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Review

Measuring renewables' impact on biosphere integrity: A review

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ABSTRACT

This study reviews 285 full-text articles on renewable energy's impact on biosphere integrity, and group them according to how biosphere integrity is defined and measured in three broad approaches: biodiversity (i.e., the richness and abundance of species), topography (i.e., land use patterns and fragmentation) and productivity (i.e., nature's provision of ecological services). The resulting typology for renewable energy's impacts on biosphere integrity enables this study to examine the literature in a systematic way and suggest directions for future research. It has been shown that the number of such studies has escalated in recent years, and the studies cover a representative coverage of renewable energy technologies; yet 80 per cent of these studies are conducted in Asia, Europe, and North America, leaving other regions underexplored. Categorizing the 285 articles according to the typology, this study find that the focus is to a greater extent on the effects on the richness and abundance of species (50 per cent), followed by the effects on land use patterns and fragmentation (35 per cent) and nature's provision of ecological services (15 per cent). Moreover, although specific technologies seem to require specific biosphere integrity indicators, there is a tendency that studies of renewable energies as a group use generic indicators like ecological footprint. This study ends by discussing the need for proxy indicators for each of the three categories (biodiversity, topography, productivity) to better examine the complexity and interactions of ecosystems. Finally, this study discusses the implication for future development and use of biosphere integrity.

1. Introduction

The aim of this article is to review how and to what extent the research literature on renewable energy has studied and quantified impacts on the environment. By "literature on renewable energy" this study refers to peer review articles of technologies or projects concerning the production, or consumption of one or more renewable energy sources (hereafter only renewables). By "impacts on the environment" this study refers to loss of biosphere integrity as suggested by the planetary boundary approach.

There are three reasons why this aim is important. First, the UN sustainable development goal (SDG) no. 7 calls for a substantial increase of the share of renewable energy in the global energy mix (e.g., UN General Assembly, 2015). Second, renewable energy inevitably demands large areas, which subsequently leads to loss of biosphere integrity (IPBES, 2019). Consequently, there will be more loss of biosphere integrity through change of land use patterns and fragmentation. Third, there is a need to identify potential indicators to know when renewable energy projects critically impact biosphere integrity (Oparaocha et al., 2022). Presently, according to the UN, there is a knowledge gap on what indicators are used in the research literature. This review contributes to filling that gap.

According to the planetary boundary approach, the planet faces two core planetary boundaries: loss of biosphere integrity and climate change (Rockström et al., 2009; Steffen et al., 2015). Each of these core boundaries has 'the potential on its own to drive the Earth system into a new state should they be substantially and persistently transgressed' (Steffen et al., 2015, p. 1). Renewable energy's impact on climate change has been studied extensively by the research community since the first IPCC report was launched in 1990 (e.g., Olabi and Abdelkareem, 2022; Owusu and Asumadu-Sarkodie, 2016). It is uncertain how and to which extent renewable energy's impacts on biosphere integrity has received similar attention. This review aims to provide additional insight into this matter.

Having said this, this study acknowledges that these two core boundaries (corresponds to SDG 13 for climate change and the SDGs 14/15 for biosphere integrity) are equally important and moreover, interlinked. Thus, both need to be addressed simultaneously so that addressing one boundary must not lead to negative consequences for the other.

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Three key approaches to biosphere integrity stand out in the literature (Holden et al., 2018, p. 160). The first approach is connected to the biosphere's productivity, that is, nature's provision of services. The best known example is the ecological footprint which uses consumption as its starting point, and translates it into the land and sea area required to produce the consumed goods and absorb the resulting waste (e.g., Wackernagel and Rees, 1996). The second approach relates to the Earth's biodiversity, that is, the richness and abundance of species. One example of this approach is to focus on threatened regions that are of high endemic importance, that is, biodiversity hotspots (e.g., Myers et al., 2000). The third approach links to topography, that is, land use patterns and fragmentation. The idea is that reduction in protected areas and fragmentation of such areas is the single greatest threat against biosphere integrity (e.g., Wilson, 2016).

Although being an immaturely studied area, there are some notable literature reviews on renewable energy's impacts on biosphere integrity (Gasparatos et al., 2017; Gibson et al., 2017; Jager et al., 2021; McCollum et al., 2018). These four reviews all address important aspect of the relation between renewable energy and biosphere integrity. However, they review interlinkages, impacts, drivers, and mechanisms involved in renewable energy's nature impacts and do not review and identify specific indicators.

Two other reviews focus on indicators. Dorning et al. (2019) review indicators for comparing environmental effects across energy sources and technologies, including renewables. Thus, in contrast to the reviews above, it explicitly addresses the way such effects are identified and measured using indicators. They review 179 papers that describe or apply energy indicators to compare environmental effects of different energy sources, and additionally includes indicators measuring social and economic aspects where these are found in their sample of literature. They find 37 unique types of environmental indicators that are used for comparing renewables. In addition, the authors provide the number of unique indicators used for each indicator type, and calculate a diversity index, indicating the variability of indicator use for measuring the same type of environmental impacts across their review sample.

Gunnarsdottir et al. (2020) review indicators for sustainable energy development. Thus, they take a broader perspective than Dorning et al. (2019), examining not only environmental effects across renewables, but also effects on other SDGs. They start by identifying the characteristics of a comprehensive and robust indicator set and use these characteristics to develop six assessment criteria: transparency of indicator selection and indicator application, conceptual framework, representative, linkages, and stakeholder engagement. They find a total of 57 indicator sets that monitor progress towards sustainable energy development or some aspects of it, and based on their evaluation criteria recommend the indicator set *Energy Indicators for Sustainable Development (EISD)* developed by multiple international organizations (International Atomic Energy Agency et al., 2005).

This review builds on and extends these reviews but differs in four respects. First, this study focuses on studies that address biosphere integrity only. Second, this study places more emphasis on the review methodology for searching, screening, and extracting data from the literature. Third, this study has a larger literature sample, including 285 articles published up to March 2022. Fourth, this study develops a typology for categorizing the indicator usage into three key approaches, depicting which aspects of biosphere integrity that are studied.

Thus, the specific research questions in this article are:

- How do studies of renewable energy's impact on biosphere integrity vary across time, geography, renewables, and biosphere integrity approaches? (Sections 3.1–3.2).
- Which impact categories and specific indicators have been used to measure impacts on biosphere integrity across renewables? (Section 3.3–3.4).

The rest of this article is organized as follows.

In section 2, this study presents the methodology. In section 3, this study presents the results from the review. In section 4 this study concludes.

2. Methodology

This study have reviewed the literature using a rapid review approach (Garritty et al., 2021), which consists of six steps: (i) defining the review question and search query, (ii) searching for literature, (iii) screening the title and abstracts, (iv) screening the full texts of articles, (v) extracting data from the final sample of articles, and (vi) analyse the extracted data from each study.

Hamel et al. (2021, p. 80) defines rapid review as a knowledge synthesis methodology, accelerating the process of a traditional systematic review by limiting some parts of the review process. The limitations are decided by the authors of this study. Following the guidance on rapid reviews, this study has delimited the scope of this review in five ways. First, this study has limited the literature search to one database for peer-reviewed articles. This study has considered the articles that resulted from the final search query. This study has not included grey literature or supplemental searching. Second, this study has limited the title and abstract screening to 20 % parallel screening by the 1st and 2nd authors, while the remaining 80 % have been screened by the 1st author. In cases where the 1st author was unsure about inclusion, the 2nd author was consulted. Third, the 1st author has screened 100 % of the full texts. In cases where the 1st author was unsure about inclusion, the 2nd author was consulted. Fourth, the 1st author extracted the data in accordance with the data extraction form that all authors defined in collaboration. In cases where the 1st author was unsure about data extraction, the 2nd author was consulted. Fifth, critical appraisal of the included articles has not been conducted. Critical appraisal has been deemed less relevant, since this study does not aim to provide an assessment of how renewable energy impacts biosphere integrity, but rather describe how these impacts have been measured in the literature sample.

2.1. Step 1: Defining the review question and search query

The three key concepts in the research question which shape the search query are renewable energy, biosphere integrity, and indicator. Renewable energy includes solar, hydro, bio, wind, geothermal, wave, tidal, and aggregated. By aggregated this study means studies using aggregated measurements on renewables, for example measurements on the total amount of renewable energy generation or share of renewable energy in total primary energy consumption. Biosphere integrity includes productivity, biodiversity, and topography approaches. Indicator includes indicator, index, indices, and metric. Documentation of the search query development is provided in the supplementary materials.

2.2. Step 2: Searching for literature

This study limited the search to be done in the literature database Scopus, only including document types categorized as article or review, and categorized with English as language. The search topics were combined into multiple different search queries, using operators made available by Scopus for making more concise searches in accordance with the scope of this review. Through an iterative process of examining the results from searches and feedback between the authors and a consulted literature searching expert at the authors' institution library, the individual search queries and the resulting combinations were refined. Final search query is presented in the following paragraph:

TITLE-ABS-KEY (((renewable OR green OR sustainable OR wind OR solar OR bio OR hydro OR water OR tidal OR geotherm* OR biomass) PRE/0 (energ* OR power OR electric*)) OR hydropower OR windpower OR solarpower OR hydroelectric* OR bioenergy) AND TITLE-

ABS-KEY ((nature OR biodivers* OR biospher* OR ecolog* OR ecosyst* OR land) W/15 (index* OR indicator* OR indice* OR metric*)) AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "re")) AND (LIMIT-TO (LANGUAGE,"English")).

The final search was conducted in Scopus on March 9th, 2022, with 932 resulting publications (records) after duplicate removal. See supplementary materials for access to the search results and documentation of developing the search query.

Search results were uploaded using CADIMA (Kohl et al., 2018). This study used the built-in functionality of detecting and removing duplicate articles,[1] resulting in 932 publications to be screened by their titles and abstracts.

Before the screening process, a consistency check was conducted on 20 publications, where the 1st and 2nd authors independently classified the same randomly selected sample of articles to uncover conflicting understanding of the criteria, and/or the need to either add more criteria or refine the existing criteria. After reviewing the random sample, CADIMA calculated the Kappa-value, which is a measurement on inter reviewer agreement, to be 0,32. The resulting Kappa-value indicated some flaws in the mutual understanding of the criteria. Therefore, 1st and 2nd authors reviewed the classifications together and adjusted the criteria to better fit the scope of this article, and the mutual understanding of these criteria.

Before continuing, addressing some important choices regarding the final search query used for providing the literature sample are in order. In the final search query, this study chose to drop the word "environment". The reason behind this choice is that "environment" are very often used for depicting greenhouse gas emissions, which fall outside the scope of this review. While this study has focused on including a variation of search words that adequately captures the literature on biosphere integrity impacts from renewable energy, there is a risk that relevant literature has been excluded from the search result. A different search query would likely provide a different literature result. This study has worked systematically to both include a high share of relevant literature according to the review criteria, while also limiting the amount of results, adhering to the rapid review methodology of a time and resource efficient review process. See supplementary materials for documentation on how the search query was developed.

Fig. 1 shows a flowchart documenting the screening process.

2.3. Step 3: Screening the titles and abstracts

The screening of the 932 publications was conducted by the 1st and 2nd authors. Each title and abstract were evaluated against two selection criteria: (i) Extraction or utilization of renewables as main subject and (ii) Indicator for quantifying impacts on nature. For articles to continue from the title and abstract stage to full text-stage, they had to be categorized as "yes" or "unclear" on both criteria. If either of the criteria were set to "no", the article was excluded. This process resulted in exclusion of 455 articles. Data containing excluded and included publications are provided in the supplementary materials.

2.4. Step 4: Screening the full texts

The 477 publications deemed as relevant after screening the titles and abstracts were then screened by their full text by the 1st author. In addition to the selection criteria described above, exclusion was made if the full text was not available through the authors' affiliated institution literature access agreements, not written in English, the publication was evaluated to be a duplication of another publication already included in the review, or the publication did not provide any data on the indicator (s) being used to quantify impacts on nature. After the full text screening, the final sample consisted of 285 full-text publications.

In the literature sample of included full text publications, the 5 journals with the highest number of publications are *Ecological Indicators* (n = 28), *Journal of Cleaner Production* (11), *Science of the Total Environment* (10), *Environmental Science and Pollution Research* (9), and *Sustainability* (8).

In the following sections this study use "number of studies", which not necessarily aligns with the number of publications. The number of studies in the figures vary depending on the data which have been the basis of the figures presented. This is a consequence of the data extraction, where multiple renewables may have been studied in the same publications, in addition to including multiple biosphere integrity approaches. These potential combinations of renewables and biosphere integrity approaches, result in multiple studies registered on the same publication, delimited by a semicolon. Code for converting the dataset from publications to studies per row are provided in the supplementary materials.

