Contributed Paper

Protecting biodiversity and economic returns in resource-rich tropical forests

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Abstract: In pursuit of socioeconomic development, many countries are expanding oil and mineral extraction into tropical forests. These activities seed access to remote, biologically rich areas, thereby endangering global biodiversity. We examined how protection of biodiversity and economic revenues can be balanced in biologically valuable regions. Using spatial data on oil profits and predicted species and ecosystem extents, we optimized the protection of 741 terrestrial species and 20 ecosystems of the Ecuadorian Amazon across a range of opportunity costs (i.e., sacrifices of extractive profit). We also applied spatial statistics to remotely sensed, historic deforestation data to focus the optimization on areas most threatened by imminent forest loss. Giving up 5% of a year's oil profits (US$221 million) allowed for a protected area network that retained an average of 65% of the extent of each species and ecosystem. This performance far exceeded that of the network produced by simple optimization for land area (which required a sacrifice of approximately 40% of annual oil profits [US$1.7 billion]) and used only marginally less land to achieve equivalent levels of ecological protection. We identified what we call emergency conservation targets: regions that are essential components of a cost-effective conservation reserve network but at imminent risk of destruction, thus requiring urgent and effective protection. Governments can use our methods when evaluating extractive-led development options to responsibly manage the associated ecological and economic trade-offs and protect natural capital.

Keywords: Amazon, biodiversity, Ecuador, fossil fuels, spatial conservation prioritization, trade-offs

Protección de la Biodiversidad y el Rendimiento Económico en los Bosques Tropicales Ricos en Recursos

Resumen: Cuando se busca el desarrollo socioeconómico, muchos países expanden la extracción de petróleo y de minerales dentro de los bosques tropicales. Estas actividades proporcionan el acceso a áreas remotas con riqueza biológica y por lo tanto ponen en peligro a la biodiversidad mundial. Examinamos cómo la protección de la biodiversidad y las ganancias económicas pueden estar balanceadas en regiones con valor biológico. Usamos datos espaciales sobre las ganancias del petróleo y sobre los pronósticos de la extensión de los ecosistemas y la distribución de las especies para optimizar la protección de 741 especies terrestres y 20 ecosistemas de la Amazonía ecuatoriana a lo largo de una gama de costos de oportunidad (es decir, los sacrificios de las ganancias de las industrias extractivas). También aplicamos estadística espacial a los datos de deforestación histórica detectados con telemetría para enfocar a la optimización en las áreas más amenazadas por la inminente pérdida del bosque. El sacrificio del 5% de las ganancias anuales provenientes del petróleo (US$221 millones) permitió la existencia de una red de áreas protegidas que retuvo un promedio de 65% de la extensión de cada ecosistema y de la distribución de cada especie. Este desempeño excedió por mucho aquél de la red de áreas protegidas producido

por una optimización simple para el área de suelo (el cual requirió un sacrificio de aproximadamente el 40% de las ganancias anuales del petróleo [US$1.7 mil millones]); además de que utilizó ligeramente menos suelo para alcanzar los niveles equivalentes de protección ecológica. Identificamos algo que llamamos objetivos de conservación de emergencia: regiones que son componentes esenciales de una red de reservas de conservación rentable, pero a la vez un riesgo inminente de destrucción, por lo que requieren protección urgente y efectiva. Los gobiernos pueden usar nuestros métodos cuando evalúen sus opciones de desarrollo llevado por la extracción para manejar responsablemente las compensaciones ecológicas y económicas asociadas y así proteger al capital natural.

Palabras Clave: Amazonía, biodiversidad, combustibles fósiles, compensaciones, Ecuador, priorización de la conservación espacial

摘要： 为了追求社会经济发展, 许多国家已将石油和矿产开采的范围扩展到了热带森林之中。这些活动为进入偏远而生物丰富的地区提供了条件, 从而会危害到全球生物多样性。本研究探索了如何在具有高生物多样性价值的地区平衡生物多样性保护与经济收入。我们利用石油收益的空间数据和物种及生态系统的预测范围, 对厄瓜多尔亚马逊地区 741 种陆地物种和 20 个生态系统保护的一系列机会成本 (即放弃的石油开采收益) 进行了优化分析。我们还将空间统计应用于森林砍伐的历史遥感数据, 以集中优先保护受森林快速丧失威胁最严重的地区。放弃每年 5% 的石油收益（2.21 亿美元）就可以建立一个平均保留每个物种或生态系统 65% 的分布范围的保护区网络, 其保护成效远远超过了简单的土地面积优化获得的保护区网络 (需要牺牲约 40% 的石油年收益 [17 亿美元]), 且只需要略少一些的土地就能达到同等程度的生态保护。本研究确定了需要紧急保护的土地, 即作为具有高成本效益的保护区网络中重要组成部分, 但面临着迫在眉睫的破坏风险, 因而需要紧急、有效保护的地区。各国政府在评估开采发展方案时, 可以使用我们的方法来可靠地管理相关的生态与经济权衡, 并保护自然资产。【翻译:胡怡思;审校:聂永刚】

保护资源丰富的热带森林的生物多样性和经济收益

空间优先保护地, 生物多样性, 化石能源, 亚马逊, 利弊权衡, 厄瓜多尔

Introduction

Despite international commitments under the Convention on Biological Diversity, global biodiversity remains in rapid, unsustainable decline (WWF 2018), which has grave implications for ecosystem functioning and services (Isbell et al. 2011; Cardinale et al. 2012). The accelerating destruction of tropical forests (Kim et al. 2015) is a principal driver of the decline (Barlow et al. 2016; Alroy 2017).

