Received: 23 October 2017 | Revised: 5 January 2018 | Accepted: 22 February 2018

DOI: 10.1111/conl.12448

LETTER

WILEY Conservation Letters
A journal of the Society for Conservation Biology
Open Access

Present and future biodiversity risks from fossil fuel exploitation

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Funding information
UK Energy Research Centre, Grant/Award Number: NE/J005924/1

Editor
Jonah Busch

Abstract
Currently, human society is predominantly powered by fossil fuels—coal, oil, and natural gas—yet also ultimately depends on goods and services provided by biodiversity. Fossil fuel extraction impacts biodiversity indirectly through climate change and by increasing accessibility, and directly through habitat loss and pollution. In contrast to the indirect effects, quantification of the direct impacts has been relatively neglected. To address this, we analyze the potential threat to >37,000 species and >190,000 protected areas globally from the locations of present and future fossil fuel extraction in marine and terrestrial environments. Sites that are currently exploited have higher species richness and endemism than unexploited sites, whereas known future hydrocarbon activities will predominantly move into less biodiverse locations. We identify 181 "high-risk" locations where oil or gas extraction suitability coincides with biodiversity importance, making conflicts between extraction and conservation probable. In total, protected areas are located on $3-15 trillion of unexploited hydrocarbon reserves, posing challenges and potentially opportunities for protected area management and sustainable financing.

KEYWORDS
biodiversity, conservation protected areas, fossil fuels, threats

1 | INTRODUCTION

At both global and local scales, biodiversity is declining in the face of growing human pressures, including habitat conversion, climate change, overexploitation, and pollution (Newbold et al., 2015; Pimm et al., 2014; Tittensor et al., 2014). Human society is currently dependent upon fossil fuels (IEA, 2014); however, it is also dependent on biodiversity and the benefits it provides, directly through resources used, such as food, fibre, and medicines, or indirectly through regulating Earth system processes, for example, carbon storage or nutrient and water cycling (Cardinale et al., 2012; Millenium Ecosystem Assessment, 2005).

Here, we explore how fossil fuel extraction can impact biodiversity and the services it provides for human society now and in the future. Even prior to extracting fossil fuels, the exploration process can impact biodiversity through habitat conversion and noise pollution from drilling exploratory wells and surveying. Terrestrially, seismic survey lines clear paths 1-12 m wide through vegetation and are a major driver of landscape fragmentation (Parish et al., 2013), and with other infrastructure they increase accessibility for settlements, logging, hunting, and agriculture (Finer & Orta-Martínez, 2010). Marine seismic surveys produce some of the most intense anthropogenic noises in the oceans (Gordon et al., 2001) and can cause physiological impacts (Jepson et al., 2005) and disrupt species' behavior (Di Iorio & Clark, 2010).

During the extraction phase of fossil fuel exploitation, there are two main impacts on biodiversity: directly through conversion, degradation, pollution, or disturbance of habitats at extraction sites (Beckmann, Murray, Seidler, & Berger, 2012; Camilli et al., 2010; O'Rourke & Connolly, 2003), and indirectly by increasing access for loggers, farmers, hunters, and settlements (Laurance, Goosem, & Laurance, 2009). These impacts extend beyond terrestrial surface-dwelling organisms (Beckmann et al., 2012; Mutter, Pavlacky, Van Lanen, & Grenyer, 2015; Sawyer, Nielson, Lindzey, & Mcdonald, 2006), to affect below-ground (Efroymson, 2004), freshwater (Fefilova, 2011), and marine ecosystems (Votier et al., 2005; White et al., 2012; Whitehead et al., 2012).

After extraction, the distribution, refinement, and use of fossil fuels again impacts biodiversity directly through habitat destruction associated with infrastructure development and pollution (Parish et al., 2013). The burning of fossil fuels also contributes to climate change through the emission of greenhouse gases such as carbon dioxide (IPCC, 2014). Most research on the biodiversity impacts of fossil fuels assesses the indirect impacts due to climate change (e.g., Bellard, Bertelsmeier, Leadley, Thuiller, & Courchamp, 2012). Far less attention has been paid to the proximate impacts on biodiversity of fossil fuel exploration and extraction (but see Holland et al., 2015; Parish et al., 2013). A study by Butt et al. (2013) showed the broad spatial congruence between fossil fuel holding geological features and areas of high terrestrial and marine biodiversity, in particular, in northern South America and the western Pacific Ocean. However, site-level analysis of actual exploitation locations and plans identifying the current and near-future biodiversity conservation risks of fossil fuel extraction are lacking.

Here, we assess the direct impacts of fossil fuel extraction in three ways. First, we evaluate the biodiversity overlap associated with present and likely future fossil fuel activities, and assess how this compares with unexploited regions. Second, we identify the likelihood of near-future oil and gas extraction activities occurring in potential exploitation areas using a random-forest analysis; modeling exploitation suitability as a function of political and socioeconomic factors and practical exploitation considerations. Finally, we apply this model to identify "high-risk" locations where high biodiversity and likelihood of future exploitation coincide, and propose potential solutions to these conflict areas.

2 | METHODS

We compiled six global and spatially explicit data sets for our analyses:

(1) Existing on-the-ground oil and gas extraction infrastructure (wells, pipelines, and refineries; IHS, 2014).

(2) Oil and gas fields—reservoirs where commercial hydrocarbon production has either been established (termed "exploited fields"), or a decision to develop had been taken by April 2014 (IHS, 2014) termed "near-future fields" and likely exploited within 1-15 years (Miller, 2011; Norwegian Petroleum Directorate, 2014). Fields are the surface footprint of underground reservoirs where the production of oil and gas can potentially directly impact biodiversity in the present (exploited fields) or the near future (near-future fields).

(3) Oil and gas contract blocks—geographic areas either licensed for exploration and/or production (termed "licensed blocks"), or where tenders were invited as of April 2014 (termed "future-exploration blocks"; IHS, 2014). Because licensed blocks delineate areas where exploration for hydrocarbons has occurred historically or will occur, they enable analysis of the potential upcoming impacts of more expansive exploration activities. "Future-exploration blocks" describe locations where future exploration and possible hydrocarbon production is likely to take place. Future-exploration blocks thus represent the more distant future of oil and gas exploration and production impacts, compared with licensed blocks.

(4) Locations of active or exploratory coal mines (SNL, 2014). We generally treated coal mines separately from oil and gas infrastructure because there were substantially fewer data points for coal compared to oil and gas infrastructure, and hence any signal from the coal data would be swamped by that from the oil and gas. Treating coal separately also allowed us to test explicitly for differences between locations with coal mines and those without.