2.5. Step 5: Extracting data from the final sample of publications

During the extraction, this study categorized articles according to their year of publication, geographical study area, renewables, and biosphere integrity approach. The biosphere integrity approaches were further specified into multiple impact categories and specific indicators. This study used a combination of 'theoretical' and "inductive" thematic analysis during the data extraction (Braun and Clarke, 2006). The three main biosphere integrity approaches were theoretically given from the research questions, whereas the impact categories and specific indicators emerged inductively during the extraction of data in form of an open coding (Maguire and Delahunt, 2017). Taken together, the thematic analysis results in a typology for renewable energy's impacts on biosphere integrity. A copy of the data extraction form is provided in the supplementary materials.

Data extraction was done using the Covidence systematic review software (2022). This process involved exporting the included full-texts from CADIMA as a single RIS-file and importing it into Covidence. Around 75 % of the article full texts were manually uploaded into Covidence, using the files retrieved from CADIMA. The final 25 % were retrieved by Covidence using its automatic full-text import functionality (version 2.0).

Note that the term "footprint" is often used interchangeably with land-use. This study has been aware of this issue during data extraction. However, there exist a risk for misinterpreting the naming used on the studied indicators and their meaning in the reviewed studies.

2.6. Data handling

All data handling and analysis were performed using the R Statistical Software, R version 4.2.2 (R Core Team, 2022), using packages provided by the Tidyverse (Wickham, 2022). All figures have been created using the ggplot2 package (Wickham et al., 2022).

2.7. Limitations of the study

The included 285 articles are a result of the specified search query. Inevitably, relevant articles – some important – will be missing from the search. This study has, however, not performed an additional "snowball search" to complement the query. Although such additional search would have included more articles, it would not – this study argues – changed the trends, shares, and typology presented in Figs. 2-5, which were the main concern.

[1] Note that the high number of duplicate publications is a result of a technical limitation of CADIMA. The originally uploaded search query only contained publications classified as articles. After a discussion, the authors decided to include reviews. Deleting the first search result was not possible, so the authors conducted the final search including both articles and reviews, uploaded this result to CAIMDA, and used CADIMA to remove the duplicate publications already included in the original search result.

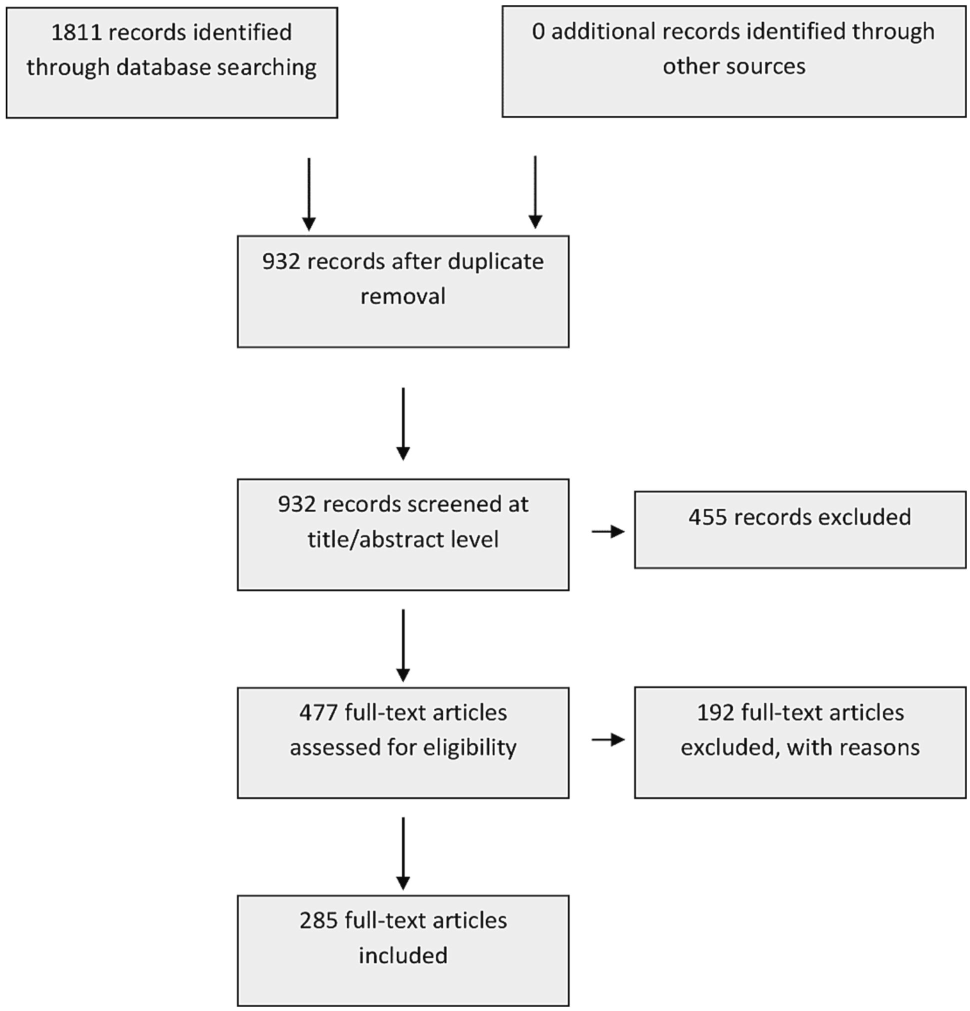

Fig. 1. Flow chart of the screening process.

3. Results and discussions

This study presents the results from the review in five parts. The first part shows the increase in studies over time and what geographical areas/regions these studies cover. The second part shows how studies vary across (i) renewables and (ii) biosphere integrity approaches. The third part shows how studies of renewable energy vary across biosphere integrity approaches typology. The fourth part presents a typology for renewable energy's impacts on biosphere integrity, which includes impact categories and examples on specific indicators. The fifth part elaborates on the specific indicators used by the different renewables.

3.1. Year of publication and geographical orientation

Fig. 2a shows a remarkable absence of studies before 2008. From 2008 onwards the number of studies increases steadily with a particularly strong increase from 2020. Thus, it took almost two decades before the renewable energy research environment responded on the challenge raised by the 1992 Convention on Biological Diversity launched at the United Nations Conference on Environment and Development (the Rio "Earth Summit"). Note the bar for 2022 only includes publications until March 9th, 2022, and should not be interpreted as a change in the yearly publication trend.

It is worth noting that the historical development of publications seems to have three "peaks" (Fig. 2a). The first peak coincides with the UN initiated Millennium Ecosystem Assessment (MEA), launched in 2005. The MEA raised serious concern over increased ecosystem degradation and biodiversity losses (Millennium Ecosystem Assessment (Program), 2005). The second peak coincides with the 2012 United Nations Conference on Sustainable Development ("Rio + 20"), which commissioned the sustainable development goals (UN General Assembly, 2012). The third peak coincides with the Global Assessment Report on Biodiversity and Ecosystem Services launched in 2019 by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES, 2019).

It is reasonable to assume that these three events spurred attention also in the global research environments. Hence, a plausible, yet speculative, explanation is that peaks in the literature are triggered by these high-level, scientific-political events.

Fig. 2b shows that the majority of studies focuses on renewable energy in Asia and Europe, followed by Northern America, Latin America and the Caribbean, and Africa. This coincides with the distribution of renewable energy generation worldwide (BP, 2022; IRENA, 2022). Few studies have a generic (no geographical focus) or global (includes all countries). Thus, the literature on renewable energy's impact on biosphere integrity is dominated by a country/regional focus rather than being generic in nature.

3.2. Renewables and main biosphere integrity approaches over time

Fig. 3a shows the trends of studies in this study sample per renewables per year, excluding geothermal and wave/tidal energy. Hydro power is the most studied renewable energy technology with a total of 137 studies, followed by bio energy (n = 79), wind energy (n = 59), solar

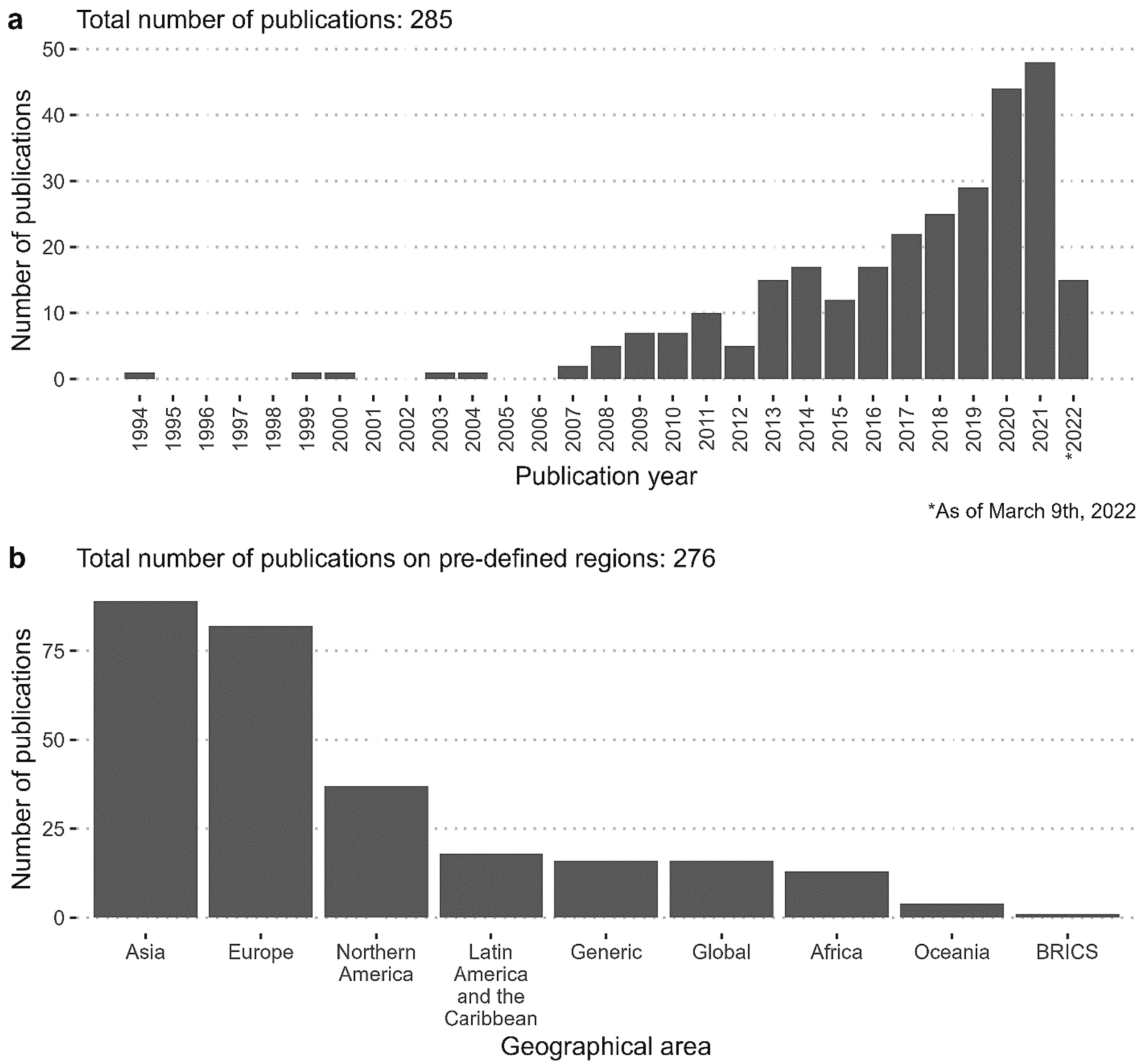

Fig. 2. Number of publications published per year (a) and number of publications per studied pre-defined region (b).

energy (n = 38), renewable energy aggregated (n = 22), wave/tidal energy (n = 11), and geothermal energy (n = 9). This order coincides well with the *ranking* of renewable energy generation by source globally (IEA, 2021). The reviewed studies hardly include traditional bioenergy, and when excluding traditional bio energy, hydropower is by far the largest modern renewable source followed by wind, solar and other renewables (the category "other" includes geothermal, biomass, waste, wave and tidal) (Ritchie et al., 2022).

Yet, this study sample has a relatively high share of bioenergy studies compared with the share of modern bioenergy in the global energy mix (20 per cent versus 10 per cent). This study sample also has a slightly higher share of wave/tidal and geothermal energy studies compared with the share of these technologies in the global energy mix (3 per cent versus 1,5 per cent). Taken together, however, the sample seems representative.

