Modeling and Analysis

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Risks to global biodiversity from fossil-fuel production exceed those from biofuel production†

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Abstract: Potential global biodiversity impacts from near-term gasoline production are compared to biofuel, a renewable liquid transportation fuel expected to substitute for gasoline in the near term (i.e., from now until c. 2030). Petroleum exploration activities are projected to extend across more than 5.8 billion ha of land and ocean worldwide (of which 3.1 billion is on land), much of which is in remote, fragile terrestrial ecosystems or off-shore oil fields that would remain relatively undisturbed if not for interest in fossil fuel production. Future biomass production for biofuels is projected to fall within 2.0 billion ha of land, most of which is located in areas already impacted by human activities. A comparison of likely fuel-source areas to the geospatial distribution of species reveals that both energy sources overlap with areas with high species richness and large numbers of threatened species. At the global scale, future petroleum production areas intersect more than double the area and a higher total number of threatened species than future biofuel production. Energy options should be developed to optimize provisioning of ecosystem services while minimizing negative effects, which requires information about potential impacts on critical resources. Energy conservation and identifying and effectively protecting habitats with high-conservation value are critical first steps toward protecting biodiversity under any fuel production scenario. Published in 2014 by John Wiley & Sons, Ltd

Keywords: biodiversity; bioenergy; biofuel; cellulosic ethanol; fossil fuel; ecosystem services; land management

Introduction

All forms of energy production have environmental consequences. Sourcing the material used for energy affects both land and water resources and the biota that they support. Species are valued for their rarity and for the ecosystem services they provide such as food, fiber, energy, the regulation of clean water and air, pollination of valuable crops, and carbon sequestration.[1] Energy development and use can affect biodiversity through enhancement or degradation of habitats, introduction of invasive species, fragmentation of habitats, or destruction of organisms or their habitats.[2–6] Greenhouse gases (GHGs) from energy production and use are affecting the world's climate,[7] resulting in further impacts to species and habitats.[1] Energy use often impacts air quality and water quality and/or quantity with cascading effects on species and their habitats. In all cases the effects of energy

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on species are context-specific with environmental effects being determined by the type of energy and initial site conditions as well as prevailing social, political, and environmental pressures.[6,8]

Fossil fuel exploration, extraction, and use have many large-scale detrimental effects on the environment.[4,9] Global carbon dioxide (CO_2) emissions from fossil fuel use were 30 276 Mt in 2010 and continue to rise.[10] Marine extraction, crude oil spills, and offshore operations contaminate water and thereby impact seabirds, whales, and invertebrates.[11–13] Seismic surveys for oil and gas can cut through natural vegetation across large regions, thereby fragmenting the land and habitats for a variety of species.[14–20] Petroleum extraction has caused large-scale subsidence in coastal regions, which is an irreversible change to the landscape.[21–23] Subterranean fractures can contaminate groundwater and alter flow patterns.[24–26] Oilfields support large wastewater-disposal evaporation ponds that cause bird fatalities.[27] Some studies suggest a link between increased seismic activity and deep-well injection of gas, waste water, and hydraulic fracturing fluids,[28–30] which can instigate changes in hydrology, habitat loss, and fragmentation.[31,32] Furthermore, fossil-fuel extraction involves a notable risk of instigating environmental catastrophes via oil spills, fires, and brine spills.[33–36]

Renewable energy has the potential to replace unsustainable fossil fuels with fewer adverse environmental consequences,[4] but all energy has some environmental costs.[37,38] While there are ethical reasons for conserving fossil resources for future generations by using more renewable energy,[39] research is needed to better understand the costs and benefits of complete renewable fuel cycles, such as the environmental impacts associated with sourcing and disposal of materials needed for solar and wind energy generation[40] and associated storage systems,[41] and effects on ecosystems from management for bioenergy.[6,42,43] Future transportation energy sources are likely to include wind power-based electric vehicles and hydrogen fuel cell vehicles.[44] But significant volumes of liquid fuels will be needed for long-haul shipping and air transport, regardless of the advances that occur to provide renewable energy alternatives to support light-duty vehicles.[48,49] Fossil petroleum and biofuels are two predominant options for meeting the specialized demands for energy-dense, liquid fuels. Biomass has been used for energy longer than petroleum, but large-scale biofuel production raises concerns about potential environmental impacts.[45] Effects of biofuel production on biodiversity are usually expressed as declines in species richness or abundance associated with habitat loss or degradation due to changes in land-cover type and management practices. Effects on biodiversity largely depend on initial conditions, species of concern, and biomass production scenarios.[47] Bioenergy offers opportunities for positive effects on biodiversity, especially when wastes, residues, and perennial crops are used as feedstock.[47] While bioenergy crop production has been identified as a threat to biodiversity in some areas, it also provides opportunities to achieve biodiversity conservation goals through site-specific management practices.[46,47]

This paper considers the locations of current and future petroleum and biofuel production and compares these to the global distribution of areas of high importance for biodiversity conservation. While other studies have shown where bioenergy might be produced in the world, our analysis compares the areas associated with the production of biofuels to those for fossil fuel with specific attention to places with high biodiversity value. This paper focuses on renewable liquid fuels that can offset future gasoline demand.[48,49]

Methodology

We build on the Butt *et al.*[9] analysis of effects of fossil fuel production on areas with high biodiversity by undertaking an analogous study of the relationship between areas of potential biofuel production and areas of high biodiversity value. Overlaying geospatially explicit data sets depicted in maps permits comparisons of the areas affected by biofuels with those affected by petroleum.

