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A spatial and temporal assessment of energy development around wilderness areas

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ABSTRACT

Global efforts to protect biodiversity have fallen short and global threats, including energy development, are prevalent. Assessing impacts of energy development helps determine if protected areas, particularly wilderness areas, can conserve biodiversity, natural habitats, and sustain ecological processes inherent in ecosystems. We quantified the amount of energy development around wilderness areas, evaluated rate of change in energy development, assessed if nearby public land provides a safeguard from energy development, and identified wilderness areas surrounded by the most energy development. We compiled national and regional data on non-renewable and renewable energy development. Across all wilderness areas, 52.8 % had ≥1 power plant or coal mine nearby. More renewable energy power plants occur around wilderness areas than non-renewable. Among all energy leases, oil and gas and wind power leases occur most often around wilderness areas. During 1990–2015, the number of oil and gas wells around wilderness areas increased by 43.5 %. Wilderness areas surrounded by >75 % public land were as likely to have a power plant or coal mine nearby as those with <25 % public land. Wilderness areas ranked highest for number of power plants or coal mines nearby occurred mostly (77 %) in the western U.S. With the continued demand for energy, wilderness areas will continue to be influenced by energy development. Our research can inform the stewardship of wilderness areas and shows that despite their remote location and strong legal protection, wilderness areas are threatened by the increasing presence of energy development in surrounding lands.

1. Introduction

Globally there have been numerous efforts to protect biodiversity, including the Aichi Biodiversity Targets initiated by the Parties to the Convention on Biological Diversity (CBD, 2010). However, these efforts have fallen short of their goals and threats to sustaining biodiversity are persistent and increasing (Convention on Biological Diversity (CBD), 2020a; Jones et al., 2018; Rehbein et al., 2020). One of these persistent threats, energy development, is occurring worldwide in and around protected areas, but little is known about the extent to which this development is influencing the biodiversity, natural habitats, and ecological processes within protected areas (Finer et al., 2008; Popescu et al., 2020; Rehbein et al., 2020; Thieme et al., 2020). Worldwide, the number of protected areas and wilderness areas impacted by an increased interest in renewable energy development has risen by about 30 % and 60 %, respectively (Rehbein et al., 2020). Iceland produces about 87 % to nearly 100 % of its energy from renewable energy resources and is the 16th largest producer of renewable energy in Europe (National Energy Authority, 2020; Sæþórsdóttir and Ólafsdóttir, 2020). However, wilderness areas are diminishing because of renewable energy development (Sæthórsdóttir et al., 2011; Sæþórsdóttir and Ólafsdóttir, 2020). Additionally, there are global efforts to expand non-renewable

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energy development in places such as the Amazon where more than two-thirds of western Amazon within Ecuador and Peru are zoned for oil and gas development (Finer et al., 2008). The areas of non-renewable energy expansion in the Amazon also contain the highest diversity of mammals, amphibians, and birds and have already been impacted by non-renewable energy development, such as deforestation and oil spills (Finer et al., 2008).

Energy development is integral to domestic prosperity in many countries because of the daily reliance on energy and its strong ties to the national economy, but it comes at a cost to protected areas, including wilderness areas (Rehbein et al., 2020; Sæórsdóttir and Saarinen, 2016). Wilderness areas are an integral part of protected area networks worldwide and even though perceptions of wilderness areas vary globally there is often a theme of uninhabited or undisturbed nature (Sæthórsdóttir et al., 2011; Tverijonaite et al., 2019). In the U.S, wilderness areas were designated by The Wilderness Act, which was intended to preserve wilderness areas as "untrammeled by man" and "protected and managed so as to preserve…natural conditions" (U.S. Public Law 88-577). Even though energy development is not allowed inside wilderness areas in the U.S., indirect impacts include permanent alteration of surrounding land and water as well as loss of core habitat through habitat fragmentation and habitat loss, and carbon emissions that contribute to climate change (Fig. S1, Aycrigg et al., 2022a; Martinuzzi et al., 2015; Thieme et al., 2020). Furthermore, in a survey of wilderness managers, energy development was recognized as a potential threat to wilderness areas (Dawson et al., 2016).

The U.S. in its efforts to become more energy independent has invested in renewable energy development, such as wind, solar, and hydroelectric. However, development of non-renewable energy sources, such as natural gas, petroleum, and coal, persists and continues to dominate the energy consumed and produced in the U.S accounting for 79 % of the total energy production in 2021 (Jones and Pejchar, 2013; EIA, 2021). Renewable energy sources are more sustainable and potentially more environmentally benign when compared to non-renewable energy (Popescu et al., 2020). Nonetheless, there are impacts, such as carbon emissions and amount of land altered for energy production (i.e., energy sprawl), associated with developing both types of energy (i.e., renewable, and non-renewable). Impacts from energy development include roads around wind farms, dams for hydroelectric energy, and habitat destruction from extraction methods (Fig. S1, Jones and Pejchar, 2013, Popescu et al., 2020, Thieme et al., 2020). For instance, in British Columbia, the impact of wind farms was considered lower than hydroelectric dams because less spatial overlap occurred with vertebrate species distributions and intact landscapes (Popescu et al., 2020).

The level of protection for public land in the U.S. varies from preserving natural conditions within protected areas, such as within wilderness areas, to providing multiple uses, such as protection from permanent alteration, but allowing for extractive uses including energy development (Aycrigg et al., 2013; Fox and Hahn, 2016). The Bureau of Land Management (BLM) and USDA Forest Service manage most of the multiple-use land in the U.S., with BLM mainly managing lands in the western U.S. (Aycrigg et al., 2013; Riley et al., 2012). One of the multiple uses overseen by BLM and USDA Forest Service is the development of oil and gas energy resources with about 88 % of federally managed public lands containing leases for oil and gas development. Solely within the Rocky Mountain region of the western U.S. there are >445,000 km^2 (~31 %) of public land in which recoverable oil and gas reserves occur (Riley et al., 2012). However, the extent of energy development including leases around wilderness areas has not been evaluated.

Human disturbance related to energy development in areas surrounding wildernesses leads to habitat fragmentation and isolation, which influences biodiversity, natural habitats, and ecological processes (Finer et al., 2008; Rehbein et al., 2020). Within a 10-km buffer around wilderness areas, 68.3 % is public land, which is mostly comprised of multiple-use land (80.5 %) managed by BLM land (27.3 %) and USDA Forest Service land (53.2 %; Aycrigg et al., 2022a). Energy development and leases on multiple-use land managed by BLM and USDA Forest Service may lead wildlife to seek out and increasingly rely on wilderness areas (Gray et al., 2016). Furthermore, undeveloped areas surrounding wilderness areas could provide a buffer to the influence of energy development and aid in conserving biodiversity (Belote and Wilson, 2020). Aycrigg et al. (2022a) found the amount of public land surrounding wilderness areas was not correlated to the projected percent increase in land use (e.g., agriculture, clear cutting) based on forecasts of land use change. However, energy development was not included as a variable in their projections and multiple-use lands were static in their land-use forecasts. Thus, a key question is whether the amount of public land around wilderness areas acts as a safeguard from energy development.

