Protecting biodiversity and economic returns in resource-rich tropical forests

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Article Impact Statement: Governments controlling resource extraction from tropical forests can arrange production and conservation to retain biodiversity and profits.

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. Here we demonstrate that conservation solutions that effectively balance the protection of biodiversity and economic revenues are possible in biologically valuable regions. Using spatial data on oil profits and predicted species and ecosystem extents, we optimise 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). For such an optimisation, giving up 5% of a year's oil profits (US$ 221 million) allows for a protected area network that retains of an average of 65% of the extent of each species/ecosystem. This performance far exceeds that of the network produced by simple land area optimisation which requires a sacrifice of approximately 40% of annual oil profits (US$ 1.7 billion), and uses only marginally less land, to achieve equivalent levels of ecological protection. Applying spatial statistics to remotely sensed, historic deforestation data, we further focus the optimisation to areas most threatened by imminent forest loss. We identify

Emergency Conservation Targets: areas that are essential to a cost-effective conservation reserve network and at imminent risk of destruction, thus requiring urgent and effective protection. Governments should employ the methods presented here when considering extractive led development options, to responsibly manage the associated ecological-economic trade-offs and protect natural capital.

Introduction

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

The extraction of fossil fuels and minerals directly contributes 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 produce their most severe impacts through long-term, indirect interactions, precipitating colonisation fronts and introducing 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 centres coalesce around extraction sites, expanding outwards 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, together 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 discussed above (Kimerling 1991; Finer et al. 2008; Suárez et al. 2009; McCracken & Forstner 2014). Despite this, the Ecuadorian government promotes oil development expansion (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 between economic, social and ecological criteria. However, conservation costs are often not analysed 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 (SCP) (Margules & Pressey 2000; Sarkar & Illoldi-Range 2010) provides a framework for examining trade-offs when planning priority conservation areas (Moilanen et al. 2005). SCP can account for spatial heterogeneity in costs (Polasky et al. 2001; 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) nor 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.

Here, using the case of the Ecuadorian Amazon, we demonstrate that solutions that protect biodiversity and economic revenues effectively are possible in biologically valuable, resource rich regions. Our approach maps heterogeneity in resource productivity and integrates the associated costs into a spatial prioritisation process. We identify conservation areas that minimise opportunity cost and evaluate economic-ecological trade-offs in explicit financial terms. Using innovations in spatial statistics and satellite remote sensing, we enhance the prioritisation by identifying dynamic habitat threats and focusing conservation efforts onto at-risk areas. These methods will be important in managing new habitat loss frontiers, where timely and cost-effective interventions may have considerable long-term conservation benefits. Moreover, our approach generates 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

The area of analysis was confined to oil blocks of the Ecuadorian Amazon (Secretaría de Hidrocarburos del Ecuador 2017), those regions bound by the oil blocks and the Ecuador-Peru border, and those regions completely contained within the oil blocks (see Fig. 1). The extent of the study region was 82,437 km^2 and it was split into a grid of 95,822 planning units (PUs) each of 0.86 km^2. Within the study region there were two types of reserves. Those referred to as *Protected Areas* (PA) 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 two 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 the smaller park surrounded by Block 29 and Block 21 (Yuralpa). Those referred to as *Untouchable Areas* (UA) (Spanish: *Zonas Intangibles*) were created by presidential decree to protect biodiversity and cultural values from extractive and industrial activities (Constitución del Ecuador 2008). The UA contained within 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 two voluntary uncontacted tribes (the Tagaeri and the Taromenane) (Finer et al. 2009). For the purposes of this study, the extents of the UAs that fall outside of the oil blocks are considered strictly protected from all extractive activities and are categorised as the 'baseline conservation area'.

Economic opportunity costs

To model *returns on investment* (and minimise the opportunity cost) of conservation prioritisation, 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 US$ 2,000 $\mathrm{km}^{-2}\cdot\mathrm{yr}^{-1}$) (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 was available. For untapped blocks, inferred production volumes were calculated from reported reserves. Appendix S2 shows the detailed calculations (with data sources) and gives the exact monetary values assigned to the regions. Appendix S5 gives a detailed account of the methods used to calculate the values and the sources used.