Fig. 3a shows that while the number of studies on hydro power has increased over time, there has been a more recent surge in the number of wind energy, solar energy and aggregated renewable energy studies. This indicates an increased attention on assessing the impact of modern renewable energy technologies on biosphere integrity. There are no significant changes in the number of wave, tidal and geothermal energy studies.

Fig. 3b shows the number of studies in this study sample per biosphere integrity approach per year. Three important findings stand out. First, the number of studies has grown considerably for all three approaches. For example, the number of studies on biodiversity has increased from two in 2007 to more than 30 in 15 years. Second, slightly more than 50 per cent of the studies focus on biodiversity, followed by topography (35 per cent) and productivity (15 per cent). Thus, the majority of these studies examines the impacts on the richness and abundance of species, followed by the impacts on land use patterns and fragmentation and finally the impact on nature's provision of ecological services. Third, the increase in the number of studies that focuses on biosphere integrity impacts has been particularly strong over the last

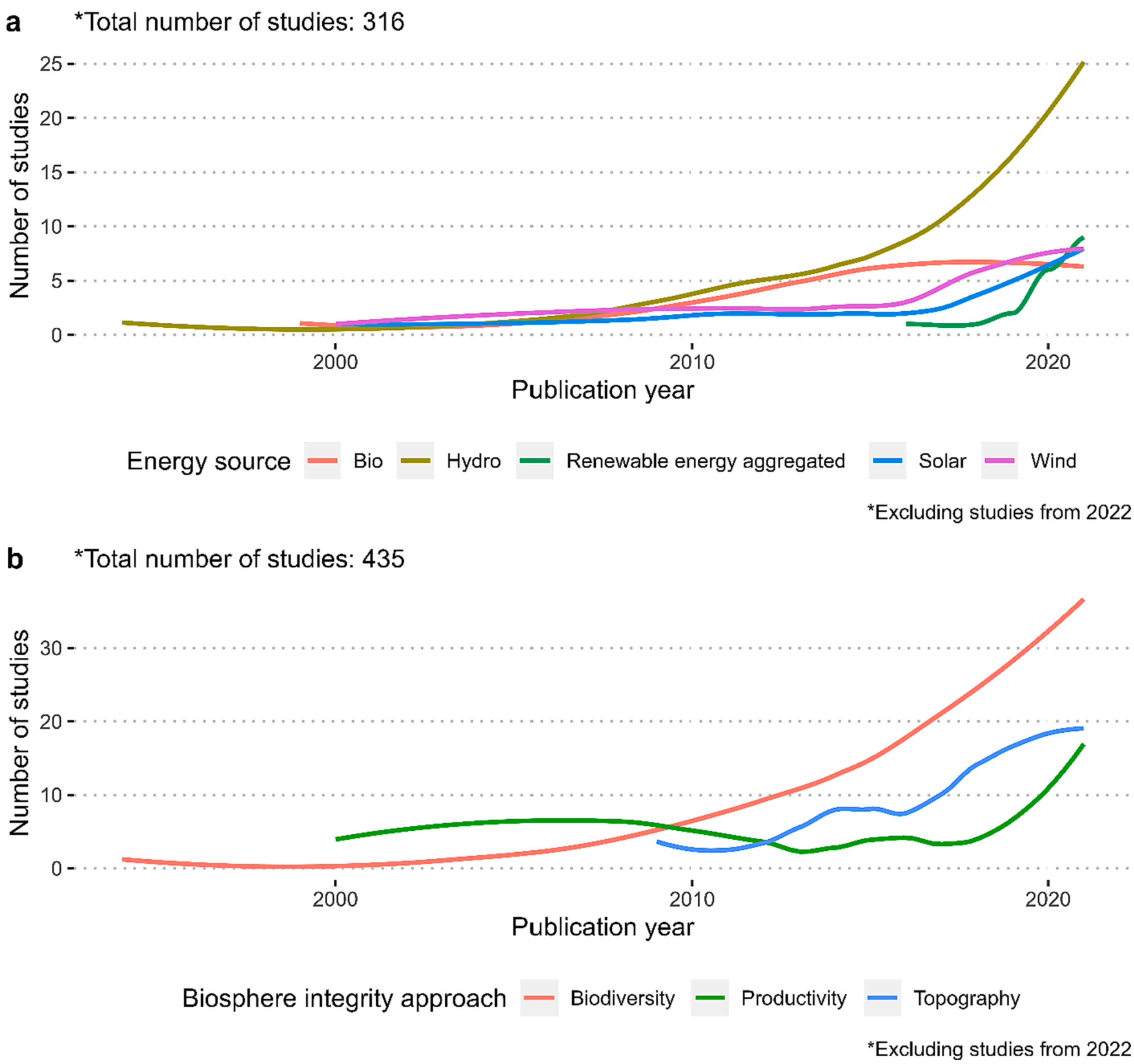

Fig. 3. Trends in number of studies conducted per renewables per year (a) and per biosphere integrity approach (b).

few years. A plausible explanation for this interest is the global attention raised by the 2019 IPBES report (IPBES, 2019).

The overall trend is that research on renewable energy projects and technologies pay increasing attention towards their effects on biosphere integrity. The reviewed studies from 2022 (up to March) show no attenuation of this trend.

3.3. Biosphere integrity approaches across renewables

Fig. 4 shows the use of the three main biosphere integrity approaches across renewables. The biodiversity approach is the most popular, and the share of studies using this approach is close to or well above 50 per cent for most renewables. This implies a trend where renewables' impact on individual species and ecosystems receives most attention. This trend is particularly strong for hydro power where almost 75 per cent of the studies focuses on biodiversity.

There are two exemptions from this trend though. First, the main parts of the studies on solar energy have focused on conditions related to topography, that is, land use patterns and fragmentation. In parallel with the strong increase in solar energy globally, there has been a growing recognition that solar energy requires large areas. This recognition also applies to wind power and bioenergy, but to a lesser extent to water, tidal and wave power.

Second, nearly all studies on aggregated renewable energy use the productivity approach. This contrasts with studies of specific renewable energy technologies that seldom use this approach. Thus, while general studies of how renewable energies prefer the use of productivity indicators, studies of a *particular* renewable energy source open up for indicators measuring biodiversity and topography.

3.4. A typology for renewable energy's impacts on biosphere integrity

This study uses inductive thematic analysis to identify impact categories used in the analyses, and then allocate these and the corresponding indicators to the three broad biosphere integrity approaches defined initially. The resulting typology for renewable energy's impacts on biosphere integrity is presented in Fig. 5.

3.4.1. The biodiversity approach

Species means studies assessing the impacts from renewable energy on specific species (e.g., Fernandes and de Souza, 2018; Illyová et al., 2017; Palmeirim et al., 2017; Sutela et al., 2013; Tourinho et al., 2020; Zhang et al., 2018). Some of the studies are mainly focusing only on impacts on the selected species, while others are using impacts on selected species as measurements on the ecosystem the species are a part of, i.e., as indicator species.

Ecosystems means studies assessing impacts from renewable energy on a collection of species and their habitat, or on a collection of species

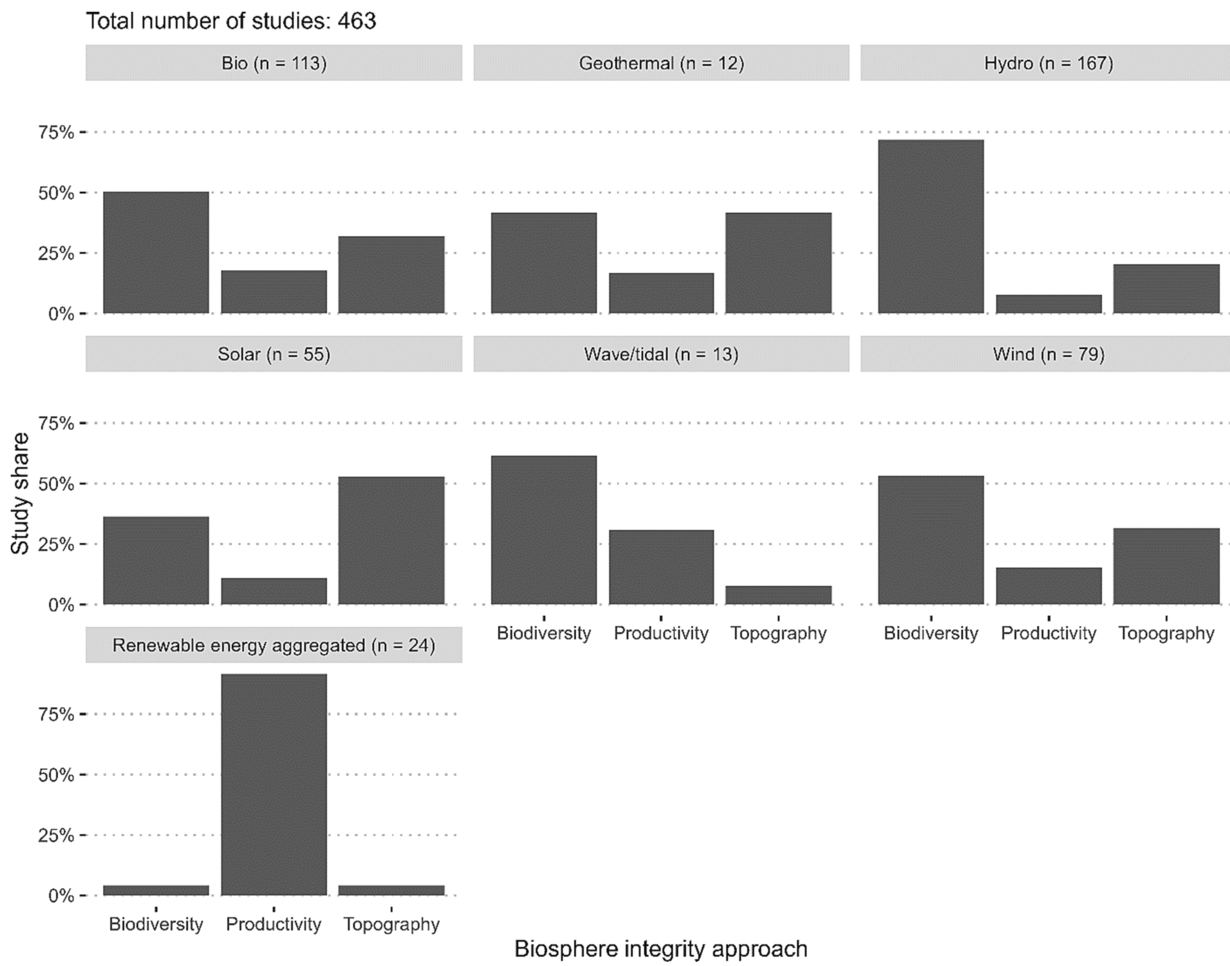

Fig. 4. Share of biosphere integrity approaches across renewables. Per cent.

constituting a community (e.g., Oliveira et al., 2019; Pan et al., 2013; Quadroni et al., 2017; Santos et al., 2010). This study use of ecosystem applies if a study is focusing on a systemic impact, with a wider scope than only individual species.

Environmental quality means studies measuring pollution or alterations of living conditions which are expected to affect the studied environment (Amor et al., 2010; Fajardy et al., 2018; Haas et al., 2014; Nukazawa et al., 2020; e.g., Wang et al., 2022). Example of studies in this study sample are studies analysing measurements of heavy metals concentrations in water streams or reservoirs connected to hydropower plants, and studies measuring hydrological alterations because of hydropower production.

3.4.2. The productivity approach

Footprints means studies translating consumption of resources into the need for land, carbon sequestration and/or water usage to provide the resources needed to fulfil the specified consumption or production. These measurements are usually referred to as ecological- and/or water footprints (e.g., Alfalih and Hadj, 2022; Altıntaş and Kassouri, 2020; Koseoglu et al., 2022; Pata, 2021; Pata et al., 2021; Wackernagel and Rees, 1996).

Ecological services mean studies quantifying the resources and regulating services that nature provides to humans. By studying the potential consequences of renewable energy development on the ecological services, this analysis can uncover potential costs measured in monetary values, which can further aid in a cost-benefit analysis (e.g., Liang et al., 2016; Pittock et al., 2017; Souter et al., 2020; Wang et al., 2010).

3.4.3. The topographic approach

Land use efficiency means studies on land use from renewable energy generation. These measurements are usually denominated as the amount of energy produced per unit of area (e.g., Bonamente et al., 2015; de Faria and Jaramillo, 2017; Laha and Chakraborty, 2021; Nasouri and Delgarm, 2022; Nock and Baker, 2019; Popescu et al., 2020). Exactly how land use is defined varies across studies, where some account for the physical area the infrastructure covers, while others include the regulated energy production area.