The extraction of fossil fuels and minerals contributes directly to tropical biodiversity loss. Forest is cleared and fragmented to establish wells, mines, pipelines, and access roads (Laurance et al. 2009; McCracken & Forstner 2014; Sonter et al. 2017). Pollution from extraction and transportation contaminates (Rosell-Melé et al. 2017) and degrades species' habitats (Kimerling 1991; Arellano et al. 2015). However, extractive activities have their most severe impacts through long-term, indirect interactions; they precipitate colonization fronts and introduce novel pressures (Wunder 2003; Sonter et al. 2017). New roads generate extensive clearing along their routes as loggers, farmers, and hunters exploit fresh resources and markets (Laurance et al. 2009; Suárez et al. 2009; Espinosa et al. 2014). Urban centers coalesce around extraction sites, expanding outward as economic activity attracts new human populations (Sonter et al. 2017).

Many of the world's highest value conservation areas lie atop valuable hydrocarbon and mineral resources (Butt et al. 2013; Finer et al. 2015). Pressure on governments to generate revenues for socioeconomic development combined with growing demand for fossil fuels (BP 2017) and minerals (Moss et al. 2013) will stress some of the world's most remote and intact ecosystems (Bardi 2014).

Our case study region, the Ecuadorian Amazon, is exceptionally rich in endemic amphibians, birds, fishes, bats, and trees (Myers et al. 2000; Bass et al. 2010; Jenkins et al. 2013). Since becoming a major oil exporter in the 1970s, Ecuador has experienced acutely the detrimental effects of extractive activities (e.g., Finer et al. 2008; Suárez et al. 2009; McCracken & Forstner 2014). Despite this, the Ecuadorian government promotes the expansion of oil development (Lessmann et al. 2016) with active and proposed concessions across almost all of the Ecuadorian Amazon (see Fig. 1). As this case exemplifies, mitigating declines in global biodiversity requires the reconciliation of biodiversity conservation with economic development and human well-being.

Inevitably, decisions on land allocation involve trade-offs among economic, social, and ecological criteria. However, conservation costs are often not analyzed or openly discussed, and rarely is the full range of potentially effective solutions thoroughly explored in resource-rich, developing countries (McShane et al. 2011). Systematic conservation planning (Margules & Pressey 2000; Sarkar & Illoldi-Range 2010) provides a framework for examining trade-offs when planning priority conservation areas (Moilanen et al. 2005). This framework can account for spatial heterogeneity in costs (Polasky et al. 2001;
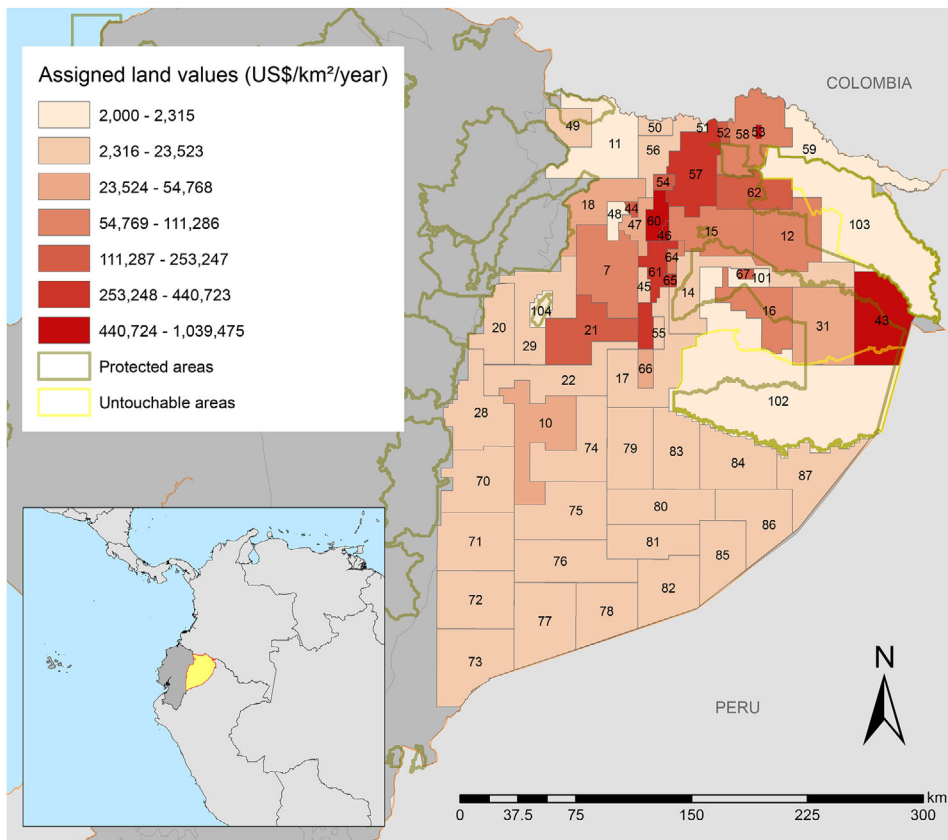
Figure 1. Assigned land values in Ecuador's oil block region. Values are equal to the profit expected from the land if it were exploited for oil or used for agriculture instead of conserved. Values are derived from oil production and reserve data and a minimum agricultural threshold of US\$2000 km^{-2}·year^{-1} is assigned to regions not subject to oil development and exhausted oil blocks. Numbers on the map <100 are oil blocks and numbers >100 are not oil regions.

