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Assessing state biodiversity conservation planning and large-scale wind and solar energy development in the United States

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ABSTRACT

The accelerating rollout of large-scale wind and photovoltaic solar (LSWS; >1 MW) projects raises key questions about how to balance the indirect impacts from renewable energy expansion with biodiversity conservation. In the United States, biodiversity conservation is, in part, operationalized through State Wildlife Action Plans (SWAPs), yet the extent to which these plans anticipate and guide LSWS development remains unclear. Using a keyword-assisted qualitative content analysis, we evaluate how LSWS-related threats and conservation opportunities are represented in SWAPs. Further, we use a GIS-based overlay analysis to quantify overlap between spatially explicit conservation priorities ('Conservation Opportunity Areas' or COAs) and areas indirectly impacted by current and projected LSWS buildout. To capture potential indirect impacts from LSWS, we apply technology-specific and project-level buffers and assess spatial overlap with SWAP-designated COAs under two land-use scenarios. We find misalignment between conservation opportunities identified in SWAPs and the trajectory of LSWS buildout. Across SWAPs, 80% identify at least one LSWS-related biodiversity threat, but 17 plans identify no LSWS-related conservation opportunity. The most common conservation opportunity identified in SWAPs is the need for additional research. Spatial analyses reveal that areas indirectly impacted by LSWS may expand rapidly, reaching more than 440,000 km^2 by 2045. Land-cover analyses show that LSWS–COA overlap occurs primarily in natural habitat and agricultural lands. States with the highest projected overlap, including Iowa, Michigan, and Montana identify few actionable conservation opportunities. These findings stress the necessity of early, coordinated LSWS planning to align LSWS and biodiversity conservation aims.

1. Introduction

Many countries are rapidly deploying large-scale (e.g., >1-MW capacity), ground-mounted photovoltaic solar and wind (LSWS) projects to supplement or replace fossil-based electricity generation. By 2030, LSWS may contribute more than 30% of global electricity, which is expected to surpass 17,000 TWh of production (International Energy Agency, 2024a). A global clean energy buildout of this degree signifies advancement towards United Nations Sustainable Development Goal 7, "Affordable and Clean Energy"; however, such progress occurs across a finite Earth where conservation planning and action is also occurring.

Fossil-fuel extraction, infrastructure, and combustion have well-documented biodiversity consequences (Harfoot et al., 2018). At the same time, replacing fossil-based energy systems with LSWS creates new conservation planning challenges as renewable infrastructure expands into landscapes that include or neighbor conservation areas (Rehbein et al., 2020). This expansion can drive both direct and indirect biodiversity impacts. Direct impacts arise from the physical footprint of project infrastructure, including turbines, panels, roads, and ancillary facilities. Indirect impacts extend beyond these footprints through altered habitat use, movement constraints, fragmentation, reduced connectivity, or other changes in ecological function (Lovich and Ennen,

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2011; Marques et al., 2020; Levin et al., 2023; Ashraf et al., 2024). It is worth noting that LSWS sites can also be designed to support positive direct impacts, such as maintaining or increasing pollinator diversity and abundance at large-scale solar sites (Blaydes et al., 2024; Graham et al., 2021; Li et al., 2026; Walston et al., 2023). These outcomes remain context-dependent, however, and depend on site design, baseline land cover, management practices, and the biodiversity metrics used to evaluate project effects.

The United States (U.S.) serves as a notable case study of the compartmentalization between renewable energy development and conservation planning. The U.S. established a net-zero target by 2050 under the Biden Administration (United States Department of State and United States Executive Office of the President, 2021), a goal aiming for roughly 60 GW of additional LSWS annually (International Energy Agency, 2024b). The nation also committed, in 2021, to conserving 30% of its lands and waters by 2030, although this was subsequently rescinded in 2025 (US Office of the Spokesperson, 2025). Regardless, such initiatives come at a critical time when over a third of U.S. wildlife is threatened by extinction and 40% of domestic ecosystems face total collapse (NatureServe, 2023). Practitioners increasingly view current and projected LSWS buildout as a biodiversity threat (Condon et al., 2025), a notion supported by increasing evidence, including documented overlap of U.S. renewable energy developments with protected areas, animal movement corridors, and current and future species ranges (Levin et al., 2023; Ashraf et al., 2024).

In the U.S., much of the frontline conservation planning occurs at the state level, notably under the guidance of State Wildlife Action Plans (SWAPs). SWAPs are non-regulatory, strategic documents designed to identify conservation priorities and threats to biological diversity within a state administrative area (Association of Fish and Wildlife Agencies, 2019). As part of this process, SWAPs designate areas prioritized for conservation efforts (herein, Conservation Opportunity Areas, 'COAs'). States submit their SWAP to the U.S. Fish and Wildlife Service and complete mandatory revisions on a ten-year cycle to receive federal conservation action funds through the State and Tribal Wildlife Grants Program. Importantly, while these documents do not regulate or enforce conservation action, they do shape implementation by defining threats and conservation actions that states use to guide federal conservation action funds and conservation programming. At least 41 SWAPs were due for a major update in 2025, creating an opportunity to identify and mitigate potential LSWS impacts.

Currently, little is known about how or if SWAPs address biodiversity threats posed by LSWS, or whether they incorporate criteria and strategies relevant to future LSWS development. Prior work has explored how LSWS overlaps with protected areas (Rehbein et al., 2020), projected species ranges (Ashraf et al., 2024), species movement corridors (Levin et al., 2023), and even how COAs may interact with urban land-use change (Carter et al., 2019). Yet, no national-scale assessment has evaluated how SWAPs represent LSWS-related threats and conservation opportunities, or quantified where COAs may intersect with potential zones of influence around current and future LSWS development. This gap is important because COAs are landscape-scale conservation planning units, making the area indirectly impacted by LSWS a more policy-relevant measure of potential ecological conflict than direct infrastructure footprints alone.

The purpose of this study is twofold. First, we examine what LSWS-related biodiversity threats and conservation opportunities are represented in SWAPs. In doing so, we use a keyword-assisted qualitative content analysis of every SWAP to code LSWS-related threat and opportunity groups. Second, we conduct a GIS-based spatial overlay analysis to quantify the area of COAs that may be indirectly impacted by LSWS in 2025, 2035, and 2045. Our results show that SWAPs identify LSWS-related biodiversity risks more often than planning responses, and that the areas indirectly impacted by LSWS may increasingly intersect state-designated conservation priorities. Based on this analysis, we provide actionable recommendations for U.S.-based practitioners facing renewable energy and biodiversity conservation tradeoffs.

2. Literature review

2.1. Biodiversity decline and impacts from LSWS development

Habitat loss and land-use and land-cover change are driving biodiversity decline at an unprecedented rate (Haines-Young, 2009; Newbold et al., 2015; Jaureguiberry et al., 2022). This loss is also deeply intertwined with climate change, necessitating integrated solutions to address both issues simultaneously (Malhi et al., 2020; Abbass et al., 2022). Renewable energy is critical for reducing greenhouse gas emissions and mitigating climate change; however, the expansion of LSWS can negatively impact biodiversity conservation if projects are not carefully planned and sited (Wang et al., 2025). This creates a spatial planning challenge because LSWS expansion is occurring alongside growing commitments to area-based biodiversity conservation. Globally, protected areas and other areas that deliver long-term biodiversity protection outside formal protected-area designations now cover substantial portions of the terrestrial surface (UNEP-WCMC and IUCN, 2024). International policy frameworks, including the Kunming-Montreal Global Biodiversity Framework, further emphasize the need to conserve at least 30% of terrestrial and inland water areas by 2030 (Convention on Biological Diversity, 2022). As conservation planning expands, areas prioritized for biodiversity protection may increasingly overlap with landscapes also targeted for agriculture, urbanization, timber harvest, and energy development (Hernandez et al., 2015; Rehbein et al., 2020; Kati et al., 2021; Condon et al., 2025).

To evaluate biodiversity impacts from LSWS, it is useful to distinguish between the spatial extent of direct and indirect impacts. Direct impacts arise from the physical footprint of project infrastructure, including energy generation infrastructure, access roads, and other ancillary facilities, and reflect areas of permanent or semi-permanent land disturbance. Indirect impacts, by contrast, extend beyond these footprints and capture broader zones of influence associated with infrastructure presence, configuration, and proximity.

For large-scale wind power, direct land disturbance from turbines, pads, and access roads represents a relatively small proportion of the total project area (Harrison-Atlas et al., 2022; Dai et al., 2024). Consequently, the land area associated with wind energy production differs substantially depending on whether analyses quantify only directly disturbed land or also include the broader area defined by turbine spacing (Harrison-Atlas et al., 2022). For large-scale solar energy projects, direct impacts are more spatially concentrated within a contiguous project boundary. Direct disturbance primarily arises from panel arrays, access roads, inverter pads, and associated infrastructure, and commonly involves grading, vegetation removal, and soil disturbance across much of the site (Murphy-Mariscal et al., 2018; Natural Resources Conservation Service, 2024; Matwani and Ojija, 2025). As a result, the land area at large-scale solar installations used exclusively for panels can comprise up to two-thirds of the total fenced area (Levin et al., 2025b).