(5) Distributions of 37,583 terrestrial, freshwater, and marine species assessed and mapped for the IUCN Red List (BirdLife International & NatureServe, 2014; IUCN, 2014). From these we calculated two measures of biodiversity: species richness, the number of species in a location, and range rarity, a measure of how uniquely important a location is for the organisms that live there.

(6) Distribution of 192,121 protected areas (PAs; IUCN & UNEP-WCMC, 2013), sites that have been formally designated for protecting species, ecosystems and the goods and services that they provide (Dudley, 2008), and 11,807 key biodiversity areas (KBAs, sites contributing significantly to the global persistence of biodiversity (BirdLife International, 2017).

Our study advances upon Butt et al. (2013) in four ways. First, by using industry-standard fossil fuel exploitation data with much greater spatial and temporal resolution (specific locations for current or future exploitation). Second, we use more updated and comprehensive biodiversity data from IUCN. Third, we consider the congruence of fossil fuel extraction with PAs and important sites for biodiversity (PAs and KBAs). Fourth, we construct predictive models for prioritizing future locations of most acute and immediate risk of exploitation. Full methodological details including a discussion of data accuracy can be found in Text S1.

3 | RESULTS

3.1 | Global biodiversity patterns

On land, the richness of assessed species varied with latitude, with the highest numbers of species located in tropical latitudes and the lowest at high latitudes, and in desert regions (Figures 1a, S1a S1b). In the oceans, the same latitudinal gradient exists but there is also a gradient from higher species diversity along coasts to relatively low species diversity in the open oceans. Highest range rarity values were found on and around islands, in mountainous regions and along coastlines (Figures 1b, S1c & d).

3.2 | Current fossil fuel production and exploration

Most infrastructure for fossil fuel extraction—wells and pipelines for oil and gas, and coal mines—was located in the Northern Hemisphere (79% by area). Most (95% by area) exploitation infrastructure was located on land, and for oil and gas it was concentrated in the south and west of the United States, Europe, and North Africa and the east of the Arabian Peninsula (Figure 2). Currently exploited fields showed a similar bias toward the Northern Hemisphere (97% by area; Figure 3a & S2) and were predominantly (82%) located on land. Marine fields were almost entirely coastal and focused in the Gulf of Mexico, North Sea, and west coast of Africa. Licensed blocks were distributed more uniformly across latitudes, with 61% on land, and 39% in the marine realm, split roughly equally between exclusive economic zones (EEZs; 18%), and the High Seas (21%; Figure 4a & S3). Some coastlines were dominated by contract blocks, for example, South America, Africa, and Australia were almost surrounded. Coal mines were located on land and at highest densities in the eastern United States, Germany, South Africa, and Western Australia (Figure 5).

3.3 | Overlap with biodiversity

In both terrestrial and marine environments, present oil and gas infrastructure occurred at locations with substantially higher species richness and range rarity than locations where no exploitation was taking place (Figure S4). The same pattern was found for active coal mines (Figure S5), oil, gas, and coal infrastructure combined (Figure S6) and for licensed contract blocks but with one exception: the species richness of terrestrial licensed contract blocks was equivalent to that of the rest of land surface (Figure S7).

3.4 | Near-future exploitation

For coal extraction, median species richness was significantly lower at exploratory than active mine sites in Europe, North America and Asia-Pacific, implying future mines in these locations will be in areas of lower species richness (Table S1 and Figure S8; $P < 0.001$, *t*-statistic of a linear model accounting for spatial autocorrelation using spatial eigenvector mapping; SEVM). In all regions, exploratory coal mines tend to be located at higher latitudes (and hence in areas with lower biodiversity) than active mines (Table S4; Figure S1). In contrast, species richness was significantly higher at exploratory versus active mines in Africa and Latin America and Caribbean (LAC) with exploratory mines typically located at lower latitudes here. Range rarity did not significantly differ between active and exploratory mines.

We analyzed the coincidence of biodiversity with both exploited and near-future oil and gas fields. For most of the world, median values of species richness were significantly lower in near-future fields compared with those currently exploited (Table S2 and Figure S9; $P < 0.001$, SEVM). This pattern holds both on land and in coastal seas, and in all regions except in the coastal seas of West Asia, where species richness was significantly greater in near-future fields, and Asia-Pacific. For species richness, the marine coastal environment of Asia Pacific showed near-future fields had lower biodiversity than those currently exploited, while terrestrially in this region the converse was true: near-future fields were significantly more species rich ($P < 0.01$, SEVM). For the LAC region, both on land and in the coastal oceans, and on land in Europe, species richness and range rarity values associated with near-future fields were significantly lower than those associated with exploited fields ($P < 0.01$, SEVM). Although we found statistically significant differences between exploited and near-future field in many regions and realms, in all cases the interquartile ranges overlapped substantially. North America was the only region where fields were located in the High Seas (four exploited and five near-future), so there was insufficient information to analyze the relationships between fields and biodiversity in this environment.

For all regions except West Asia, near-future marine fields were located further offshore than exploited fields (Table S5), which may partly explain observed patterns of species richness and range rarity (in the same way as for present marine