Petroleum resource regions were identified based on mapped oil and gas reserves that are already producing or expected to produce at least one billion barrels of oil equivalent. Mapped reserves of petroleum tend to include natural gas and natural gas liquids in addition to oil. Both oil and natural gas are used for liquid transportation fuels. We included the technically recoverable petroleum resources, which are those quantities of oil and gas producible using currently available technology and industry practices, regardless of economic or accessibility considerations. The technically recoverable petroleum resources are often used to make energy policy decisions.

To produce the petroleum dataset, we followed the steps outlined in the supplementary material of Butt *et al.*[9] However, we did not include coal deposit regions in our maps because coal is not considered a feasible source of liquid transportation fuel. A second difference is that our study includes combined oil and gas reserve units that lie north of the Arctic Circle. While documented biodiversity is low in these Arctic land and sea areas, it is important to consider the worldwide potential for disturbance from the extraction of oil and gas since future fossil fuels will be increasingly extracted from more remote and previously undisturbed areas.[4,9] Per the US Geological Survey (USGS): 'The extensive Arctic continental shelves may constitute the geographically largest unexplored prospective area for petroleum remaining on Earth.'[50] Furthermore energy development activities in the Arctic could have far-reaching climate-change impacts due to the high sensitivity of those ecosystems to disturbance and warming, and due to the potential to release large amounts of greenhouse gases (CO_2 and methane) currently stored below the permafrost layer. Even if ecosystem impacts were minimized, the mere combustion of fossil reserves could lead to climate change with catastrophic impacts on biodiversity; the Global Carbon Project calculates that two-thirds of known reserves must remain in the ground to retain a 50% chance of keeping future temperature rises from exceeding 2°C.[51]

Our map of significant petroleum resource areas combines information derived from several USGS studies, including (i) the *World Assessment of Undiscovered Oil and Gas Resources*[52] that evaluated undiscovered technically recoverable conventional oil and gas resources of the world exclusive of the United States; (ii) 2013 updates to the *National Oil and Gas Assessment Province Boundaries* for conventional and continuous oil and gas resources within the United States;[53] and (ii) the *Circum-Arctic Resource Appraisal: Estimates of Undiscovered Oil and Gas North of the Arctic Circle*[50] that considered areas expected to have at least a 10% chance of one or more significant (conventional) oil or gas accumulations using existing technologies.

Our map of potential areas for biomass production over the near term focuses on the most likely biofuel production scenarios for each of three major regions: the USA based on detailed analysis of multiple resources, Brazil based on detailed analysis and existing guidelines for sugarcane expansion, and the rest of the world, which is assumed to follow the least expensive and most expedient method of utilizing previously cleared and underutilized 'pastureland'. Pasturelands are a broad land-use category that includes areas previously cleared or degraded but not in current crops. Pasturelands occupy areas large enough to meet growing demands for food, fiber, feed, and biofuel out to 2030 with minimal carbon costs and even a potential carbon gain, which would help slow climate change.[54,55] Realization of this potential requires establishment of advanced second-generation feedstocks and associated technologies.[55] Improved management of pasturelands has been prioritized because (i) pasturelands are underutilized,[55] (ii) second-generation feedstocks can utilize pasturelands without incurring environmental costs,[55,56] and (iii) agricultural intensification could free up land currently used for agriculture.[55]

To generate these data layers, we aggregated datasets for potential biofuel production areas based on national resource assessments in the USA[56] and Brazil[57] and the distribution of agricultural pasturelands in the rest of the world.[58] Each of the three datasets is described below. To improve map readability and interpretation at the global scale, generalized polygons were hand drawn around all of the biomass areas at a scale of 1:20 000 000. The aggregated biomass resource areas layer was, therefore, generated at a resolution that is not appropriate for analysis at local scales. These biomass polygons were subsequently converted to a 0.1° grid to permit map algebra calculations with the petroleum and species geographic layers.

US biomass resource areas were derived from county-wide estimates of sustainable US bioenergy production potential for a combination of all agricultural, forest, and secondary resources (including municipal wastes) developed for the US Department of Energy's 2011 *Billion Ton Update*.[56] The data represent a county-by-county inventory of potentially available primary biofuel feedstocks based on the supply curve at a particular price for each individual feedstock. Although the USA set renewable fuel standard (RFS) targets for cellulosic bioenergy production to be met by 2022, we chose to map biomass resources for 2030 in order to enable enough time for ramp-up of biofuel production from multiple feedstocks. Resources are based on a mid-range scenario of 2% yield growth and a mid-point price scenario of $60 per dry ton.[56,59] For each US county, the data were summed in metric tons per year and divided by the county area in order to determine the average yield in Mg/ha per year. Only private agricultural and managed forest lands that were in production in the USA prior to 2007 were assumed to be available to source biomass annually.[56] US land areas where biofuel production is prohibited, such as National Park Service lands, were excluded.