Land use suitability means studies assessing landscape indicators relevant for the placement of renewable energy infrastructure (Li, 2018; Naseri et al., 2021; Nguyen et al., 2021; Omitaomu et al., 2015; Rösch et al., 2013). For example, instead of quantifying the impacts on land use, these studies incorporate indicators that are relevant when estimating the potential for renewable energy generation in a particular location. These types of studies are usually at the border of this review scope, since these suitability considerations usually are focusing more on practical aspects of placement, like slope of the mounting surface for solar PV-panels, or avoidance of farmland to avoid expropriation. This study has not included studies that only have evaluated land-use effects on visual properties (scenic effects).

3.5. Impact categories and specific indicators across renewables

Fig. 4 shows how biosphere integrity approaches vary across renewables. Fig. 5 shows that each approach contains several impact categories and gives examples of specific indicators. In this section this study elaborates on impact categories and specific indicators used for

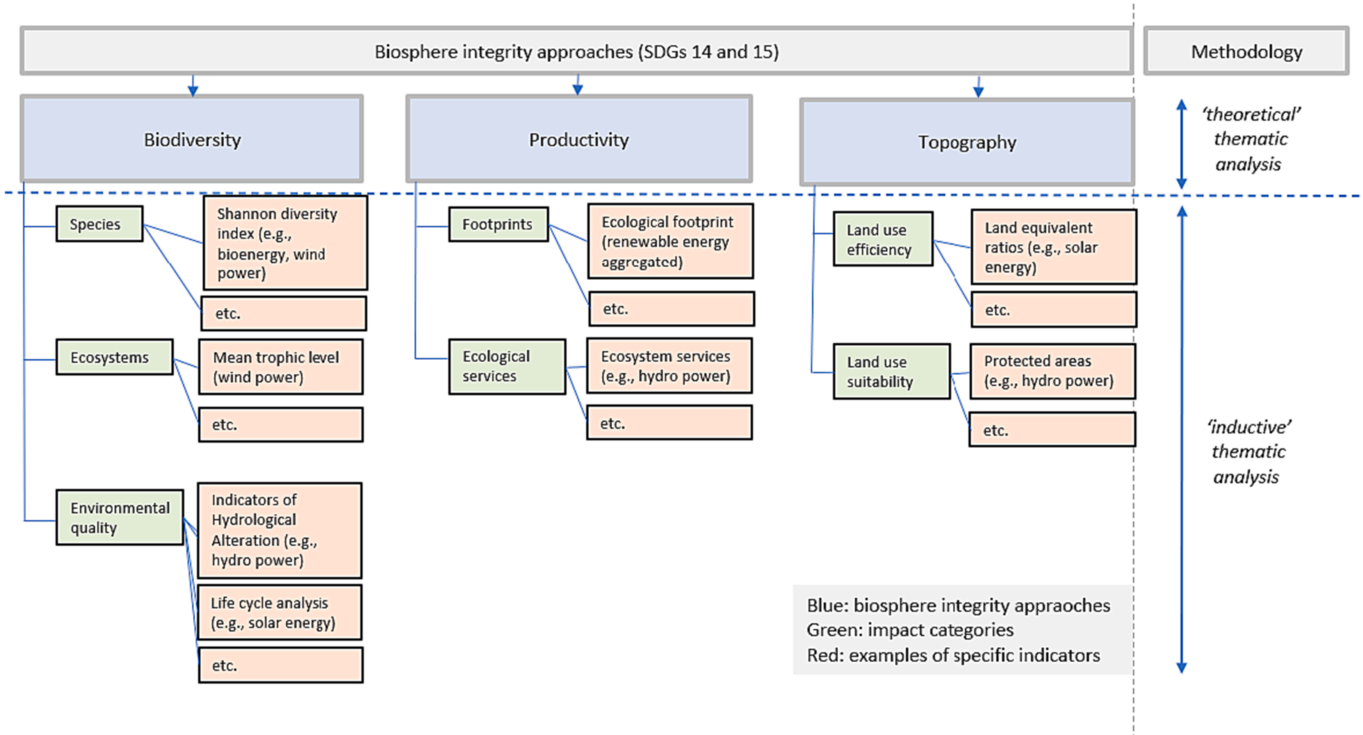

Fig. 5. A typology for renewable energy's impacts on biosphere integrity. The figure shows examples of specific indicators, see text for a full description. Methodology is indicated on the right side.

each renewable energy source. This study has chosen not to elaborate on the studies categorized with tidal/wave and geothermal, since the number of studies within these categories are low. However, note that the wave/tidal studies are often overlapping with the offshore wind studies.

3.5.1. *Hydro power*

For the studies on hydro, the biosphere integrity approaches were categorized as follows: 72 % on biodiversity, 8 % on productivity, and 20 % on topography (Fig. 4).

In the biodiversity approach, the set of indicators named Indicators of Hydrological Alteration (IHA) are most used within this study sample (Armanini et al., 2014; Gunawardana et al., 2021; Li et al., 2018; Lu et al., 2018; Yan et al., 2021). These indices measure the environmental quality, i.e., abiotic factors affecting living conditions for species found in the water stream and accompanying vegetation, like minimum and maximum flow rate, and changes in flow rate at different temporal resolutions. Within the flow index studies, quite a few assess the significance of temporal resolution on the flow data, where some settle for monthly averages, other argue for using daily averages, or even hourly flow data (Bejarano et al., 2017; Bevelhimer et al., 2015; Haas et al., 2014; Meile et al., 2011). Some also focus on the difference in using a fixed minimum ecological flow, and a dynamically set minimum flow which is set relative to the natural flow above the reservoir (Gorla and Perona, 2013; Lu et al., 2018; Luo et al., 2021; Niayifar and Perona, 2017). For hydropower with reservoirs, this is especially relevant, as the generation of power directly influence the flow rate downstream, potentially resulting in ecologically harmful curtailment of the water flow during times of low electricity generation, and in too large flow during periods of hydropeaking because of high price periods or other events necessitating high electricity generation. Balancing the economic benefits of high production during high price periods, and ecological effects downstream are a key issue for reducing the trade-offs between renewable energy production and biosphere integrity impacts.

Indicators used on the productivity approach are diverse. In some studies, ecosystem services are valuated, like impacts on fishery production (Pittock et al., 2017), and benefits from flood control (Hurford et al., 2020; Liang et al., 2016). Other studies provide numbers on the ecological footprint from hydropower, comparing it to other energy technologies (Biekša et al., 2021; Huijbregts et al., 2008; Jess, 2010; Pata and Aydin, 2020).

Quantifying topography impacts are either related to general land-use numbers for hydropower (Zarco-González et al., 2021), or on the landscape impacts from damming hydropower, using metrics used to quantify landscape fragmentation (Diáz et al., 2019; Liu et al., 2013; Ouyang et al., 2009). Furthermore, studies on landscape fragmentation can either focus on measuring fragmentation in general, or dive deeper into the understanding of how the fragmentation affect the ecosystem in question, for example through the establishment of artificial islands and the isolation of species (Palmeirim et al., 2017). These types of studies have been categorized with both biodiversity and topography approaches. Another interesting approach is to analyse the overlap between existing and planned renewable energy infrastructure, including hydropower, and protected areas (Popescu et al., 2020).

3.5.2. *Bio energy*

For the studies on bio, the biosphere integrity approaches were categorized as follows: 50 % on biodiversity, 18 % on productivity, and 32 % on topography (Fig. 4).

In the biodiversity approach, an emphasis is put on assessing development in biodiversity metrics when arable land is transformed to growing bioenergy crops (Chiatante et al., 2019; Haga et al., 2020; Haughton et al., 2016; Langeveld et al., 2012; Nunez et al., 2020). A common focus for these studies is on converting marginal lands, generally defined as unproductive farmland, to grow bioenergy crops. This assessment is usually carried out by counting species present in the research area, and then calculates a biodiversity metric, like the Shannon diversity index (Chiatante et al., 2019). Short rotational crops (SRC) are often presented as a promising bio energy crop type which has favourable attributes for biodiversity (Haughton et al., 2016; Langeveld et al., 2012; Petzold et al., 2014). Studies on forest ecosystems are also well represented in the study sample, where the main focus are directed towards the biodiversity effects of utilizing harvest residues for energy purposes, and the importance of dead wood in the forest for local biodiversity in general, or for selected species that also may be included as indicator species (Akujärvi et al., 2021; Grodsky et al., 2020; Sullivan et al., 2011; Verkerk et al., 2011). The most cited publication overall in this study sample is the study by (Alkemade et al., 2009), which describe a model for analysing effects on the biodiversity from a range of drivers, including growing bioenergy fuels. They use the indicator named mean abundance of original species relative to their abundance in undisturbed ecosystems (MSA) and calculate this by using numbers on marginal effects on MSA from different land-use types detected in the literature. Specifically for bioenergy, the authors model a scenario where bioenergy fuel from forests is provided for climate mitigation, and the effects this has on land-use and the MSA. A newer application of the MSA indicator is conducted in (Nunez et al., 2020).

In the productivity approach, the studies are evenly distributed between the footprints and ecological services categories. There are no obvious indicators used in the ecosystem service studies, which includes (Guo et al., 2016; Krause et al., 2017; Matthies et al., 2016; Meyer et al., 2015). For the footprints studies, some provide inference between bioenergy and footprint indicators on a national level, including ecological footprint (Alfalih and Hadj, 2022; Biekša et al., 2021; Shah et al., 2021), while others apply ecological footprint calculations in life cycle assessments of bioenergy (Huijbregts et al., 2008).

Considering the topography studies on bioenergy, 92 % focus on land-use efficiency, and the remaining 8 % study land-use suitability. Given the wide-ranging possibilities for bioenergy regarding both energy sources and energy carriers, the studies are diverse in their scope. Some study the land use effects of growing biomass on croplands, both productive and unproductive (Dolan et al., 2022; Evans et al., 2010; Leal et al., 2013; Miyake et al., 2015; Rösch et al., 2013). When crop grown biomass are considered, land use change (LUC) effects are an important topic. These effects are included in the studies by (Leal et al., 2013; Tan et al., 2009; Untenecker et al., 2017). When considering the potentials for carbon capture and storage, bioenergy carbon capture and storage (BECCS) are a known alternative. In light of land-use change, this has been studied by (Fajardy et al., 2018; Hanssen et al., 2022). (Hanssen et al., 2022) have linked the calculated land use to global terrestrial vertebrate species richness, combining the biosphere approaches of biodiversity and topography.

3.5.3. Wind energy

For the studies on wind, the biosphere integrity approaches were categorized as follows: 53 % on biodiversity, 15 % on productivity, and 32 % on topography (Fig. 4).

The biodiversity studies within wind energy differs between the onshore and offshore variants. Onshore wind studies are focusing on bird collisions (Battisti et al., 2020; Bose et al., 2018; Cole and Dahl, 2013), and also on potential impacts on ecosystems which are close to the wind power infrastructures (Pătru-Stupariu et al., 2019; Santos et al., 2010; Winder et al., 2014). Offshore wind studies, on the other hand, are focusing more on the artificial reef effects that the foundations of the wind turbines introduce, and the possible implications these structures have on the affiliated ecosystem and species during operation (Nogues et al., 2021; Pezy et al., 2020; Raoux et al., 2017; Reubens et al., 2013), and some also incorporate potential effects restricted fishing will have around the offshore wind infrastructure. More specifically, a special interest is directed towards the changes in food webs and the affiliated trophic level compositions (Pezy et al., 2020; Raoux et al., 2019; Raoux et al., 2017). These studies apply ecological network analysis, and model possible outcomes based on the model's knowledge on species interactions. An indicator used to assess these effects are changes in the mean trophic level (MTL) (Raoux et al., 2019, p. 8). Note that many of these studies rely on modelling, and not measurements on offshore wind infrastructure currently operating. One study has performed measurements on artificial structures offshore which is intended to mimic offshore wind infrastructure, calculating the Shannon diversity index for assessing the biodiversity effects (Bender et al., 2020).

There are 10 studies applying productivity approaches, where 6 of these apply footprint measurements to compare wind energy with other energy technologies, without specifying onshore and offshore technologies (Biekša et al., 2021; Browne et al., 2010; Huijbregts et al., 2008; Jain et al., 2020; Jess, 2010). The ecosystem service methods are applied on the remaining 4 studies, where the most concrete example is the study by (Cole and Dahl, 2013) providing calculations on monetary compensations for white-tailed eagle collisions at an onshore wind-power plant at Smøla, Norway.