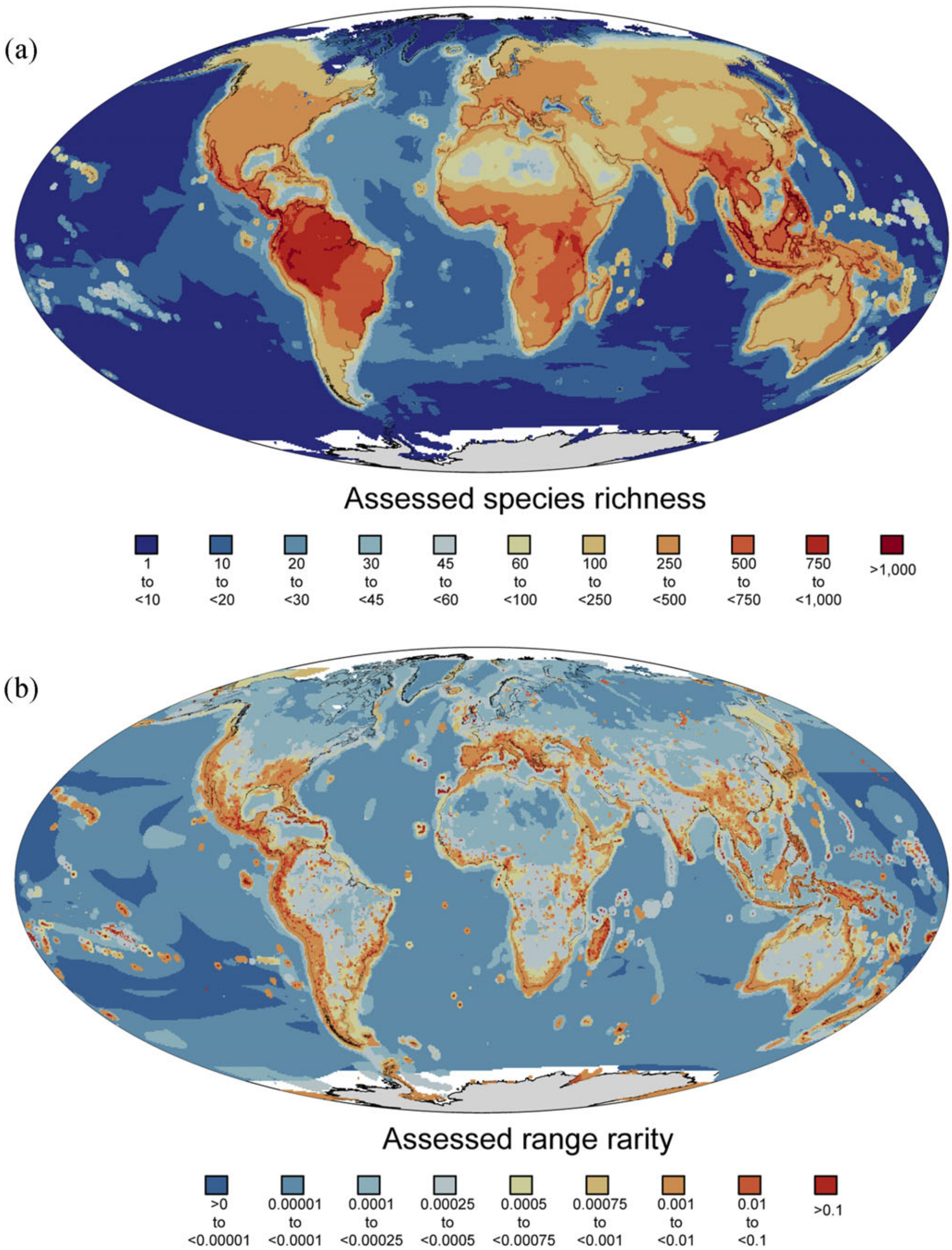

FIGURE 1 Global species richness (a) and mean range rarity (b) from the distributions of terrestrial, freshwater, and marine species assessed and mapped by the IUCN Red List (BirdLife International & NatureServe 2014; IUCN 2014)

infrastructure). For all terrestrial regions except Africa and Asia-Pacific, near-future fields were located at significantly higher latitudes than exploited fields (Table S5).

3.5 | Longer-term exploitation

On land, future-exploration blocks were generally associated with lower species richness and range rarity than licensed blocks (Table S3 and Figure S10). This implies that the direct biodiversity impacts associated with upstream oil and gas development could be lower in the longer-term future than those that have already occurred or might occur in the near future. The LAC region was the exception to this pattern. Here, median species richness was higher in future-exploration blocks compared with licensed blocks. The significance of findings for Africa was low because the sample size of future-exploration blocks was small and these were very narrowly distributed.

Median values for species richness and range rarity associated with marine future-exploration blocks were significantly higher than licensed blocks in the coastal seas of Europe, West Asia, and LAC, although the difference for Europe was

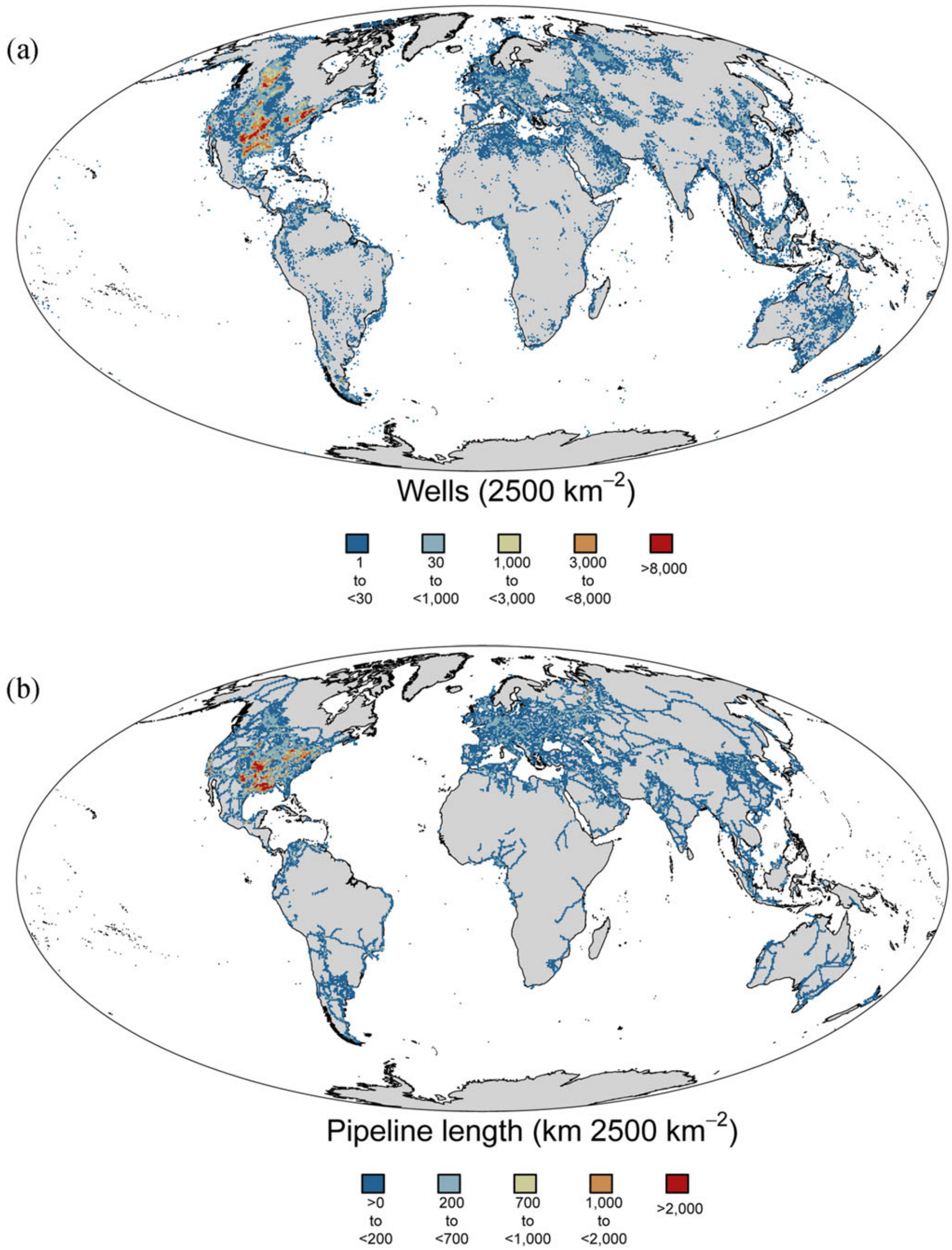

FIGURE 2 Global density of oil and gas wells (a) and pipeline length (b) at 50 km × 50 km resolution

