The influence of the global electric power system on terrestrial biodiversity

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Given its total contribution to greenhouse gas emissions, the global electric power sector will be required to undergo a fundamental transformation over the next decades to limit anthropogenic climate change to below 2 °C. Implications for biodiversity of projected structural changes in the global electric power sector are rarely considered beyond those explicitly linked to climate change. This study uses a spatially explicit consumption-based accounting framework to examine the impact of demand for electric power on terrestrial vertebrate biodiversity globally. We demonstrate that the biodiversity footprint of the electric power sector is primarily within the territory where final demand for electric power resides, although there are substantial regional differences, with Europe displacing its biodiversity threat along international supply chains. The relationship between size of individual components of the electric power sector and threat to biodiversity indicates that a shift to nonfossil sources, such as solar and wind, could reduce pressures on biodiversity both within the territory where demand for power resides and along international supply chains. However, given the current levels of deployment of nonfossil sources of power, there is considerable uncertainty as to how the impacts of structural changes in the global electric power system will scale. Given the strong territorial link between demand and associated biodiversity impacts, development of strong national governance around the electric power sector represents a clear route to mitigate threats to biodiversity associated with efforts to decarbonize society over the coming century.

biodiversity | energy | climate change | conservation | sustainability

Human economic activity is exerting a profound influence on global biodiversity (1, 2) that has substantial implications for human wellbeing and society (3–5). However, over the last 50 y, understanding causal links between economic activity and environmental impacts has become increasingly difficult. A major reason for this is that globalization has created a spatial disconnect between the final consumption of goods and services and their production and the associated environmental impacts (6). This decoupling of production and consumption means that the drivers of environmental impacts, such as land use and land cover change (7), are in part attributable to demand from outside the country where impacts are occurring. Implications of this spatial decoupling have been explored predominantly for greenhouse gas emissions (8–10) but also, for water use (11), land use and cover change (12, 13), and material use (14) among others. A common finding is that developed countries often displace the environmental consequences of demand for goods and services along international supply chains to developing countries (1). In the case of biodiversity, across the global economy up to 30% of species threats are associated with international trade (1). From a policy perspective, this decoupling represents a substantial challenge in terms of assigning responsibility for biodiversity threats and implementing governance measures to address them (15, 16).

To date, research into the influence of the global electric power sector on biodiversity has primarily examined proximate drivers of biodiversity threat (17–21). Such studies highlight that both fossil and nonfossil sources of electric power have the potential to negatively impact biodiversity through various mechanisms. Given the electric power sector's contribution to greenhouse gas emissions (22), there is a critical need to identify options for transformation of the global electric power sector (23, 24) that are compatible with international targets to reduce greenhouse gas emissions (25) and the loss of biodiversity (26). Failure to integrate biodiversity and climate targets could lead to the adoption of energy pathways that address greenhouse gas emissions but undermine our ability to meet targets to improve the conservation status of species. For example, the majority of scenarios in the Intergovernmental Panel on Climate Change Fifth Assessment Report—based on a database of 1,184 transformation pathways—rely on biomass energy with carbon capture and storage (BECCS) to meet climate targets (27). Although this negative emission technology would limit the direct impact of climate change on species, the reliance on BECCS has raised questions about the implications for biodiversity associated with the required large-scale land use change for feedstock production (21, 28–30).

This study addresses a critical research gap by examining the relationship between biodiversity and the global electric power sector from a consumption-based perspective. As noted in the recent Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services report (5), transformation

Significance

Understanding the relationship between the global electric power sector and biodiversity is central to identifying sustainable pathways to decarbonization. This study examines the relationship between the global electric power sector and threats to biodiversity. The biodiversity footprint of the electric power sector is primarily within the territory where demand for power resides, although substantial regional differences exist. The relationship between supply technologies and threats to biodiversity indicates that a shift to some nonfossil sources could reduce pressures on biodiversity, although there is uncertainty in how threats will scale given current deployment levels of nonfossil sources. The strong territorial link between electric power demand and biodiversity threat provides clear routes for governments to effectively manage biodiversity impacts of electric power transitions.

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toward sustainability must take into account both the local impacts of economic activity and telecoupling (6): that is, the geographic displacement of impacts through international trade. To contribute to our understanding of the sustainability of different energy pathways, this study has 2 objectives: first, to examine the global electric power sector as a driver of threats to biodiversity, taking into account telecoupling, and second, to examine the empirical relationship between the size of different components of the electric power sector and threats to biodiversity. To address these objectives, we trace industrial sector-based threats to biodiversity across the international supply chains of 8 electric power sectors (that together compose the global electric power sector) using environmentally extended multiregional input–output analysis (MRIOA), a technique commonly used in footprinting. Following Lenzen et al. (1), for each of the 8 electric power sectors, we associate sector-based threats to species with the implicated commodities. These include threats from mining fuel sources, manufacturing power generation infrastructure (e.g., wind turbines and power stations), fuel processing, transportation, and distribution as well as broader links within the economy, such as those associated with service sectors.