Both renewable and non-renewable energy development occurs where the most energy can be extracted or gathered (Popescu et al., 2020). Sources of energy are not distributed evenly across the U.S., which means energy development will be focused on specific regions and will occur more often around specific wilderness areas (Copeland et al., 2011). Using a multivariate metric of future change to rank wilderness areas, Aycrigg et al. (2022a) projected 32 wilderness areas will undergo the most land use, land cover, and climate change by 2050. This information informs current and future wilderness management and can slow or halt the projected change. Similarly, ranking wilderness areas surrounded by the most energy development will inform the balance between conserving biodiversity and its habitat with the energy demands of the U.S.

Assessing the impacts of energy development is vital to understanding if protected areas, particularly wilderness areas, can conserve biodiversity, natural habitats, and sustain ecological processes inherent in undeveloped ecosystems. Therefore, our goal is to quantify the amount of energy development, including leases around wilderness areas and the rate of change in energy development around wilderness areas over time. Our objectives are to (1) assess the amount (i.e., number, density, and percent area) of energy development (e.g., non-renewable and renewable) including energy leases within 10-km and 20-km buffers around wilderness areas, (2) evaluate how energy development has changed over time, (3) evaluate if wilderness areas are buffered from energy development by percent public land surrounding them, and (4) identify individual wilderness areas with the highest amount (i.e., number, density) of energy developments in the surrounding area. We used the term energy development to refer to power plants, coal mines, energy leases, and oil and gas wells.

2. Materials and methods

2.1. Data description

2.1.1. Wilderness areas

We obtained boundaries for all wilderness areas within NWPS for the contiguous U.S. (CONUS) from Wilderness Connect (https://www.wilderness.net/; accessed April 2017). This included all wilderness areas managed by federal agencies (i.e., U.S. Fish and Wildlife Service, USDA Forest Service, BLM, and National Park Service), which totaled 714 wilderness areas. Although some wilderness areas are split by managing agency (i.e., USDA Forest Service and BLM), we grouped wilderness areas by name for our analysis.

2.1.2. Energy

We obtained data on renewable and non-renewable energy from multiple sources to assess the amount of energy development occurring in proximity to wilderness areas. For our purposes, we designated energy development to include power plants, coal mines, energy leases, and oil and gas wells.

At the national scale we obtained energy data from the U.S Energy Information Administration (EIA, 2018). The non-renewable energy data included coal mines and coal, natural gas, and petroleum power plants. The renewable energy data included biomass, geothermal, hydroelectric, pumped storage, solar, and wind power plants. All the power plants included, which were point location data, have a capacity of >1 MW and are operating on standby, temporarily out of service, or permanently out of service (EIA, 2018). Energy from biomass refers to any source of heat energy from non-fossil biological materials (e.g., wood pellets, agricultural crops, municipal solid waste) which are burned to generate heat and electricity (Field et al., 2007, EIA, 2018). Geothermal (i.e., heat from within the Earth) power plants use hydrothermal resources (i.e., water and heat) from dry steam wells or hot water wells to power a turbine to generate electricity (EIA, 2018). Hydroelectric power plants rely on water to generate electricity and are typically located on or near a water source (EIA, 2018). Pumped storage is a type of hydroelectric storage in which water is pumped from a lower altitude to a higher altitude water source and then released to flow down to the lower altitude water source to power hydro turbines and generate energy (EIA, 2018). Also at the national scale, we obtained summarized oil and gas well head information (i.e., point location data) scale on federal and state public lands from WhiteStar Corporation (https://www.whitestar.com).

We obtained leases (i.e., polygon data) for energy (e.g., non-renewable, and renewable) on land managed by the BLM across the western U.S. (LR2000 reports, https://reports.blm.gov/reports/lr2000/). These data were aggregated and supplied by The Wilderness Society as part of their Federal Land Use and Transparency Tool (FLURTT).

2.1.3. Public lands

To evaluate if wilderness areas are buffered from energy development by percent public land in the surrounding 10-km and 20-km buffers, we used the geodatabase PAD-US (Version 1.4), which is an inventory of public land and private protected areas, to assess the amount of public land surrounding wilderness areas (USGS, 2016). Public lands included land managed by federal and state agencies (e.g., BLM and state natural resource agencies). We used PAD-US to calculate the total area of public land within each 10-km and 20-km buffer surrounding wilderness areas (USGS, 2016). We included public land designated as protected or multiple use.

2.2. Data analysis

2.2.1. Wilderness area buffers

To quantify the number, density, and percent area of energy development surrounding wilderness areas, we used two buffer distances, 0–10 km, and 0–20 km. These buffer distances provide two different scales of impact for evaluating energy development by providing a contrast between energy development occurring immediately around wilderness areas, and energy development occurring in the vicinity and potentially beyond adjacent public lands with protected status. Furthermore they have been effective in assessing land use change near protected areas in the U.S. and other countries and have been used in previous assessments of land use and land cover change around wilderness areas (Arturo Sánchez-Azofeifa et al., 2002; Aycrigg et al., 2022a; Gaveau et al., 2009; Martinuzzi et al., 2015). Buffer area was our unit of analysis, and each buffer area was treated independently even if buffer areas overlapped between wilderness areas.

2.2.2. Energy data analysis

To estimate the amount of energy development around wilderness areas (i.e., objective 1), we intersected the locations for non-renewable and renewable power plants obtained from EIA with our 10-km and 20-km buffers surrounding wilderness areas (EIA, 2018). Total number and density for each type of non-renewable and renewable power plant were summarized for each wilderness area buffer. If a single power plant occurred in more than one wilderness buffer, we included it in the count for all wilderness areas with which it intersected.

In addition, we quantified and reported the percent area of energy leases (renewable and non-renewable) around wilderness areas based on BLM energy lease data (i.e., polygon data). We evaluated energy leases separately from power plants and coal mines because the features differ spatially (i.e., points vs. polygons). We calculated the percent area of each buffer on which energy leases have occurred over the last approximately 100 years up to 2020. For our analysis, we designated open leases as leases that were either active or pending and included closed leases because these leases may have been open and active in the past and could be opened again in the future.