Stewart & Possingham 2005; Carwardine et al. 2008), but previous applications to extractive activities have not distinguished levels of economic productivity across a landscape (Bicknell et al. 2017) or evaluated opportunity costs in explicit financial terms (Cameron et al. 2008; Moore et al. 2016), nor have they accounted for the imminence of ecological impacts. These circumstances create an imperative to develop analyses that explore trade-off scenarios comprehensively.

We used the case of the Ecuadorian Amazon to explore ways to protect biodiversity and economic revenues effectively in biologically valuable, resource-rich regions. We mapped heterogeneity in resource productivity and integrated the associated costs into a spatial prioritization process. We sought to identify conservation areas that minimize opportunity cost and evaluate economic–ecological trade-offs in explicit financial terms. Using innovations in spatial statistics and satellite remote sensing, we aimed to enhance the prioritization by identifying dynamic habitat threats and focusing potential conservation efforts on at-risk areas. Such methods will be important in managing new habitat-loss frontiers, where timely and cost-effective interventions may have considerable long-term conservation benefits. Moreover, we attempted to generate information on the losses, costs, and benefits of the trade-off scenarios, so that decision makers can openly discuss and negotiate them.

Methods

Study Area

Our study area was confined to the oil blocks of the Ecuadorian Amazon (Secretaría de Hidrocarburos del Ecuador 2017), regions bound by the oil blocks and the Ecuador–Peru border, and regions completely contained within the oil blocks (Fig. 1). The extent of the study region was 82,437 km^2, and it was sectioned into a grid of 95,822 planning units, each 0.86 km^2. Within the study region, there were 2 types of reserves: protected areas and untouchable areas (*zonas intangibles*). Protected areas are defined by the Ministry of the Environment of Ecuador and include national parks and ecological reserves (Columba Zárate 2013). Yasuni National Park and Cuyabeno Wildlife Reserve are the 2 largest ones in the study area, and they both have large overlaps with the oil blocks in the region. Sumaco Napo-Galeras National Park is smaller and is surrounded by block 29 and block 21 (Yuralpa). Untouchable areas (UAs) were created by presidential decree to protect biodiversity and cultural values from extractive and industrial activities (Constitución del Ecuador 2008). The UA in Cuyabeno Wildlife Reserve is known as the Cuyabeno-Imuya UA, and the UA that overlaps with the Yasuni National Park is the Tagaeri-Taromenane UA. In principle, these areas are

off limits to oil extraction, but there is a small overlap between these areas and the oil blocks, and part of the Ishpingo oilfield, for which there are plans for development (Argus Media 2014), lies within the Tagaeri-Taromenane UA. The Tagaeri-Taromenane UA is home to 2 voluntarily uncontacted tribes (Tagaeri and the Taromenane) (Finer et al. 2009). For the purposes of this study, the extents of the UAs that fall outside the oil blocks were considered strictly protected from all extractive activities and were categorized as the baseline conservation area.

Economic Opportunity Costs

To model returns on investment (and minimize the opportunity cost) of conservation prioritization, the value of land was mapped across the study area in terms of expected annual profitability. The economic value of a parcel of land in regions not expected to produce oil was assumed to be equivalent to expected profitability from using the land for agriculture (estimated to be $2,000 km^{-2}·year^{-1}) (all monetary units are in U.S. dollars) (Naidoo & Iwamura 2007). For active oil blocks, revenues and costs were calculated from production volumes, oil price, and unit extraction cost values taken from publicly available government reports. The average price and production volumes were taken for 2016, the latest year for which comprehensive official data were available. For untapped blocks, inferred production volumes were calculated from reported reserves. Detailed calculations, data sources, and exact monetary values assigned to the regions are in Supporting Information. A detailed account of the methods used to calculate the values and the sources used is also in Supporting Information.