Economic analysis is based on the Global Trade Analysis Project (GTAP) Power MRIO model that represents supply chain inputs and outputs of the entire global economy across 68 economic sectors within 140 countries and country groupings (subsequently, countries) in 2010 (31, 32). The GTAP Power disaggregates the global electric power sector into 8 individual sectors based on technology. These are nuclear, coal, gas, hydroelectric, wind, oil, solar, and other (which includes bioenergy and geothermal) (33). The analysis presented here considers both the electric power sector as a whole and each of the discrete electric power sectors representing different technologies for power generation. The size of the electric power sector(s) is represented in economic terms as required for MRIOA. Peters (33) provides a comprehensive methodology detailing the construction of unique electric power production structure for each technology and country.

Our focus on the electric power sector is justified, as in 2017, fossil fuels accounted for 64.5% of electricity production, primarily from coal and natural gas (34). The substantial role of fossil fuels means that the electric power sector accounts for over 30% of greenhouse gas emissions (22, 33, 35). Scenarios that explore routes to limit greenhouse gas emissions, therefore, project a substantial transformation of the electric power sector over the coming decades with decarbonization of electricity generation occurring at the same time as substantial growth in end use (24, 36). Indeed, the electric power sector is viewed as one of the easiest and most rapid sectors to decarbonize, meaning that there is a pressing need to understand the possible implications of this beyond benefits from reduced greenhouse gas emissions (36, 37).

Implications of the global electric power sector for biodiversity are based on 34,074 species/country/threat records derived from the International Union for Conservation of Nature (IUCN) Red List. The IUCN Red List is recognized as the most comprehensive resource on the conservation status of species globally (38). This analysis, using an adapted version of Lenzen et al. (1), is based on a spatially explicit measure of “fractional species threat” (1) that represents the sum of threats to biodiversity associated with the economic activity within focal countries and electric power sectors (*Materials and Methods* and *SI Appendix*, Fig. S1). The measure of fractional species threat reflects our understanding that the influence of an individual pressure on a species is complex, as interaction between factors, such as climate, agriculture, urbanization, natural resource exploitation, etc., may have a cumulative impact (7). Our approach, therefore, enables us to identify whether the threat to biodiversity from a country’s final demand for electric power resides territorially or is displaced internationally and whether biodiversity threats within a country are a result of domestic or international demand.

Results

The Global Electric Power Sector as a Driver of Threats to Biodiversity. In common with other footprinting techniques, results from our analysis enable us to enumerate for a focal country (e.g., the United States) the impact that final demand for electric power has on biodiversity, accounting for threats from the beginning of the production chain (e.g., extraction of raw materials, such as coal) to the end (final demand for electricity). By incorporating the global dimension of biodiversity threat along production chains, the method can provide insight into the sustainability of a country’s electric power sector. Our results distinguish between territorial impacts and international impacts for each focal country (e.g., the United States). Territorial impacts of demand for electric power are defined as the impact on biodiversity that occurs within the focal country itself to meet its own demand. In footprinting analysis, the international impact on biodiversity explicitly recognizes that, in a globalized world, international trade can create a disconnect between final demand and its environmental consequence. International impacts are, therefore, defined as impacts on biodiversity associated with demand for electric power that have been displaced outside the focal country along international supply chains.

Of the total threat to biodiversity associated with the global electric power sector, the majority (76.70%) was found to be territorial: that is, impacts on biodiversity are associated with economic activity in the countries where final demand for electric power resides. However, this aggregate global value hides substantial differences between countries and regions in the impact of the electric power sector on biodiversity (Fig. 1). Europe, as a region, has a greater international than territorial impact, with 57.77% of the biodiversity threat associated with Europe’s electric power sector displaced outside the region along international supply chains. Disaggregating from regions to countries, in total 47 of the 140 countries analyzed have an electric power sector with a greater international than territorial impact on biodiversity, the top 5 being Japan, the United States, China, India, and the United Kingdom (*SI Appendix*, Table S1).

Impacts on biodiversity can also be considered from an export production perspective. This is defined as the fractional species threat in a country that becomes embodied in goods and services that are exported to meet demand for electric power in other countries (Fig. 1). Latin America, as a region, has the highest export production impacts with 25.68% of biodiversity threat within the region embodied in goods and services that are primarily exported to Europe and North America to meet final demand for electric power there (Fig. 1). As with the consumption-based measure, this aggregate regional view hides substantial differences between countries. Colombia, Indonesia, Australia, South Africa, and the rest of Oceania are the top 5 countries in terms of the biodiversity impacts embodied in goods and services that are exported to meet demand for electric power elsewhere (*SI Appendix*, Table S1). In the case of Colombia and Indonesia, the biodiversity impact embodied in goods and services that are exported to meet international demand from the electric power sector is greater that the territorial impacts on biodiversity driven by their own electric power demand.