not found to be statistically significant after accounting for spatial autocorrelation (Table S3). Elsewhere in coastal seas and in the High Seas, the species richness and range rarity associated with future-exploration blocks were lower than the values associated with licensed contract blocks. For the High Seas, biodiversity levels were much lower than in the coastal regions. Future-exploration blocks in the High Seas were located in a much narrower latitudinal range, closer to the equator (17.5°S-47.6°N), than their licensed counterparts (47.1°S-75.1°N).

The interquartile ranges of biodiversity values associated with licensed and future-exploration blocks were often overlapping, and so despite the statistically significant differences for many regions, the effect size, or the difference in biodiversity associated with a future-exploration blocks as compared with licensed blocks, was small.

3.6 | Overlap between fossil fuel extraction and PAs

Near-future fields, in comparison with exploited fields, had a greater proportional overlap with PAs in North America, Europe, West Asia, and Africa. Furthermore, for all regions with the exception of Asia and Pacific, they overlapped with

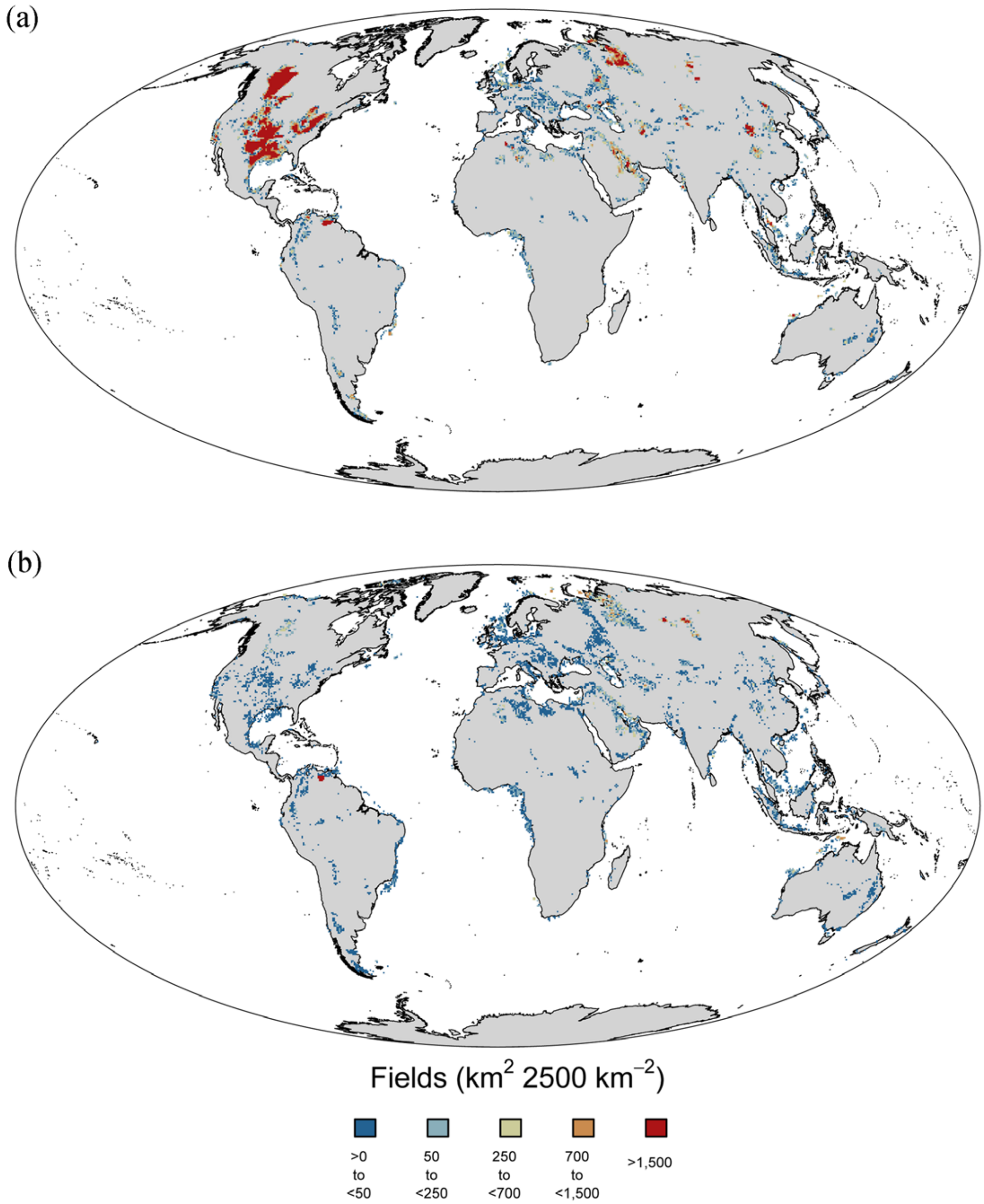

FIGURE 3 Global density of exploited (a) and near-future oil and gas fields (b) at 50 km × 50 km resolution

more strictly PAs (IUCN management categories I-IV Pas; Figure 6), in which exploration and extraction of mineral resources has been deemed incompatible with their effective management (Dudley, 2008).

3.7 | Identification of high-risk fields

For both oil and gas fields, gross domestic product (GDP) and government effectiveness (a measure of the quality of civil service and its independence from political pressure) were the most important predictors of a field's exploitation likelihood. The likelihood of exploitation increased with improving government effectiveness but decreased with increasing GDP (Text S1 and Table S6). For oil and gas, the location of a field inside a PA prior to the commencement of production was a poor predictor of exploitation status, irrespective of the IUCN management category (Table S6).