Production volumes, extraction costs, and oil prices vary over time. Oil prices vary on the shortest time scales and with the greatest relative swings. To address potential sensitivity of the optimization approach to fluctuations in oil price, the economic productivity of land was also mapped for 3 other realistic oil price scenarios (2 higher and one lower [details in Supporting Information]).

Ideally, the future value of the land would also be assessed (and discounted appropriately) so that the net present value (NPV) could be calculated. Unfortunately, the required data (including on reserves) are not publicly available, so a single-year view was taken (see Discussion).

Conservation Features

A set of 741 species distributions models (SDMs), including 83 amphibians, 266 birds, 49 heliconiine butterflies, 32 mammals, and 311 vascular plants, were used to determine which areas of the landscape should be protected. Details of how the SDMs were calculated are in Support-

ing Information and Lessmann et al. (2016). The analysis also included maps of the 20 ecosystems present in the study area (Ministerio de Ambiente del Ecuador 2012); they provide a coarse-level filter to ensure representation of as wide a range of habitats as possible (Ardron et al. 2010). See Supporting Information for details of the conservation features, including species and ecosystem names.

Spatial Conservation Prioritizations

The conservation planning software Zonation (Moilanen et al. 2005) was used to set conservation priorities to maximize the retention of the distributions of 761 conservation features. Areas with substantial human interference were deemed unsuitable for conservation and excluded from the analysis. The baseline conservation areas were given prioritized inclusion in all conservation scenarios with no incurred cost.

We produced 2 spatial prioritization plans. The first did not account for the heterogeneity in productive value of land across the region and was simply optimized for ecological protection in a given land area (i.e., spatially optimized). The second aimed to maximize protection for a given opportunity cost level (or sacrifice of profit [i.e., cost-optimized]) based on the opportunity cost map described above. The iterative prioritization approach sought, at each instance, to define a network that contributed to the protection of the range of the least well-represented species or ecosystem, thereby maintaining the greatest overall diversity across the landscape. Details of the optimization approach are in Supporting Information.

The ecological–economic trade-off curve (Fig. 2b) was equivalent to a production possibility frontier (pareto frontier), with oil and ecological protection as the 2 goods produced (Supporting Information). Similar efficient frontiers have been generated for ecological protection versus economic returns from forestry and agriculture (Polasky et al. 2005; Mönkkönen et al. 2014). The range of solutions we generated can allow policy makers to better assess and balance the risks of alternative development plans. Configurations away from this efficient frontier may have to be considered when other stakeholders and criteria are incorporated into the decision-making process (e.g., rights of indigenous communities).

To explore the sensitivity of the prioritizations to fluctuations in oil price, the cost-optimized prioritization procedure was also run for 3 alternative oil price scenarios (Supporting Information).

The solutions we applied were inherently static, but inputs were affected by dynamic processes (e.g., oil price, varying production rates, and changing climate) and involved evolving uncertainties (e.g., size and location of deposits). The prioritizations should be recognized as a snapshot and used cautiously when informing
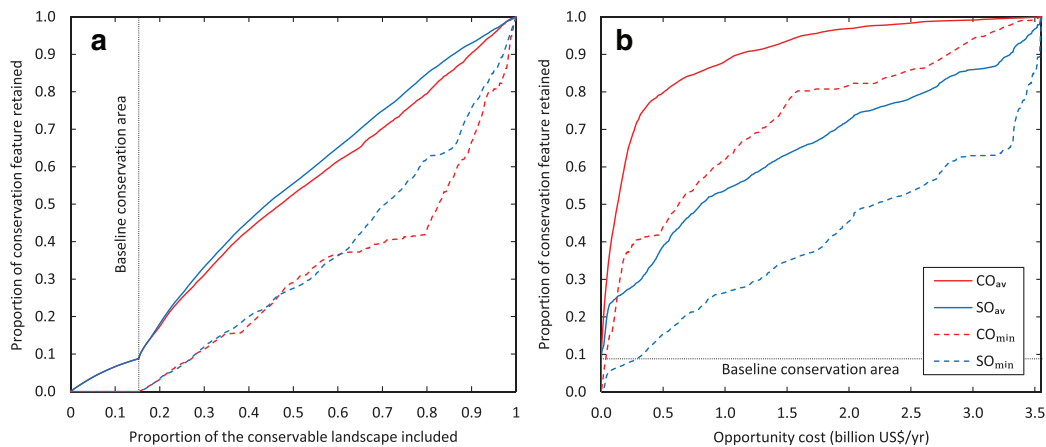
Figure 2. The (a) spatial and (b) financial efficiency of ecological protection of the cost-optimized (CO) and spatially optimized (SO) prioritizations (solid lines, average proportion of conservation feature distributions retained; dashed lines, proportion retained of the least represented conservation feature [minimum]; dotted vertical [a] and horizontal [b] lines, threshold for the baseline conservation scenarios [i.e., only strictly protected areas included]).

future reserve networks. The oil price sensitivity analysis provided reassurance that the plans were robust to one of the more volatile uncertainties of the system. The analysis should be updated and refined when new information becomes available.