Indirect spatial impacts associated with LSWS arise from the broader zone of influence created by infrastructure placement and operation. For large-scale wind energy, indirect impacts can result from turbine spacing and the occupation of airspace by moving structures, which can elicit avoidance behavior by volant and migratory species (Masden et al., 2009; Marques et al., 2020; Santos et al., 2022). For large-scale solar energy, indirect impacts can arise when grading and vegetation clearing within fenced areas create conditions that favor invasive species and intensify habitat degradation beyond the area directly occupied by generation infrastructure (Murphy-Mariscal et al., 2018; Natural Resources Conservation Service, 2024; Matwani and Ojija, 2025). Across both technologies, construction and maintenance activities can alter vegetation structure, induce soil compaction, and modify surface hydrology beyond areas of permanent direct impact, including along access corridors and near facility boundaries (Bošnjaković et al., 2024;

Dai et al., 2024). Disturbance-tolerant plant species may also expand outward from project sites, extending effects into surrounding landscapes (Bošnjaković et al., 2024; Dai et al., 2024). Other indirect impacts from LSWS, such as habitat fragmentation and reduced habitat connectivity, can complicate biodiversity conservation under climate-driven species range shifts (Grodsky and Hernandez, 2020; Lambert et al., 2023; Ashraf et al., 2024; Jarčuška et al., 2024; Young et al., 2024; Li et al., 2026).

Studies increasingly examine indirect impacts of LSWS because measures of direct land conversion alone do not capture the full spatial extent through which energy infrastructure interacts with surrounding landscapes (Rehbein et al., 2020; Dunnett et al., 2022; Niebuhr et al., 2022). Accordingly, the area indirectly impacted by LSWS is commonly represented using buffer- and proximity-based measures that reflect the spatial extent of impacts to landscape-scale ecological processes (Diffendorfer et al., 2019; Dunnett et al., 2022). Indirect impacts from LSWS are not governed by a single spatial scale, making their recognition and treatment, in large part, contingent on how regulatory frameworks define and prioritize them.

2.2. *Legal protections for biodiversity in the United States*

In the U.S., federal legal protections, such as the Endangered Species Act, National Environmental Policy Act, and Migratory Bird Treaty Act, establish foundational safeguards for biodiversity. While these federal frameworks provide critical oversight, the impacts of renewable energy development on biodiversity often materialize at the sub-national level, highlighting the exigent role of state and local governments in managing the impacts of LSWS projects (Lovich and Ennen, 2011; Hernandez et al., 2014; Grodsky and Hernandez, 2020; Grodsky, 2021; Kosciuch et al., 2021; Young et al., 2024).

The State and Tribal Wildlife Grants Program provides federal conservation funding to states and territories, which must develop and update SWAPs at least every ten years to remain eligible. Here, SWAPs establish a baseline for conservation planning through eight required elements, including identification of Species of Greatest Conservation Need, key threats, and recommended statewide conservation actions (Association of Fish and Wildlife Agencies, 2019) (Fig. 1).

Importantly, SWAPs do not impose legal mandates or land-use restrictions. Instead, they rely on collaborative partnerships among agencies, researchers, landowners, and community stakeholders that are intended to guide conservation priority actions (Lauber et al., 2009). This non-regulatory approach fosters flexibility in conservation approaches and broad engagement across stakeholder groups. However, variation across SWAP content can create inconsistencies in how biodiversity goals are articulated, prioritized, and connected to implementation frameworks across states. For instance, adaptive biodiversity conservation approaches are mentioned across SWAPs; however, few of these plans include a framework for their implementation (Fontaine, 2011).

Variability in SWAP content extends to how states identify and prioritize COAs (Association of Fish and Wildlife Agencies, 2019). States have autonomy to distinguish the extent and composition of COAs, which provides flexibility in prioritizing key biodiversity-relevant criteria (e.g. (Levin et al., 2025a; Condon et al., 2026)) but hinders their comparability across jurisdictions. This flexibility also allows for variation in the methods used to identify COAs. Some states, such as Wisconsin, identified COAs through expert elicitation, while others, like California, opted for quantitative analyses (Carter et al., 2019). Other research highlights how discrepancies in COAs and patterns of housing development expansion can present geographically explicit challenges for biodiversity conservation (Carter et al., 2019).

3. Methodology

3.1. *State Wildlife Action Plan content analysis*

Our study comprised two methodological blocks. Block 1, which concluded in December 2024, analyzes how SWAPs characterize LSWS-related biodiversity threats and conservation opportunities. Block 2, which concluded in October 2025, evaluates where current and projected LSWS buildout may intersect SWAP-designated COAs.

We first manually reviewed each SWAP to identify how LSWS development was framed as a conservation challenge and where opportunities existed to strengthen conservation planning around LSWS expansion. Using the links provided by the Association of Fish and

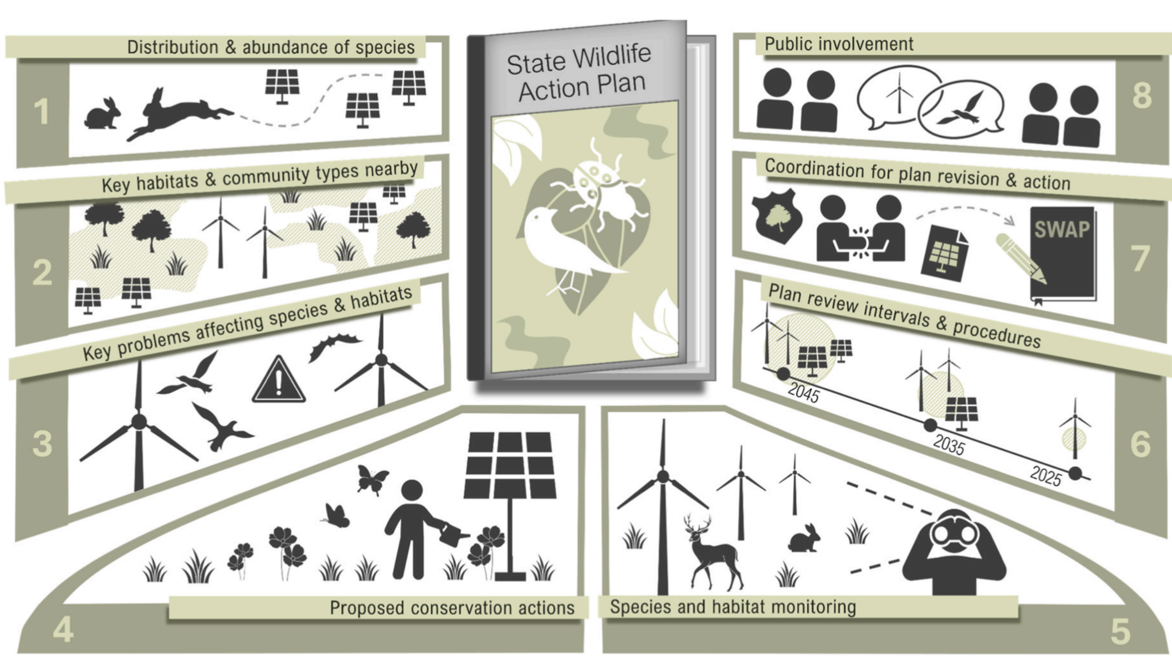

Fig. 1. Eight primary elements and their connection to large-scale wind and solar (LSWS) development from State Wildlife Action Plans (SWAPs) in the United States. Each SWAP is required to incorporate each of the eight elements; however, the extent and complexity of these elements varies. Each element includes opportunities to integrate LSWS planning and review. Icons used are from NounProject ™.

Wildlife Agencies (Association of Fish and Wildlife Agencies, 2024) and an online query, we created a database of every SWAP (n = 55) (Supplementary Material 1), including the District of Columbia (DC) and U.S. territories American Samoa (AS), the Commonwealth of the Northern Mariana Islands (NMI), the U.S. Virgin Islands (VI), and Puerto Rico (PR). We noted the latest revision date of each SWAP (herein, 'SWAP update year') and its anticipated next major revision, when specified. For SWAPs that did not specify the next revision date, we assigned a date ten years from the latest revision date following the decadal revision timeline.

We manually searched each SWAP using the following structured keywords, in order: "energy"; "solar"; "wind"; "renewable"; "alternative"; and "turbine", following the protocol of Ashraf et al. (2024) . This keyword list was designed to capture both general energy-planning language and technology-specific references to wind and solar development. Passages containing these keywords were copied directly from each SWAP and manually pasted into a state-structured coding workbook. Because searches were conducted manually rather than through regular expressions, keyword hits were reviewed as returned by each SWAP document search interface and retained only when the surrounding passage was relevant to renewable energy–biodiversity planning (e.g., 'energy' would sometimes refer to fossil fuel energy development).

We then manually reviewed the state-level coding workbook to document how states report threats from LSWS and opportunities to improve planning (herein, 'SWAP-based planning indicators') (Michalak and Lerner, 2008). We treated a threat as any passage that identified LSWS or other energy infrastructure as a source of or contributor to adverse pressure on biodiversity. We considered a conservation opportunity as any passage that identified a direct response to avoiding, reducing, or better managing LSWS—biodiversity interactions. Because SWAPs vary in how specifically they describe these responses, we retained both direct actions and enabling conditions as planning indicators. Planning indicators characterize LSWS representation in SWAPs, not overall state implementation capacity or regulatory readiness.