The Brazilian biomass production areas incorporated into our map of global biomass resources is limited to the maximum extent of ethanol-related agricultural expansion that could occur based on Brazil's Sugarcane Agricultural Zoning map (ZAE Cana map).[57] That map reflects the specific areas authorized by law for sugarcane expansion and was intended to minimize risks to biodiversity by excluding forests and other areas of high conservation value.[57] For our production estimate, the lands authorized in the

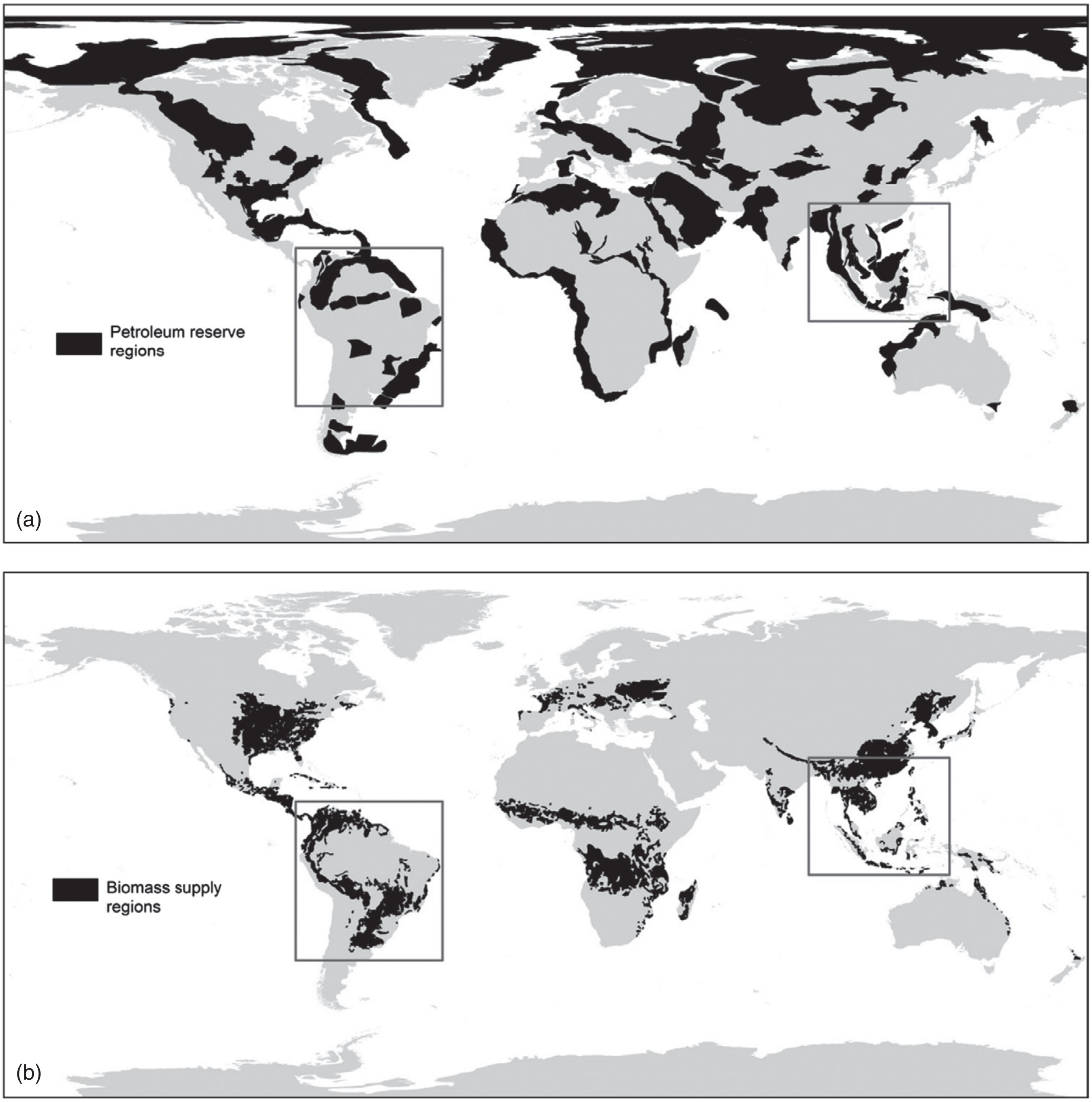

Figure 1. Areas currently used or projected for near-term use for energy production from (a) existing petroleum reserves and (b) maximum potential biomass-based biofuel production. (Boxes are areas depicted in Figs 5 and 6.)

ZAE on former pastures and mixed pastures as well as current sugarcane croplands were used.

To illustrate locations of potential biomass supply areas for the rest of the world in 2030, we began with the delineations in Ramankutty *et al.*[58] for global pasturelands. To estimate the biomass productivity on these pasturelands, we used the 0.5° global map of simulated perennial switchgrass productivity (in Mg of dry biomass per ha per year) that was developed using the Environmental Policy Integrated Climate (EPIC) cropping systems model and field data obtained from over 1400 observations and five continents.[60] A majority of global pastureland area occurs in the eight ecological zones where field-testing data supported model calibration.[60] Productivity was defined as the average annual value based on 30 years of switchgrass simulation (1981–2010) for the portion of pastureland reported in each grid cell. The mapped area of productive pasturelands is representative of the area that can be used by a variety of dedicated bioenergy crops worldwide. Grid cells for the USA and Brazil data were removed from the dataset to prevent double-counting. The pastureland map gives a general idea of future potential biomass for energy production areas around the globe.

However, our mapped area is exaggerated because it portrays entire grid cells for which average values meet the specifications of our analysis, for example reported by Ramankutty *et al.*[58] as containing a share of pastureland and having a potential annual productivity of at least 10 Mg/ha [per the Kang *et al.*[60] simulation]. Mapping exaggerates the pastureland area because many grid cells containing only a small fraction of pasture (along with forests and other land classes) are reported as pastureland. If a polygon has at least 1% of its area in productive pastureland, it is included in the map. This procedure creates a bias that exaggerates the visualization of potential areas impacted by biomass but fulfills our aim to reflect broad areas of human disturbance around the world. While undisturbed high diversity tropical forests are not considered for biofuel production, forest systems are reflected in those polygons containing areas where humans have previously cleared some trees and created pastureland.