We recognize that even though we have energy lease data going back about 100 years, wilderness areas were not legally designated until 1964. Past energy leases may not influence the designation of wilderness areas, but their presence in the vicinity of wilderness areas could influence the current or future ecological integrity of wilderness areas to conserve biodiversity, natural habitats, and sustain ecological processes in undeveloped ecosystems. Additionally, current and future energy leases can occur in the same location as past energy leases.

To assess the cumulative impacts of energy development over time, we evaluated how the development of oil and gas wells has changed over time using point location data summarized across each buffer area (i.e., 10-km and 20-km) around each wilderness area (i.e., objective 2). We calculated the total number and density (i.e., number of wells/km^2) of oil and gas wells for 1990, 2000, 2010, and 2015. This indicated how the number and density of oil and gas wells have cumulated during 1990–2015. For our analysis, we used drilled oil and gas wells to assess the number and density of wells surrounding each wilderness area.

We recognize there are a wide range of types and ages of oil and gas wells, which have different impacts on the area surrounding wilderness areas, but we believe the nationwide oil and gas wells data used here provides a reasonable and conservative representation of those impacts.

2.2.3. Public land analysis

We calculated the total area of public land within each 10-km and 20-km buffer surrounding wilderness areas based in PAD-US (USGS, 2016; objective 3). To assess if public lands buffered wilderness areas from energy development, we evaluated the total area of public land surrounding wilderness areas with the density of power plants and coal mines in the 10-km and 20-km buffers using data from the U.S Energy Information Administration. We used a regression analysis and calculated coefficients of determination (i.e., R^2 values). If public lands are buffering wilderness areas from surrounding energy development, we would expect fewer power plants and coal mines occurring in the 10-km and 20-km buffers with more public land area.

2.2.4. Ranking analysis

We ranked wilderness areas to identify individual wilderness areas with the highest number and density of energy development (i.e., power plants and coal mines) in the vicinity (i.e., objective 4). To explore patterns around wilderness areas we highlighted wilderness areas with the highest number and density of power plants and coal mines based on EIA data in each of four categories. The four categories were (1) non-renewable within 10-km buffer, (2), non-renewable within 20-km buffer, (3) renewable within 10-km buffer, and (4) renewable within 20-km buffer. Even though we highlighted the wilderness areas with the highest number and density of power plants and coal mines in the vicinity, our data can be used to rank all wilderness areas in each of these four categories.

3. Results

3.1. Wilderness areas and surrounding buffers

We included 714 wilderness areas in our analysis around which we created 10-km and 20-km buffers (Fig. S2). These 714 wilderness areas total 21,976,268 ha in CONUS. Most wilderness areas occur west of the Mississippi River (n = 563) with California having the highest number of wilderness areas (n = 149) and total area of wilderness (6,055,900 ha; Aycrigg et al., 2022b). Wilderness areas plus the 10-km and 20-km buffers included 11.8 % and 25.8 % of the total area of CONUS.

3.2. Energy development around wilderness areas

There were 192 (26.9 %) wilderness areas with at least 1 power plant or coal mine within 10-km and 377 (52.8 %) within 20-km. Coal mines, coal power plants, and petroleum power plants occurred rarely around wilderness areas (Fig. 1). However, natural gas power plants were the most common among non-renewable power plants with the highest number occurring in the southwestern U.S. (Fig. 1). Even though the number of wilderness areas with ≥6 non-renewable power plants or coal mines was low, more wilderness areas in the southwest had ≥6 natural gas power plants within 20-km than anywhere else in the U.S. (Fig. 1, Table S1). The Great Swamp National Wildlife Refuge Wilderness in New Jersey had 7 natural gas power plants within 20 km, which is the highest number in the eastern U.S. (Fig. 1, Table S1). While no other wilderness areas had ≥6 coal mines within 10-km or 20-km, the Stone Mountain Wilderness in Virginia was a notable exception, having 16 coal mines within 20-km (Fig. 1, Table S1).

Our results showed that 175 (24.5 %) wilderness areas had ≥1 renewable energy power plant within 10 km and 332 (46.5 %) within 20 km. Among the renewable energy power plants, biomass and geothermal power plants occurred rarely around wilderness areas (Fig. 1). Solar and wind power plants near wilderness areas were more common particularly within the southwestern U.S. (Fig. 1). However, Great Swamp National Wildlife Refuge Wilderness in New Jersey had the most solar power plants within 20 km (n = 31; Table S2). Hydroelectric power plants had the highest number of power plants within the 10-km and 20-km buffers surrounding wilderness areas among renewable energy power plants (Fig. 1). Most hydroelectric power plants occurred near wilderness areas along the west coast (i.e., California, Oregon, and Washington) with several also in the intermountain west (i.e., Colorado and Utah), northeastern (i.e., Vermont), southeastern (i.e., Tennessee), and the upper midwestern (i.e., Wisconsin) U.S.

Eight wilderness areas had >7 either non-renewable power plants, coal mines, or renewable power plants within 10 km and 45 within 20 km (Table S3). However, across all wilderness areas, the number of renewable energy power plants surrounding wilderness areas was higher than non-renewable for both buffer distances (Fig. 2, Tables S1 and S2).