We developed the final threat and opportunity groups inductively from the extracted SWAP content. After keyword-relevant passages were organized by state, we reviewed the text to identify recurring themes across SWAPs. Categories were assigned only when supported by the extracted content. For example, passages that directly referenced best management practices were coded under "integrate best management practices," while passages describing conservation easements, land acquisition, or land leases were coded under "establish conservation easements." This approach allowed the final groups to reflect the language and planning content explicitly documented in the SWAPs.

We inventoried the threats and opportunities identified by each state and aggregated them into representative groups. Ambiguous passages were revisited after the initial coding round and assigned to the most specific applicable group. A complete list of definitions for the SWAP-based planning indicators is presented in Supplementary Material 2.

3.2. Analyzing intersections between renewable energy and Conservation Opportunity Areas

Our second aim was to describe current and forthcoming interactions between spaces designated for conservation and renewable energy development. We evaluated COAs, following Carter et al. (2019) , to understand how LSWS may overlap with SWAP-prioritized areas for biological conservation. The integration of spatially-explicit COAs within SWAPs is recommended but not required (Association of Fish and Wildlife Agencies, 2019), thereby allowing states the discretion to define them uniquely or not at all. Importantly, COAs may extend beyond regulated spaces, making them vulnerable to land-use and land-cover change pressures.

To ensure we used updated COAs, we conducted a web-based search to identify open-access data for each state and territory. Where data were unavailable and the SWAP showed evidence of spatially-explicit COAs (i.e., COA maps provided within the SWAP), we contacted state agencies responsible for SWAP management. We supplemented our data gaps with COA data from Carter et al. (2019) () (Fig. 2). Supplementary Material 1 provides a jurisdiction-level inventory of the SWAPs and COA datasets used, including source, availability, inclusion in the spatial analysis, and relevant links.

We represented LSWS buildout through multiple data sources. First, we used the polygons from the Wikisolar dataset, which delineates the footprint (polygons) of large-scale solar projects to their fenceline, which is most appropriate for conservation-related studies of large-scale solar outcomes (Levin et al., 2025b). Secondly, we used point geodata from the United States Geological Survey (USGS) utility-scale wind turbine database (https://energy.usgs.gov/uswtdb/) to represent direct large-scale wind buildout area through 2025.

We used the Net Zero America Project E+ scenario to represent projections of potential LSWS buildout areas to 2035 and 2045. This scenario assumes aggressive end-use electrification and relatively unconstrained supply options for achieving net-zero by 2050 (Larson et al., 2021). The E+ scenario comprises two land-use cases: base land-use assumptions (BLUA) and constrained land-use assumptions (CLUA). Both the BLUA and CLUA assume that renewable energy development is constrained and evaluated by over sixty data layers, including environmental exclusion zones in the Protected Areas Database of the U.S. (Leslie et al., 2021; U.S.Geological Survey, 2021); however, the CLUA also avoids siting projects within areas of low human modification index on Theobald's scale (Theobald, 2013) and prime farmland. These cases (herein, 'scenarios') were chosen as open-access conservative estimates of potential LSWS buildout in the U.S., and align with existing research on spatially-explicit renewable energy and wildlife interactions (Levin et al., 2023). This approach is useful for national-scale scenario analysis, but it may overestimate ecological influence where projected areas include land that is not ultimately developed or functionally affected by LSWS infrastructure.

Before analysis, we retained the 2035 and 2045 wind and solar polygons for the E + BLUA and CLUA scenarios, excluded the NZA 2025 projections in favor of the updated USGS and WikiSolar reference data, split features at state boundaries, and dissolved overlapping polygons by technology. Additional preprocessing details are provided in Supplementary Material 3. For large-scale wind, we defined the direct land use impacts to be the land area permanently altered by the installation of a wind turbine and its associated foundation infrastructure within the project site boundary. We estimated directly impacted areas using a conversion factor of 0.03–0.17 ha/MW (Denholm et al., 2009), for which we report the average and domain range. Although this range is broad, it should be interpreted as a generalized estimate, as turbine footprints vary across manufacturers, hub heights, geotechnical conditions, and project designs, and detailed turbine-level data were not available for all sites or projected development. We provide direct-impact estimates to illustrate the variability in defining areas impacted by large-scale wind.

Indirect impacts attenuate with distance from infrastructure and vary by species, ecological context, geography, and impact pathway. For this reason, defining a single spatial extent that captures all potential impacts across the entire U.S. is inherently challenging. This is especially true for wind, where displacement distances of various bird, bat, and mammal taxa range from a few hundred meters to multiple kilometers (Tolvanen et al., 2023). We delineated the indirectly impacted area from large-scale wind in 2025 as a 700-m buffer on each turbine, which we interpret as a generalized planning threshold rather than a taxon-specific boundary. This buffer aligns with those applied in studies abroad (e.g. (Łopucki et al., 2017; Santos et al., 2022; Klich et al., 2024),), while also representing a midrange of response distances observed for four U.*S. species* sensitive to large-scale wind energy development: Le Conte's sparrow (*Ammospiza leconteii*) (400-m) (Stevens et al., 2013;

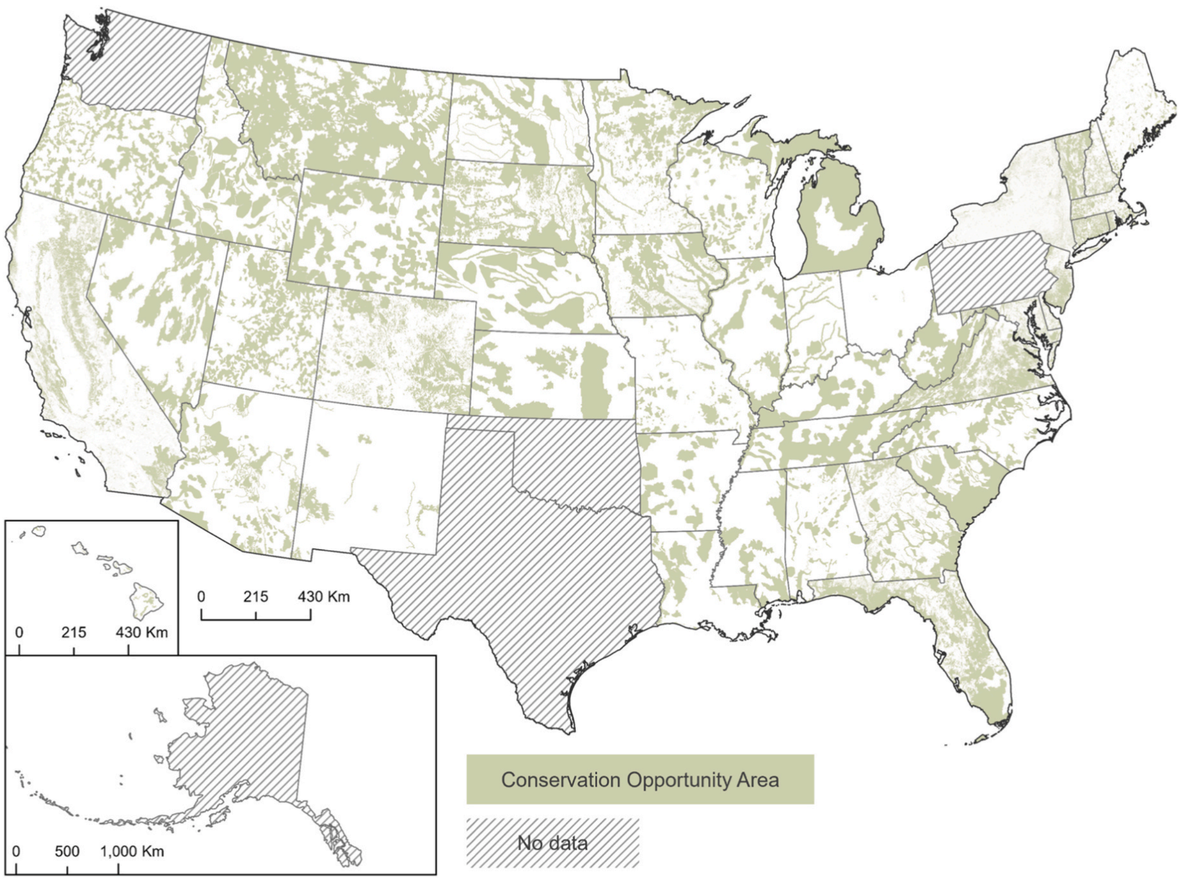

Fig. 2. Analyzed Conservation Opportunity Areas (COAs), identified as geographic areas of priority for conservation action, in the United States. Green areas show the extent of COAs within each state. Gray-hatched states did not have COA data available. Due to the unavailability of COA data for Alaska, Texas, Oklahoma, Pennsylvania, and Washington and renewable energy buildout data for Hawaii, these states were excluded from the modeling analyses. Additionally, due to unavailability of COA data for U.S. territories American Samoa (AS), the Commonwealth of the Northern Mariana Islands (NMI), the U.S. Virgin Islands (VI), and Puerto Rico (PR), these territories were also excluded from the overlay analyses. Map lines delineate study areas and do not necessarily depict accepted national boundaries. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Shaffer and Buhl, 2016), golden eagle (*Aquila chrysaetos*) (800-m) (Gedir et al., 2025), greater prairie-chicken (*Tympanuchus cupido*) (1-km) (Winder et al., 2015), and greater sage-grouse (*Centrocercus urophasianus*) (1.5-km) (Lebeau et al., 2017). Because this threshold cannot capture the full range of ecological responses to development, we also evaluated wider buffers (i.e., 1-km and 5-km) to test broader zones of influence, described below. We provide further detail on the limitations of and opportunities for future research to improve upon this method within Supplementary Material 3.