The species richness data were created by obtaining the number of different species present in each ecoregion from the World Wildlife Fund's (WWF's) Wildfinder Database (http://worldwildlife.org/pages/wildfinder) and joining those data to the WWF Terrestrial Ecoregions of the World (TEOW) polygons. The 0.1° grids of threatened terrestrial and marine species distribution were built from 2012 International Union for Conservation of Nature (IUCN) Red List of Threatened Species datasets (http://www.iucnredlist.org/). Butt *et al.*[9] created a 0.1° grid and then performed a spatial query to label the center point of each grid cell with the total number of overlapping threatened species polygons contained in all five input IUCN datasets (terrestrial mammals, reptiles, amphibians, marine mammals, and birds). They then split the resulting raster into terrestrial and marine rasters for display purposes. We apply the same procedures for our maps.

Both the petroleum and biofuel production layers are overlain on biodiversity layers of species richness and threatened terrestrial and marine species as prepared by Butt *et al.*[9] We also add biofuel production areas to the same two inset areas (i.e., South America and Southeast Asia) that Butt *et al.*[9] highlighted to describe biodiversity risks from fossil fuel extraction.

Results

Significant petroleum resource areas are compared to future potential biofuel production locations (c. 2030) in Fig. 1. Projected petroleum production areas cover over 5.8 billion ha (Fig. 2) and extend over oceans, remote portions of the Arctic, and arid lands where biomass production would be unfeasible and landscapes would remain relatively undisturbed but for fossil fuel extraction (Fig. 1(a)). Biofuel feedstock production areas are projected to affect potentially 2.0 billion ha (Fig. 2). USA and Brazil alone have the potential to produce 691 billion liters of biofuel – about 13% of estimated demand for liquid transportation fuel while potentially minimizing or even reducing overall impacts and risks to biodiversity from transportation fuel production. Biomass areas include counties with agricultural, forest, and urban resources sustainably available in the USA,[56] sugarcane expansion areas in Brazil,[57] and potential areas for dedicated energy crops planted on current pasturelands[58] of Western Europe, Southeast Asia, Central and South America, and Africa (Fig. 1(b)). These areas have soils, climate, topography, infrastructure, and management practices that can support bioenergy crops. These are also areas where human settlement and land uses have already generated significant impacts on species and biodiversity.

Production of either biofuel or petroleum has the potential to adversely impact areas of high species

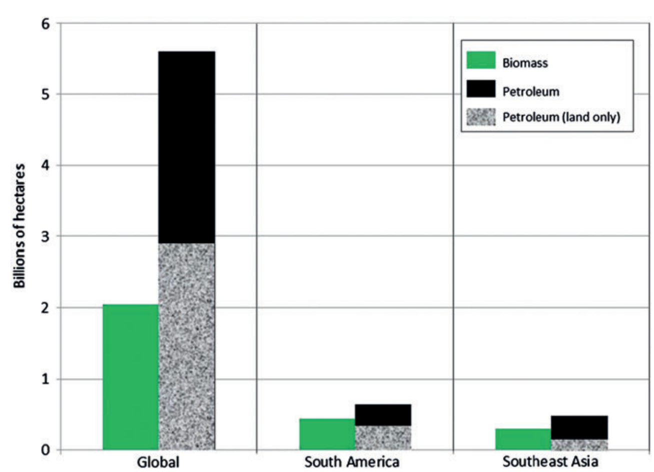

Figure 2. Histogram of areas potentially affected by biomass resources (totaling 2.0 billion ha) and petroleum extraction for liquid transportation fuel production (totaling 5.8 billion ha).