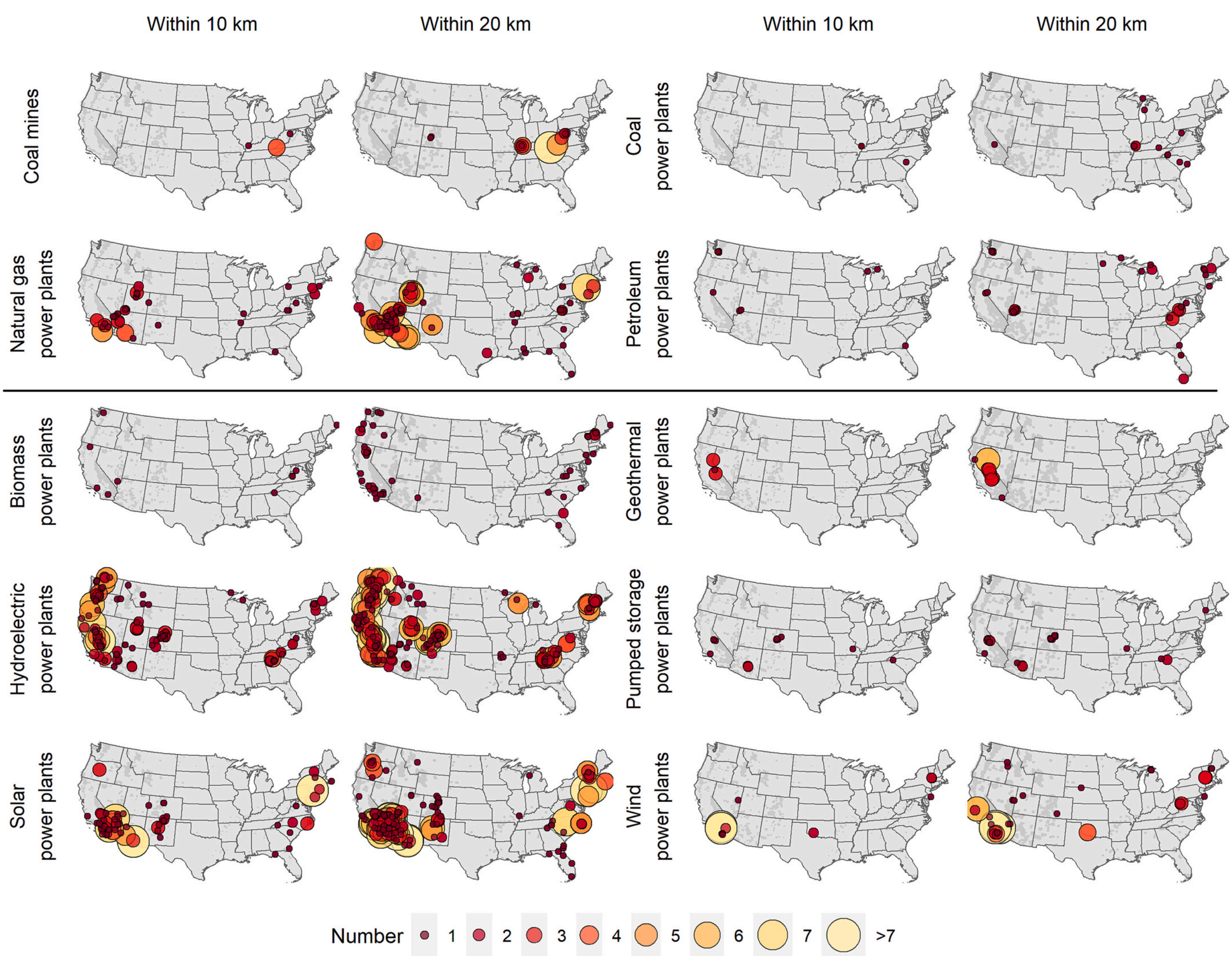

Fig. 1. Non-renewable power plants, coal mines, and renewable power plants within 10 and 20 km of wilderness areas. Non-renewable power plants include coal, natural gas, and petroleum power plants (top 2 rows). Renewable energy power plants include biomass, geothermal, hydroelectric, pumped storage, solar, and wind power plants (bottom 3 rows).
These data are based on U.S. Energy Information Administration (EIA, www.eia.gov, last update Oct. 2018).

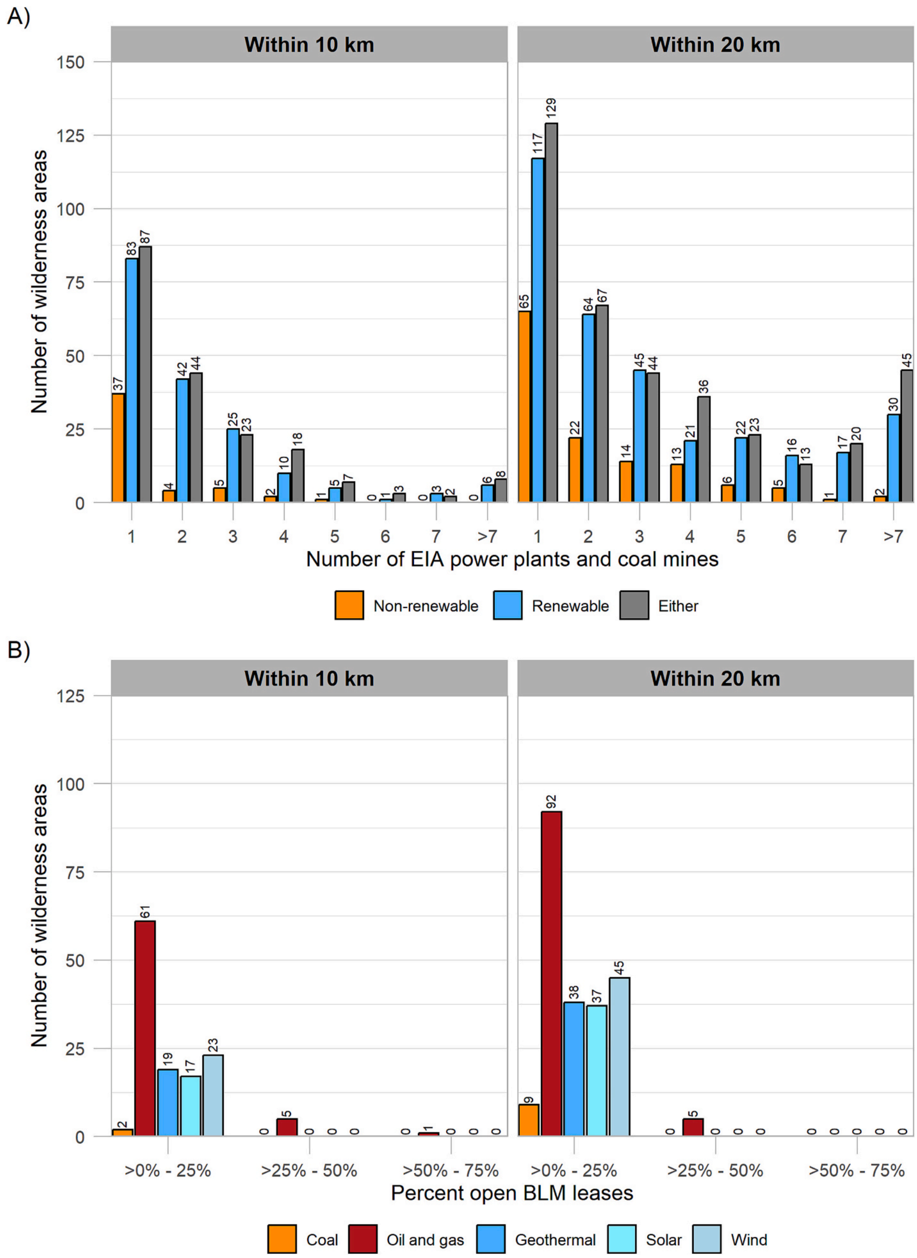

Fig. 2. Number of wilderness areas with non-renewable power plants, coal mines, renewable power plants or either within 10-km or 20-km buffer of wilderness areas (top). The either category includes wilderness areas with either a renewable or non-renewable energy power plant or coal mine within the two buffers. These data are based on U.S. Energy Information Administration (EIA, www.eia.gov, last update 2018). Number of wilderness areas with percent area of non-renewable (coal, oil, and gas), renewable (geothermal, solar, wind) energy leases within 10 or 20 km buffer on lands managed by BLM (bottom). These data are based on the Federal Land Use and Resource Transparency Tool (FLURTT) developed by The Wilderness Society which provides the most recent spatial dataset of energy development by automating the aggregation of tabular data from the BLM LR2000 database (https://reports.blm.gov/reports/lr2000) and creating spatial data with the selection and manipulation of the Public Land Survey System. These data were aggregated and supplied by The Wilderness Society and there is a potential for errors in these data due to formatting inconsistences within BLM's LR2000 underlying database.