We did not address habitat fragmentation directly in the prioritization, but it could have an impact on the quality of the suggested reserve networks. An additional tool to assess and optimize network connectivity for the species present would make the plans more robust, but would be complex given the number and diversity of species present and is beyond the scope of this work.

Spatial Statistics and Emerging Hotspots

We analyzed 30-m spatial resolution forest loss data for the start of 2001 to the end of 2015 (Hansen et al. 2013). Spatiotemporal patterns in forest loss were assessed to identify regions containing emerging hotspots of forest loss (Harris et al. 2017) and thereby identify where landscapes were exposed to imminent threats (Fig. 4). The region was broken into 2.25 km × 2.25 km bins, and a number of forest-loss events were aggregated within them. By comparing the amount of forest loss in a bin with its neighbors (in space and time) and with those across the whole study area, areas that contain a statistically significant clustering of forest loss were identified. We used the Getis–Ord Gi∗ statistic (Ord & Getis 1995) to identify significant spatial clustering and the Mann–Kendall trend test (Mann 1945; Kendall & Gibbons 1990) to determine whether a statistically significant temporal tend existed (details in Supporting Information).

Emergency Conservation Targets

By assessing trends in forest loss, it is possible to determine where preventative measures would be most beneficial. The final piece of our analyses combined the cost-optimized spatial conservation solution with the dynamic threat evaluation of the emerging hotspot analysis. We define emergency conservation targets (ECTs) as the regions of intersection between the area of the cost-optimized prioritization that retains an average of 60% of all conservation features and the area that falls under a forest-loss hotspot. A forest-loss hotspot contains a statistically significant clustering of deforestation as defined by emerging hotspot analysis (Supporting Information). These areas are key to a cost-effective conservation reserve network and at imminent risk from deforestation pressure, and so require urgent and effective protection. We evaluated the proportion of each oil block designated as ECT to provide a platform for identifying administrative regions where efforts should be focused to prevent further oil exploitation and establish protected areas that prevent further encroachment.

Results

Productive Land Value

The productive value of land was concentrated in a few highly productive blocks to the north and east of the region (Fig. 1). Much of the highest value oil-producing land overlapped with areas that were the most biodiverse (Supporting Information). Figure 1 highlights the magnitude of variation in land value and the potential for value trade-offs. For example, the productive value of land in the most valuable block (Sasha, block 60,
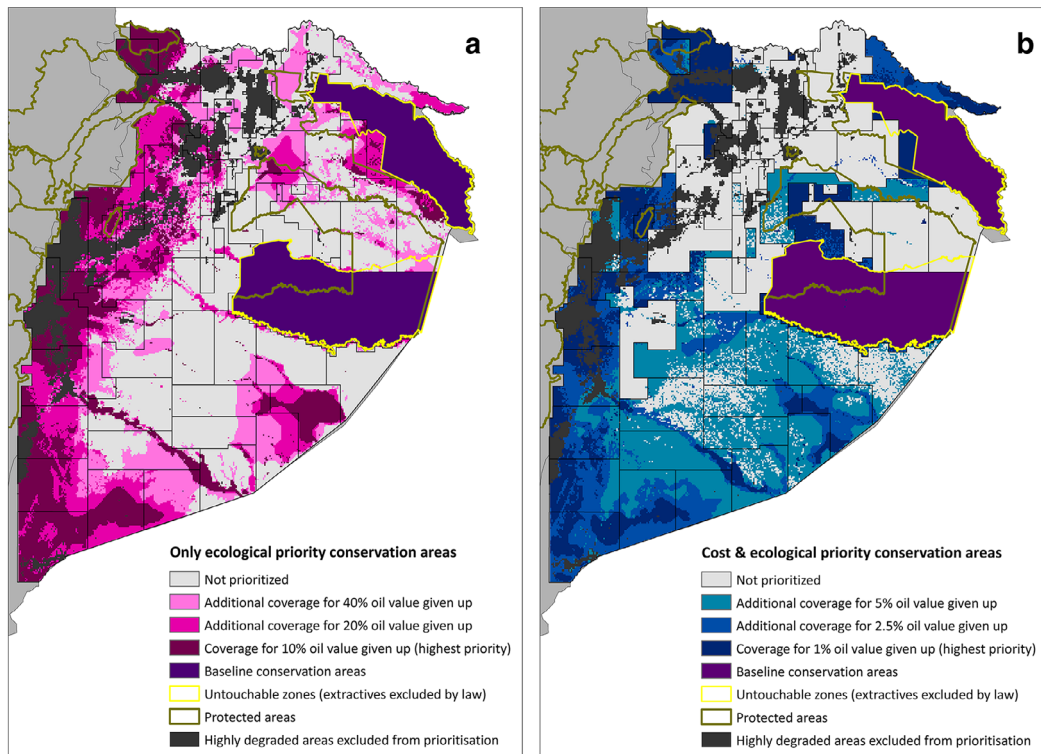
Figure 3. Priority conservation areas in the Ecuadorian Amazon's oil block region that become available for conservation at various opportunity costs levels: (a) prioritization optimized to achieve maximum retention of conservation features for a given area of land included in the conservation network showing scenarios of forgoing 10%, 20%, and 40% of annual oil profits and (b) prioritization optimized to achieve maximum coverage of conservation features for a given opportunity cost showing scenarios of forgoing 1%, 2.5%, and 5% of annual oil profits.

