a continuous raft or checkerboard of smaller rafts), could all be altered to manipulate impacts. In addition to the overall design, the materials used could be selected to alter response. For example, both the amount and quality of shortwave radiation reaching the water surface could be manipulated by altering the spectral properties of the PV panels to influence water body processes (Traverse *et al* 2017): PAR could be attenuated to reduce productivity rates, and UV transmittance maximised to increase the photodegradation of dissolved organic carbon and contaminants (Alvarez *et al* 2005).

4.1.4. Underpinning best practice

To use the field, modelling and innovation knowledge produced to promote judicious decisions, best practice guidelines focussed on water body impacts, as produced for ground-mount solar parks (BRE 2014a, 2014b), and included in broader floatovoltaic guidelines (World Bank Group, ESMAP & SERIS 2019) should be collaboratively developed. Whilst understanding impacts of floatovoltaics on ecosystem properties and processes is key, to inform decisions it will be essential to quantify the effects on ecosystem services and natural capital. In particular, highlighting potential design and operation decisions that promote positive synergies and reduce trade-offs for individual water bodies and potentially informing hosting water body selection. Taking such a techno-ecological synergy approach to floatovoltaic innovation will lead to both energy system and ecological benefits, improving the overall sustainability of rapidly accelerating means of low carbon electricity generation (Hernandez *et al* 2019). For example, deploying in areas of water shortage could reduce evaporative loss and thus increase water availability. Furthermore, the location of the floatovoltaic array on the water body could be chosen for a specific benefit. For example, using the physical structure to minimise the movement of algal blooms to recreational areas or towards the water intake.

5. Conclusion

Floatovoltaics are showing signs of being the next global renewable energy phenomenon, with increasing capacities and installations across Europe, North America, South America and Asia. Understanding of the impacts on freshwater body properties and processes is poorly resolved, despite the critical role of water bodies in the supply of ecosystem services upon which society relies. Universally predicting the impacts of floatovoltaics on ecosystem properties, processes and service provision is prohibited by the complexity of water body function alongside complications associated with different floatovoltaic designs and water body characteristics. Synthesis of theoretical understanding through a decision tree approach can inform freshwater floatovoltaic deployments that seek to minimise detrimental effects and maximise ecosystem co-benefits through innovative system designs and informed siting decisions as well as resolving where uncertainties prevail and risks remain. Ultimately, researchers across disciplines, industry and regulators that co-develop information and innovations may support more judicious floatovoltaic deployment with positive implications for ecosystem services and natural capital beyond those associated with low carbon electricity supply.

Data availability statement

No new data were created or analysed in this study.

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