Topography measurements are a common metric when wind power is discussed, and this is also prevalent in this study sample. Among the wind energy studies on topography, nearly all of them are applied to onshore wind or on the generic wind option. These studies usually use a measurement on land-use to compare wind power with other energy sources and technologies, relying on secondary sources for providing the land-use measurements (Copp et al., 2022; de Faria and Jaramillo, 2017; Grachev, 2018; Hong et al., 2014; Laha and Chakraborty, 2021). Some notable studies are the literature review conducted by (van Zalk and Behrens, 2018, p. 146), which presents statistical distributions on measurements of selected indicators used in the literature for comparing energy technologies, including land-use. (Diffendorfer et al., 2019; Guo et al., 2020; Jones and Pejchar, 2013) provide a more holistic view on land-use by using landscape metrics to study the ecological effects onshore wind infrastructure impose on the landscape, accounting for landscape fragmentation effects and the implications that can have on impacted ecosystems. Lastly, (Popescu et al., 2020) conducted a GIS-analysis for detecting overlap of existing and planned wind power infrastructure with areas of significance for biodiversity in the Canadian province of British Columbia.

3.5.4. Solar energy

For the studies on solar, the biosphere integrity approaches were categorized as follows: 36 % as biodiversity, 11 % as productivity, and 53 % as topography (Fig. 4).

For the biodiversity approaches on solar energy, environmental quality is the main impact category, with 16 studies across all categorized solar technologies. Among these 16 studies, a high share consists of life cycle analysis (LCA) studies, which usually apply measurements of contamination for assessing impacts on biosphere integrity, called mid-point indicators. An LCA can also include impact assessments on end-point indicators, which aggregate the impacts from the mid-point phase into cause and effects categories often named human health, ecosystem quality and resource depletion. A selection of studies from this study sample applying LCA methodologies are (Amor et al., 2010; Guarino et al., 2020; Rashedi and Khanam, 2020; Ratner and Lychev, 2019). In light of the LCA focus above, one interesting study by (Huijbregts et al., 2008), which has been referred to previously in this review, compares an LCA impact assessment method (Ecoindicator 99) with ecological footprint (EF) calculations. This approach is interesting since they compare two of this study's defined biosphere integrity approaches (biodiversity and productivity). One main finding is that the numbers from EF and LCA usually coincide with each other, but that the calculated ecological footprint are less impacted in cases where "relative high mineral consumption and process-specific metal and dust emissions" are involved compared to the LCA calculations (Huijbregts et al., 2008, p. 1). In the ecosystem impact category, no studies are conducted on specific solar energy infrastructure, but are more general in their assessment of trade-offs between biosphere integrity and solar energy infrastructure. A common focus of these studies is on reducing these trade-offs (Agha et al., 2020; Haga et al., 2020; Hernandez et al., 2019).

Productivity is the biosphere integrity approach with the lowest share among the solar energy studies. The main focus among these studies is on applying footprint measurements in projections of solar energy development, and compare these with other energy sources or technologies (Biekša et al., 2021; Jain et al., 2020; Krotscheck et al., 2000). The study by (Prinsloo et al., 2021) differs some from the others in the footprint category, where they focus on developing a framework for evaluating floating solar photovoltaic infrastructure, like benefits on ecosystem services of reduced evapotranspiration from water reservoirs.

Topography is the biosphere integrity approach with the highest share of studies among solar energy studies. Within the topography approach, 81 % focus on land-use efficiency, and the remaining 19 % study land-use suitability. One unique possibility for solar energy, both photovoltaic and heat, is the flexibility of placement. These possibilities are also investigated in the literature sample, including (Bonamente et al., 2015; Hernandez et al., 2019; Nordberg et al., 2021). Acknowledging the possibilities for using solar power plant areas for other activities, (Nordberg et al., 2021) describe an indicator for quantifying land sharing named land equivalent ratios (LERs) on an area combined with both agriculture, conservation, and solar electricity generation. A higher LER translates to a more efficient use of the land area in question, compared to only using the area for a single purpose, for example agriculture. So, with a LER higher than 1, the solar power plant is expected to increase the crop yield or improve the living conditions for the species targeted for conservation. Another category of studies in this review sample conduct scenario analysis on a future energy system for a specified area, usually on a country level (Copp et al., 2022; Hong et al., 2014; Jia et al., 2016; Laha and Chakraborty, 2021; Nock and Baker, 2019). In these studies, land use is included as a relevant indicator for evaluating the different energy scenarios.

3.5.5. Renewables aggregated

Renewables aggregated means studies that use an aggregated indicator for quantifying renewable energy in general. There is no focus on specific energy sources or technologies. All included studies in this study sample use data on national levels, attempting to assess a statistical inference on whether renewable energy impact biosphere integrity, and the strength of this impact.

For the studies on renewables aggregated, 92 % used indicators categorized as productivity approaches, biodiversity and topography were each included in 4 % of the studies (Fig. 4).

The most common indicator for measuring impacts on biosphere integrity is ecological footprint (EF), which this study has categorized within the productivity approach, illustrated in Fig. 5. To provide a sample from the review, Altıntaş and Kassouri (2020), Koseoglu et al. (2022), Zhang et al. (2020), Wang and Dong (2019) all use ecological footprint as the dependent variable for their selected samples of studied countries, and include measurements of renewable energy, for example share of renewable energy in primary energy consumption, or share of renewable energy capacity in total energy generating capacity as an explanatory variable.

One notable exception is the study conducted by Bhuiyan et al. (2018) which is categorized with all three biosphere integrity approaches of biodiversity, productivity, and topography. They include measurements on forest area (topography), aquaculture production (productivity), and the Global Environment Facility (GEF) benefits biodiversity index (biodiversity) within a panel data regression analysis on selected Asian countries.

Renewable energy aggregated is the energy category with the most uneven distribution between studies of biosphere integrity approaches, and the highest share categorized as productivity approach. This study finds two notable reasons behind this distribution. First, when establishing causational relationships between variables in statistical analysis, it is necessary to provide a plausible link between the variables in question. Ecological footprint is derived from national accounts and are therefore intricately linked to the consumption of resources. This is also the case for renewable energy consumption. Second, numbers on ecological footprint are available for many nations and across long time series, making it easily available and versatile for applying various statistical methods.

4. Conclusions

This study review 285 full-text articles on renewable energy's impact on biosphere integrity, and show how these studies vary across time, geography, renewables, and, most importantly, choice of biosphere integrity measurement approaches. This study shows which impact categories and specific indicators have been used to measure impacts on biosphere integrity across renewables. Moreover, this study group these in three broad biosphere integrity measurement approaches: biodiversity, topography, and productivity. The conclusions from this review are:

- *Time*: The number of articles on renewable energy's impact on biosphere integrity has increased steadily since 2008. The increase has been particularly strong after 2020.
- *Geography*: Nearly 80 per cent of the publications have used Asia, Europe, and North America as study areas.
- *Renewables*: Hydro is most studied with a total of 137 publications, followed by bio (n = 79), wind (n = 59), solar (n = 38), renewable energy aggregated (n = 22), wave/tidal (n = 11), and geothermal (n = 9). This order coincides well with the ranking of renewable energy generation by source globally.
- *Biosphere integrity approach*: Slightly more than 50 per cent of the studies focus on biodiversity, followed by topography (35 per cent) and productivity (15 per cent) (Fig. 4). Thus, the focus is more on the effects on the richness and abundance of species and less on the effects on land use patterns and fragmentation. Only a small fraction of the studies focuses on nature's provision of ecological services.
- *Impact categories*: For each biosphere integrity approach, this study has identified relevant impact categories (se typology in Fig. 5). The biodiversity approach includes the impact categories species, ecosystems, and environmental quality. The productivity approach includes the impact categories footprints and ecological services. The topographic approach includes the impact categories land use efficiency and land use suitability.
- *Specific vs. generic indicators*: Generic indicators are seldom used in analyses of one specific renewable energy technology. Rather, these analyses often use specific indicators tailored to elicit the technology's particular impacts on biosphere integrity. The exemption is studies of renewables as a group (aggregated). Here ecological footprint is by far the most common indicator and serves as a generic indicator for assessing renewables' impact on biosphere integrity.

Overall, this review shows that the research literature on renewable energy pays considerable attention to biosphere integrity impacts. The number of studies grows year by year and most of the renewables' impacts on biosphere integrity are covered by specific indicators. There is, however, little consensus on a shortlist of standardized indicators used across all renewables; and some argue we should not expect one due to the complexity in the impacts across time, place, and scale (Oparaocha et al., 2022).

Yet, we need to address and better understand these complexities, and this includes finding methods to quantify the complexity and interactions of ecosystems. A sensible first step would be to increase the use of proxy indicators for the impacts of renewables on biosphere integrity (Oparaocha et al., 2022). Obviously, specific indicators are needed for assessing the local impacts of concrete renewable energy projects. The proxy indicators are mainly needed to compare the impacts on biosphere integrity *across* renewables. One proxy indicator for all impact categories seems like a stretch, but one proxy indicator for each of the three biosphere integrity approach categories seems reasonable. These proxy indicators should meet all relevant criteria for indicators (e.g., Holden et al., 2018, pp. 120–121), and, moreover, build on the decade-long knowledge on renewables' impacts on biosphere integrity presented in this review.

Although contested, ecological footprint is currently the dominant proxy indicator for productivity. However, ecological footprint is not an adequate proxy for the two other categories: biodiversity and topography. Thus, finding proxy indicators that compare impacts on biodiversity and topography across renewables is an important line of further research.

Finally, this study would like to draw attention to two important policy implications of this review. First, all renewables inevitably require large land areas and thus potentially impact biosphere integrity negatively. It is therefore of outmost importance that renewables' negative impacts on biosphere integrity are taken into account in all relevant planning and concession processes to mitigate these impacts.

Second, SDG no. 7 aims at substantially increase the share of renewables in the global energy mix. All policies that support this aim must, however, assess interactions with other SDGs. Of particular interest is the positive interactions (synergies) with SDG 13 on climate change and the above-mentioned negative interactions (trade-offs) with SDG 14 and 15 on life on land and below water (biosphere integrity). Thus, renewable energy policies must encourage renewables to combat climate change while simultaneously mitigate negative impacts on biosphere integrity. There is definitely no room for trading off biosphere integrity to meet other SDGs.

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.

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Appendix A

Supplementary materials and research data

- Replication data and code can be accessed by using the following URL: https://doi.org/10.18710/YSKQPX