Our analysis identified 675 near-future oil and gas fields (from the total of 12,297) whose properties (low total GDP, medium-to-high government effectiveness, and high recoverable oil volume or low distance to a gas pipeline) were favorable for exploitation. (Figures S11 & S12; Table S6). Of

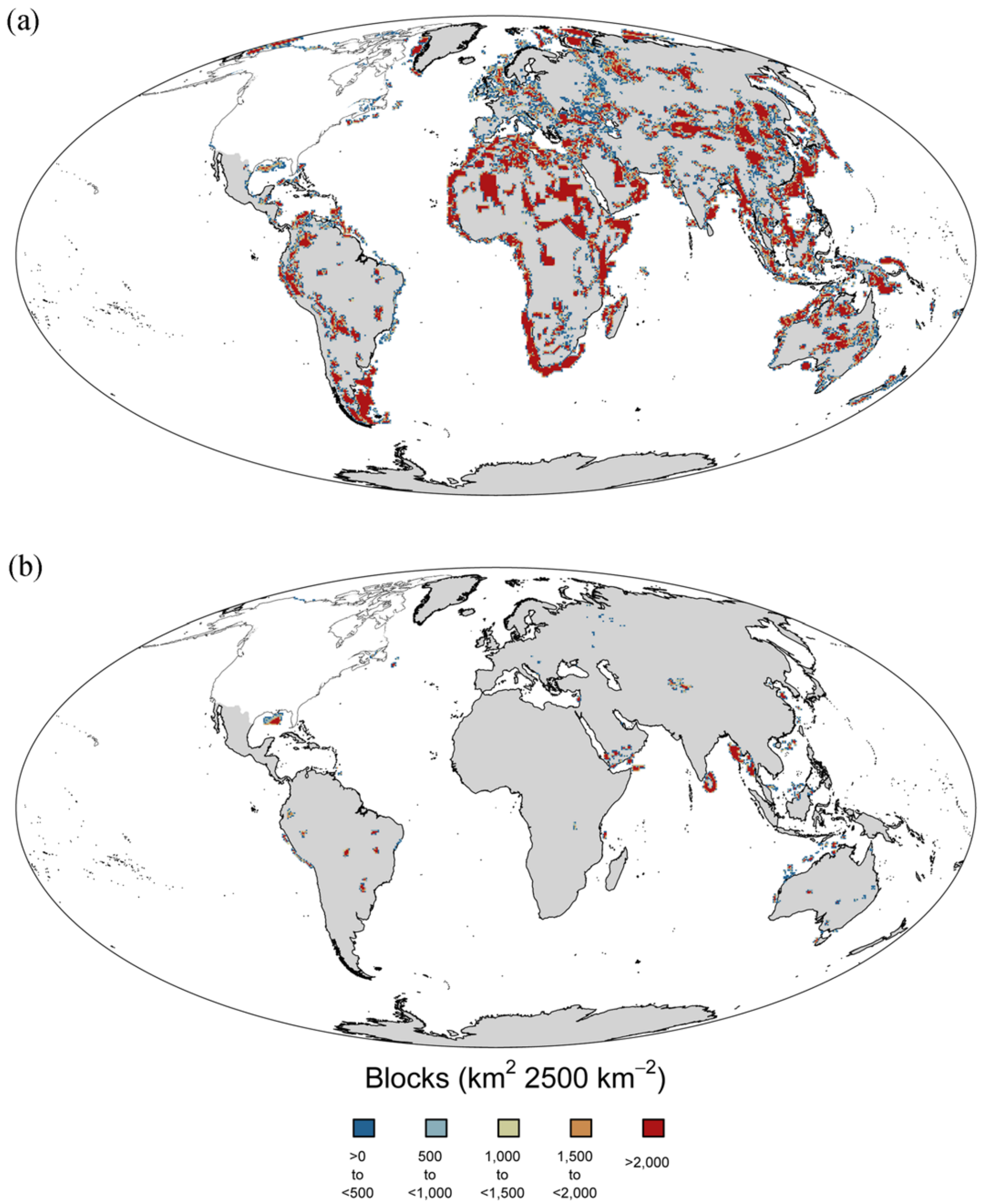

FIGURE 4 Global density of licensed (a) and future-exploration oil and gas contract blocks (b) at 50 km × 50 km resolution. Data for licensed and future-exploration contract blocks were unavailable for terrestrial North America (shown in white)

these, 181 are deemed "high-risk fields" (HRFs; Figure S13) likely posing the greatest conservation challenge. These were assessed to be most likely to be exploited while also containing 28 times more species and 18 times the range rarity values compared with average areas on the globe, or were contained within a KBA (contributing seven HRFs) that did not have a high value in our layers of range rarity and species richness. The HRFs identified are distributed between 60°N and 53°S, with noticeable clusters in the northern Andes, around the Gulf of Mexico, the west coast of Africa, Eastern Europe, and in northeast Africa and the Middle East (Figure 7). Oil and gas volumes in HRFs represent only a small proportion (0.75-0.78% of oil, 0.07% of gas) of global reserves that have been identified as "unburnable" to achieve a 2°C warming target (Mcglade & Ekins, 2014; Table S7).

4 | DISCUSSION

Our analysis compares current, near-future, and longer-term direct potential impacts of fossil fuel extraction on biodiversity, rather than broad fossil fuel bearing geological provinces, and advances previous work further by providing more detailed and predictive analysis of present and identified