In addition to examining the geographic distribution of biodiversity threat associated with the electric power sector, the MRIO allows disaggregation of international supply chains to determine in which economic sectors biodiversity threat is embodied. This provides understanding of the impacts of activities most closely associated with electric power demand (e.g., extraction, refining, production, and operation) as well as upstream impacts embodied within the commodities

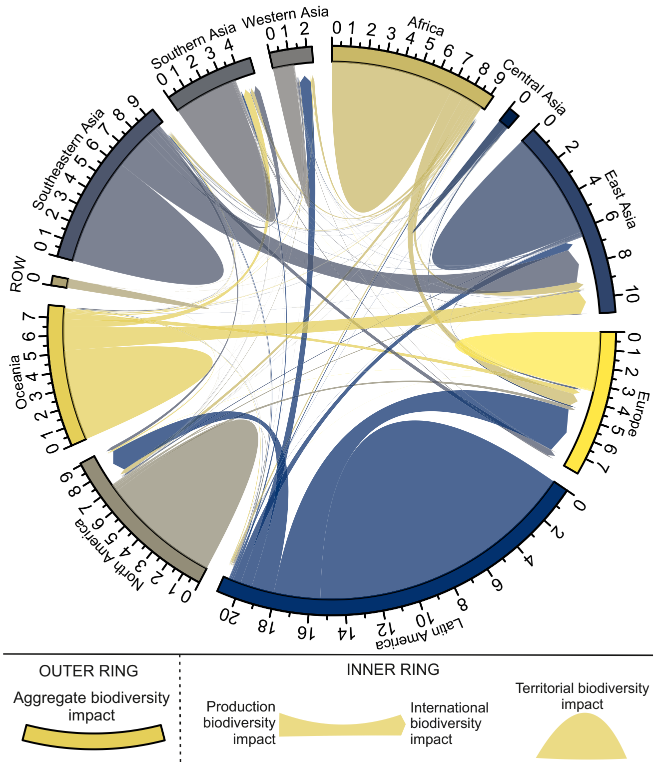

Fig. 1. Chord diagram depicting threats to biodiversity (expressed as fractional species threat) associated with the global electric power sector and transfer of threat between regions. The outer ring of the chord diagram represents aggregate threat to biodiversity associated with each region. This has 3 components depicted in the inner ring of the chord diagram. The territorial component is depicted as a hump shape, indicating the demand and impact on biodiversity that occur within the same focal region (e.g., North America). Arrows indicates flows of biodiversity threat. International impacts are depicted as the head of the arrow and illustrate the impacts on biodiversity that occur outside the focal region to meet demand for electricity within the focal region. The origin of the arrow depicts impacts on biodiversity associated with production activities in the focal region that are driven by demand for electricity in another region. From a consumption-based perspective, the impact of demand for electricity in a focal region is the sum of territorial (hump shape) and international (head of arrows) impacts. Total impact on biodiversity within a focal region is the sum of territorial (hump shape) and production for export (origin of the arrow) impacts. ROW, Rest of World.

(e.g., minerals) used in the manufacture of electric power technologies (e.g., solar panels, turbines, etc.) or associated with supporting services needed for operation (e.g., road infrastructure). For ease of interpretation, the 68 GTAP sectors are grouped into 6 categories: agriculture, domestic, energy, forestry, manufacturing, and supporting (*SI Appendix*, Table S2 shows detailed groupings).

Our analysis finds that activity most directly related to the electric power sector (grouped as energy) has a greater territorial than international impact on biodiversity for 110 of the 140 countries (Fig. 2). This contrasts with biodiversity impacts farther up the supply chain, where the international impacts are greater for domestic (112 countries), manufacturing (111 countries), agriculture (102 countries), forestry (96 countries), and supporting (88 countries) (Fig. 2) sectors. This trend is consistent when considered for individual electric power sectors (*SI Appendix*, Figs. S2 to S9); however, we note that, 1) for sectors within individual countries, this trend can be reversed and that 2) each country has both a territorial and international impact, with the balance differing on a country by country basis.

Relationship between the Size of Electric Power Sectors and Fractional Species Threat. Quantile regression (39, 40) was used to examine the relationships between the level of economic activity of each electric power sector and fractional species threat. Quantile regression enables estimates of relationships comparable with other techniques based on central tendency (i.e., the 0.50 quantile describes the relationship for the median) but also, provides insights into relationships at extremes (e.g., quantiles tau < 0.25 and > 0.75). In this study, such extremes are of interest, as they are indicative of the response of biodiversity threat to structural changes within electric power sectors (e.g., an increase in the size of the solar sector) and unmeasured variables that may ameliorate impacts of energy sectors on biodiversity.