$ 1,000,000 km$^{-2} \cdot$year^{-1}) was 450 times that of the land in the lowest value active block (Vinita, block 59, $2300 km$^{-2} \cdot$year^{-1}). The latter's low land value, large spatial extent, and proximity to an existing protected area (Cuyabeno Wildlife Reserve) mean that it could form part of a feasible and effective conservation plan.

The value of oil-producing land in the alternative oil price scenarios scaled linearly with oil price. In the low-price scenario, the complex reserves at block 20 (Pungarayacu) were uneconomical and its land value reverted to the agricultural value. The opportunity cost maps for the alternative scenarios are in Supporting Information.

Spatial Conservation Prioritization

To reach a given level of protection, marginally more land was required for the cost-optimized plan than the spatially optimized solution (Fig. 2). For example, to protect an average of 60% of each conservation feature, 58.3% of the conservable land in the study area was required in the cost-optimized plan compared with 54.7% in the spatially optimized plan (equivalent to 2700 km^2 more land). However, considerably greater opportunity costs were incurred by the spatially optimized solution

compared with the cost-optimized solution. In the cost-optimized solution, foregoing 5% of total annual profits of the entire study region (approximately $221 million) accommodated the protection of an average of 65% of each conservation feature and included 65% of total land available for conservation. For the spatially optimized solution, an equivalent sacrifice of oil profits allowed for the protection of an average of only 27.5% of each conservation feature, and coverage was just 26% of the conservable land. To achieve an equivalent level of protection, spatial optimization required forgoing approximately 40% of total oil profits ($1.8 billion to retain an average of 67.5% of each conservation feature and 62.5% of the land available for conservation). The superior performance of the cost-optimized solution demonstrated the importance of considering variations in the productive value of land when designing efficient reserve networks. The performance by taxonomic group is in Supporting Information.

The heterogeneity of costs across the region caused some significant differences in the 2 outputs (Fig. 3). Several blocks across the north and center of the landscape featured prominently in the spatially optimized solution, but not in the cost-optimized prioritization due
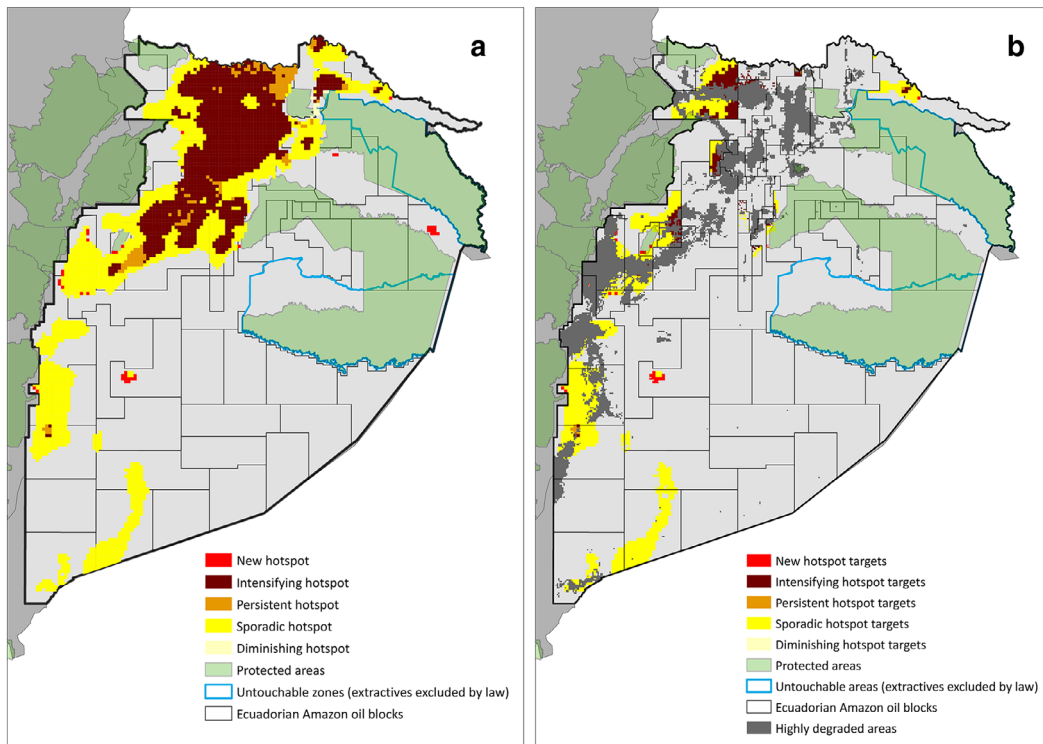
Figure 4. (a) Emerging forest-loss hotspots in the Ecuadorian Amazon oil block and (b) areas essential for a reserve network that protects at least 60% of conservation features and imminently threatened by forest loss (emergency conservation targets).