3.3. *Energy leases on BLM land surrounding wilderness areas*

Among open non-renewable energy leases on BLM land, oil and gas leases most often occurred around wilderness areas (Fig. 2). Including both open and closed oil and gas leases, there were 502 (70 %) wilderness areas having >1 ha of oil and gas leases within 10 km and 556 (78 %) within 20 km (Fig. S3, Table S4). Much of this leased area was categorized as closed, but closed leases may have been open and active in the past and could be opened again. There were 15 wilderness areas with >90 % of the 10-km buffer area comprised of oil and gas leases and 6 wilderness areas with >90 % of the 20-km buffer area comprised of oil and gas leases (Table S4). Most of the coal leases occurred around wilderness areas in Colorado (Fig. S3).

On BLM land among open renewable energy leases, wind leases most often occurred around wilderness areas (Fig. 2). Both open and closed renewable energy leases surrounding wilderness areas occurred in the western U.S. with the wind and solar leases mostly in the southwest and geothermal leases mostly in Washington, Oregon, and California (Fig. S3). Wilderness areas with the highest percent area of the 10-km and 20-km buffer in renewable energy leases were all in California (i.e., 59 % for 10-km buffer surrounding El Paso Mountains Wilderness, 37 % for 20-km buffer surrounding North Algodones Dunes Wilderness, Tables S5 and S6).

3.4. *Cumulative impacts of energy development over time*

During 1990 to 2015, the number of oil and gas wells within 10 km of wilderness areas increased by 28.6 % (2100 wells to 2700 wells) and this value increased to 43.5 % (6900 wells to 9900 wells) within 20 km of wilderness areas (Fig. 3, Table S7). The highest density of oil and gas wells near wilderness areas occurred in Colorado and New Mexico within the 10-km and 20-km buffers (Fig. 3).

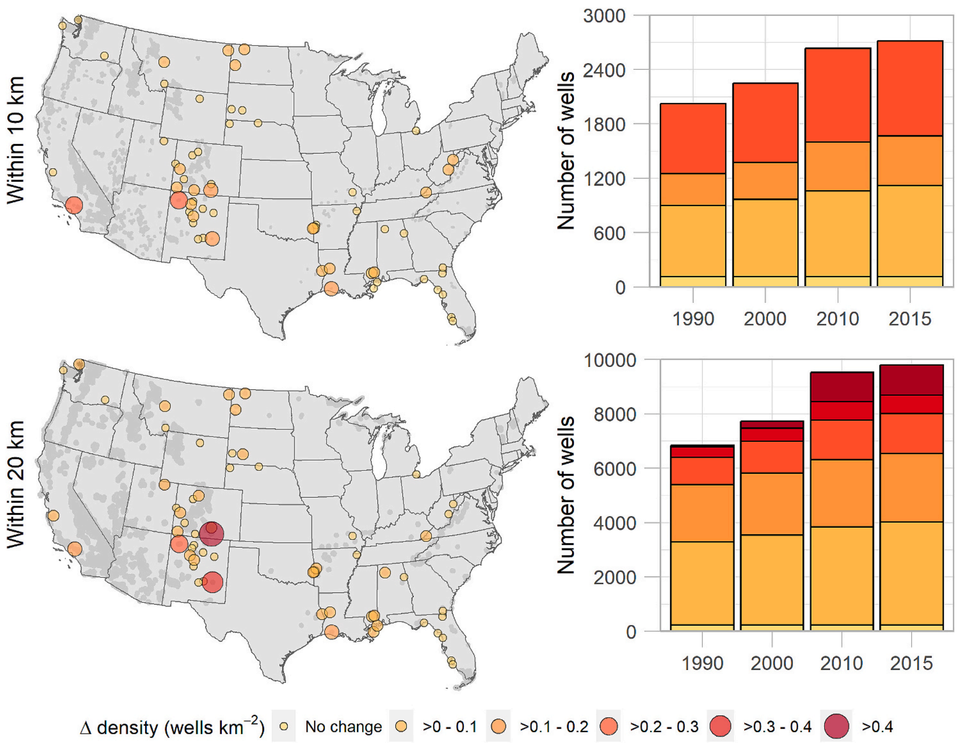

Fig. 3. Over time, the cumulative number and spatial distribution of change in density of drilled oil and gas wells within 10-km and 20-km buffers around wilderness areas in the contiguous U.S. in 1990, 2000, 2010, and 2015. Larger darker red circles indicate a higher change in density of wells (wells/km^2) between 1990 and 2015. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Data from WhiteStar Corporation (https:/www.whitestar.com).

3.5. Energy development in relation to percent public land around wilderness areas

We found no relationship between the number of power plants or coal mines and the percentage of surrounding public land within 10 km or 20 km (Fig. S4). This suggests presence of public land did not provide a buffer to energy development. Wilderness areas with high percentages (>75 %) of public land in the surrounding buffers were as likely to have a power plant or coal mine as those with low percentages (<25 %). For non-renewable energy power plants and coal mines, the regression lines had R^2 values ≤0.2 in both buffer areas. While for renewable energy power plants, most R^2 values were 0 with biomass power plants having the highest R^2 value of 0.03 (Fig. S4).

3.6. Ranking of wilderness areas

Among the four categories of (1) non-renewable within 10-km buffer, (2), non-renewable within 20-km buffer, (3) renewable within 10-km buffer, and (4) renewable within 20-km buffer a total of 35 unique wilderness areas (5 %) fell into the top ranked for the highest number or density of power plants and coal mines in the surrounding area (Table 1). This number includes both non-renewable power plants, coal mines, and renewable power plants, however, we ranked non-renewable power plants and coal mines separately from renewable power plants. Within the vicinity of these wilderness areas were a total of 36 non-renewable power plants or coal mines and 109 renewable power plants within 10 km. Within 20 km there were 91 non-renewable power plants or coal mines and 230 renewable power plants. Most of these wilderness areas (n = 27, 77 %) occurred in four western U.S. states (71 %, California, Nevada, Utah, and Arizona) with 12 occurring in California alone. However, not all the highest ranked wildernesses were in the West; there were 2 in each of New Jersey, Vermont, and Virginia (Table 1).