Overall, there is a positive relationship between the size of each of the 8 electric power sectors and fractional species threat (Fig. 3). This relationship is consistent across all quantiles (Fig. 3 and *SI Appendix*, Table S2). Comparison of territorial and international impacts for the 8 electric power sectors at the median (i.e., tau = 0.50) provides a first-order understanding of the relationship between demand for electric power and biodiversity threat, and therefore, we initially consider results at this quantile

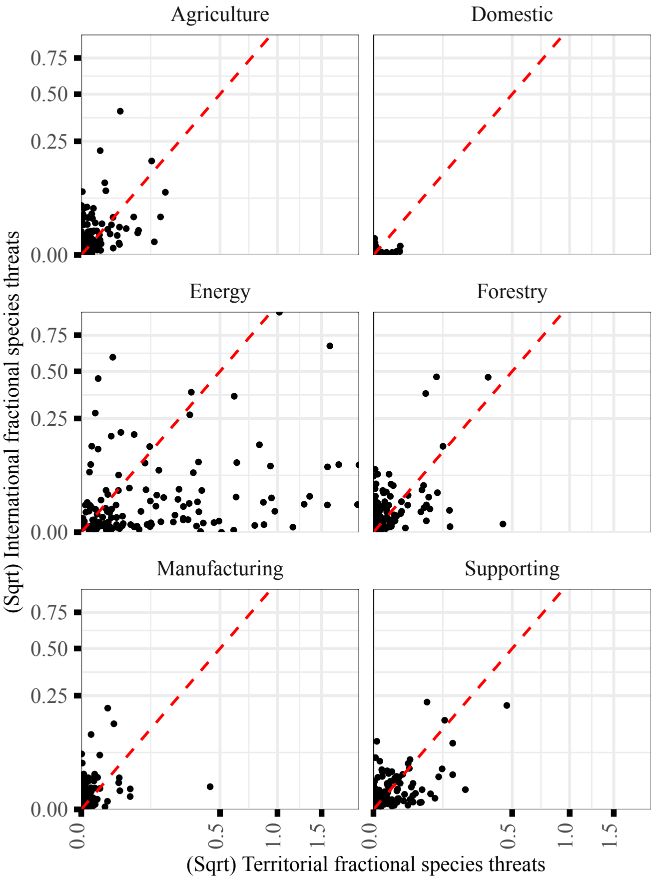

Fig. 2. The balance between territorial and international impacts on biodiversity for major groupings of economic sectors. Each point represents the biodiversity impact associated with demand for electric power in each of the 140 countries within the GTAP. The straight line represents a 1-to-1 relationship. Points below the line indicate that the country has a greater territorial than international impact on biodiversity associated with demand for its electric power sector. Points above the line indicate that the country has a greater international than territorial impact on biodiversity associated with demand for its electric power sector. Plotted data are square root-transformed values for fractional species threat. Due to differences in the size of electric power sectors, plot axes have been square root transformed to aid interpretation. Each point represents a different country (n = 140). Sqrt, square root.