to the high opportunity cost. The cost-optimized solution relied more on the relatively low-cost southern oil blocks and block 59 (Vinita) to preserve conservation features. Both solutions ranked blocks in the south as high priority. (These areas contain several rare or unique features, including inundated forests along the rivers and evergreen forests unique to the lower slopes of the Andes mountains [Ministerio de Ambiente del Ecuador 2012].) Several regions had low importance in both solutions because they are heavily disturbed or have features that are well conserved elsewhere.

The cost-optimized prioritization was robust to fluctuations in oil price; the spatial arrangement of priority areas across the different oil price scenarios remained broadly consistent (Supporting Information). In the reduced-cost scenario, affordable protection of some conservation features was identified in the deactivated block 20, and less emphasis was placed on protecting areas around the existing protected areas. As price was reduced further, more of the oil blocks became deactivated and, as opportunity cost across the region became more homogenous, the prioritization began to resemble that of the spatially optimized solution. A lasting reduction in oil price would reduce the threat to the forest from oil extraction, making such a prioritization less urgent. In the scenarios of higher oil prices, a greater emphasis

was placed on conservation in the remaining agricultural areas due to their relative affordability.

Prioritizing Threatened Land

From the start of 2001 to the end of 2015, the Ecuadorian Amazon lost 1833 km^2 of forest, 2.3% of total cover, at an average rate of 122 km$^2 \cdot$year^{-1}, with an upward trend in the rate of loss (Supporting Information). Over 20% of the study region intersected with a loss hotspot, half of them were new, intensifying, or persistent hotspot areas (Fig. 4a & Supporting Information). The most acute forest loss was close to the historic oil center of the Ecuadorian Amazon, and this loss intensified over time. Fourteen oil blocks had >90% of their areas covered in hotspots, and 10 blocks were entirely covered. Three blocks (46, 54, and 60) had their entire extents covered by intensifying hotspots, and 3 others (50, 51, and 56) had their entire extents covered by intensifying or persistent hotspots.

There was an area of new hotspots in block 43 (ITT) at the Tiputini oil field. Extraction only recently commenced there and has been controversial due its potential impacts on pristine areas and voluntarily uncontacted communities. The presence of hotspots here showed that the recent expansion of oil extraction in Ecuador

resulted in perceptible declines in forest cover. Loss also occurred inside and close to the boundaries of protected areas. For example, some of Cuyabeno Wildlife Reserve to the northeast of the region was affected by new, intensifying, and sporadic hotspots that coincided with oil wells. Hotspot coverage tended to overlap with those blocks of higher value land reflected in the positive correlation between the land value and forest loss intensity within a block ($\rho = 0.464$).

Of the land included in the cost-optimized solution that retained an average of 60% of conservation features (Supporting Information), 12% was covered by a hotspot. Blocks with >15% of their extent were categorized as ECTs to provide a platform for identifying administrative regions where efforts should be focused to prevent further oil exploitation and establish protected areas that prevent further encroachment (Supporting Information). Because these blocks were away from the highest value known oil reserves, protected area status may be feasible.

A significant portion of the northern blocks that had ceased producing oil (11, 48, and 51) was categorized as an ECT, and contained high-value conservation areas threatened by imminent forest loss. The percentage of each block covered by ECT is given in Supporting Information.

Discussion

Our new, adaptive approach for cost-effective conservation planning is for use in regions of high ecological and economic value, and it accounts for the imminence of threats. It recognizes that some areas of high economic value may not be feasible to protect and instead seeks complementary areas to achieve ecological goals. Our analyses demonstrate that integrating the spatial heterogeneity of extractive opportunity costs across a landscape can significantly increase the performance and viability of conservation prioritizations. We found that substantial ecological protection could be achieved with minimal impacts on extractive profits, indicating that governments can chose configurations of extraction and conservation that retain revenues for socioeconomic development while substantially protecting biodiversity.

Greater spatial resolution of land value and hence more efficient solutions would be possible if consistent production data on individual wells and fields were available. Furthermore, an analysis that includes potential future land values (as well as current) would provide a more comprehensive assessment of the economic–ecological trade-offs presented and enable more efficient decisions in the future. Unfortunately, consistent, spatially resolved data on reserves are not publicly available, and there is uncertainty around future oil prices and extraction costs. This makes effectively discounting future values and calculating the NPV of land extremely

imprecise. If oil and agricultural productivity were to remain constant across the landscape, discounting future values would make no difference to the spatial arrangement of the prioritizations presented here. However, the time course of oil productivity will vary across the landscape (e.g., as reserves are depleted), whereas agricultural productivity is likely to remain relatively constant. This could have significant implications for the arrangement of conservation priorities. Decision makers with access to information on reserves are urged to build on our analysis by including potential future values.