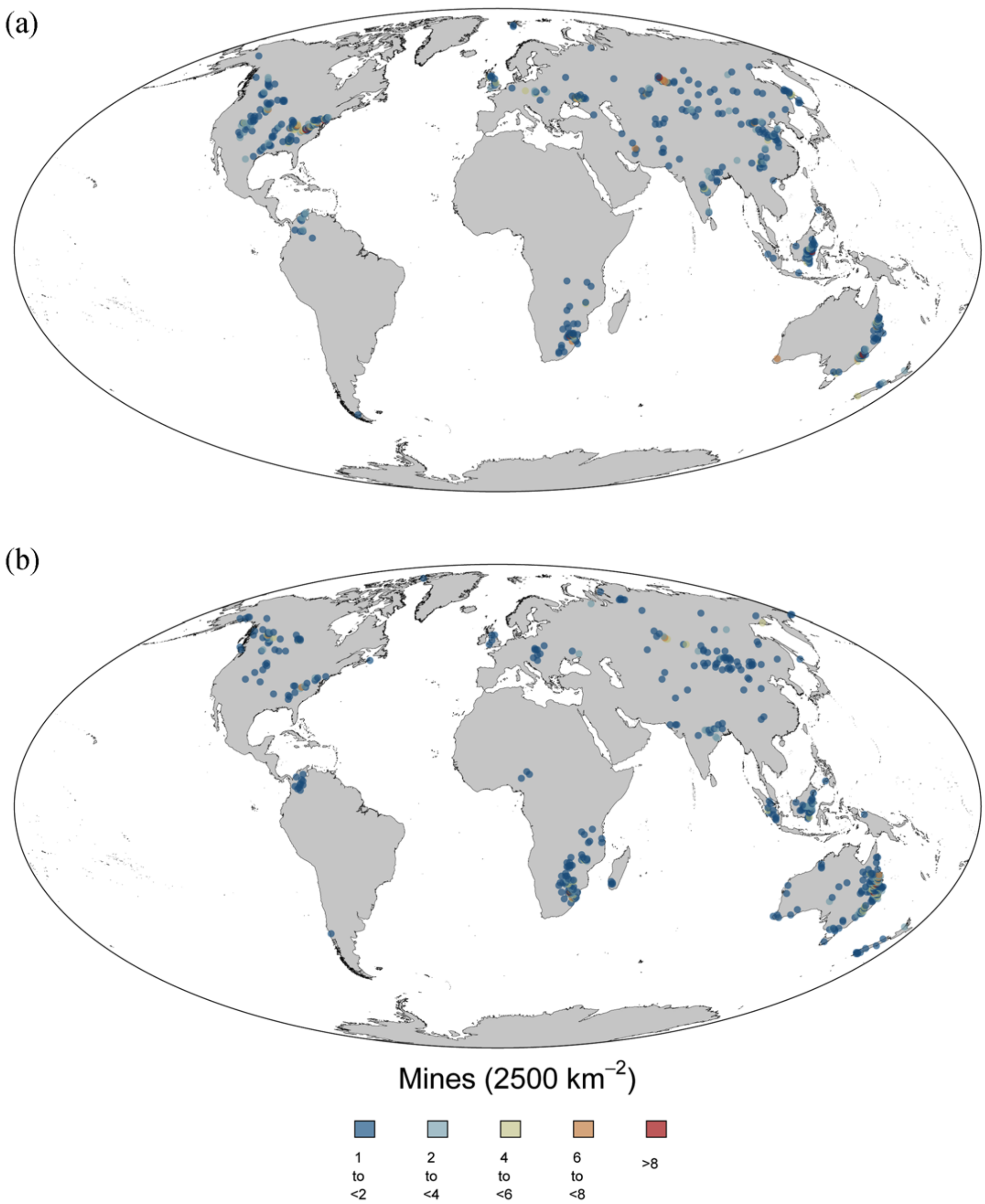

FIGURE 5 Global density of active (a) and exploratory coal mines (b) at 50 km × 50 km resolution. Mine densities are shown as points located at cell centers for visualization purposes

future development locations. Currently exploited oil and gas infrastructure tends to be found where species richness and range rarity are higher, both on land and sea, than the locations with no infrastructure. In the sea, the exploitation is generally located close to the coast (34% of all EEZ cells are <100 km from the coast compared with 70% of exploited EEZ cells; Figure S14), and continental shelves tend to be more biodiverse than the open ocean (Tittensor et al., 2010). On land, extensive areas of low species richness (e.g., northeastern Canada and Russia, south Sahara, and central Australia) coincide with no current fossil fuel extraction infrastructure (Figures 1, 2, 5 and S15). Many of these areas are, however, covered by licensed blocks, and thus possibly have been or will be impacted by exploration activities (Figure 4a).

Future exploration will generally move into regions with lower species richness and range rarity by moving further offshore in the oceans and into higher latitudes and more remote areas on land. However, near-future (1-15 years) oil and gas exploitation in West Asia and terrestrially in Asia Pacific is likely to occur in more species-rich locations. The Asia Pacific region contains some of the highest levels of biodiversity globally (Figure 1; Pimm et al. 2014) and so these findings are concerning. Future coal extraction in Africa and LAC is also likely to occur in more species-rich locations than currently