References

Agha, M., Lovich, J.E., Ennen, J.R., Todd, B.D., 2020. Wind, sun, and wildlife: Do wind and solar energy development "short-circuit" conservation in the western United States? Environ. Res. Lett. 15 https://doi.org/10.1088/1748-9326/ab8846.
Akujärvi, A., Repo, A., Akujärvi, A.M., Liski, J., 2021. Bridging mapping and simulation modelling in the ecosystem service assessments of boreal forests: effects of bioenergy production on carbon dynamics. Forest Ecosyst. 8 https://doi.org/10.1186/s40663-021-00283-2.
Alfalih, A.A., Hadj, T.B., 2022. Financialization, natural resources rents and environmental sustainability dynamics in Saudi Arabia under high and low regimes. Resour. Policy 76. https://doi.org/10.1016/j.resourpol.2022.102593.
Alkemade, R., Van Oorschot, M., Miles, L., Nellemann, C., Bakkenes, M., Ten Brink, B., 2009. GLOBIO3: A framework to investigate options for reducing global terrestrial biodiversity loss. Ecosystems 12, 374–390. https://doi.org/10.1007/s10021-009-9229-5.
Altıntaş, H., Kassouri, Y., 2020. Is the environmental Kuznets Curve in Europe related to the per-capita ecological footprint or CO2 emissions? Ecol. Ind. 113 https://doi.org/10.1016/j.ecolind.2020.106187.
Amor, M.B., Lesage, P., Pineau, P.-O., Samson, R., 2010. Can distributed generation offer substantial benefits in a Northeastern American context? A case study of small-scale renewable technologies using a life cycle methodology. Renew. Sustain. Energy Rev. 14, X2885–X2895. https://doi.org/10.1016/j.rser.2010.08.001.
Armanini, D.G., Idigoras Chaumel, A., Monk, W.A., Marty, J., Smokorowski, K., Power, M., Baird, D.J., 2014. Benthic macroinvertebrate flow sensitivity as a tool to assess effects of hydropower related ramping activities in streams in Ontario (Canada). Ecol. Ind. 46, 466–476. https://doi.org/10.1016/j.ecolind.2014.07.018.
Battisti, C., Ferri, V., Luiselli, L., Amori, G., 2020. Introducing ecological uncertainty in risk sensitivity indices: The case of wind farm impact on birds. Zool. Ecol. 30, 11–16. https://doi.org/10.35513/21658005.2020.1.2.
Bejarano, M.D., Sordo-Ward, Á., Alonso, C., Nilsson, C., 2017. Characterizing effects of hydropower plants on sub-daily flow regimes. J. Hydrol. 550, 186–200. https://doi.org/10.1016/j.jhydrol.2017.04.023.
Bender, A., Langhamer, O., Sundberg, J., 2020. Colonisation of wave power foundations by mobile mega- and macrofauna – a 12 year study. Mar. Environ. Res. 161 https://doi.org/10.1016/j.marenvres.2020.105053.
Bevelhimer, M.S., McManamay, R.A., O'Connor, B., 2015. Characterizing Sub-Daily Flow Regimes: Implications of Hydrologic Resolution on Ecohydrology Studies. River Res. Appl. 31, 867–879. https://doi.org/10.1002/rra.2781.
Bhuiyan, M.A., Jabeen, M., Zaman, K., Khan, A., Ahmad, J., Hishan, S.S., 2018. The impact of climate change and energy resources on biodiversity loss: Evidence from a panel of selected Asian countries. Renew. Energy 117, 324–340. https://doi.org/10.1016/j.renene.2017.10.054.
Biekša, K., Zonienė, A., Valiulė, V., 2021. Sustainable investment—a solution to reduce environmental footprint. Energies 14. https://doi.org/10.3390/en14113104.
Bonamente, E., Pelliccia, L., Merico, M.C., Rinaldi, S., Petrozzi, A., 2015. The multifunctional environmental energy tower: Carbon footprint and land use analysis of an integrated renewable energy plant. Sustainability (Switzerland) 7, 13564–13584. https://doi.org/10.3390/su71013564.
Bose, A., Dürr, T., Klenke, R.A., Henle, K., 2018. Collision sensitive niche profile of the worst affected bird-groups at wind turbine structures in the Federal State of Brandenburg, Germany. Sci. Rep. 8 https://doi.org/10.1038/s41598-018-22178-z.
BP, 2022. bp Statistical Review of World Energy 2022. Statistical Review of World Energy. British Petroleum. No. 71.
Braun, V., Clarke, V., 2006. Using thematic analysis in psychology. Qual. Res. Psychol. 3, 77–101. https://doi.org/10.1191/1478088706qp063oa.
Browne, D., O'Regan, B., Moles, R., 2010. Use of multi-criteria decision analysis to explore alternative domestic energy and electricity policy scenarios in an Irish city-region. Energy 35, 518–528. https://doi.org/10.1016/j.energy.2009.10.020.
Chiatante, G., Giordano, M., Meriggi, A., 2019. Bird Diversity in Short Rotation Coppice in Northern Italy. Ardea 107, 5–17. https://doi.org/10.5253/arde.v107i1.a10.
Cole, S.G., Dahl, E.L., 2013. Compensating white-tailed eagle mortality at the Smøla wind-power plant using electrocution prevention measures. Wildl. Soc. Bull. 37, 84–93. https://doi.org/10.1002/wsb.263.
Copp, D.A., Nguyen, T.A., Byrne, R.H., Chalamala, B.R., 2022. Optimal sizing of distributed energy resources for planning 100% renewable electric power systems. Energy 239. https://doi.org/10.1016/j.energy.2021.122436.
Covidence systematic review software, 2022.
de Faria, F.A.M., Jaramillo, P., 2017. The future of power generation in Brazil: An analysis of alternatives to Amazonian hydropower development. Energy Sustain. Dev. 41, 24–35. https://doi.org/10.1016/j.esd.2017.08.001.
Diáz, G., Arriagada, P., Górski, K., Link, O., Karelovic, B., Gonzalez, J., Habit, E., 2019. Fragmentation of Chilean Andean rivers: Expected effects of hydropower development. Rev. Chil. Hist. Nat. 92 https://doi.org/10.1186/s40693-019-0081-5.
Diffendorfer, J.E., Dorning, M.A., Keen, J.R., Kramer, L.A., Taylor, R.V., 2019. Geographic context affects the landscape change and fragmentation caused by wind energy facilities. PeerJ 2019. https://doi.org/10.7717/peerj.7129.
Dolan, F., Lamontagne, J., Calvin, K., Snyder, A., Narayan, K.B., Di Vittorio, A.V., Vernon, C.R., 2022. Modeling the Economic and Environmental Impacts of Land Scarcity Under Deep Uncertainty. Earth's Future 10. https://doi.org/10.1029/2021EF002466.
Dorning, M.A., Diffendorfer, J.E., Loss, S.R., Bagstad, K.J., 2019. Review of indicators for comparing environmental effects across energy sources. Environ. Res. Lett. 14 https://doi.org/10.1088/1748-9326/ab402d.
Evans, A., Strezov, V., Evans, T.J., 2010. Sustainability considerations for electricity generation from biomass. Renew. Sustain. Energy Rev. 14, 1419–1427. https://doi.org/10.1016/j.rser.2010.01.010.
Fajardy, M., Chiquier, S., Mac Dowell, N., 2018. Investigating the BECCS resource nexus: Delivering sustainable negative emissions. Energ. Environ. Sci. 11, 3408–3430. https://doi.org/10.1039/c8ee01676c.
Fernandes, I.O., de Souza, J.L.P., 2018. Dataset of long-term monitoring of ground-dwelling ants (Hymenoptera: Formicidae) in the influence areas of a hydroelectric power plant on the Madeira River in the Amazon Basin. Biodivers. Data J. 6 https://doi.org/10.3897/BDJ.6.e24375.
Garritty, C., Gartlehner, G., Nussbaumer-Streit, B., King, V.J., Hamel, C., Kamel, C., Affengruber, L., Stevens, A., 2021. Cochrane Rapid Reviews Methods Group offers evidence-informed guidance to conduct rapid reviews. Journal of Clinical Epidemiology 130, 13–22. https://doi.org/10.1016/j.jclinepi.2020.10.007.
Gasparatos, A., Doll, C.N.H., Esteban, M., Ahmed, A., Olang, T.A., 2017. Renewable energy and biodiversity: Implications for transitioning to a Green Economy. Renew. Sustain. Energy Rev. 70, 161–184. https://doi.org/10.1016/j.rser.2016.08.030.
Gibson, L., Wilman, E.N., Laurance, W.F., 2017. How Green is 'Green' Energy? Trends Ecol. Evol. 32, 922–935. https://doi.org/10.1016/j.tree.2017.09.007.
Gorla, L., Perona, P., 2013. On quantifying ecologically sustainable flow releases in a diverted river reach. J. Hydrol. 489, 98–107. https://doi.org/10.1016/j.jhydrol.2013.02.043.
Grachev, V.A., 2018. Energy technologies and sustainable development. Int. J. Mech. Eng. Technol. 9, 382–390. https://doi.org/10.1017/cbo9781139168762.003.
Grodsky, S.M., Hernandez, R.R., Campbell, J.W., Hinson, K.R., Keller, O., Fritts, S.R., Homyack, J.A., Moorman, C.E., 2020. Ground beetle (Coleoptera: Carabidae)

response to harvest residue retention: Implications for sustainable forest bioenergy production. Forests 11. https://doi.org/10.3390/f11010048.

Guarino, F., Longo, S., Hachem Vermette, C., Cellura, M., La Rocca, V., 2020. Life cycle assessment of solar communities. Sol. Energy 207, 209–217. https://doi.org/10.1016/j.solener.2020.06.089.

Gunawardana, S.K., Shrestha, S., Mohanasundaram, S., Salin, K.R., Piman, T., 2021. Multiple drivers of hydrological alteration in the transboundary Srepok River Basin of the Lower Mekong Region. J. Environ. Manage. 278 https://doi.org/10.1016/j.jenvman.2020.111524.

Gunnarsdottir, I., Davidsdottir, B., Worrell, E., Sigurgeirsdottir, S., 2020. Review of indicators for sustainable energy development. Renew. Sustain. Energy Rev. 133, 110294 https://doi.org/10.1016/j.rser.2020.110294.

Guo, M., Richter, G.M., Holland, R.A., Eigenbrod, F., Taylor, G., Shah, N., 2016. Implementing land-use and ecosystem service effects into an integrated bioenergy value chain optimisation framework. Comput. Chem. Eng. 91, 392–406. https://doi.org/10.1016/j.compchemeng.2016.02.011.

Guo, X., Zhang, X., Du, S., Li, C., Siu, Y.L., Rong, Y., Yang, H., 2020. The impact of onshore wind power projects on ecological corridors and landscape connectivity in Shanxi, China. J. Clean. Prod. 254 https://doi.org/10.1016/j.jclepro.2020.120075.

Haas, N.A., O'Connor, B.L., Hayse, J.W., Bevelhimer, M.S., Endreny, T.A., 2014. Analysis of Daily Peaking and Run-of-River Operations with Flow Variability Metrics, Considering Subdaily to Seasonal Time Scales. J. Am. Water Resour. Assoc. 50, 1622–1640. https://doi.org/10.1111/jawr.12228.

Haga, C., Maeda, M., Hotta, W., Inoue, T., Matsui, T., Machimura, T., Nakaoka, M., Morimoto, J., Shibata, H., Hashimoto, S., Saito, O., 2020. Scenario Analysis of Renewable Energy-Biodiversity Nexuses Using a Forest Landscape Model. Front. Ecol. Evol. 8 https://doi.org/10.3389/fevo.2020.00155.

Hamel, C., Michaud, A., Thuku, M., Skidmore, B., Stevens, A., Nussbaumer-Streit, B., Garritty, C., 2021. Defining Rapid Reviews: a systematic scoping review and thematic analysis of definitions and defining characteristics of rapid reviews. J. Clin. Epidemiol. 129, 74–85. https://doi.org/10.1016/j.jclinepi.2020.09.041.

Hanssen, S.V., Steinmann, Z.J.N., Daioglou, V., Čengić, M., Van Vuuren, D.P., Huijbregts, M.A.J., 2022. Global implications of crop-based bioenergy with carbon capture and storage for terrestrial vertebrate biodiversity. GCB Bioenergy 14, 307–321. https://doi.org/10.1111/gcbb.12911.

Haughton, A.J., Bohan, D.A., Clark, S.J., Mallott, M.D., Mallott, V., Sage, R., Karp, A., 2016. Dedicated biomass crops can enhance biodiversity in the arable landscape. GCB Bioenergy 8, 1071–1081. https://doi.org/10.1111/gcbb.12312.

Hernandez, R.R., Armstrong, A., Burney, J., Ryan, G., Moore-O'Leary, K., Diédhiou, I., Grodsky, S.M., Saul-Gershenz, L., Davis, R., Macknick, J., Mulvaney, D., Heath, G.A., Easter, S.B., Hoffacker, M.K., Allen, M.F., Kammen, D.M., 2019. Techno–ecological synergies of solar energy for global sustainability. Nat. Sustain. 2, 560–568. https://doi.org/10.1038/s41893-019-0309-z.

Holden, E., Linnerud, K., Banister, D., Schwanitz, V.J., Wierling, A., 2018. The Imperatives of Sustainable Development: Needs, justice, limits, 1st ed. Routledge, Oxford.

Hong, S., Bradshaw, C.J., Brook, B.W., 2014. South Korean energy scenarios show how nuclear power can reduce future energy and environmental costs. Energy Policy 74, 569–578. https://doi.org/10.1016/j.enpol.2014.05.054.

Huijbregts, M.A.J., Hellweg, S., Frischknecht, R., Hungerbühler, K., Hendriks, A.J., 2008. Ecological footprint accounting in the life cycle assessment of products. Ecol. Econ. 64, 798–807. https://doi.org/10.1016/j.ecolecon.2007.04.017.

Hurford, A.P., McCartney, M.P., Harou, J.J., Dalton, J., Smith, D.M., Odada, E., 2020. Balancing services from built and natural assets via river basin trade-off analysis. Ecosyst. Serv. 45 https://doi.org/10.1016/j.ecoser.2020.101144.

IEA, 2021. Key World Energy Statistics 2021, Key World Energy Statistics. International Energy Agency.

Illyová, M., Beracko, P., Vranovský, M., Matečný, I., 2017. Long-term changes in copepods assemblages in the area of the Danube floodplain (Slovak–Hungarian stretch). Limnologica 65, 22–33. https://doi.org/10.1016/j.limno.2017.05.001.

International Atomic Energy Agency, United Nations Department of Economic and Social Affairs, International Energy Agency, Eurostat, European Environment Agency, 2005. Energy indicators for sustainable development: guidelines and methodologies. International Atomic Energy Agency, Vienna.