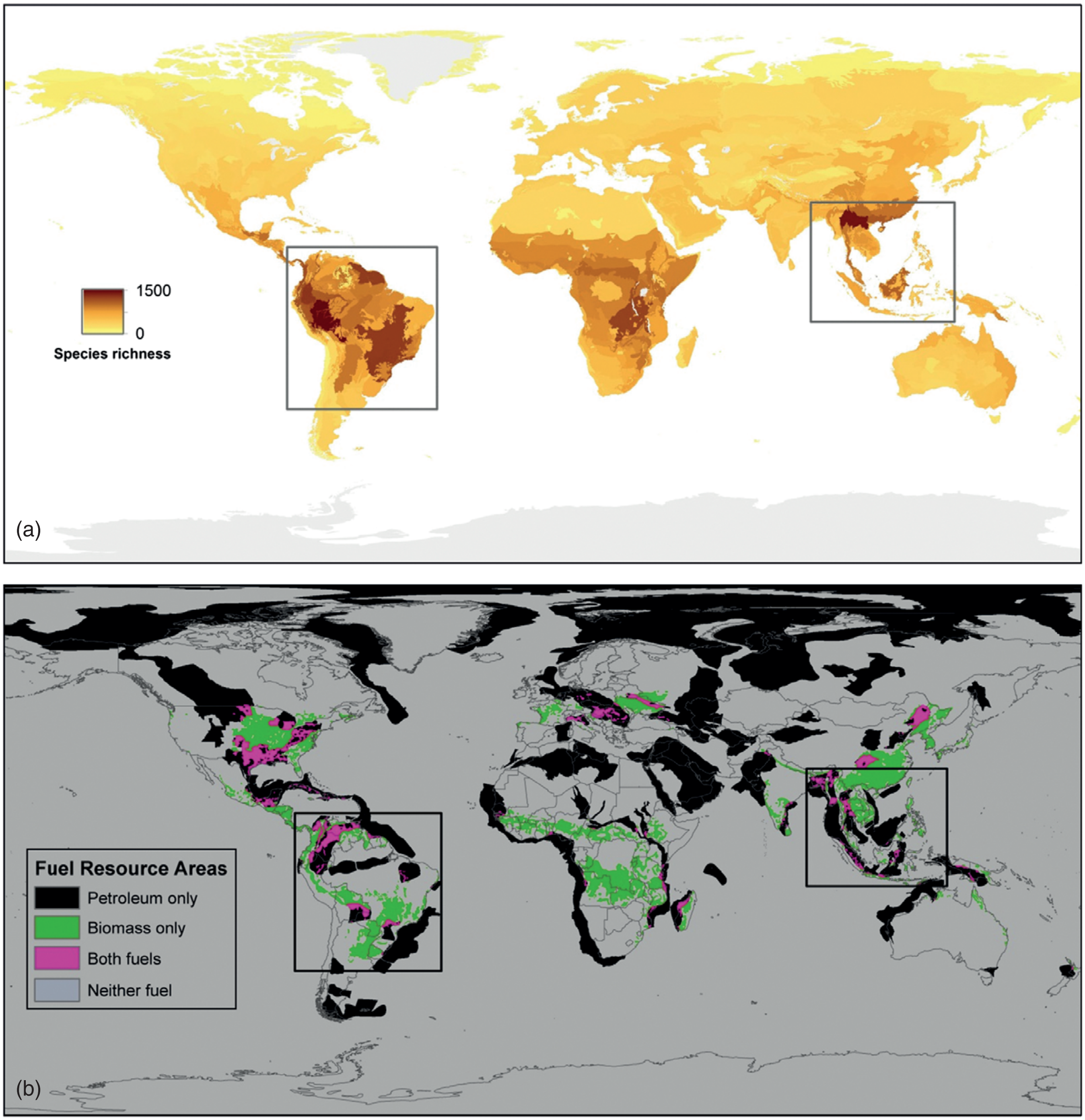

Figure 3. (a) Global map of species distribution (number of species of terrestrial mammals, reptiles, amphibians, and birds and marine mammals per ecoregion). (b) Distribution of fuel resource areas for petroleum only, biomass only, and both fuel types. (Boxes correspond to areas depicted in Figs 5 and 6.)

richness and biodiversity. Yet, striking differences are evident in the distributions of the two types of fuel production areas across the globe in relation to biodiversity. Global terrestrial species richness is shown in Fig. 3(a) while current and potential resource areas for petroleum and biomass fuels are depicted in Fig. 3(b) highlighting where the two energy resource production areas overlap. The terrestrial species richness of the land areas potentially affected by each fuel is shown in Fig. 4.