For solar, we equate the directly impacted area to two-thirds of the full project polygon (to the fenceline), aligned with findings from Levin et al. (Levin et al., 2025b). Unlike wind, where the physical disturbance is concentrated at turbine pads and indirect impacts extend outward through noise and motion, large-scale solar sites can concentrate local impacts within a defined and often fenced project boundary. Accordingly, treating the entire project polygon as the zone of indirect impact provides a consistent representation of solar disturbance, acknowledging that many impacts are contained within the site-level transformation.

We developed a spatial overlay workflow in ESRI's ArcGIS Pro™ to quantify overlap between LSWS developments and COAs for 2025, 2035, and 2045. A detailed methodology, including workflow parameters, is provided in Supplementary Material 4. Our representation of indirect impacts from LSWS through 2025 utilized the 700-m turbine buffers and Wikisolar polygons to the fenceline, while projected buildout in 2035 and 2045 used the Net Zero America polygons which already characterize broader development areas (herein, the 'baseline' scenario). The workflow calculates the overlapping area between each COA and the indirectly impacted area from each LSWS polygon and then sums the values within a user-defined boundary area (i.e., states). It then outputs a summary table showing the overlap for each state, both aggregating and disaggregating the results by LSWS type.

To evaluate the sensitivity of our results to broader assumptions about LSWS influence, we repeated the overlap analysis with expanded site buffers of 1- and 5-km around areas indirectly impacted by LSWS, following Rehbein et al. (2020) . The purpose of examining these additional buffers was to account for potential broader landscape-scale impacts generated by projects (e.g., large-scale solar impeding wildlife movement patterns (Levin et al., 2023)).

The results from the 2025, 2035, and 2045 scenarios were summarized in Excel™. We calculated LSWS–COA overlap area and the percentage of mapped COA area overlapped by areas indirectly impacted by LSWS across 2025, 2035, and 2045. Additionally, we compared the BLUA and CLUA scenarios to examine how excluding prime farmland and natural landscapes as candidate sites for LSWS may shift development toward other landscapes. Because raw overlap area tends to rank states with larger land bases or larger COA networks more highly, we report both absolute LSWS–COA overlap area and the percentage of each state's mapped COA area that overlaps areas indirectly impacted by LSWS. Further, because COA extent, shape, composition, and management intent vary across states, we interpret overlap descriptively as a planning indicator rather than applying inferential statistical tests.

4. Results

4.1. State Wildlife Action Plans identify LSWS risks more often than planning responses

We reviewed 55 SWAPs, covering all U.S. states, the District of Columbia, and the U.S. territories of American Samoa, the Commonwealth of the Northern Mariana Islands, Guam, Puerto Rico, and the Virgin Islands. Nearly all SWAPs were last updated in 2015 (n = 39) (Fig. 3). At least 41 SWAPs were due for a major update in 2025.

The structured content analysis revealed 11 and 13 distinct groups of threats and opportunities, respectively (Table 1), related to renewable energy development. We found the most commonly identified threat group was mortality to birds and bats (n = 40), followed by habitat loss or conversion (n = 25) and fragmentation (n = 21). At least 25% of the SWAPs mentioned impacts on migratory species or their routes, as well as behavioral changes in species. On average, SWAPs identified three threat groups, with California mentioning the most (n = 9), followed by Arizona, Colorado, Delaware, Georgia, Maine, North Carolina, Nebraska, and New Jersey (n = 7). Ten SWAPs did not identify any threat groups; however, some SWAPs – such as Montana – are only partially published online.

We identified 13 conservation opportunity groups mentioned within SWAPs. Of these groups, the most commonly identified needs were for more research on renewable energy and wildlife interactions (n = 23), the implementation of best management practices (n = 19), the practice of low-impact siting and design (n = 18), and engagement of stakeholders or formation of collaborative partnerships (n = 16). On average, the SWAPs mentioned two conservation opportunity groups, one fewer than for threats. California identified the most groups (n = 12), followed by Arizona and Georgia (n = 8). Seventeen SWAPs did not mention any conservation opportunity groups, comprising 30% of the sample.

Table 1
Grouped threats from renewable energy and opportunities to improve conservation planning as documented in 55 United States State Wildlife Action Plans (SWAPs) and ranked by count (the latest SWAP revision years spanned 2011 - 2023).

Threat Group	Count (number of SWAPs)
Bird and bat mortality	40
Habitat loss or conversion	25
Habitat fragmentation	21
Impacts to migratory species or routes	18
Species behavior alterations	15
Non-bird/bat mortality	12
Species movement alterations	10
Other impacts	10
Loss in species abundance or diversity	7
Water quality or quantity alterations	6
Flyway impacts	6
Opportunity Group	**Count (number of SWAPs)**
Increase research	23
Integrate best management practices	19
Practice low-impact siting and design	18
Increase stakeholder engagement and partnerships	16
Increase public engagement and outreach	13
Reference guidelines in energy/wildlife management plan	10
Other opportunities	7
Adopt more LSWS & biodiversity policies	6
Use conservation easements	4
Designate LSWS buildout zones	3
Improve environmental review processes	3
Increase funding	3
Increase use of voluntary/required mitigation efforts	2

Threats and opportunities to conserve biodiversity stem from interactions with large-scale (e.g., >1 MW capacity) ground-mounted photovoltaic solar and onshore wind technologies (LSWS). Biodiversity conservation threats and opportunities are grouped by common categories (i.e., threat and opportunity groups). Counts refer to the number of SWAPs that mention each threat or opportunity group. We provide definitions for threat and opportunity categories in Supplementary Material 2.

4.2. Existing LSWS buildout is unevenly reflected in SWAP-based planning indicators

California, Texas, and Kansas had the most installed LSWS area as of their respective SWAP years (Fig. 4). However, SWAP-based planning indicators did not consistently track existing buildout. Illinois and Iowa, for example, had comparatively high LSWS buildout but identified only average or below-average numbers of threat and opportunity groups.

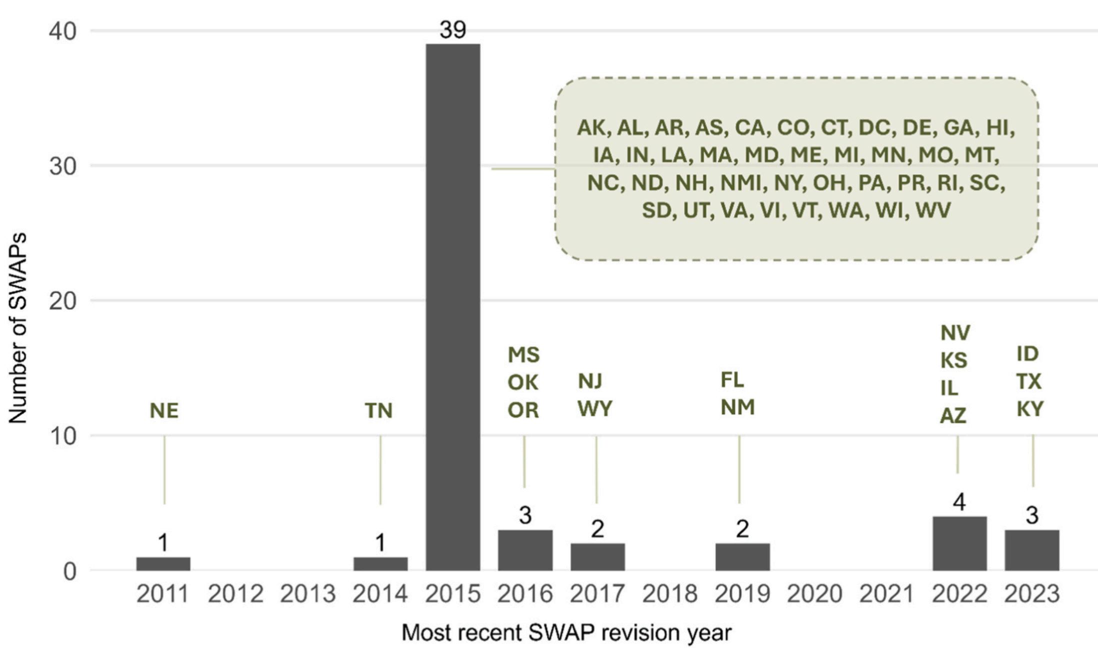

Fig. 3. Most recent State Wildlife Action Plan (SWAP) revision year for each U.S. state included in this study. The data were collected in 2025; some states may have since completed newer revisions.