Our method demonstrates that dynamic threats, identified remotely from satellite data, can be integrated into the spatial prioritization process enhancing its precision and effectiveness. Previous conservation prioritization studies have sought to avoid proximity to human influence (Ban & Klein 2009; Lessmann et al. 2016), but this tends to focus conservation efforts on less vulnerable regions. Our approach instead identifies areas where cost-effective conservation is viable and highlights the subset of areas currently under threat that require immediate attention. This is an effective approach for situations in which new access occurs far from existing human populations, as is often the case for extractive industries. The focus on dynamic threats is effective for addressing declines in biodiversity because it attempts to mitigate proximate sources of damage rather than simply to avoid them. By focusing conservation resources in areas where ecological objectives can be cost-effectively achieved and where threat of degradation is imminent, proactive conservation strategies can be developed for forest regions where resources extraction conflicts with biodiversity.

Identifying administrative regions that contain a large proportion of ECT facilitates the adaptation of extractive development plans to fulfil both conservation and economic goals and the determination of the locations of priority conservation interventions. Some oil blocks in the north of the study area highlighted by the ECT analysis provided cost-effective reserve land in an otherwise problematic part of the landscape because they had a low opportunity cost of conservation due to their exhausted status. However, a further evaluation of the extent to which the environments have been degraded by past oil production and the potential for restoration would be required before deeming them viable conservation areas. Southern block 74 contained a substantial region of new hotspot targets. The proximate cause of the forest loss should be identified before it expands and intensifies. The ECT surrounding the protected area to the west of the region (Sumaco Napo-Galeras National Park) can be viewed as a warning and an opportunity to valuably expand an existing conservation area.

In other analyses, biodiversity hotspots are defined broadly, often extending over several countries or vast oceanic extents (Myers et al. 2000). Our combination of spatial conservation prioritization and emerging

forest-loss hotspot analysis identified ecologically important regions under imminent threat of habitat loss. These regions were defined with high spatial resolution (∼2.25 km) and thus allowed truly local-level intervention. However, targeted local interventions may, in effect, lead to damage elsewhere (spillover). This further highlights the need to update plans dynamically as new remotely sensed data become available. Although the identified ECTs are the areas that require the most urgent interventions, they are not the only regions that need to be conserved. To achieve adequate, long-term ecological protection, the remaining priority regions in the cost-optimized network would need to be protected once the ECTs are secure.

Our techniques were used to design pragmatic conservation networks for the Ecuadorian Amazon, a region of exceptional ecological value that contains significant oil deposits. Such an approach has inherent risks, not least due the uncertainties associated with the ecological and economic relationships involved and the difficulty of incorporating their temporal evolution (Arponen et al. 2010). However, we believe our innovative solutions can help balance the needs of stakeholders and provide a way forward in a high-stakes situation. The Ecuadorian government could use our results to inform its decisions on the locations and boundaries of new and existing extractive concessions and on which areas to include in an expanded protected area network. We demonstrated that in this region, extractive activities are associated with the continued emergence of forest-loss frontiers, emphasizing the urgent need to find conservation solutions that balance the trade-offs between economic and ecological goals.

Future work should expand this analysis to include the other western Amazon oil-producing regions, including in Peru, Colombia, Brazil, and Bolivia (Finer et al. 2015), as well as other regions where there exist significant biodiversity risks from extractive activities, including in Papua New Guinea and the Congo Basin (Butt et al. 2013). To facilitate this, governments and resource industries should cooperate to create a high-resolution global map of oil and mineral deposit value.

Acknowledgments

Supporting Information

The list of conservation features (Appendix S1), land value data and calculations (Appendix S2), hotspot and emergency conservation target data (Appendix S3), extended results (Appendix S4), and methodological details including the software and settings used (Appendix S5) are available online. The authors are solely responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author. Species distribution models are available on Harvard Dataverse (identifier https://doi.org/10.7910/DVN/TB6KSC). Ecosystem extent maps used in this study are available from the Ministry of the Environment of Ecuador website http://mapainteractivo.ambiente.gob.ec/. All other input layers required to recreate the Zonation prioritizations and run information are available on figshare at https://figshare.com/projects/Ecuador_oil_fields_prioritisations/37217. Spatially (area) optimized prioritization outputs (https://doi.org/10.6084/m9.figshare.6958595) and cost optimized prioritization output (https://doi.org/10.6084/m9.figshare.6958580) are available on figshare. The emerging hotspot analysis outputs are available from figshare (identifier https://doi.org/10.6084/m9.figshare.6981485). The Python code used in the emerging hotspot analysis is available on Github from https://github.com/elizabethgoldman/emerging_hotspots_factor. The R code and input data used to generate the opportunity cost map layers is available from https://github.com/PatBall1/land_value.

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