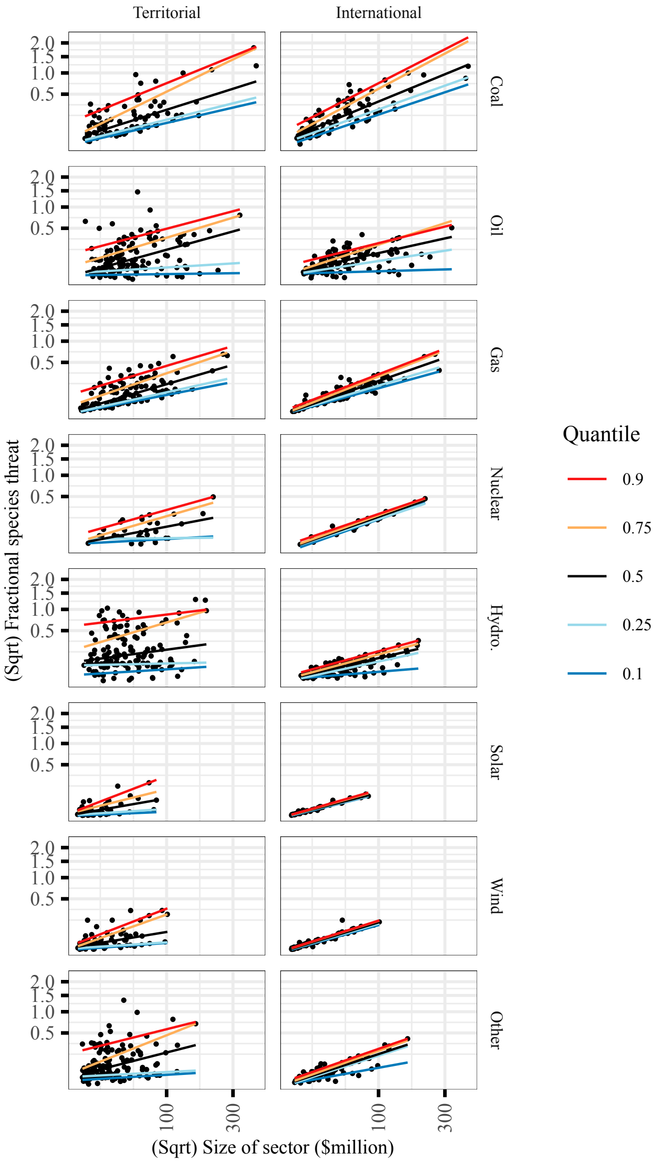

Fig. 3. Quantile regression indicating the relationship between economic size of each electric power sector and the international and territorial biodiversity impacts. All quantiles and sectors exhibit a positive relationship between economic activity and fractional species threat. Comparison of identical quantiles illustrates differences in rate of change of biodiversity threat with increasing size of the corresponding electric power sector. Differences between extreme quantiles indicate that there are unmeasured processes that lead to differing biodiversity impacts between countries for a given level of economic activity within the corresponding electric power sector. Due to differences in the size of electric power sectors, plot axes have been square root transformed to aid interpretation. Sqrt, square root.

(Fig. 4). Territorially, nuclear, solar, and wind were found to have the lowest level of fractional species threat across the range of economic activity associated with them. At low levels of economic activity within countries, hydroelectric power exhibits the highest level of fractional species threat of all of the energy sectors. However, the rate of change of fractional species threat associated with hydroelectric is lower than for the fossil and other electric power sectors such that, as economic activity increases to above $100 million, these latter sectors exert a greater impact on biodiversity. Internationally, again based on the median relationship (tau = 0.50) (Fig. 4), coal exerts the greatest threat to biodiversity across all levels of economic activity. Across the remaining electric power sectors, levels of fractional species threat are closely aligned at low levels of economic activity before diverging as the level of economic activity increases. This is driven by differing rates of change in the relationship between economic activity within electric power sectors and fractional species threat (*SI Appendix*, Table S2).

With respect to territorial impacts, across all quantiles the rate of change of the slope for the relationship between economic activity and fractional species threat is consistently highest for coal (*SI Appendix*, Table S2). For the remaining electric power sectors, the rate of change at lower quantiles (tau = 0.1 and 0.25) is next highest for gas, nuclear, and hydroelectric. At higher quantiles, the rate of change is next highest for other (tau = 0.75) and hydroelectric (tau = 0.90). Coal, oil, gas, hydroelectric, solar, wind, and other exhibit significant differences between extreme quantiles (e.g., tau < 0.25 and > 0.75) as shown by diverging lines in Fig. 3 (*SI Appendix*, Tables S3 and S4). This indicates an increasing rate of change in threat to biodiversity across the distribution.

Internationally, the rate of change of fractional species threat with increasing economic activity is again highest for coal across all quantiles. Of the remaining electric power sectors, there is more consistency in the order of the rate of change than found territorially. Gas, nuclear, and other exhibit consistently higher rates of change than the remaining electric power sectors across all quantiles. Hydroelectric and solar consistently exhibit the lowest rates of change. As with results from our territorial analysis, interquantile regression tests indicate that, for all electric power sectors, there are significant differences between extreme quantiles (Fig. 3 and *SI Appendix*, Table S4).

Together, results of our quantile regression can be interpreted in two ways. First, the positive relationships between economic activity and fractional species threat for all electric power sectors at all quantiles (e.g., tau = 0.90) indicates that growth in a specific electric power sector would be associated with an increase in biodiversity impact. However, differing rates of change between electric power sectors provide an indication of options for growth in generating capacity that will minimize impacts on biodiversity. This has important implications for climate policy that explores

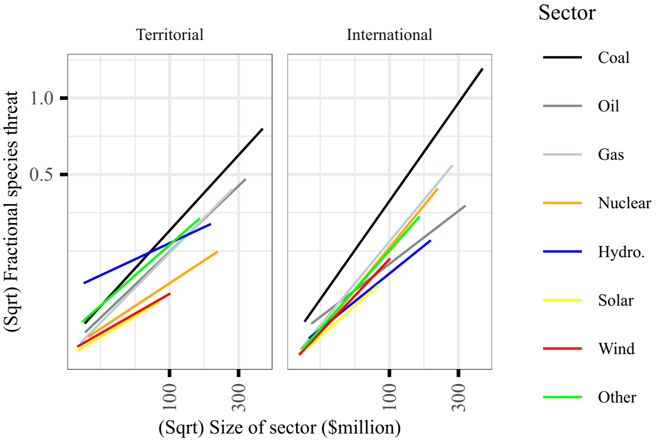

Fig. 4. Slope of quantile regression estimate for the median (tau = 0.50) describing the relationship between size of each electric power sector and territorial and international impacts on biodiversity. Plotted data are square root-transformed values for fractional species threat. For a given level of economic activity, the order of the lines from top to bottom indicates which sector has the greatest impact on biodiversity. Change in this order is driven by differing rates of change in the relationship between increasing economic activity within electric power sectors and fractional species threat. Due to differences in the size of electric power sectors, plot axes have been square root transformed to aid interpretation. Sqrt, square root.