4. Discussion

Multiple threats including the development of energy sources influence the persistence of biodiversity, natural habitats, and ecological processes within protected areas (Asamoah et al., 2022; Convention on Biological Diversity (CBD), 2020a; Jones et al., 2018; Popescu et al., 2020; Rehbein et al., 2020; Thieme et al., 2020). These threats are occurring globally in and around wilderness areas, but we sought to understand the extent of energy development impacts occurring around wilderness areas within the U.S. We found regional differences in the types of energy development and cumulative impacts over time between wilderness areas. Among non-renewable energy power plants, natural gas power plants had the highest number within the 10-km and 20-km buffers surrounding wilderness areas in the southwestern U.S. Wilderness areas in the eastern U.S. had the highest number of coal mines nearby. While among renewable energy power plants, solar and wind power plants near wilderness areas were more common, also in the southwestern U.S. When evaluating the amount of oil and gas leasing on BLM land, we found most wilderness areas had >1 ha of oil and gas leases on BLM land within both 10 km and 20 km. Among the renewable energy leases on BLM land, wind leases more often occurred in the vicinity of wilderness areas with most in the southwestern U.S. Additionally, the cumulative impacts of energy development over time have increased because the number of oil and gas wells around wilderness area increased by 28 % and 43 % during 1990–2015 within 10-km and 20-km, respectively. Furthermore, the percentage of public land surrounding wilderness areas does not provide a buffer to the occurrence of power plants and coal mines. The wilderness areas with the most non-renewable and renewable power plants within the 10-km and 20-km buffers occurred in the western U.S. Our intent is to inform and prioritize wilderness management to conserve the biodiversity, natural habitat, and ecological processes inherent in wilderness areas.

4.1. Energy development around wilderness areas

With over half (52.8 %) of all wilderness areas having at least 1 energy development (i.e., power plant or coal mine) within 20-km, energy sprawl is likely to have an observable influence. Energy sprawl is the land use footprint of energy development and the largest driver of land use change in the U.S., which is expected to increase by

Table 1
Wilderness areas with the highest number (i.e., count) and density (number/km^2) of non-renewable power plants, coal mines, and non-renewable power plants within 10 and 20 km of wilderness areas. Each wilderness area included ranked highest by count or density or both in at least one of four categories: (1) non-renewable within 10-km buffer, (2) non-renewable within 20-km buffer, (3) renewable within 10-km buffer, and (4) renewable within 20-km buffer. The values for the 20-km buffer are cumulative with the 10-km buffer. Wilderness areas are listed alphabetically. NA = Not ranked as highest in that category.

Wilderness name	State	Non-renewable				Renewable			
		10-km buffer		20-km buffer		10-km buffer		20-km buffer	
		Count	Density	Count	Density	Count	Density	Count	Density
Beartown	Virginia	NA	NA	5	0.003	NA	NA	NA	NA
Boulder Creek	Oregon	NA	NA	NA	NA	6	0.009	NA	NA
Brigantine	New Jersey	2	0.003	NA	NA	NA	NA	NA	NA
Bristol Cliffs	Vermont	NA	NA	NA	NA	NA	0.006	NA	0.006
Bucks Lake	California	NA	NA	NA	NA	7	0.009	NA	NA
Cottonwood Canyon	Utah	3	0.005	5	0.003	NA	NA	NA	NA
Cucamonga	California	NA	NA	NA	NA	NA	NA	33	0.018
George D Aiken	Vermont	NA	NA	NA	NA	NA	0.008	NA	0.007
Great Swamp	New Jersey	2	0.004	7	0.004	9	0.019	32	0.020
Jacumba	California	NA	NA	NA	NA	NA	NA	NA	0.007
John Muir	California	NA	NA	NA	NA	16	NA	22	NA
Joshua Tree	California	NA	NA	5	NA	9	NA	29	NA
Kaiser	California	NA	NA	NA	NA	7	0.010	NA	NA
Magic Mountain	California	3	0.005	5	0.003	NA	NA	13	0.007
Mount Naomi	Idaho/Utah	2	NA	NA	NA	NA	NA	NA	NA
Mount Olympus	Utah	3	0.004	6	0.003	NA	NA	NA	NA
Mount Timpanogos	Utah	NA	NA	6	0.003	NA	NA	NA	NA
Muddy Mountains	Nevada	NA	NA	6	NA	NA	NA	NA	NA
North Maricopa Mountains	Arizona	4	0.004	NA	NA	NA	NA	NA	NA
North McCullough	Nevada	NA	NA	NA	NA	7	0.011	NA	0.006
Otay Mountain	California	5	0.011	6	0.005	NA	NA	NA	NA
Otis Pike Fire Island High Dune	New York	NA	NA	NA	0.003	NA	NA	NA	0.007
Panther Den	Illinois	NA	0.002	NA	NA	NA	NA	NA	NA
Pusch Ridge	Arizona	NA	NA	6	NA	NA	NA	NA	NA
Saguaro	Arizona	NA	NA	5	NA	10	NA	16	NA
San Gorgonio	California	NA	NA	NA	NA	15	0.010	30	0.009
San Jacinto	California	3	0.003	NA	NA	23	0.021	28	0.010
Sandia Mountain	New Mexico	NA	NA	5	NA	NA	NA	NA	NA
Sheep Mountain	California	NA	NA	NA	NA	NA	NA	14	NA
South McCullough	Nevada	NA	NA	NA	NA	NA	NA	13	NA
Stateline	California	NA	NA	NA	NA	NA	0.007	NA	NA
Stone Mountain	Virginia	4	0.008	16	0.010	NA	NA	NA	NA
Wabayuma Peak	Arizona	2	NA	NA	NA	NA	NA	NA	NA
Warm Springs	Arizona	3	NA	NA	NA	NA	NA	NA	NA
Woolsey Peak	Arizona	NA	NA	8	0.003	NA	NA	NA	NA

These data are based on U.S. Energy Information Administration (EIA, www.eia.gov, late update Oct. 2018).

200,000–800,000 km^2 by 2040 (Trainor et al., 2016). Both renewable and non-renewable energy development cause energy sprawl (McDonald et al., 2009). However, renewable energy sources, such as solar and wind, have an initial component of energy sprawl (e.g., roads) at the time of construction of wind farms and solar arrays, but once established there is no increase in energy sprawl because the land area is re-used year after year (Trainor et al., 2016).

With respect to wilderness areas, once the initial impacts from construction of renewable energy are incurred there are minimal additional impacts. In other words, the footprint of renewable energy development could be constant through time if no new development occurs. But the impacts of energy sprawl associated with renewable energy could lead to dispersal of invasive species into wilderness areas, increased habitat fragmentation, and habitat loss around wilderness areas, which reduces connectivity between wilderness areas and other protected areas as well as reduces core habitat (Agha et al., 2020; Aycrigg et al., 2022a; Rehbein et al., 2020).