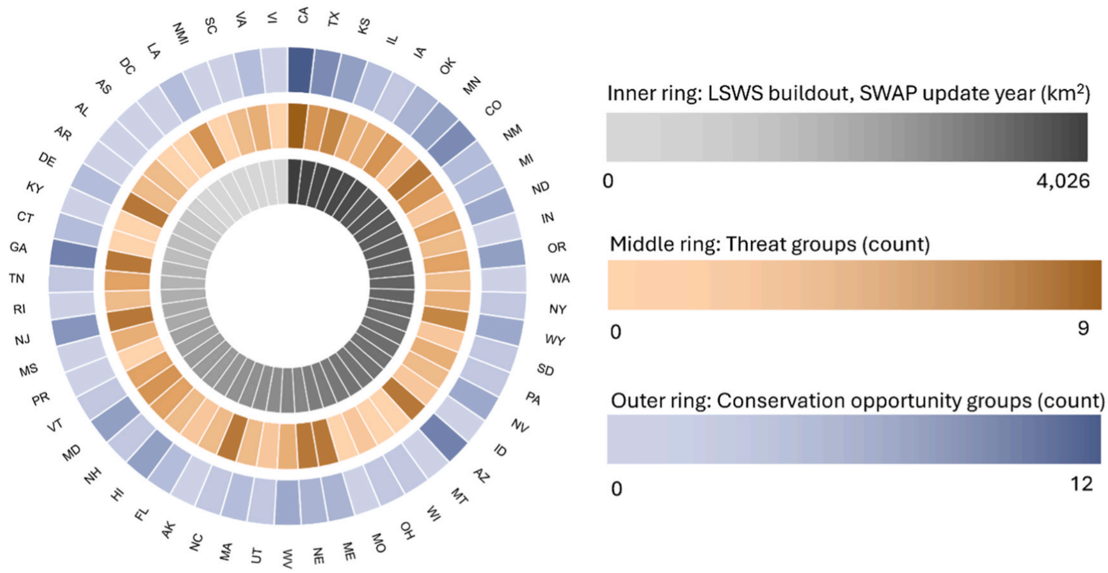

Fig. 4. Alignment between large-scale wind and solar (LSWS) buildout and planning indicators in State Wildlife Action Plans (SWAPs). States are ordered clockwise by descending total LSWS buildout as of the year of the most recent SWAP update. Each state is represented by three concentric rings: the inner ring shows total LSWS buildout area in km^2, the middle ring shows the number of LSWS-related threat groups identified in the SWAP, and the outer ring shows the number of LSWS-related conservation opportunity groups identified in the SWAP. States are labeled by their two-letter abbreviation code for readability.

Conversely, several states with lower installed LSWS capacity identified multiple threat groups.

4.3. Potential LSWS exposure to COAs expands through 2045

Across the examined years and land-use scenarios, the area indirectly impacted by LSWS expanded substantially, increasing from 58,951 km^2 in 2025 to more than 437,000 km^2 by 2045 (Table 2). Compared to LSWS buildout at the most recent SWAP updates, indirectly impacted area increased by 29,789 km^2 in 2025 and was projected to reach 408,134 – 414,711 km^2 by 2045. This expansion was driven primarily by large-scale wind, which accounted for most of the estimated indirect impact area across scenarios. Conversely, in 2025, large-scale solar accounted for approximately 2019 – 2277 km^2 more directly impacted area than wind, despite having 55 GW less installed capacity. By 2045, estimated LSWS capacity exceeded 2.19 TW, contributing total direct and indirect land impacts of approximately 20,470 – 20,600 km^2 and 437,297 – 443,874 km^2, respectively. Full technology-specific indirect impact, direct impact, and capacity estimates are reported in Supplementary Material 4.

Overlap between indirectly impacted areas and COAs also increased over time, rising from 9989 km^2 in 2025 to 109,902 km^2 under BLUA 2045 and 115,426 km^2 under CLUA 2045. However, these overlaps represented a relatively small share of total mapped COA area across examined states, increasing from less than 1% in 2025 to approximately 5% by 2045.

State-level percent COA overlap revealed unevenness in projected exposure (Fig. 5). While national overlap between the area indirectly impacted by LSWS and COAs remained modest across scenarios (range: 0.1 – 5%), proportional exposure was higher in a subset of states, including Arkansas, Missouri, Indiana, Iowa, Illinois, and West Virginia (Fig. 5). We provide the full data for all states and scenarios in Supplementary Material 4.

4.4. Land-cover composition contextualizes exposed Conservation Opportunity Areas

Land-cover composition provided additional context for interpreting where projected LSWS–COA exposure occurred (Fig. 6). Across all scenarios, natural habitat and agriculture accounted for most of the overlap between areas indirectly impacted by LSWS and COAs (94–96% of the total overlap area). In 2025, wind-associated overlap was primarily agricultural (59%), while solar-associated overlap occurred more often in natural habitat (53%).

Future scenarios shifted LSWS–COA overlap across technologies toward larger shares of natural habitat. This shift was strongest under CLUA and was driven primarily by large-scale wind. Under BLUA, natural habitat accounted for 58% of total LSWS–COA overlap in 2035, and 59% in 2045. This trend is heightened under CLUA, where natural habitat accounted for 68% of LSWS–COA overlap in 2035, and 67% in 2045.

Table 2
Scenario-level summary of LSWS expansion and exposure to COAs.

Land-use Scenario	LSWS indirect impact area (km^2)	LSWS area change from SWAP update years (km^2)	LSWS-COA overlap area (km^2)	Share of COA area overlapped (%)
2025 Reference	58,951	+29,789	9989	<1%
BLUA 2035	231,611	+202,449	53,905	2%
CLUA 2035	243,736	+214,574	64,377	3%
BLUA 2045	443,874	+414,711	109,902	5%
CLUA 2045	437,297	+408,134	115,426	5%

Values summarize areas indirectly impacted by LSWS at a national level. Change from SWAP update years represents the difference between each scenario and LSWS buildout in the year of each state's most recent SWAP update, summed across states. Share of COA area overlapped is calculated as total LSWS–COA overlap area divided by total mapped COA area across states included in the spatial analysis.

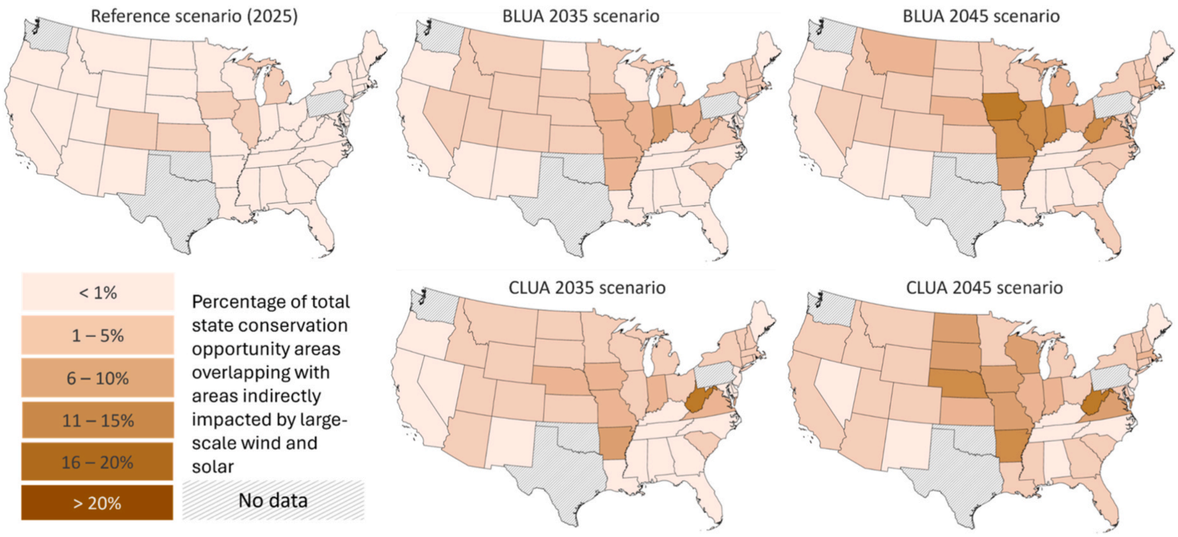

Fig. 5. Maps showing the percentage of each state's mapped Conservation Opportunity Area (COA) network overlapping areas indirectly impacted by large-scale wind and solar. Maps show the percentage of each state COA network overlapping areas indirectly impacted by large-scale wind and solar under the five land-use scenarios: Reference 2025, 2035 Base Land-Use Assumptions (BLUA), 2035 Constrained Land-Use Assumptions (CLUA), 2045 BLUA and 2045 CLUA. Map lines delineate study areas and do not necessarily depict accepted national boundaries.