IPBES, 2019. Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Zenodo. https://doi.org/10.5281/ZENODO.6417333.

IRENA, 2022. Renewable Energy Statistics 2022. Renewable Energy Statistics, International Renewable Energy Agency, Abu Dhabi.

Jager, H.I., Efroymson, R.A., McManamay, R.A., 2021. Renewable energy and biological conservation in a changing world. Biol. Conserv. 263, 109354 https://doi.org/10.1016/j.biocon.2021.109354.

Jain, S., Gupta, S., Thomas, N., Bandyopadhyay, S., 2020. Capacity Expansion of Electricity Sector Using Multiple Sustainability Indicators. Process Integr. Optimiz. Sustain. 4, 51–65. https://doi.org/10.1007/s41660-019-00099-2.

Jess, A., 2010. What might be the energy demand and energy mix to reconcile the world's pursuit of welfare and happiness with the necessity to preserve the integrity of the biosphere? Energy Policy 38, 4663–4678. https://doi.org/10.1016/j.enpol.2010.04.026.

Jia, X., Li, Z., Wang, F., Foo, D.C.Y., Tan, R.R., 2016. Multi-dimensional pinch analysis for sustainable power generation sector planning in China. J. Clean. Prod. 112, 2756–2771. https://doi.org/10.1016/j.jclepro.2015.10.102.

Jones, N.F., Pejchar, L., 2013. Comparing the ecological impacts of wind and oil & gas development: A landscape scale assessment. PLoS One 8. https://doi.org/10.1371/journal.pone.0081391.

Kohl, C., Mcintosh, E., Unger, S., Haddaway, N., Kecke, S., Schiemann, J., Wilhelm, R., 2018. Online tools supporting the conduct and reporting of systematic reviews and systematic maps: A case study on CADIMA and review of existing tools. Environ. Evidence 7. https://doi.org/10.1186/s13750-018-0115-5.

Koseoglu, A., Yucel, A.G., Ulucak, R., 2022. Green innovation and ecological footprint relationship for a sustainable development: Evidence from top 20 green innovator countries. Sustain. Dev. https://doi.org/10.1002/sd.2294.

Krause, A., Pughl, T.A.M., Bayer, A.D., Doelman, J.C., Humpenöder, F., Anthoni, P., Olin, S., Bodirsky, B.L., Popp, A., Stehfest, E., Arneth, A., 2017. Global consequences of afforestation and bioenergy cultivation on ecosystem service indicators. Biogeosciences 14, 4829–4850. https://doi.org/10.5194/bg-14-4829-2017.

Krotscheck, C., König, F., Obernberger, I., 2000. Ecological assessment of integrated bioenergy systems using the Sustainable Process Index. Biomass Bioenergy 18, 341–368. https://doi.org/10.1016/S0961-9534(99)00096-3.

Laha, P., Chakraborty, B., 2021. Low carbon electricity system for India in 2030 based on multi-objective multi-criteria assessment. Renew. Sustain. Energy Rev. 135 https://doi.org/10.1016/j.rser.2020.110356.

Langeveld, H., Quist-Wessel, F., Dimitriou, I., Aronsson, P., Baum, C., Schulz, U., Bolte, A., Baum, S., Köhn, J., Weih, M., Gruss, H., Leinweber, P., Lamersdorf, N., Schmidt-Walter, P., Berndes, G., 2012. Assessing Environmental Impacts of Short Rotation Coppice (SRC) Expansion: Model Definition and Preliminary Results. Bioenergy Res. 5, 621–635. https://doi.org/10.1007/s12155-012-9235-x.

Leal, M.R.L.V., Horta Nogueira, L.A., Cortez, L.A.B., 2013. Land demand for ethanol production. Appl. Energy 102, 266–271. https://doi.org/10.1016/j.apenergy.2012.09.037.

Li, Z., 2018. Study of site suitability assessment of regional wind resources development based on multi-criteria decision. Clean Techn. Environ. Policy 20, 1147–1166. https://doi.org/10.1007/s10098-018-1538-y.

Li, D., Wan, W., Zhao, J., 2018. Optimizing environmental flow operations based on explicit quantification of IHA parameters. J. Hydrol. 563, 510–522. https://doi.org/10.1016/j.jhydrol.2018.06.031.

Liang, C., Xin, S., Dongsheng, W., Xiuying, Y., Guodong, J., 2016. The ecological benefit–loss evaluation in a riverine wetland for hydropower projects – A case study of Xiaolangdi reservoir in the Yellow River, China. Ecol. Eng. 96, 34–44. https://doi.org/10.1016/j.ecoleng.2015.12.037.

Liu, S., Zhao, Q., Wen, M., Deng, L., Dong, S., Wang, C., 2013. Assessing the impact of hydroelectric project construction on the ecological integrity of the Nuozhadu Nature Reserve, southwest China. Stoch. Env. Res. Risk A. 27, 1709–1718. https://doi.org/10.1007/s00477-013-0708-z.

Lu, W., Lei, H., Yang, D., Tang, L., Miao, Q., 2018. Quantifying the impacts of small dam construction on hydrological alterations in the Jiulong River basin of Southeast China. J. Hydrol. 567, 382–392. https://doi.org/10.1016/j.jhydrol.2018.10.034.

Luo, Q., Chiu, M.-C., Tan, L., Cai, Q., 2021. An Environmental Flow Framework for Riverine Macroinvertebrates During Dry and Wet Seasons Through Non-linear Ecological Modeling. Front. Ecol. Evol. 9 https://doi.org/10.3389/fevo.2021.734716.

Maguire, M., Delahunt, B., 2017. Doing a Thematic Analysis: A Practical. Step-by-Step Guide for Learning and Teaching Scholars, p. 8.

Matthies, B.D., Kalliokoski, T., Eyvindson, K., Honkela, N., Hukkinen, J.I., Kuusinen, N. J., Räisänen, P., Valsta, L.T., 2016. Nudging service providers and assessing service trade-offs to reduce the social inefficiencies of payments for ecosystem services schemes. Environ. Sci. Policy 55, 228–237. https://doi.org/10.1016/j.envsci.2015.10.009.

McCollum, D.L., Echeverri, L.G., Busch, S., Pachauri, S., Parkinson, S., Rogelj, J., Krey, V., Minx, J.C., Nilsson, M., Stevance, A.-S., Riahi, K., 2018. Connecting the sustainable development goals by their energy inter-linkages. Environ. Res. Lett. 13, 033006 https://doi.org/10.1088/1748-9326/aaafe3.

Meile, T., Boillat, J.-L., Schleiss, A.J., 2011. Hydropeaking indicators for characterization of the Upper-Rhone River in Switzerland. Aquat. Sci. 73, 171–182. https://doi.org/10.1007/s00027-010-0154-7.

Meyer, M.A., Chand, T., Priess, J.A., 2015. Comparing bioenergy production sites in the southeastern US regarding ecosystem service supply and demand. PLoS One 10. https://doi.org/10.1371/journal.pone.0116336.

Millennium Ecosystem Assessment (Program) (Ed.), 2005. Ecosystems and human well-being: synthesis. Island Press, Washington, DC.

Miyake, S., Smith, C., Peterson, A., McAlpine, C., Renouf, M., Waters, D., 2015. Environmental implications of using "underutilised agricultural land" for future bioenergy crop production. Agr. Syst. 139, 180–195. https://doi.org/10.1016/j.agsy.2015.06.010.

Myers, N., Mittermeier, R.A., Mittermeier, C.G., da Fonseca, G.A.B., Kent, J., 2000. Biodiversity hotspots for conservation priorities. Nature 403, 853–858. https://doi.org/10.1038/35002501.

Naseri, M., Hussaini, M.S., Iqbal, M.W., Jawadi, H.A., Puya, M., 2021. Spatial modeling of solar photovoltaic power plant in Kabul, Afghanistan. J. Mt. Sci. 18, 3291–3305. https://doi.org/10.1007/s11629-021-7035-5.

Nasouri, M., Delgarm, N., 2022. Investigating the Role of Bushehr Nuclear Power Plants (BNPPs) in Line with Achieving the Perspective of Sustainable Energy Development in Iran. J. Therm. Sci. https://doi.org/10.1007/s11630-022-1576-y.

Nguyen, D.-T., Truong, M.-H., Phan, D.-T., 2021. Gis-based simulation for solar farm site selection in south-central Vietnam. GeoJournal. https://doi.org/10.1007/s10708-021-10454-x.

Niayifar, A., Perona, P., 2017. Dynamic water allocation policies improve the global efficiency of storage systems. Adv. Water Resour. 104, 55–64. https://doi.org/10.1016/j.advwatres.2017.03.004.

Nock, D., Baker, E., 2019. Holistic multi-criteria decision analysis evaluation of sustainable electric generation portfolios: New England case study. Appl. Energy 242, 655–673. https://doi.org/10.1016/j.apenergy.2019.03.019.

Nogues, Q., Raoux, A., Araignous, E., Chaalali, A., Hattab, T., Leroy, B., Lasram, B.R.F., David, V., Le Loc'h, F., Dauvin, J.-C., Niquil, N., 2021. Cumulative effects of marine renewable energy and climate change on ecosystem properties: Sensitivity of ecological network analysis. Ecol. Ind. 121 https://doi.org/10.1016/j.ecolind.2020.107128.

Nordberg, E.J., Julian Caley, M., Schwarzkopf, L., 2021. Designing solar farms for synergistic commercial and conservation outcomes. Sol. Energy 228, 586–593. https://doi.org/10.1016/j.solener.2021.09.090.

Nukazawa, K., Kajiwara, S., Saito, T., Suzuki, Y., 2020. Preliminary assessment of the impacts of sediment sluicing events on stream insects in the Mimi River, Japan. Ecol. Eng. 145 https://doi.org/10.1016/j.ecoleng.2020.105726.

Nunez, S., Verboom, J., Alkemade, R., 2020. Assessing land-based mitigation implications for biodiversity. Environ. Sci. Policy 106, 68–76. https://doi.org/10.1016/j.envsci.2020.01.006.

Olabi, A.G., Abdelkareem, M.A., 2022. Renewable energy and climate change. Renew. Sustain. Energy Rev. 158, 112111 https://doi.org/10.1016/j.rser.2022.112111.

Oliveira, D.M.S., Cherubin, M.R., Franco, A.L.C., Santos, A.S., Gelain, J.G., Dias, N.M.S., Diniz, T.R., Almeida, A.N., Feigl, B.J., Davies, C.A., Paustian, K., Karlen, D.L., Smith, P., Cerri, C.C., Cerri, C.E.P., 2019. Is the expansion of sugarcane over pasturelands a sustainable strategy for Brazil's bioenergy industry? Renew. Sustain. Energy Rev. 102, 346–355. https://doi.org/10.1016/j.rser.2018.12.012.

Omitaomu, O.A., Singh, N., Bhaduri, B.L., 2015. Mapping suitability areas for concentrated solar power plants using remote sensing data. J. Appl. Remote Sens. 9 https://doi.org/10.1117/1.JRS.9.097697.

Oparaocha, S., Ibrekk, H.O., Bergem, M., Kauer, A.C., Mbuthi, P., Lodhi, I., Vleuten, F. van der, McQueen, D., Zhang, D., Signore, S., Watson, S., Srivastava, L., Cozzi, L., Lans, D. van der, Mehlwana, M., Foster, S., Lispergue, R.C., Liu, H., Sedaoui, R., Dubois, O., Pearce-Oroz, G., Ferroukhi, R., Held, S., Radka, M., Violetti, D., Kitio, V., Thapa, R.R., Emtairah, T., Schroderus-Fox, H., Adair-Rohani, H., Papathanasiou, D., Gueye, M.K., Fohgrub, T., Schroth, D., Mogaibel, H., Chiliquinga, B., Adib, R., Nakicenovic, N., Skierka, K., Power, K., Takada, M., 2022. Addressing Energy's Interlinkages with other SDGs, SDG7 Policy Brief. United Nations.

Ouyang, W., Skidmore, A.K., Hao, F., Toxopeus, A.G., Abkar, A., 2009. Accumulated effects on landscape pattern by hydroelectric cascade exploitation in the Yellow River basin from 1977 to 2006. Landsc. Urban Plan. 93, 163–171. https://doi.org/10.1016/j.landurbplan.2009.07.001.

Owusu, P.A., Asumadu-Sarkodie, S., 2016. A review of renewable energy sources, sustainability issues and climate change mitigation. Cogent Eng. 3, 1167990. https://doi.org/10.1080/23311916.2016.1167990.