Our results showed that 175 (24.5 %) wilderness areas had ≥1 renewable energy developments (e.g., power plants) within 10 km and 332 (46.5 %) within 20 km. The energy sprawl associated with these renewable energy developments could be higher because our results do not include the number of wind turbines, solar panels, or roads associated with each energy development. Therefore, the impacts of renewable energy sprawl could have long-term and far-reaching impacts on wilderness areas especially with the growth in renewable energy facilities and national policies focused on expanding renewable energy development (Obama, 2017, Executive Order No. 14008, 2021, H. R.5376 – Inflation Reduction Act of 2022).

Contrastingly, non-renewable energy development (e.g., power plant) has an ever-increasing energy sprawl because new deposits of coal, petroleum, and natural gas are continually needed after previous deposits have been extracted (Trainor et al., 2016). A continual need to find new coal, petroleum, or natural gas deposits will lead to more energy development through siting of new power plants in strategic locations central to newly developed deposits. Based on our results, the impact of non-renewable energy sprawl will be most evident in the eastern U.S., which has the highest number of coal mines within 10 and 20 km (Fig. 1) and in the southwestern U.S, which has the highest growth in oil and gas wells within 10 and 20 km between 1990 and 2015 (Fig. 3). The impact of sprawling power plants near wilderness areas is likely to be most evident in the southwestern U.S., which has the highest number of natural gas power plants within 10 and 20 km (Fig. 1). It is estimated that up to 83 % of all energy sprawl is associated with non-renewable energy development (Trainor et al., 2016).

4.2. *Cumulative impacts over time*

The cumulative effects over time of energy development (e.g., oil and gas wells) may have the largest impacts on wilderness areas, the wildlife therein, and the ecosystem services provided. We found the number and density of oil and gas wells increased by 28.6 % within 10-km and 43.5 % within 20-km of wilderness areas during 1990–2015 (Fig. 3). With a cumulative increase in oil and gas wells over time there is an associated increase in roads, pipelines, and well pads, which expands the impacts over larger extents (Copeland et al., 2011; McDonald et al., 2009; Trainor et al., 2016). Greater sage grouse, a species whose population has declined by 17–47 % over most of its range, have lower lek attendance and survival in areas with higher densities of oil and gas wells (Connelly and Braun, 1997; Harju et al., 2010; Hovick et al., 2014). To prevent further population declines, greater sage grouse need undisturbed lekking grounds, brooding habitat, and sufficient habitat to survive (Aldridge and Boyce, 2007; Holloran and Anderson, 2005; Holloran et al., 2010; Hovick et al., 2014; Naugle et al., 2011).

The number of oil and gas wells within 20-km of wilderness areas during 1990–2015 was about three times more than within 10 km (2100 vs 6900 and 2700 vs 9900) and the density of wells was higher within the 20-km compared to the 10-km buffer (Fig. 3). This could indicate more energy development (e.g., oil and gas wells) is occurring further from wilderness areas, but it could also indicate the progression of energy development is from the 20-km buffer into the 10-km buffer and within the next 25 years the number of oil and gas wells within the 10-km buffer could be as high as the values we evaluated with the 20-km for 1990–2015. McDonald et al. (2009) estimated that by 2030 the amount of new land impacted by energy development would exceed 206,000 km^2, an area larger than the size of Nebraska. Furthermore, national policies could increase the number of oil and gas wells around wilderness areas by increasing the number of oil and gas lease sales on public lands (H.R.5376 – Inflation Reduction Act of 2022).

We focused on cumulative impacts over time and did not consider synergistic impacts of different energy developments or different land use activities occurring simultaneously spatially or temporally. However, this would be a vital next step in understanding how wilderness areas can maintain biodiversity and ecological processes under the continued demand for energy development.

4.3. *Presence of public lands around wilderness areas*

The presence of public land within the vicinity of a wilderness area does not buffer it from energy development (i.e., power plants and coal mines, Fig. S4). More than 75 % of all wilderness areas are managed by BLM and USDA Forest Service and wilderness areas are typically located within larger parcels of public land, such as BLM and USDA Forest Service land (Cole and Landres, 1996; Dietz et al., 2015). Outside of wilderness areas these agencies are mandated to manage their lands as multiple use (Dietz et al., 2015) including renewable energy development and resource extraction through non-renewable energy development. Our finding is particularly relevant because often models used for projecting land use and land cover change in the U.S. assume no change on multiple-use public land, which for energy development is not a valid assumption (Lawler et al., 2014; Sohl et al., 2014). These public lands surrounding wilderness areas do not buffer wilderness areas from the impacts of energy development.

4.4. *Ranking of wilderness areas*

To inform strategies for future conservation planning involving wilderness areas, we ranked wilderness areas by the number and density of power plants and coal mines in the vicinity (Table 1). There were 35 (5 %) unique wilderness areas with up to 91 non-renewable power plants and coal mines and up to 230 renewable power plants within 20 km (Table 1).

Even though there was a western bias in where these wilderness areas occurred, wilderness areas in New Jersey and Virginia were among the highest ranked for number and density of power plants and coal mines. The Eastern Wilderness Act (U.S. Public Law 93-622), which designated 15 new wilderness areas was signed in 1975, 11 years after The Wilderness Act (U.S. Public Law 88-577). The Eastern Wilderness act recognized the need to identify and preserve areas in the eastern U.S. because of threats from development and uses inconsistent with the protection of wilderness character (U.S. Public Law 93-622). Consequently, wilderness areas in the eastern U.S. are closer to urban areas and smaller in size than wilderness areas in the western U.S. (i.e., western wilderness areas are >3.5 times larger, on average than eastern wilderness areas; (Aycrigg et al., 2022b; Dawson and Hendee, 2009). For example, Stone Mountain Wilderness in Virginia is 13.2 km^2 with 16 coal mines within 20 km, while the Great Swamp National Refuge Wilderness in New Jersey, is 14.8 km^2 with 31 solar energy plants within 20 km. The smaller size of the eastern wilderness areas increases the density of power plants and coal mines within the vicinity and places them in the top ranked wilderness areas.