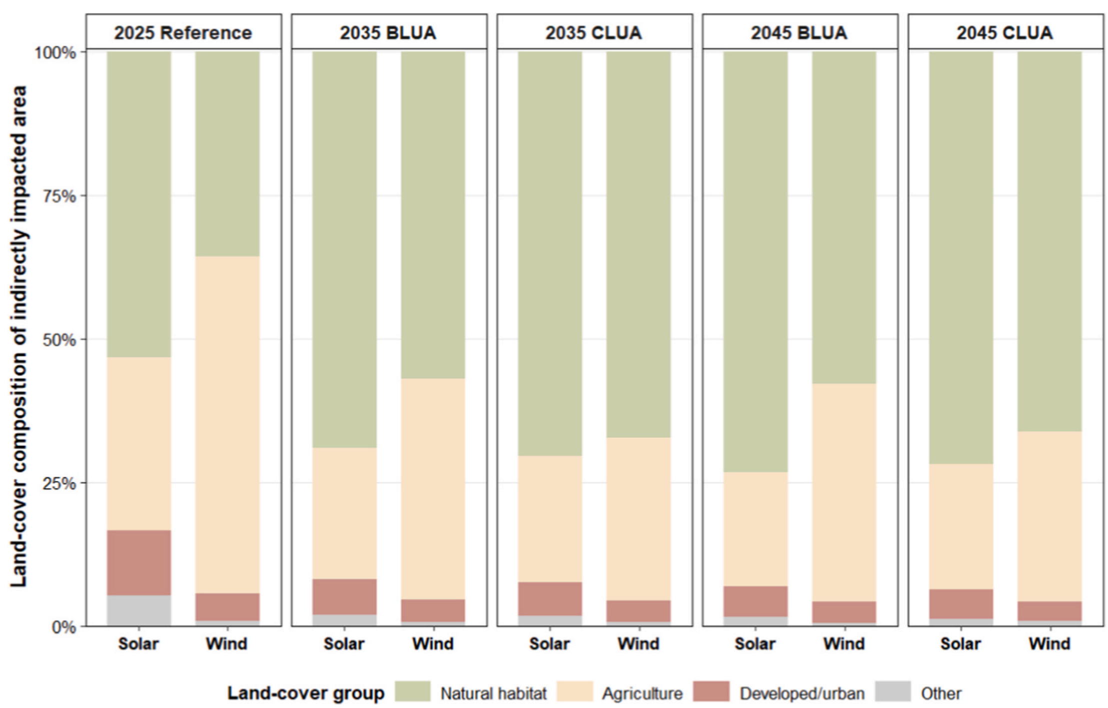

Fig. 6. Land-cover composition of Conservation Opportunity Areas indirectly impacted by large-scale wind and solar across scenarios. Bars show the percentage of indirectly impacted area by broad land-cover group for large-scale solar and wind. Land-cover classes are distinguished by the National Land Cover Database 2025; Dewitz (2026), and correspond to the following groups: Natural habitat contains forest, shrub/scrub, grassland/herbaceous, and wetland classes; Agriculture contains pasture/hay and cultivated crops; Developed/urban contains developed open space and low-, medium-, and high-intensity developed classes; and Other contains open water, barren land, and remaining classes.

4.5. Land-use constraints redistribute projected COA exposure

Land-use assumptions embedded within LSWS projection scenarios shifted the geography of projected LSWS–COA overlap. Relative to BLUA, CLUA increased projected LSWS-COA overlap by 10,472 km^2 in 2035 and 5525 km^2 in 2045. When normalized by national COA area, these increases corresponded to only 0.45 and 0.24 percentage points, respectively. However, state-level differences were larger and spatially uneven. Proportional COA exposure ranged from 6 percentage points higher under BLUA to 20 percentage points higher under CLUA in 2035, and from 11 percentage points higher under BLUA to 11 percentage points higher under CLUA in 2045 (Fig. 7).

In 2035, CLUA increased COA exposure in several states, including West Virginia and Virginia. The largest absolute increase occurred in West Virginia, where projected LSWS–COA overlap increased by 7761 km^2 relative to BLUA. In contrast, Illinois, Montana, Michigan, Wyoming, Nevada, and Indiana showed lower overlap under CLUA than BLUA. By 2045, the redistribution pattern associated with CLUA became

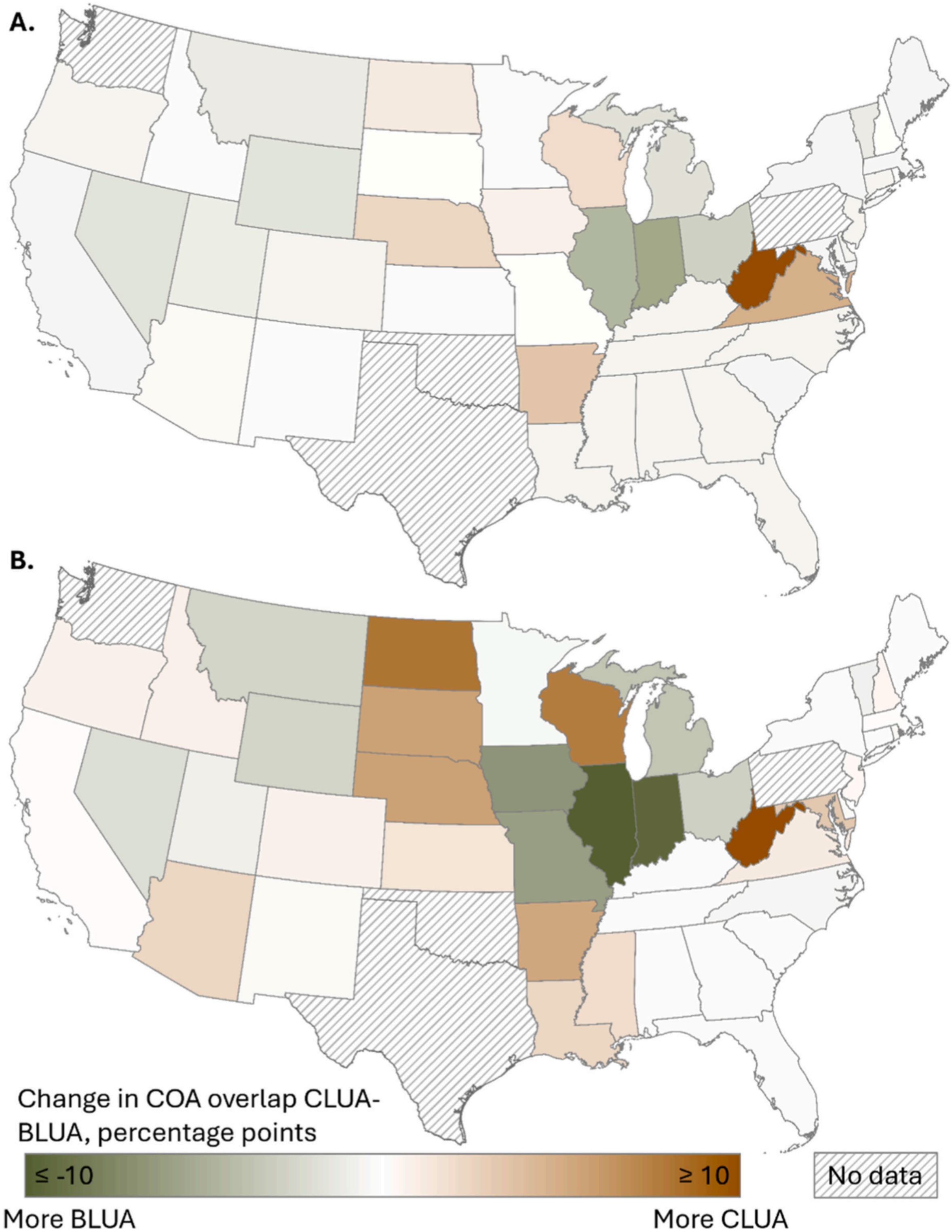

Fig. 7. Difference in projected percentage of Conservation Opportunity Area (COA) overlap between land-use scenarios. Maps show the state-level percentage-point difference in COA overlap between Base Land-Use Assumptions (BLUA) and Constrained Land-Use Assumptions (CLUA) for **A**. 2035 and **B**. 2045. Orange indicates states where CLUA resulted in higher projected COA overlap than BLUA; green indicates states where BLUA resulted in higher projected COA overlap than CLUA; white indicates little to no difference between land-use scenarios. Gray hashed states were not included in the spatial overlap analysis. Map lines delineate study areas and do not necessarily depict accepted national boundaries. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

more concentrated in the upper Midwest. Relative to BLUA, projected overlap under CLUA increased most in South Dakota, North Dakota, Nebraska, West Virginia, and Wisconsin, while BLUA produced higher proportional overlap in Montana, Iowa, Illinois, Michigan, Wyoming, Indiana, Nevada, and Missouri.

4.6. Buffer sensitivity changes the magnitude of overlap but preserves areas of exposure

Increasing the buffer distance around LSWS increased estimated LSWS–COA overlap across scenarios and changed the relative exposure of some states. Under the 2025 Reference scenario, national overlap increased from 9989 km^2 under the baseline to 23,266 km^2 with the 1-km buffer and 106,652 km^2 with the 5-km buffer. Future scenarios showed similar sensitivity, with the 1-km buffer increasing national overlap by up to two times relative to baseline and the 5-km buffer increasing overlap by up to five times.

Despite these increases in overlap magnitude, larger buffers did not fundamentally alter the recurring geography of exposure. Under the 2025 Reference scenario, the 1-km buffer produced patterns similar to the baseline analysis, with the highest overlap concentrated in Iowa, Michigan, Colorado, Kansas, and South Dakota. The 5-km buffer expanded this geography, elevating North Carolina and Virginia among the highest-overlap states. Iowa remained the highest-overlap state across baseline, 1-km, and 5-km assumptions in 2025, increasing from 2067 km^2 to 3856 km^2 and 12,225 km^2, respectively. Future buildout scenarios showed a similar pattern, indicating that buffer assumptions affect overlap magnitude more than the broader identification of recurring exposure areas.