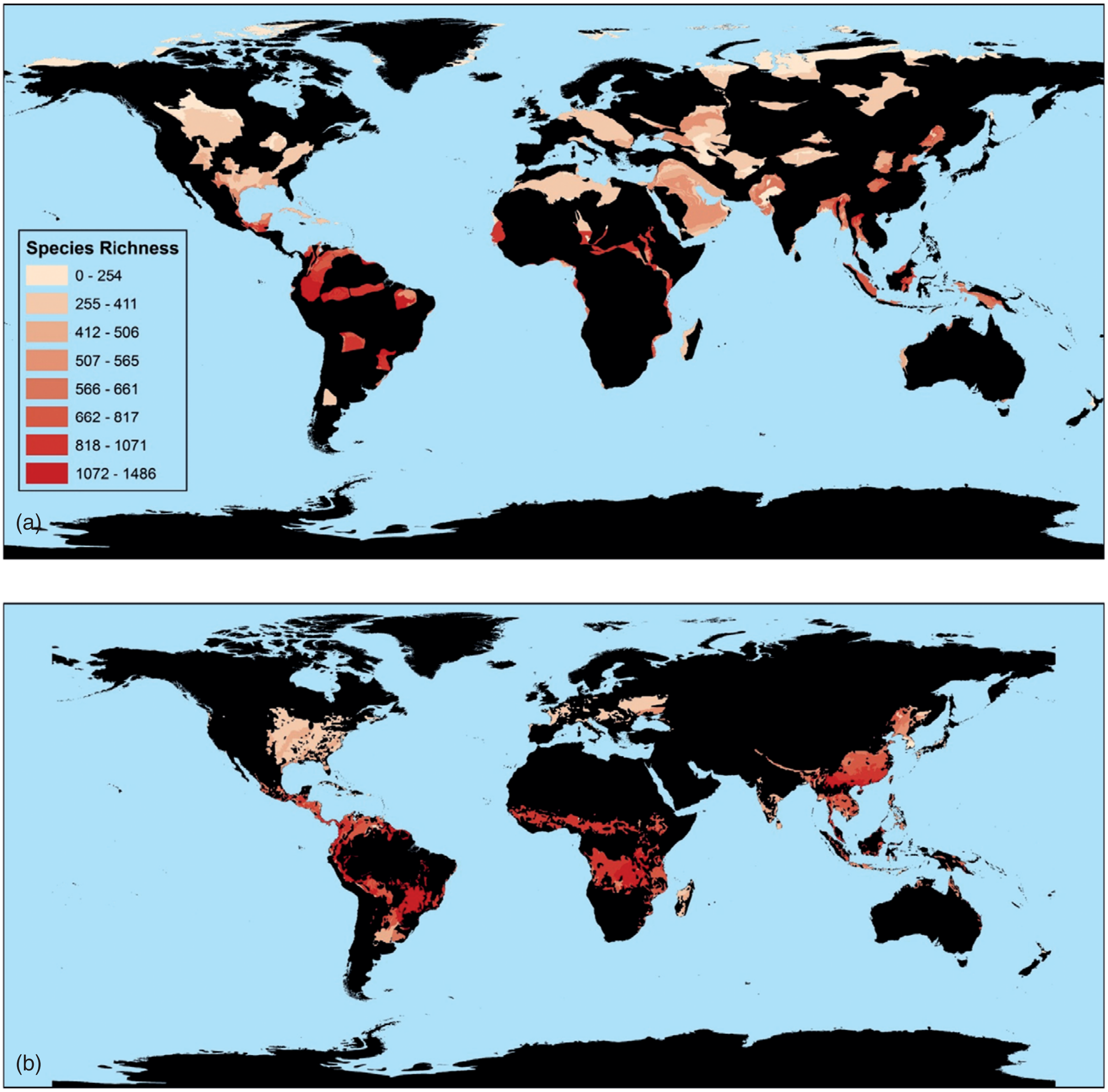

Figure 4. Number of terrestrial species in each ecoregion for those areas with (a) existing petroleum reserves (areas in black do not contain petroleum reserves) and (b) maximum potential biofuel feedstock production c. 2030 (areas in black cannot support significant biofuel feedstock production typically because of climate or soils limitations).

Two detailed maps illustrate how petroleum and biomass production areas compare to areas with especially high numbers of threatened and endangered marine and terrestrial species found across South America (Fig. 5) and Southeast Asia (Fig. 6). Differences in the intersection of fuel production areas and threatened species are evident across the globe. Petroleum production areas visibly have a larger potential to impact ecologically sensitive areas such as deserts and tundra, coastal zones, and offshore marine areas (Figs 3, 5, and 6).

Threatened terrestrial and marine species will likely be impacted by both fossil fuel and biomass resource development (Fig. 7). Globally, fossil fuels affect more threatened species including moderately diverse areas of the planet,

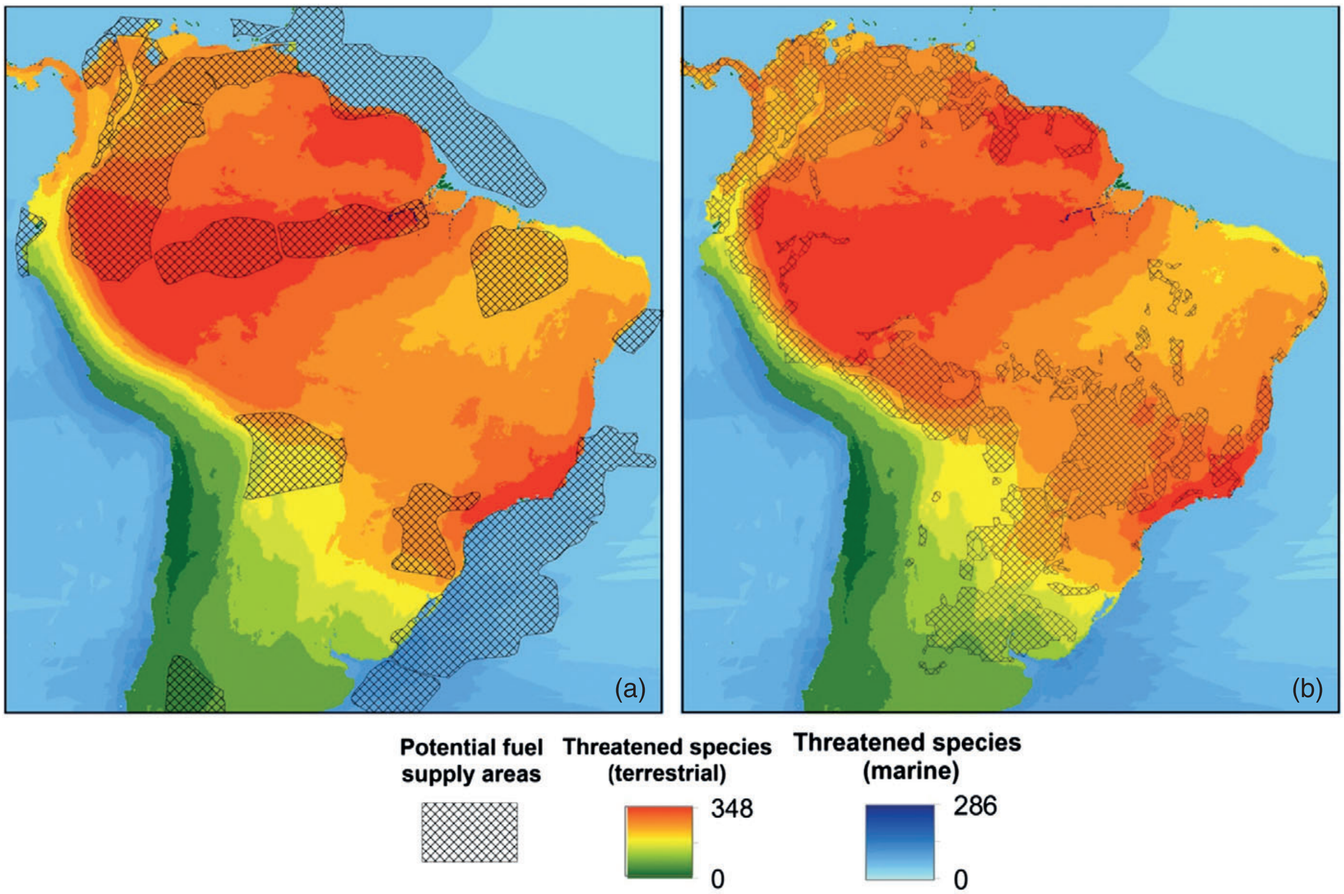

Figure 5. Map of (a) existing petroleum reserves and (b) maximum potential biofuel production areas across a portion of South America with high numbers of threatened terrestrial and marine species (depicting number of threatened species ranges within each 0.1° grid cell). Map area corresponds to the left box depicted in Figs 1 and 3.

for example areas that harbor between one and 100 threatened species; whereas biofuels have greater potential to impact areas with 50 to 200 threatened species (Fig. 7). At the global scale, future petroleum production areas potentially intersect a larger area and higher total number of threatened species, but biofuel production potentially affects areas with higher concentrations of species.