structural changes in the global electric power system. Second, differences between extreme quantiles indicate that there are unmeasured processes that lead to differing biodiversity impacts between countries for a given level of economic activity within an individual electric power sector. These could be governance or technology related or may arise through ecological processes, such as patterns of global species richness that will determine exposure of species to economic activity associated with electric power sectors.

Discussion

The results of our study have important implications for transformation of the global electric power sector to reduce greenhouse gas emissions. The impact on biodiversity of economic activity directly related to the electric power sector is primarily within the country where final demand for power occurs (Figs. 1 and 2). This contrasts with much of the literature relating to consumption-based accounting that highlights the disconnect between consumers and their environmental impacts (12, 14, 41) and the barrier that this places in terms of consumer responsibility (15, 16). In demonstrating an overall trend toward territorial impacts (Figs. 1 and 2), notably in activity most directly related to the electric power system (Fig. 2), results from this study indicate a strong link with consumers. As discussed in previous studies (42–45), adoption of best practice in relation to technology, the environment, and governance can help mitigate the nonclimate impact of electric power production on biodiversity. Given the strong territorial link, countries have a far greater incentive and ability to manage impacts of electric power demand than exist in other sectors, where a higher proportion of impacts is displaced internationally.

With respect to how structural changes in the global electric power sector will impact biodiversity and the implications of this for identifying pathways to decarbonization, our results are more equivocal. Economic value of each of the 8 electric power sectors considered in this study is strongly correlated with the size of the sectors in gigawatt hours per year (*SI Appendix*, Fig. S10). This is because the economic size of the sector is calculated as a function of the power output of the sector and the levelized cost of generation (33). As global reliance on fossil sources of electric power (notably coal) decreases, results from our quantile regression indicate that there will be a corresponding decrease in threat to biodiversity (Fig. 3). In the short term, benefits will be realized through a reduction in activities relating to extraction, processing, and distribution and the associated environmental impacts that threaten species (45, 46). Longer term, biodiversity may benefit as areas are restored (47) or through mechanisms, such as legacy infrastructure, providing habitat (48), although there are substantial uncertainties about the realized benefits of decommissioning (49).

There is considerable uncertainty in how impacts on biodiversity associated with nonfossil sources will scale beyond the current size of nonfossil sectors. While the last decades have seen a sharp rise in the contribution of nonfossil sources of electric power to the global electric power sector, fossil sources still dominate (50). Pathways to decarbonization identified in numerous scenario exercises suggest that growth in nonfossil sectors will increase far beyond current levels. Although results from our quantile regression indicate that the solar and wind sectors often have lower rates of change of biodiversity threat than other electric power sectors, their comparatively small size makes it difficult to extrapolate with much confidence how impacts might scale. A number of previous studies, primarily focused on bioenergy, have suggested that benefits to biodiversity may initially accrue compared with fossil sources but that there are tipping points, whereby large-scale concentrated deployment has a negative impact through mechanisms such as homogenization of the landscape (19, 51, 52). Nonfossil electric power sources, such as bioenergy, wind, hydroelectric, and solar, have substantial spatial footprints associated with both the technologies themselves and the infrastructure required to service them (53). As change in land use and land cover is a leading threat to biodiversity (54), transformation of the electric power sector over the coming decades may have substantial negative impacts.

As a result of this uncertainty around scaling of biodiversity impacts, future energy pathways that envisage shifts toward nonfossil sources of electricity must consider direct impacts on biodiversity. Given that, for many countries, our analysis found that impacts of electric power sectors on biodiversity were greatest territorially, nations have an opportunity to ameliorate the impacts of energy policy by incorporating detailed local-scale biodiversity data to inform the decision-making process. For example, areas, such as the Sahara and Sahal, have been identified as having substantial potential for generation of renewable electric power from solar and wind given their climate and proximity to Europe, the Middle East, and sub-Saharan Africa (55). Modeling studies have demonstrated that large-scale deployment in this region could deliver climate benefits by reducing greenhouse gas (GHG) emission from fossil fuels and would lead to important shifts in both rainfall and vegetation patterns that could deliver societal benefits, such as increased agricultural production (55). However, the biodiversity of the Sahara and Sahel region (and desert regions in general) is often overlooked, with a recent study reporting a catastrophic decline in megafauna in this region (56). The few studies that have examined the impacts of large-scale solar farms on wildlife globally have reported that substantial mitigation is often needed to reduce the impacts on species (17, 18).