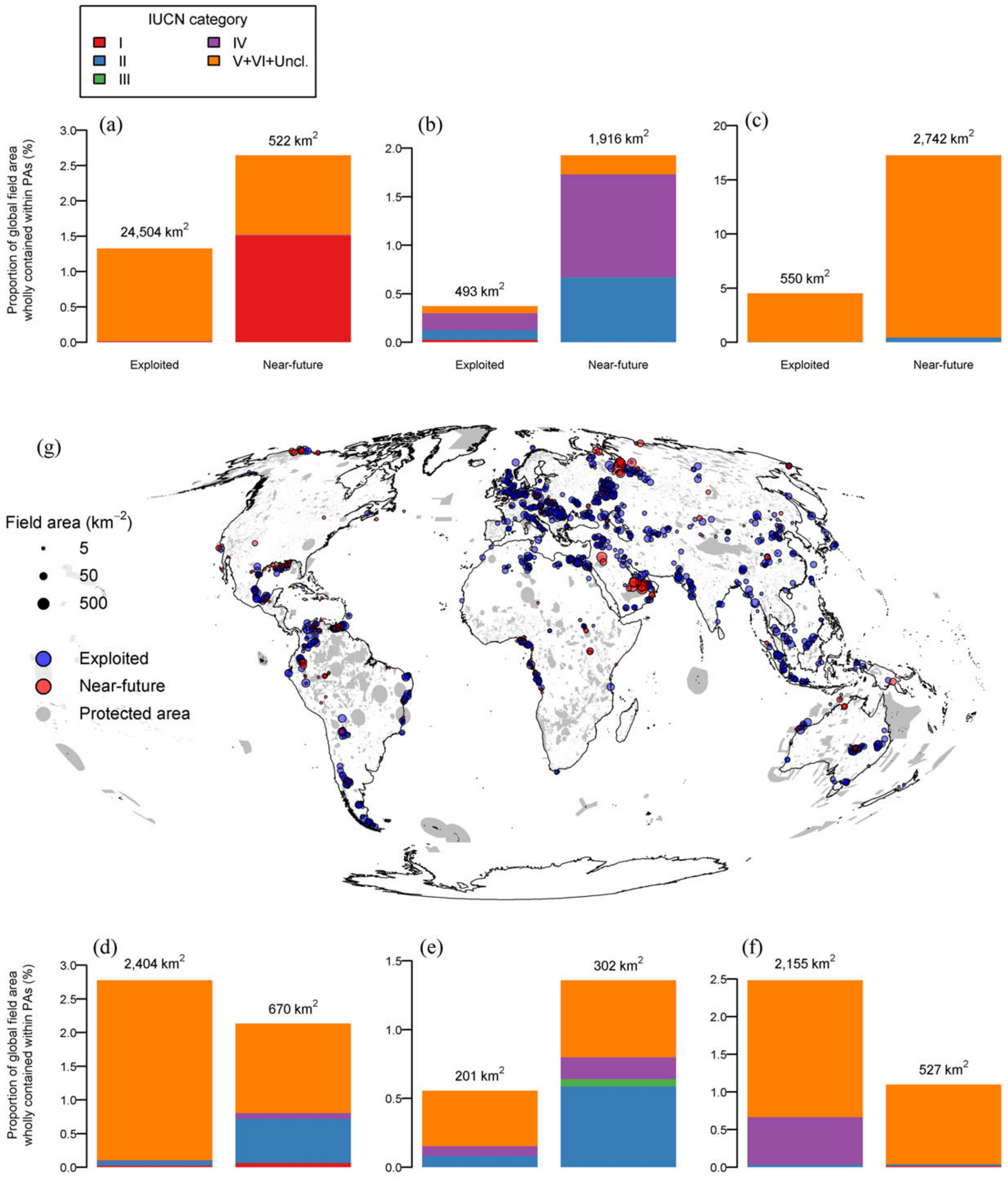

FIGURE 6 Proportions of oil and gas field area overlapping PAs (gray polygons) of different IUCN PA management categories by UN regions: North America (a), Europe (b), West Asia (c), LAC (d), Africa (e), and Asia Pacific (f). Absolute area of overlap across all IUCN management categories is shown above histograms. Location of fields overlapping with PAs are shown in (g). Shading is used so that points can be visualized even where their spatial locations coincide, so darker points indicate higher densities of fields overlapping PAs

active mines because exploratory mines are typically found at lower, more species-rich latitudes. This is concerning because mining for minerals has been shown to drive extensive deforestation in the Brazilian Amazon (Sonter et al., 2017).

Longer-term oil and gas development appears likely to occur predominantly in regions of lower species richness and range rarity but there are notable exceptions. On land, longer-term future exploration and development in the LAC region will likely occur in areas of higher species richness than areas of current exploration. In the coastal seas of West Asia and LAC, longer-term future oil and gas exploration might also shift into areas with higher range rarity

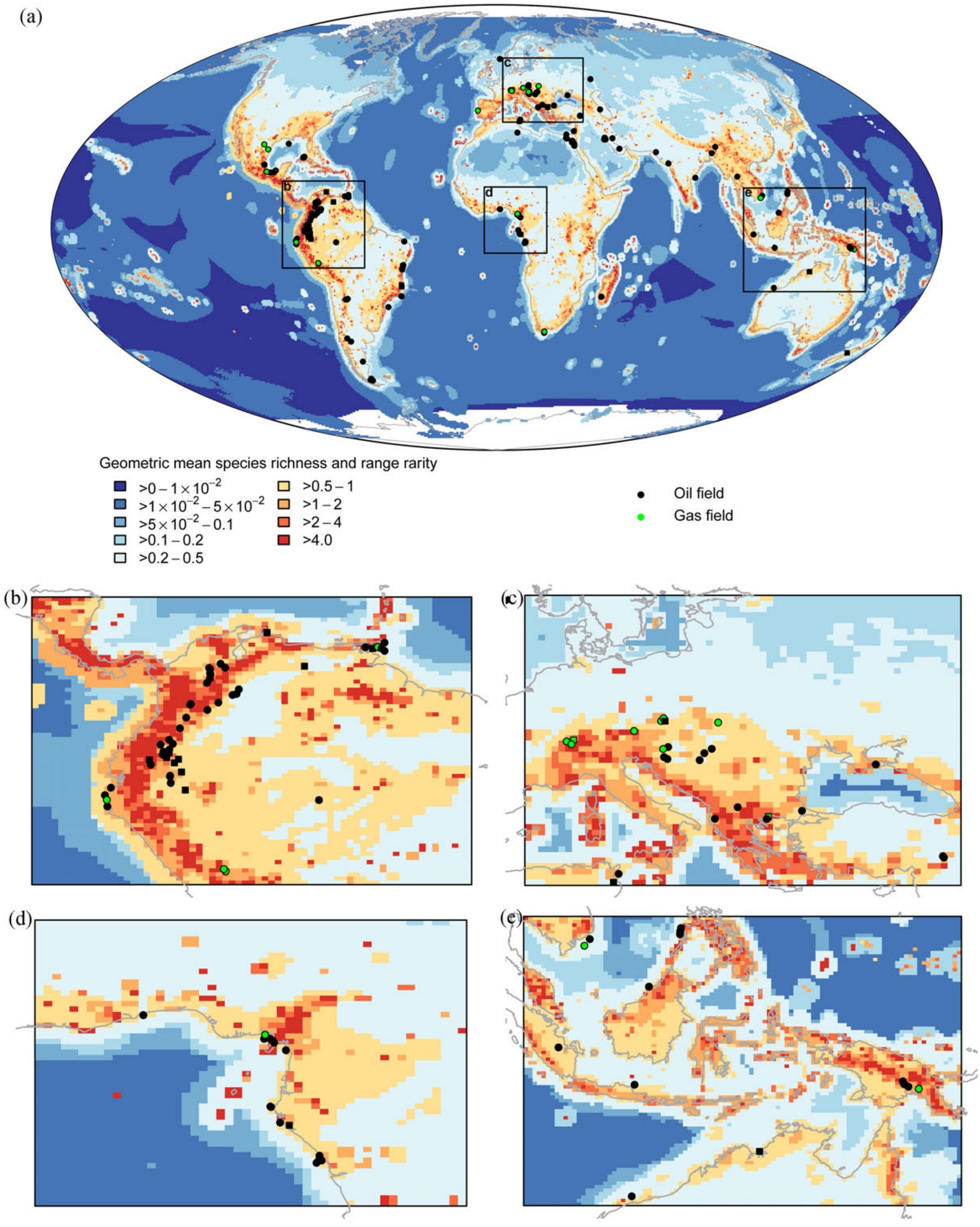

FIGURE 7 Locations (field centroids) of potential high conservation conflict in oil (red) and gas fields (blue) shown on a map of geometric mean of species richness and range rarity (a) with insets showing details for Northern Andes (b), South Eastern Europe (c), northern West Asia (d), and West Africa (e). Fields inside PAs are shown as squares and outside as circles

than areas of current exploration in these coastal regions. For LAC, coastal future-exploration blocks are constrained to subtropical regions—primarily the Brazilian coast, between 10°S and 15°S, and the Peruvian coast—which is richer with more small-ranged species compared to the Argentinean coast, along which many licensed contract blocks are located.