4.5. *Conservation implications*

The demand for renewable and non-renewable energy will continue; however, the impacts of energy development on wilderness areas can be reduced through energy conservation efforts and proactive planning. Energy conservation will lessen the demand for energy and decrease cumulative impacts of energy development by reducing the number of new energy developments. In fact, Trainor et al. (2016) showed that for every 1 % reduction in energy consumption an estimated 7850–8300 km^2 of energy sprawl could be avoided. Before energy development begins, it is important to consider suitable siting of new energy developments in already disturbed areas, discuss plans to maintain biodiversity, and decide upon potential mitigation responses (Agha et al., 2020; Copeland et al., 2011; Cowell, 2010; McDonald et al., 2009; Nadaï and van der Horst, 2010). Furthermore, incorporating energy development into existing infrastructure, and co-locating power plants for renewable and non-renewable energy can reduce energy sprawl and preserve natural habitats in and around wilderness areas (Trainor et al., 2016; Tverijonaite et al., 2019). Policies requiring energy developments to consider impacts on wilderness areas and provide for mitigation of those impacts could diminish the threat of continued energy development around wilderness areas (e.g., Executive Order No. 14008, 2021).

The 35 wilderness areas ranked highest for number and density of power plants and coal mines in the surrounding area merit increased attention from resource managers and decision makers. Concern for these wilderness areas is justified because energy demand will continue to increase as will the associated energy sprawl. Even though the Biden's Administration Executive Order 14008 (2021) suspends new oil and natural gas leases on public lands, it excludes oil and natural gas leases in Wyoming, and existing leases are still in place, which means there is continued support for the development of non-renewable energy and increased demand for energy will rely on renewable energy sources and existing oil and gas leases (Executive Order No. 14008, 2021, Cha et al., 2022). The energy sprawl associated with renewable energy is stable through time if no new development occurs (Trainor et al., 2016). However, with most new leases paused for oil and gas and national polices for expanding the development of renewable energy, continued sprawl from new development of renewable energy is likely (H.R.5376 – Inflation Reduction Act of 2022). This could lead to more energy sprawl through construction of new wind farms and solar arrays. Wilderness areas ranked highest for renewable energy development may undergo further energy development and sprawl within the 10-km and 20-km buffers (Table 1). The risks include isolation of ecological processes and species as well as habitat fragmentation. Furthermore, wilderness managers who steward wilderness areas not ranked highest for energy development (n = 679) could proactively minimize these risks posed by energy developments around wilderness areas.

Wilderness managers can use our assessment of energy development to strategically mitigate the impacts of increased energy demand and sprawl. Thorough and extensive pre-development assessments for siting new energy developments, including risk assessments, would be important to evaluate existing energy development and its impacts on wilderness areas (Arnett et al., 2007; Northrup and Wittemyer, 2013;

Popescu et al., 2020). This is particularly important for the 35 wilderness areas, in our assessment, to be most impacted by surrounding energy developments. Information gathered in a pre-development assessment could reduce habitat fragmentation, isolation of ecological processes, and energy sprawl (Agha et al., 2020; Jones et al., 2015). Additionally, siting energy development far from important wildlife habitat in wilderness areas, such as nesting habitat or migration routes, will lessen the risk of wildlife fatalities and lower the risk of decreased survival and reproduction (Dai et al., 2015; Hovick et al., 2014; Jones et al., 2015; Pocewicz et al., 2013). Most importantly, with the expected growth of energy development more wilderness areas may experience similar impacts as those currently ranked highest for the most energy development in the vicinity. We highlighted the wilderness areas with the most energy development in the vicinity, but our results can evaluate energy development around all wilderness areas.

5. Conclusions

Retaining the integrity of existing wilderness areas is clearly stated in the post-2020 zero-draft of the global biodiversity framework by the Convention on Biological Diversity (Convention on Biological Diversity (CBD), 2020b). Our assessment provides an important step towards understanding the influence of energy development on the integrity of existing wilderness areas. Our research indicates regional differences in types of energy development and cumulative impacts over time among wilderness areas.

International and National policies on energy development on public lands, such as wilderness areas, (e.g., Executive Order 14008 2021, H. R.5376 – Inflation Reduction Act of 2022) can influence the rate of energy development but will not halt energy development (Sæórsdóttir and Saarinen, 2016). Instead, the emphasis will be shifted from non-renewable to renewable energy development. Currently renewable energy developments in the vicinity of wilderness areas, such as solar energy and hydroelectric, are concentrated in the western and southwestern U.S. (Fig. 1). It is in these regions that a shift to more renewable energy development would necessitate wilderness managers being proactive in managing the impacts to wilderness areas.

Even though energy development is integral to economic development and infrastructure it indirectly impacts the ecological integrity of wilderness areas, which threatens existing biodiversity, natural habitat, and ecological processes (DeFries et al., 2007; Hansen and Defries, 2007; Rehbein et al., 2020; Aycrigg et al., 2022a). Wilderness areas are intended to be areas where ecological integrity is maintained and biodiversity protected, but with the number of energy developments around wilderness areas, particularly in the southwestern U.S. and along the West Coast, the undisturbed character may be better described as least disturbed. Furthermore, climate induced changes in carbon emissions related to energy development will influence the ecological integrity of wilderness areas. If this is the future of wilderness areas within the Anthropocene, then we need to recognize they will undergo changes related to indirect impacts of energy development, including a decrease in area of core habitat (Aycrigg et al., 2022a), change in extent and composition of plant communities (Peters et al., 2019), change in frequency of extreme weather events related to climate change (Aycrigg et al., 2022a), and a decrease in abundance and diversity of species (Chase et al., 2020; Shackelford et al., 2018). Even if wilderness areas are considered least disturbed, they still provide baseline information for understanding how ecosystems adapt to indirect impacts of energy development (Belote et al., 2015; Cole and Landres, 1996). Furthermore, recognizing wilderness areas with the most energy development in the surrounding area provides wilderness managers with information to support conservation of the 'untrammeled' character integral to wilderness areas.

Worldwide, wilderness areas will continue to be influenced by land use activities, such as energy development, occurring outside their boundaries. Therefore, the stewardship of wilderness areas is vital. Wilderness managers can use research results, such as ours, to inform the protection and stewardship of the biodiversity and ecological processes unique to wilderness areas (Fox and Hahn, 2016).

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CRediT authorship contribution statement

Jocelyn Aycrigg: Conceptualization, Funding acquisition, Investigation, Validation, Methodology, Project administration, Supervision, Roles/Writing – original draft, Writing – review & editing. T. Ryan McCarley: Conceptualization, Data Curation, Formal Analysis, Investigation, Methodology, Validation, Visualization, Roles/Writing – original draft, Writing – review & editing. R. Travis Belote: Conceptualization, Funding acquisition, Investigation, Methodology, Writing – review & editing. Sebastian Martinuzzi: Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Writing- review & editing. Mackensie Bosher: Data curation, Investigation, Methodology, Writing – review & editing. Connor Bailey: Data curation, Investigation, Methodology, Writing – review & editing. Matt Reeves: Data curation, Investigation, Methodology, Writing – review & editing.

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Declaration of competing interest

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

Data availability

The data used in this manuscript are shared in the tables and figures in the Appendix.

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