To place our analysis in an international context, a number of authors have noted that there is the potential for incompatibility between United Nations Sustainable Developments Goals (UN SDGs) (57, 58), which include targets for biodiversity (UN SDG Goal 15), energy (UN SDG Goal 7), and climate (UN SDG Goal 13). Given the strong territorial component, our analysis indicates that countries have a greater ability and incentive to effectively manage transformation of their electric power sector, ensuring compatibility with other globally agreed targets, such as those relating to biodiversity. This calls for regulation and strong governance within countries but also, for the transfer of knowledge and technology relating to electric power sectors between countries to facilitate best practice in minimizing impacts on biodiversity. Much of global biodiversity is situated in countries where future demand for electric power is likely to increase most rapidly and in which the highest potential for deployment of nonfossil sources exists (21). Results of our interquantile comparisons suggest that there are opportunities to scale reliance on nonfossil sources of electric power in such a way as to minimize implications for biodiversity. Ultimately, successful transformation of the global electric power sector should be judged not only on achieving emission reduction targets but also, on the wider environmental implications of the actions that we take to meet them.

Materials and Methods

The GTAP-MRIO Table. The GTAP constructs a database of harmonized country/region input–output tables and trade data between nations on a regular basis (31, 32). The GTAP Power, the version used in this analysis, is constructed from 2010 global economic data containing domestic and international monetary transactions between 68 economic sectors and final consumers (made up of mainly households and government) across 140 countries/regions following the method outlined in refs. 33 and 59. This includes a disaggregated electricity sector from the original GTAP database. Trade data between countries/regions are prioritized, and input–output tables make the links between the trade sets. This compiles a global database of monetary transactions describing bilateral trade patterns, production, consumption, and intermediate use of commodities and services. A number of global MRIO models are available (60), with the current choice based on the disaggregation of the electricity sector, as this is the primary focus of our research.

Creating a Satellite Account of Biodiversity Impacts. *SI Appendix*, Fig. S1 provides a schematic representation of the steps taken to construct our biodiversity indicator. Information on biodiversity is based on the distributions of 3,916 amphibians (61), birds (62), and mammals (63) coded in the IUCN Red List (64) into 1 of 3 categories: critically endangered, endangered, or vulnerable.

The first step in our analysis was to establish the relationship between each of the IUCN threat categories, independent of species, and each of the 68 economic sectors within the GTAP database. Our species database contained threats to species across 226 IUCN threat categories attributable to a mixture of human (e.g., agriculture) and natural (e.g., natural disasters) processes. Detailed reading of the IUCN documentation relating to threat categories (65) allowed us to establish a link between 155 IUCN threats and the corresponding GTAP sectors, with the remaining threat categories not being represented, primarily as they relate to natural processes. Following the method and nomenclature of ref. 1, data were stored in binary K × C concordance matrix $\mathbf{B_1}$, assigning a value of 1 to those industrial sectors that corresponded directly to each threat. Here, K = 155 IUCN threats, and C = 68 economic sectors. Matrix $\mathbf{B_1}$ was postmultiplied with C × T concordance matrices $\mathbf{B_2}^{(c)}$ that relate sectors to countries. This yields 140 K × T binary concordance matrices $\mathbf{B}^{(c)}$ linking IUCN threats to sectors in the 140 countries/regions represented in the GTAP database.

The second step of the analysis normalized $\mathbf{B}^{(c)}$ to $\mathbf{N}^{(c)}$ using two different forms of weighting. For climate change, GHG emissions per industrial sector were used, and in all other cases, industrial output (millions of US dollars) was used. This normalization step ensures that the rows of the concordance matrix $\mathbf{N}^{(c)}$ sum to 1 to prevent multiple counting of IUCN threats.

The third step of the analysis relates to processing of the Red List records. Here, IUCN individual species records are linked to corresponding entries $\mathbf{N}^{(c)}$. The resultant matrix **C** describes the relationship between each individual entry of species/country/threat within the IUCN database and the corresponding country/sector represented in $\mathbf{N}^{(c)}$. Matrix **C** is then aggregated by entries referring to the same country/species record to create matrix $\mathbf{C_{ag}}$. Rows within this matrix refer to country/species, and columns refer to the corresponding country/sectors that are attributed to the threats. In an advance of the approach used by Lenzen et al. (1), alternative processing of data was carried out to weight $\mathbf{C_{ag}}$ by the extent of occurrence of each individual species (66, 67) and overlap with areas of economic activity (65) to create matrix **R**. In the original method, matrix **R** assumed equal weighting. Extent of occurrence has previously been incorporated into similar analysis by Moran and Kanemoto (68), who used such an approach to pinpoint hotspots of threatened species based on species overlap. Our analysis further advances this by utilizing data on human population pressure (population density), human land use and infrastructure (built-up areas, night-time lights, land use/land cover), and human access (coastlines, roads, railroads, navigable rivers) captured within the Global Human Influence Index (69). As such, an individual threat to a species is represented as a function of the distribution of the species (e.g., the proportion of the species range in each country) and the intensity of human influence within that range as measured by the Global Human Influence Index and is normalized to 1.