5. Discussion

5.1. A blind spot in state wildlife action planning

Despite the accelerating growth of LSWS, we find variation in how SWAPs address LSWS–biodiversity interactions. Across SWAPs, LSWS-related biodiversity threats are identified more often than planning responses. Eighty percent of SWAPs identify at least one biodiversity threat from LSWS, while only 69% identify at least one conservation opportunity. The conservation opportunities that do emerge are primarily calls for additional research (n = 23), emphasizing a broader uncertainty or lack of clarity around LSWS–biodiversity interactions. Best management practices are also commonly referenced (n = 19), but SWAPs rarely identify specific guidance documents or peer-reviewed literature that could translate these practices into siting or review processes. Importantly, 17 SWAPs, including those from Arkansas, Missouri, and Montana, identify no LSWS-related conservation opportunities.

This planning–response gap reflects, in part, the timing and context in which many SWAPs were last revised. States with substantial LSWS buildout in 2025, such as Illinois and Iowa, identified few threat or opportunity groups during their latest SWAP revision, suggesting that SWAP treatment of LSWS does not always keep pace with development pressure. Market shifts and policy changes, including new renewable energy incentives, accelerated LSWS development after many plans were written. In these cases, SWAPs may lag behind the siting pressures and ecological implications of LSWS now underway. As states revise their SWAPs, they will need to interpret where LSWS exposure is increasing and why it matters for conservation planning.

5.2. Land-cover contextualizes conservation management

Land-use and land-cover composition help contextualize what LSWS–COA overlap represents on the ground. Across scenarios, the COAs indirectly impacted by LSWS were primarily composed of natural habitat and agricultural land-cover classes, which vary in ecological function and composition. For natural-habitat COAs, the central concern may be whether LSWS development would alter the ecological conditions that make these areas conservation priorities in the first place. Forest, shrubland, grassland, and wetland COAs may be valued for existing habitat structure, species occupancy, hydrologic function, restoration potential, or landscape connectivity, among other factors. The ecological pathways also differ by technology. Large-scale solar can replace vegetation and alter soils across a contiguous, fenced site, while wind retains more ground cover but can alter habitat use and connectivity beyond individual turbine pads (Hernandez et al., 2014; Tolvanen et al., 2023). Because species in these areas may depend on existing habitat conditions and connectivity, policy responses in natural-habitat COAs should therefore emphasize avoidance, followed by technology-specific design and mitigation where development cannot be avoided.

Our findings also show LSWS overlaps with COAs in working landscapes, where conservation value can depend on balancing productivity with broader conservation goals (Kremen and Merenlender, 2018). Here, large-scale wind may co-exist with agriculture, but still generate ecological risks related to bird collisions, behavioral disturbance, species displacement, and habitat fragmentation (Tolvanen et al., 2023). For example, Le Conte's Sparrows occupying hayfields and lightly grazed pastures were less likely to use suitable habitat near turbines, while longer-term studies have documented displacement among several grassland bird species (Stevens et al., 2013; Shaffer and Buhl, 2016). Solar-associated overlap may raise questions about direct site conversion, fencing, drainage, soil disturbance, vegetation management, and long-term restoration (Hernandez et al., 2014; Walston et al., 2018). However, solar development directed toward lower-conflict agricultural land may provide greater opportunities to retain or restore habitat functions through native groundcover and pollinator-focused management. Partial panel shade, for example, can extend floral availability and provide forage for pollinators in water-limited agricultural environments (Graham et al., 2021). Although siting these projects in agrarian landscapes may reduce broad ecological impacts, failure to identify and integrate agricultural land-use values into planning early can spark disputes that can delay or block projects (Susskind et al., 2022). Working-land COAs therefore require planning approaches that integrate conservation goals with land-use governance and technology-specific mitigation.

The U.S. Midwest illustrates how LSWS exposure can complicate conservation planning in working landscapes. In this region, many conservation priorities are embedded within agricultural systems, where habitat value often depends on field margins, grasslands, wetlands, riparian corridors, remnant habitat patches, and landscape connectivity (Atwell et al., 2010; Schulte et al., 2017). Large-scale wind and solar are already being sited within this working-land context: between 2012 and 2020, 70% of large-scale solar and 94% of large-scale wind in the Midwest occurred on croplands (Maguire et al., 2024). These projects may preserve some agricultural uses, especially for wind, while still altering habitat use by birds, bats, and other farmland-associated species.

Variation in the biodiversity value and management context of land-cover types highlights the value of multi-criteria decision analysis for LSWS planning. Multi-criteria decision analysis is commonly used in spatial planning to integrate competing objectives by weighing land-use priorities and identify areas for development (Condon et al., 2026). For SWAPs, COAs provide the spatial conservation layer through which these tradeoffs could be evaluated. Applying multi-criteria decision analyses to COAs could help states assess LSWS suitability across energy, agricultural, ecological, and social criteria (Stoms et al., 2013; Hise et al., 2022; Levin et al., 2025a; Condon et al., 2026). This approach could help states define where LSWS is compatible with COA priorities and where project design or mitigation should respond to the land-cover context.

5.3. Land-use constraints redistribute conservation exposure

Land-use constraints can protect selected values while shifting exposure elsewhere. Under CLUA, avoiding prime farmland and areas of low human modification increased projected LSWS–COA overlap by 10,472 km^2 in 2035 and 5525 km^2 in 2045 relative to BLUA. This finding suggests a key planning tradeoff: constraints designed to protect farmland or intact landscapes can redirect projected development pressure toward other state-designated conservation priorities. Policy frameworks that treat farmland protection, biodiversity conservation, and renewable energy development as separate objectives may miss important redistribution effects.

West Virginia illustrates the implications of redirected COA exposure. Under CLUA, West Virginia showed the largest absolute increase in projected LSWS–COA overlap relative to BLUA. Our analysis indicated that, under CLUA 2035, 80% of wind-associated COA overlap and 60% of solar-associated COA overlap occurred on deciduous forested land-cover types. This increase occurred in a state where deciduous broadleaf forests cover roughly 78% of the landscape, primarily as commercial timberland owned by private entities (Childs, 2005). Forest fragmentation owing to land-use development is already recognized as a forest management concern in the state, inhibiting landscape-scale conservation efforts (Morin et al., 2024). One major energy-related source of forest conversion in central Appalachia is mountaintop coal mining, where upper-elevation forests are cleared, topsoil is stripped, and excess rock is placed into adjacent valleys and streams (Palmer et al., 2010). This dominant driver of land-use change has driven widespread forest loss, altered hydrology, water quality degradation, and reduced local biodiversity (Palmer et al., 2010). Federal policy has responded to these impacts through stronger review of surface coal mining under the Clean Water Act (Kika, 2011), reflecting a need for targeted safeguards when energy development creates cumulative ecological effects.

The legacy of fossil fuel land-cover change creates a planning rationale for directing forthcoming LSWS development away from forested conservation landscapes where feasible. Renewable generation remains a small share of West Virginia's electricity portfolio (U.S. Energy Information Administration, 2024), leaving many LSWS siting decisions early enough to shape through policy, permitting, and agency review. The state has identified low-impact siting for wind as a conservation opportunity in its SWAP, but this guidance must be translated into operational requirements or review procedures to affect project outcomes. For wind, where viable resource areas may be tied to forested ridgelines, early review should evaluate species risks and cumulative landscape effects before permitting (Kunz et al., 2007; Bennun et al., 2024). For solar, disturbed mine lands and brownfields offer a clear low-conflict siting pathway that could reduce development pressure on forests (The Nature Conservancy, 2021). Here, SWAPs could support policy implementation by identifying COAs that should trigger additional review or defining how indirect and cumulative impacts should be evaluated during siting.

5.4. Integrating conservation priorities into renewable energy planning

Incorporating LSWS into SWAPs could make state biodiversity priorities more actionable in siting, permitting, environmental review, and mitigation. When LSWS is absent from SWAPs, or referenced only in broad terms, state-identified conservation priorities may remain disconnected from the governance processes shaping project outcomes. Clearer SWAP guidance is especially important because LSWS siting authority varies widely across states. Some states centralize review through state-level agencies, while others assign authority based on project size, project ownership, or local jurisdiction (Enterline and Valainis, 2024). As a result, SWAPs could provide a more consistent biodiversity planning foundation by identifying LSWS-related threats and conservation actions before projects move through review. This is salient for high-overlap states that identify few LSWS-related conservation opportunities, where SWAP revisions could translate COA exposure into project review triggers, wildlife-agency consultation expectations, low-conflict siting criteria, and funding or incentive priorities for mitigation and disturbed-land development.

Identifying LSWS threats or opportunities in a SWAP does not make them actionable. For SWAP priorities to affect renewable energy development, states can employ implementation pathways that connect conservation concerns to the agencies and procedures that shape siting and mitigation. In high-overlap states that identify few conservation opportunities, SWAP revisions could recommend that proposed LSWS projects intersecting mapped COAs trigger pre-application review by the state wildlife agency, with avoidance and mitigation measures carried into the siting decision. Because SWAPs are non-regulatory, a companion plan or formal agency review protocol could translate this priority into a repeatable procedure. In California, for example, the state Department of Fish and Wildlife created an Energy Development Companion Plan to explicitly translate the goals of the 2015 SWAP into priorities for reducing pressures from large-scale energy development (Blue Earth ConsultantsLLC, 2016). The companion plan links these priorities to siting and permitting review, strategic mitigation lands, transmission planning, and environmental screening for LSWS development. Similar companion plans could help other states move from broad SWAP priorities to the procedural settings where LSWS siting and mitigation decisions are made.