Discussion

Global production of both fossil fuel and biofuel for transportation purposes raises concerns for biodiversity. Risks from fossil fuel extraction and biofuel production exist where there is a co-occurrence of energy resource areas with areas of high numbers of terrestrial and marine species or many threatened species. Effects on biodiversity are likely on all continents (Figs. 1) and are of special concern in areas supporting high biodiversity (Figs. 3, 4, 5 and 6).

Fossil fuel production across land, permafrost, ice, and seascapes potentially impacts an area twice the size of that estimated for biofuels (Fig. 2). Furthermore, accidental large-scale spills associated with fossil fuel extraction and use result in impacts that remain in place over a long-term and large extent.[4] Fossil fuel demand is an important driver of environmental disturbance in remote and sensitive areas, which otherwise would not be at risk.[4,9,17] History suggests that even when areas are recognized as reserves for biodiversity protection, fossil fuel exploration often proceeds whereas most biofuel production has thus far been limited to previously disturbed lands. Cumulative environmental effects of petroleum production relative to biofuels are likely to be larger in extent and duration and less reversible than those of biofuel production.[4]

Because some areas with large number of threatened species are at risk from fossil fuels and biofuels (Fig. 7), those areas should be identified and either protected from development or managed in such a way as to reduce

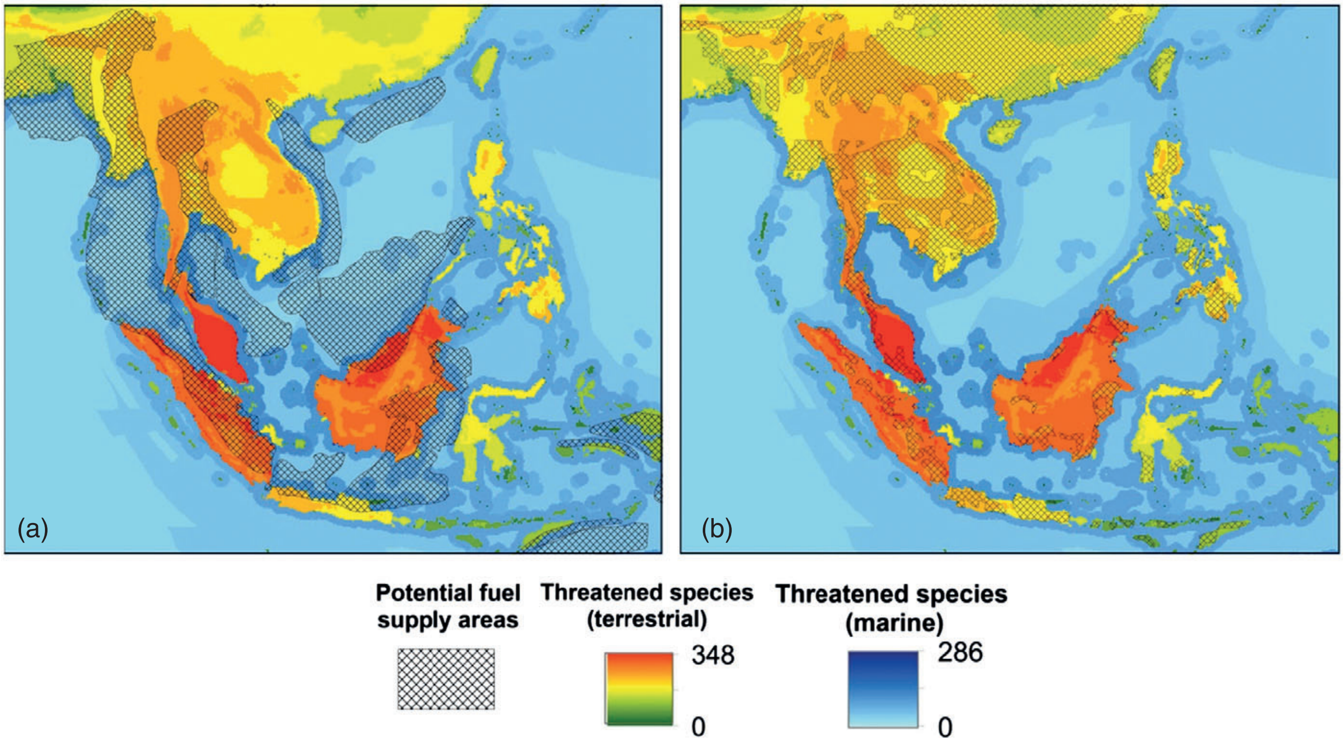

Figure 6. Map of (a) existing petroleum reserves and (b) maximum potential biofuel production areas across a portion of Southeast Asia with high numbers of threatened terrestrial and marine species (depicting number of threatened species ranges within each 0.1° grid cell). Map area corresponds to the right box depicted in Figs 1 and 3.

susceptibility of threatened species. The risks to biodiversity of energy extraction activities can be reduced if effective policies are put in place to protect areas of high biodiversity importance.[54]