The final step of the analysis aggregates matrix **R** based on species identity to produce a new matrix $\mathbf{R_{ag}}$, which describes species threats against exerting sectors. This matrix conforms to the standard format required for EE-MRIO analysis.

EE-MRIO Analysis. In the environmentally extended input–output analysis presented here, threats to biodiversity induced by GTAP Power sectors are reallocated through complex supply chains to the finished products in which they become "embodied" using the standard input–output equation originating from Leontief (70) and used by many in footprint analysis. Within our EE-MRIO model, fractional species threat for a focal country/region is the sum of embodied biodiversity threats for that country/region resulting from absolute demand for finished products from all 68 GTAP sectors. For an individual GTAP electric power sector (e.g., wind) within the focal country/region, fractional species threat in the final product provided by the sector can be traced back to the sectors and countries/regions that threaten biodiversity using standard input–output techniques.

Formally, environmentally extended input–output analysis enables calculation of total fractional species threat associated with final demand for a product using the equation $\boldsymbol{F} = \boldsymbol{f_x}\mathbf{Ly}$. Here, $\boldsymbol{F}$ is total fractional species threat of consumption, $\boldsymbol{f_x}$ is a measure of direct fractional species threat per dollar of sectorial output, **y** is the specific demand, and **L** is the Leontief inverse $(\boldsymbol{I} - \boldsymbol{T}\hat{x})^{-1}$ of the multiregion input–output table $\boldsymbol{T}$ that describes the global supply chain network. Multiplying the sectorial production requirements globally **L** by the fractional species threat of each sector $\boldsymbol{Fx}$ for the specified demand **y** calculates total fractional species threat $\boldsymbol{F}$. The spatial distribution of fractional species threat can be calculated globally, $\boldsymbol{F_{\mathrm{total}}}$, for a region demand, such as the United States ($\boldsymbol{F_{\mathrm{USA}}}$), or demand for a specific commodity, such as petroleum ($\boldsymbol{F_{\mathrm{P}}}$). From this equation, it can be calculated that, for example, demand for petroleum $\mathbf{y_p}$ not only impacts within biodiversity the petroleum sector itself but also, drives threats to biodiversity associated with other sectors worldwide required as inputs upstream in the production of petroleum, representing the global supply chain network described by the multiregion input–output table $\boldsymbol{T}$.

For each of the 140 countries/regions represented in the EE-MRIO, we calculated fractional species threat for 8 electricity sectors: coal, oil (combined base and peak), gas (combined base and peak), nuclear, hydroelectric (combined base and peak), solar, wind, and other (which includes waste, bioenergy, geothermal, and tidal). Similarly, we extract the economic value aggregated to these 8 electric power sectors (millions of US dollars) for use in subsequent analysis. Economic value of the electric power sectors is strongly correlated with the size of the sectors in gigawatt hours per year (*SI Appendix*, Fig. S10), as it is constructed based on the power output of that sector and the levelized cost for the production of 1 unit of energy (33).

Statistical Analysis. The second stage of the analysis, presented in Figs. 3 and 4, used quantile regression (40) to examine the relationship between the economic size of each electric power sector and territorial and international fractional species threat. In contrast to ordinary least squares methods that provide a conditional mean estimate, quantile regression has the advantage of estimating conditional quantiles, providing a robust estimator to outliers. This is of interest when the response variable can exhibit heterogeneous variability to the covariates, implying the importance of considering extreme bounds of the distribution.

Prior to quantile regression for each of the possible combinations of electric power sector and territorial/international impact, the log-likelihood function was used to determine the value of lambda within the Box–Cox family of power transformations. Calculated values for lambda were typically in the range of 0.3 to 0.7 based on the maximum log likelihood for obtaining minimum sum of squared errors. Based on this, for interpretability, a square root transformation was performed on the data. Quantile regression analysis with values of tau of 0.10, 0.25, 0.5, 0.75, and 0.90 representing the corresponding percentiles (e.g., tau 0.10 equals the 10th percentile) was then performed to examine the relationship between economic size of each electric power sector and fractional species threat. Following calculation of quantile regression coefficients, a Wald test was computed to test for significant differences between quantiles (71, 72).

Data Access. The biodiversity data used in this analysis are freely available from the IUCN and Birdlife International at https://www.iucnredlist.org/. Economic data from the GTAP are not freely available but can be obtained from https://www.gtap.agecon.purdue.edu/. Code used in analysis is available on request.

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