Implementation can be further supported, in large part, by coordinated partnerships with state wildlife agencies (Wilkinson, 1999; Chadwick, 2007; Meretsky et al., 2012; Association of Fish and Wildlife Agencies State Solar-Wildlife Working Group, 2024). Some states already require this partnership: In Colorado, renewable energy projects reviewed by the Public Utilities Commission must conduct pre-development wildlife surveys, use those surveys to avoid, minimize, and mitigate impacts, and coordinate with Colorado Parks and Wildlife during project design (Colorado Parks and Wildlife, 2021). Yet, these partnerships remain inconsistent across the U.S. Nearly half of all states and two territories do not mandate input or consultation with their associated state wildlife agency office for large-scale solar development (Association of Fish and Wildlife Agencies, 2021). In addition, over 80% of states report relying on voluntary approaches to reduce biological impacts, sometimes after LSWS developers invested considerable time and resources in project completion (Association of Fish and Wildlife Agencies, 2021). Given that environmental controversy can delay or cancel LSWS projects (Susskind et al., 2022), explicit LSWS treatment in SWAPs could help normalize earlier engagement among developers, permitting agencies, and state wildlife agencies.

Decision-support tools can support the implementation of SWAP priorities in LSWS development, but their value depends on how exposure assumptions are interpreted. Our buffer sensitivity results show that changing the assumed zone of influence alters the amount and geography of LSWS–COA overlap. Accordingly, LSWS–COA overlap should guide the level of review assigned to a place, rather than define ecological impact. Persistent overlap across buffer assumptions provides a stronger basis for early coordination and site assessment, while overlap contingent on broader buffers can be treated as a lower-certainty signal for LSWS interactions that requires project-level scoping. States can apply this logic through climate-smart siting and biodiversity-focused spatial screening, such as GIS-based multi-criteria decision-making analyses (Ashraf et al., 2024; Levin et al., 2025a; Condon et al., 2026). Similar approaches could help states use COAs as practical inputs for LSWS siting and review.

States do not need to wait for the next ten-year SWAP revision cycle to begin integrating LSWS into conservation planning. Given the pace of LSWS expansion, states can update LSWS buildout data and COA overlap assessments between formal revisions and use those results to develop interim guidance for near-term siting and design. North Carolina provides one example of this approach. Although the 2015 North Carolina SWAP did not explicitly address solar development, solar growth accelerated soon after the plan was released. The North Carolina Wildlife Resources Commission published voluntary large-scale solar siting guidance in 2017 to address this emerging land-use pressure before the next formal SWAP update (North Carolina Wildlife Resources Commission, 2017). This guidance recommended practices to reduce habitat conversion and fragmentation, including the establishment of native vegetative buffers around perennial streams and native groundcover within solar facilities. The state later developed a pollinator-friendly scorecard for large-scale solar, helping to standardize habitat assessments at these sites (EPRI, 2021). States can use similar interim tools to keep SWAP priorities connected to siting decisions already underway as LSWS expands.

5.5. Limitations and future directions

Our findings should be interpreted in light of several limitations. First, our spatial analysis identifies potential exposure between LSWS development and COAs. The ecological significance of COAs intersecting areas indirectly impacted by LSWS depends on actual species presence, habitat quality, land-use context, project design, site management practices, and mitigation measures. This distinction is especially important for projected 2035 and 2045 buildout, where spatial polygons represent potential development areas rather than final project footprints. Our results should therefore be interpreted as planning-oriented indicators of potential exposure areas, rather than predictions of realized ecological impact.

Second, our buffer approach simplifies ecological responses to LSWS infrastructure with 700-m, 1-km, and 5-km buffers. Species responses to LSWS infrastructure vary by taxon, habitat, technology type, project design, and landscape context (Tolvanen et al., 2023). Future analyses could improve upon our approach by applying species-, habitat-, or region-specific response buffers where sufficient data are available. We encourage states and practitioners to adapt our workflow using more granular ecological, land-use and project-level data that reflect local conservation priorities. For future national-scale analysis, renewable energy buildout projections could be paired with focal species distributions or habitat suitability models to derive taxon- and habitat-specific responses (see (Ashraf et al., 2024) as an example).

Third, the composition of COAs differs substantially across states in their criteria, spatial resolution, extent, and conservation objectives. Reporting the share of mapped COA area overlapped helps contextualize differences in state and COA area, but this metric does not normalize for ecological factors such as habitat quality, species composition, conservation intent, or management status. Thus, the conservation concern for a state with a small COA network and high proportional overlap may differ from that of a state with many expansive COAs and lower proportional overlap. Future work could improve comparability among networks by classifying COAs according to ecological function or management priority.

Fourth, our SWAP analysis captures plan content rather than implementation. Our coding procedure reflects opportunities explicitly connected to LSWS in the retrieved passages, so these metrics should be interpreted as planning indicators. Future work could pair SWAP content analysis with permitting records, agency interviews, and project-level mitigation data to evaluate actual implementation.

Finally, our analysis focuses on land-based wind and solar development and excludes offshore wind. Although offshore wind may affect conservation priorities in coastal states, it is governed through distinct federal and state marine planning processes and interacts with different ecological systems than land-based LSWS (Bureau of Ocean Energy Management, 2019). Incorporating this technology would require additional marine and coastal conservation datasets that were beyond the scope of this terrestrial-focused analysis. Future work could extend this framework to offshore wind by pairing projected offshore wind buildout with marine spatial planning data and species-, habitat-, or marine-use-specific impact buffers.

6. Conclusion

As LSWS deployment accelerates, states have an opportunity to refine planning structures and embed biodiversity conservation earlier in the development process. Although most SWAPs recognize LSWS as a potential biodiversity threat, nearly one-third do not identify corresponding conservation opportunities or strategies. Where such strategies are identified, they often carry limited procedural weight and may exert little influence over the pace, location, or design of LSWS development. Even so, SWAPs remain a critical foundation for state-level biodiversity planning as a congressionally mandated, nationwide framework that identifies conservation priorities and guides funding allocation. Our findings highlight the need to strengthen linkages between SWAPs, LSWS development, and interagency planning processes so that conservation priorities inform siting and planning decisions more directly.

Our analysis shows that conservation planning and LSWS development are, in some regions, proceeding on partially separate tracks. This disconnect is especially relevant in the Midwest and Southeast, where projected LSWS growth intersects with relatively limited SWAP-based conservation opportunity planning. Spatial results further show that potential LSWS–COA exposure varies by state, year, and land-use scenario. Some states, including Iowa, Kansas, and Illinois, repeatedly emerge as areas of potential LSWS–COA conflict, while others, such as Montana, Nebraska, and West Virginia, become more prominent under specific temporal or land-use assumptions. These patterns are relatively limited in 2025 but become more pronounced under 2035 and 2045 scenarios, highlighting the importance of translating broad planning concepts in SWAPs into more concrete approaches for LSWS siting and design. The value of this translation is exemplified by a reoccurring call from states for best management practices, low-impact development strategies, and improved environmental review, which can help inform LSWS decision-making.

Our analysis establishes a baseline for future research to validate our spatial workflow and investigate how governance structures shape the alignment between conservation and renewable energy goals. While our focus is on the U.S., we offer a framework for evaluating whether biodiversity plans are keeping pace with renewable energy expansion and whether mapped conservation priorities are being translated into siting, review, and mitigation decisions. This framework is relevant to similar tensions emerging globally, from European efforts to balance large-scale wind expansion with Natura 2000 habitats (European Environment Agency, 2024; Garthe et al., 2025) to large-scale solar development across Asia (Pratiwi and Juerges, 2020; Rehbein et al., 2020). For countries revising National Biodiversity Strategies and Action Plans under the Convention on Biological Diversity, our findings suggest that biodiversity plans should be evaluated for whether they identify renewable energy pressures, assess exposed conservation priorities under alternative land-use scenarios, and connect those priorities to spatial planning, environmental assessment, and mitigation guidance. Comparative national case studies could further clarify how different governance structures, ecological contexts, and land-use constraints shape renewable energy and biodiversity alignment across jurisdictions (Jackson, 2011; Santangeli et al., 2016).

Our findings should be interpreted in the broader context of energy transitions. Fossil-energy systems have produced long-term biodiversity impacts through extraction, land-cover change, infrastructure networks, and greenhouse gas emissions (Butt et al., 2013). Renewable energy expansion introduces additional spatial pressures but occurs across landscapes already altered by these legacies. Examining how biodiversity planning adapts within this transition can clarify how existing conservation frameworks align with the spatial and institutional dynamics of LSWS development.

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CRediT authorship contribution statement

Daphne Condon: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Validation, Visualization, Writing – original draft, Writing – review & editing. **Nikunj Bhartia:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Validation. **Sarah M. Jordaan:** Funding acquisition, Writing – review & editing. **Elizabeth L. Kalies:** Funding acquisition, Writing – review & editing. **Benjamin P. Narwold:** Data curation, Writing – original draft, Writing – review & editing. **Freya Robinson:** Data curation, Investigation, Writing – original draft. **Rebecca R. Hernandez:** Funding acquisition, Investigation, Project administration, Supervision, Writing – review & editing.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enpol.2026.115512.

Data availability

The geospatial workflow and model used in this study are available through Figshare at https://doi.org/10.6084/m9.figshare.30422422. The underlying spatial datasets were obtained from publicly available state, federal, and open-access sources described in the Methods and Supplementary Material.

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