One interpretation of these findings is that the more easily exploitable fields—those closer to coastlines and centers of population density—have been exploited, and the pressure from oil and gas exploration and production is moving to more remote areas, such as high altitudes or deeper seas. Although global hydrocarbon activities appear to be moving into less biodiverse locations, these can still hold unique and important biodiversity and we note that the data available to understand biodiversity patterns are taxonomically limited, which we discuss in more detail below. Where fossil fuel activities do expand, there may therefore be profoundly negative consequences for local biodiversity. LAC stands out because of the high levels of biodiversity found there and because future activities appear to be moving into locations with higher biodiversity in this region, as shown previously for the Western Amazon (Butt et al., 2013), a critically important area for biodiversity (Finer, Jenkins, Pimm, Keane, & Ross, 2008). Future exploration blocks in this region are found in areas of higher biodiversity than current licensed blocks; thus the anticipated exploration across the region could have severe direct and indirect impacts on biodiversity even if no commercially viable reserves are found (Finer & Orta-Martínez 2010). Habitat conversion, fragmentation, pollution, and increased accessibility from oil and gas activities could interact with agricultural expansion—the largest historical driver of deforestation in the Amazon (Rodrigues et al., 2009)—to exacerbate threats to biodiversity in the region.

Our findings on the overlap of fossil fuel extraction with PAs are also concerning as they suggest that designation of a PA offers little safeguard against fossil fuel extraction, even within PAs with the most strict management designations where extractive activity is deemed incompatible with effective management.

We identify 181 HRFs that support high biodiversity and are favorable for exploitation—including fields inside existing PAs. Interestingly, just 9 of these HRFs are inside PAs with IUCN management categories I-IV and 16 lie within PAs with less stringent management categories. Given that most HRFs (156) are unprotected, better enforcement of existing PAs would still leave biodiversity unprotected in most HRFs.

One option would be to prohibit exploitation or strengthen existing policies, laws, and regulations to limit exploitation within HRFs, where the biodiversity impacts of exploitation are likely to be greater. These fields are generally small (median area 4.8 km^2), and contain relatively low volumes of hydrocarbons; therefore, preventing their exploitation would not substantially contribute to climate mitigation efforts, but would provide substantial local biodiversity benefits.

Given the likely increase in coincidence between PAs and fossil fuel extraction in the future, and the overall ineffectiveness of PAs in preventing exploitation, an alternative option would be to return a portion of the economic revenue derived from fossil fuel extraction inside PAs to support efforts to enhance their effectiveness for conserving biodiversity. Globally, we estimate that 7.7 (±3.4; 95% CI) billion barrels of recoverable oil and 322 (±143) billion meter cube of gas lie in near-future fields wholly contained beneath PAs. Valued at $3-15 trillion (Text S1), these reserves are equivalent to c. 200-1,000 years of funding for the entire terrestrial PA network (James, Gaston, & Balmford, 1999). Note that we do not advocate that any PA is opened for development in exchange for a biodiversity-related economic benefit, but instead, where oil or gas extraction does already occur within or adjacent to a PA, a proportion of the financial benefits could be returned to mitigate negative impacts, e.g., supporting the costs of enforcement or training to improve management effectiveness, as part of a package of impact mitigation measures (Kiesecker, Copeland, Pocewicz, & McKenney, 2010). Any such response should be conducted in line with international best practice, such as adherence to the mitigation hierarchy that prioritizes avoidance and minimization of impact over restorative or compensatory activities, and that ensures that any financial compensation for negative impacts is additional and does not replace current or future sources of PA funding (Githiru et al., 2015).

As many highly biodiverse locations lie outside the existing PA network—86% of HRFs and 95% of all near-future fields are located outside PAs—there is a need to consider expanding PA coverage in biodiverse regions at risk of potential fossil fuel extraction activity and to implement robust impact assessment and mitigation strategies irrespective of protection status (Finer, Jenkins, & Powers, 2013). Two mitigation options that are particularly important for mitigating impacts are roadless development, to reduce disturbance and limit access for exploitation in remote and inaccessible areas, and directional drilling, to access reserves from outside sensitive areas (Finer et al., 2008; Laurance et al., 2009).

Current data sets cannot identify the specific locations of future fossil fuel extraction activity because this will depend on the outcome of exploration activities, and even prior to exploration, political and economic drivers could alter the extent of these activities and associated potential biodiversity risks. We mitigated against this by using future-exploration blocks and areas of likely near-future exploitation. The biodiversity data we used are taxonomically biased and might also incorporate spatial bias in the present (Text S1), while the biodiversity patterns of the future might differ from those of today as a result of climate change (Bellard et al., 2012), habitat conversion (Newbold et al., 2015; Visconti et al., 2016), invasive species (Bellard, Genovesi, & Jeschke, 2016), exploitation (Parry, Barlow, & Peres, 2009), and other pressures.

As a result of the Paris Agreement of December 2015, which includes the intention to limit temperature increase to 1.5°C (Hulme, 2016), one potential future is that fossil fuel demand decreases by 85% by 2040 (IEA 2014), which would reduce the risk of hydrocarbon extraction and biodiversity conflict or overlap. However, most scenarios assume our reliance on fossil fuels remains substantial (Riahi et al., 2017). Fossil fuel infrastructure (oil and gas wells, pipelines and refineries, and coal mines) is currently sited in locations of higher biodiversity than sites without infrastructure. Although future fossil fuel activities are likely to move to locations with lower biodiversity, the expansion could nonetheless endanger sites of high local biodiversity and this seems most likely in Africa, Asia Pacific, and LAC. The HRFs identified here are areas where oil and gas exploitation represent an imminent and substantial risk to nature. Limiting or prohibiting exploitation in these HRFs, backed up by effective enforcement, may represent an "easy-win" in terms of enhancing biodiversity conservation under present trajectories of fossil fuel extraction. In addition to reliance on fossil fuels, society is also ultimately and completely reliant upon the goods and services provided by biodiversity (Millenium Ecosystem Assessment, 2005). Our results should help in developing new approaches to safeguarding areas of importance for biodiversity.

ACKNOWLEDGMENTS

We thank IHS, in particular Michael Reader and Kevin Chandler, for their assistance with retrieving oil and gas data and interpreting it. This work was partially funded by UKERC project NE/J005924/1. We are grateful to Felix Eigenbrod, Matt Walpole, Drew Purves, and Melissa Tolley for helpful comments on the manuscript.

AUTHOR CONTRIBUTIONS

MBJH and DPT designed the analyses. MBJH conducted analyses and with DPT co-led the manuscript writing. SK, AA, and SB conducted spatial analyses of oil and gas data and, together with SHMB, JH, MIJ, VK, JPWS, and NDB coauthored the manuscript.

The authors declare they have no competing financial interests.

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SUPPORTING INFORMATION

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How to cite this article: Harfoot MBJ, Tittensor DP, Knight S, et al. Present and future biodiversity risks from fossil fuel exploitation. *Conservation Letters*. 2018;11:e12448. https://doi.org/10.1111/conl.12448