Plenty of pastureland (which include previously disturbed, underutilized land) is available for bioenergy crop production worldwide,[56–58] and use of previously disturbed land minimizes threats to biodiversity. According to one global estimate, the net biomass potential of available land area is 10 times more than the combined demand of food, feed, fiber, and energy.[61] Estimates of land available for crop expansion without deforestation (i.e., previously cleared, underutilized land) ranges from 500 million to 4900 million ha[62] based on data from the Food and Agriculture Organization (FAO).[43] This enormous range is due to the difficulty inherent in classifying pastureland, grassland, and marginal land and the different temporal scales of analysis. Exclusive of protected areas and lands used for food and grazing, as many as 780 million ha are available worldwide for bioenergy crops.[42] For comparison, fires burn over 330–430 million ha each year,[63] and new development and urban expansion occur on about 4 million ha each year (adding 120 million ha of new area by 2030).[64]

While bioenergy crop production has been identified as a threat to biodiversity in some areas, it also provides opportunities to improve biodiversity compared to prior conditions through location-specific crop management systems.[45,47,65] Lack of proper land management is a critical factor affecting habitat degradation and loss[66] and GHG emissions. Proper management includes integrated agricultural systems and offering incentives (or imposing regulations) that conserve or even enhance ecosystem services.[46,47] Perennial grasses can enhance biodiversity of plants, methanotropic bacteria, arthropods, and birds when planted on marginal lands as compared to corn plantings,[67] and such land-use changes have occurred where corn productivity is low. Landscape design of bioenergy plantings can benefit ecosystem services, for example through improved water quality[68] and other benefits to habitats that support enhanced biodiversity.[1] Furthermore, biofuels provide economic incentives to avoid development activities (e.g. urban expansion) that threaten biodiversity.[69] Urban expansion instigates decline in undeveloped lands that support high biodiversity.[70] Society can benefit from biofuels not only by stimulation of rural development but also via reduction in C emissions in the substitution of

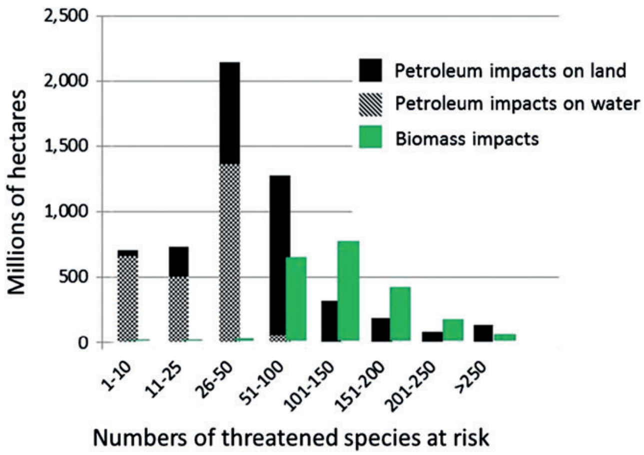

Figure 7. Histogram of the area impacted by fossil fuel and biofuel production relative to numbers of threatened species at risk.

fossil fuels with biofuels and enhanced energy security by reduced dependence on fossil fuel.[71]

Hence protection of high diversity and high conservation value areas needs to be implemented via regulation or economic incentives. Experience to date suggests that regulations and economic incentives may limit where bioenergy crops are grown[47,49] but are less likely to deter exploration for petroleum around the world.[17]

Biodiversity risks from biofuels can be limited if biomass is grown on previously cleared land or derives from plant residues.[54] Alternatively management practices can be employed such as avoiding harvest during nesting season and other times when organisms or their habitats may be susceptible (e.g. during drought, migration times, and other times critical to wildlife requirements).[72] Unlike fossil fuel production, biofuels can be produced sustainably from biomass collected exclusively from previously disturbed lands that are distant from areas of high biodiversity. Furthermore agriculture and forestry residues and urban wastes are ubiquitous, but these biofuel feedstocks have little value at present.

Conclusions

Petroleum exploration is projected to affect more than 5.8 billion ha of land and water while biofuels would affect 2.0 billion ha. Much of the area impacted by fossils fuel is located in remote, fragile terrestrial ecosystems or offshore oil fields that would remain relatively undisturbed if not for interest in fossil fuel production. In contrast, future biomass production for biofuels would be located in areas already impacted by human activities. While all energy supply options have some detrimental impacts on biodiversity, energy development choices involve trade-offs.

Consideration of areas with high diversity and high numbers of threatened species indicates that fossil fuels and biofuels are likely to have distinct effects on biodiversity. Biofuel effects are likely to be smaller in extent (Fig. 7) and duration and more reversible than fossil fuels. Furthermore focusing biofuel production on previously disturbed lands near areas of consumption facilitates the logistics of moving heavy feedstocks and poses fewer risks to critical repositories of biodiversity than petroleum exploration and exploitation across far-flung and remote areas.

Energy options should be developed to minimize environmental impacts given the constraints of each particular production region. The analysis of overall effects should include social, economic and environmental costs and benefits associated with exploration, site preparation, development, production, transport, and use. As energy demand increases, opportunities to reduce environmental impacts must be evaluated and deployed. Energy conservation is clearly the first option that should be used since no single renewable technology can entirely meet global energy demands.

Measures to identify and protect highly valued species and their habitats should be implemented and enforced prior to initiating energy development that puts species and habitats at risk. Priority areas for biodiversity conservation should rely on high-resolution data reflecting multiple taxa.[73] Sound policies for land management and land-use efficiency should be employed. [46,74] Efficient production and use of bioenergy can be part of an effective strategy to reduce near-term pressures on biodiversity caused by fossil fuels and to support the development of more sustainable, renewable liquid fuel production alternatives that will be necessary in the long run.

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