Palmeirim, A.F., Vieira, M.V., Peres, C.A., 2017. Non-random lizard extinctions in land-bridge Amazonian forest islands after 28 years of isolation. Biol. Conserv. 214, 55–65. https://doi.org/10.1016/j.biocon.2017.08.002.

Pan, B., Wang, Z., Li, Z., Yu, G.-A., Xu, M., Zhao, N., Brierley, G., 2013. An exploratory analysis of benthic macroinvertebrates as indicators of the ecological status of the Upper Yellow and Yangtze Rivers. J. Geog. Sci. 23, 871–882. https://doi.org/10.1007/s11442-013-1050-6.

Pata, U.K., 2021. Linking renewable energy, globalization, agriculture, CO2 emissions and ecological footprint in BRIC countries: A sustainability perspective. Renew. Energy 173, 197–208. https://doi.org/10.1016/j.renene.2021.03.125.

Pata, U.K., Aydin, M., 2020. Testing the EKC hypothesis for the top six hydropower energy-consuming countries: Evidence from Fourier Bootstrap ARDL procedure. J. Clean. Prod. 264, 121699 https://doi.org/10.1016/j.jclepro.2020.121699.

Pata, U.K., Aydin, M., Haouas, I., 2021. Are natural resources abundance and human development a solution for environmental pressure? Evidence from top ten countries with the largest ecological footprint. Resour. Policy 70. https://doi.org/10.1016/j.resourpol.2020.101923.

Pătru-Stupariu, I., Calotă, A.-M., Santonja, M., Anastasiu, P., Stoicescu, I., Biriş, I.A., Stupariu, M.-S., Buttler, A., 2019. Do wind turbines impact plant community properties in mountain region? Biologia 74, 1613–1619. https://doi.org/10.2478/s11756-019-00333-9.

Petzold, R., Butler-Manning, D., Feldwisch, N., Glaser, T., Schmidt, P.A., Denner, M., Feger, K.-H., 2014. Linking biomass production in short rotation coppice with soil protection and nature conservation. Iforest 7, 353–362. https://doi.org/10.3832/ifor1168-007.

Pezy, J.-P., Raoux, A., Dauvin, J.-C., 2020. An ecosystem approach for studying the impact of offshore wind farms: A French case study. ICES J. Mar. Sci. 77, 1238–1246. https://doi.org/10.1093/icesjms/fsy125.

Pittock, J., Dumaresq, D., Orr, S., 2017. The Mekong River: trading off hydropower, fish, and food. Reg. Environ. Chang. 17, 2443–2453. https://doi.org/10.1007/s10113-017-1175-8.

Popescu, V.D., Munshaw, R.G., Shackelford, N., Montesino Pouzols, F., Dubman, E., Gibeau, P., Horne, M., Moilanen, A., Palen, W.J., 2020. Quantifying biodiversity trade-offs in the face of widespread renewable and unconventional energy development. Sci. Rep. 10 https://doi.org/10.1038/s41598-020-64501-7.

Prinsloo, F.C., Schmitz, P., Lombard, A., 2021. Sustainability assessment framework and methodology with trans-disciplinary numerical simulation model for analytical floatovoltaic energy system planning assessments. Sustainable Energy Technol. Assess. 47 https://doi.org/10.1016/j.seta.2021.101515.

Quadroni, S., Crosa, G., Gentili, G., Espa, P., 2017. Response of stream benthic macroinvertebrates to current water management in Alpine catchments massively developed for hydropower. Sci. Total Environ. 609, 484–496. https://doi.org/10.1016/j.scitotenv.2017.07.099.

R Core Team, 2022. R: A Language and Environment for Statistical Computing.

Raoux, A., Tecchio, S., Pezy, J.-P., Lassalle, G., Degraer, S., Wilhelmsson, D., Cachera, M., Ernande, B., Le Guen, C., Haraldsson, M., Grangeré, K., Le Loc'h, F., Dauvin, J.-C., Niquil, N., 2017. Benthic and fish aggregation inside an offshore wind farm: Which effects on the trophic web functioning? Ecol. Ind. 72, 33–46. https://doi.org/10.1016/j.ecolind.2016.07.037.

Raoux, A., Lassalle, G., Pezy, J.-P., Tecchio, S., Safi, G., Ernande, B., Mazé, C., Loc'h, F.L., Lequesne, J., Girardin, V., Dauvin, J.-C., Niquil, N., 2019. Measuring sensitivity of two OSPAR indicators for a coastal food web model under offshore wind farm construction. Ecol. Ind. 96, 728–738. https://doi.org/10.1016/j.ecolind.2018.07.014.

Rashedi, A., Khanam, T., 2020. Life cycle assessment of most widely adopted solar photovoltaic energy technologies by mid-point and end-point indicators of ReCiPe method. Environ. Sci. Pollut. Res. 27, 29075–29090. https://doi.org/10.1007/s11356-020-09194-1.

Ratner, S.V., Lychev, A.V., 2019. Evaluating environmental impacts of photovoltaic technologies using data envelopment analysis. Adv. Syst. Sci. Applic. 19, 12–30. https://doi.org/10.25728/assa.2019.19.1.651.

Reubens, J.T., Vandendriessche, S., Zenner, A.N., Degraer, S., Vincx, M., 2013. Offshore wind farms as productive sites or ecological traps for gadoid fishes? - Impact on growth, condition index and diet composition. Mar. Environ. Res. 90, 66–74. https://doi.org/10.1016/j.marenvres.2013.05.013.

Ritchie, H., Roser, M., Rosado, P., 2022. Energy [WWW Document]. Our World in Data. https://ourworldindata.org/energy.

Rockström, J., Steffen, W., Noone, K., Persson, A., Chapin III, F.S., Lambin, E., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H.J., Nykvist, B., de Wit, C.A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P.K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R.W., Fabry, V.J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., Foley, J., 2009. Planetary boundaries: Exploring the safe operating space for humanity. Ecol. Soc. 14 https://doi.org/10.5751/ES-03180-140232.

Rösch, C., Aust, C., Jörissen, J., 2013. Envisioning the sustainability of the production of short rotation coppice on grassland. Energy Sustain. Soc. 3 https://doi.org/10.1186/2192-0567-3-7.

Santos, M., Bastos, R., Travassos, P., Bessa, R., Repas, M., Cabral, J.A., 2010. Predicting the trends of vertebrate species richness as a response to wind farms installation in mountain ecosystems of northwest Portugal. Ecol. Ind. 10, 192–205. https://doi.org/10.1016/j.ecolind.2009.04.014.

Shah, S.A.R., Naqvi, S.A.A., Nasreen, S., Abbas, N., 2021. Associating drivers of economic development with environmental degradation: Fresh evidence from Western Asia and North African region. Ecol. Ind. 126 https://doi.org/10.1016/j.ecolind.2021.107638.

Souter, N.J., Shaad, K., Vollmer, D., Regan, H.M., Farrell, T.A., Arnaiz, M., Meynell, P.-J., Cochrane, T.A., Arias, M.E., Piman, T., Andelman, S.J., 2020. Using the freshwater health index to assess hydropower development scenarios in the sesan, srepok and sekong river basin. Water (Switzerland) 12. https://doi.org/10.3390/w12030788.

Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., De Vries, W., De Wit, C.A., Folke, C., Gerten, D., Heinke, J., Mace, G.M., Persson, L.M., Ramanathan, V., Reyers, B., Sörlin, S., 2015. Planetary boundaries: Guiding human development on a changing planet. Science 347. https://doi.org/10.1126/science.1259855.

Sullivan, T.P., Sullivan, D.S., Lindgren, P.M.F., Ransome, D.B., Bull, J.G., Ristea, C., 2011. Bioenergy or biodiversity? Woody debris structures and maintenance of red-backed voles on clearcuts. Biomass Bioenergy 35, 4390–4398. https://doi.org/10.1016/j.biombioe.2011.08.013.

Sutela, T., Aroviita, J., Keto, A., 2013. Assessing ecological status of regulated lakes with littoral macrophyte, macroinvertebrate and fish assemblages. Ecol. Ind. 24, 185–192. https://doi.org/10.1016/j.ecolind.2012.06.015.

Tan, R.R., Ballacillo, J.-A.-B., Aviso, K.B., Culaba, A.B., 2009. A fuzzy multiple-objective approach to the optimization of bioenergy system footprints. Chem. Eng. Res. Des. 87, 1162–1170. https://doi.org/10.1016/j.cherd.2009.04.004.

Tourinho, A.L., Benchimol, M., Porto, W., Peres, C.A., Storck-Tonon, D., 2020. Marked compositional changes in harvestmen assemblages in Amazonian forest islands induced by a mega dam. Insect Conserv. Divers. 13, 432–444. https://doi.org/10.1111/icad.12398.

UN General Assembly, 2012. The future we want.

UN General Assembly, 2015. Transforming our world: the 2030 Agenda for Sustainable Development.

Untenecker, J., Tiemeyer, B., Freibauer, A., Laggner, A., Luterbacher, J., 2017. Tracking changes in the land use, management and drainage status of organic soils as indicators of the effectiveness of mitigation strategies for climate change. Ecol. Ind. 72, 459–472. https://doi.org/10.1016/j.ecolind.2016.08.004.

van Zalk, J., Behrens, P., 2018. The spatial extent of renewable and non-renewable power generation: A review and meta-analysis of power densities and their application in the U.S. Energy Policy 123, 83–91. https://doi.org/10.1016/j.enpol.2018.08.023.

Verkerk, P.J., Lindner, M., Zanchi, G., Zudin, S., 2011. Assessing impacts of intensified biomass removal on deadwood in European forests. Ecol. Ind. 11, 27–35. https://doi.org/10.1016/j.ecolind.2009.04.004.

Wackernagel, M., Rees, W.E., 1996. Our ecological footprint: reducing human impact on the earth. New Society Publishers, Gabriola Island, BC; Philadelphia, PA, New catalyst bioregional series.

Wang, J., Dong, K., 2019. What drives environmental degradation? Evidence from 14 Sub-Saharan African countries. Sci. Total Environ. 656, 165–173. https://doi.org/10.1016/j.scitotenv.2018.11.354.

Wang, G., Fang, Q., Zhang, L., Chen, W., Chen, Z., Hong, H., 2010. Valuing the effects of hydropower development on watershed ecosystem services: Case studies in the

Jiulong River Watershed, Fujian Province, China. Estuar. Coast. Shelf Sci. 86, 363–368. https://doi.org/10.1016/j.ecss.2009.03.022.
Wang, Y., Wu, N., Tang, T., Cai, Q., 2022. Small run-of-river hydropower dams and associated water regulation filter benthic diatom traits and affect functional diversity. Sci. Total Environ. 813 https://doi.org/10.1016/j.scitotenv.2021.152566.
Wickham, H., Chang, W., Henry, L., Pedersen, T.L., Takahashi, K., Wilke, C., Woo, K., Yutani, H., Dunnington, D., 2022. ggplot2: Create Elegant Data Visualisations Using the Grammar of Graphics.
Wickham, H., 2022. tidyverse: Easily Install and Load the Tidyverse.
Wilson, E.O., 2016. Half-earth: our planet's fight for life. Liveright Publishing Corporation, a Division of w.w, First ed. Norton & Company, New York.
Winder, V.L., McNew, L.B., Gregory, A.J., Hunt, L.M., Wisely, S.M., Sandercock, B.K., 2014. Space use by female Greater Prairie-Chickens in response to wind energy development. Ecosphere 5. https://doi.org/10.1890/ES13-00206.1.
Yan, M., Fang, G.-H., Dai, L.-H., Tan, Q.-F., Huang, X.-F., 2021. Optimizing reservoir operation considering downstream ecological demands of water quantity and fluctuation based on IHA parameters. J. Hydrol. 600 https://doi.org/10.1016/j.jhydrol.2021.126647.
Zarco-González, Z., Monroy-Vilchis, O., Antonio-Némiga, X., Endara-Agramont, A.R., 2021. Land use change around hydroelectric dams using Landsat multi-temporal data: a challenge for a sustainable environment in Mexico. Geocarto Int. https://doi.org/10.1080/10106049.2021.1933212.
Zhang, P., Li, K.-F., Wu, Y.-L., Liu, Q.-Y., Zhao, P.-X., Li, Y., 2018. Analysis and restoration of an ecological flow regime during the Coreius guichenoti spawning period. Ecol. Eng. 123, 74–85. https://doi.org/10.1016/j.ecoleng.2018.08.009.
Zhang, S., Zhu, D., Zhang, J., Li, L., 2020. Which influencing factors could reduce ecological consumption? Evidence from 90 countries for the time period 1996–2015. Appl. Sci. (Switzerland) 10. https://doi.org/10.3390/app10020678.