Production volumes, extraction costs and oil prices vary in time, with oil prices varying on the shortest time scales and with the greatest relative swings. To address potential sensitivity of the optimisation approach to fluctuations in oil price, the economic productivity of land was also mapped for three other realistic oil price scenarios (two higher and one lower; see Appendix S5 for details.

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) is not publicly available and 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 help determine which areas of the landscape should be protected. Appendix S5 and Lessmann et al. (2016) give details of how the SDMs were calculated. The analysis also includes maps of the 20 ecosystems present in the study area (Ministerio de Ambiente del Ecuador 2012) that provide a coarse-level filter to ensure the representation of as wide a range of habitats as possible (Ardron et al. 2010). Appendix S1 gives details of the conservation features including species/ecosystem names.

Spatial conservation prioritisations

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

We produced two spatial prioritisation plans. The first did not account for the heterogeneity in productive value of land across the region and was simply optimised for ecological protection in a given land area (i.e. *spatially optimised*). The second aimed to maximise protection for a given opportunity cost level (or sacrifice of profit i.e. *cost optimised*) utilising the opportunity cost map described above. The iterative prioritisation approach sought, at each instance, to define a network that contributes to the protection the range of the least well represented species/ecosystem, thereby maintaining the greatest overall diversity across the landscape. Appendix S5 gives details of the optimisation approach and software, including the data layers supplied and settings used.

To explore the sensitivity of the prioritisations to fluctuations in oil price, the cost optimised prioritisation procedure was also run for three alternative oil price scenarios (see Appendix S5).

Spatial statistics and emerging hot spots

We analysed 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 hot spots of forest loss (Harris et al. 2017) and thereby identify where habitats are exposed to imminent threats (see Figure 4). The region was broken into 2.25 km by 2.25 km 'bins' and the number of forest loss events were aggregated within them. By comparing the amount of forest loss in a bin to its neighbours (in space and time) and to those across the whole study area, areas that contain a statistically significant clustering of forest loss are identified. The Getis-Ord Gi* statistic (Ord & Getis 1995) is used to identify significant spatial clustering and the Mann-Kendall trend test (Mann 1945; Kendall & Gibbons 1990) identifies whether a statistically significant temporal tend exists. Details of the method are given in Appendix S5.

Emergency conservation targets

By assessing the trends in forest loss, it is possible to determine where preventative measures would be most beneficial. The final piece of analysis combines the cost-optimised spatial conservation solution with the dynamic threat evaluation of the emerging hot spot analysis. We define Emergency Conservation Targets (ECT) as the regions of intersection between the area of the cost-optimised prioritisation that retains an average of 60% of all conservation features and the area that falls under a forest loss hot spot. A forest loss hot spot contains a statistically significant clustering of deforestation as defined by emerging hot spot analysis (see Appendix S5). 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.

Results

Productive land value

The productive value of land is concentrated in a few highly productive blocks to the north and east of the region (see Fig. 1). Much of the highest value oil producing land overlaps areas that are the most biodiverse (see species richness map in Appendix S5), highlighting the importance of finding cost-effective conservation strategies. Figure 1 also 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, US$ 1,000,000 $\mathrm{km}^{-2}\cdot\mathrm{yr}^{-1}$) is 450 times that the land in the lowest value active block (Vinita, Block 59, US$ 2,300 $\mathrm{km}^{-2}\cdot\mathrm{yr}^{-1}$). 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.

Greater spatial resolution of land value would be possible if consistent production data on individual wells and fields were available. Similarly, comprehensive spatial information on the size of reserves would allow the calculation NPV of the land which would support more informed and efficient decisions for the future.

The value of oil producing land in the alternative oil price scenarios scales linearly with the 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 presented in Appendix S4.

Spatial conservation prioritisation

Figure 2 shows how efficiently levels of ecological protection are achieved in the spatially optimised and cost optimised prioritisation approaches with respect to (a) the land area included in the reserve networks and (b) the oil profits foregone.

To reach a given level of protection, marginally more land is required for the cost optimised plan than the spatially optimised solution. For example, to protect an average of 60% of each conservation feature, 58.3% of the conservable land in the study area is required in the cost optimised plan compared to 54.7% in the spatially optimised plan (equivalent to 2,700 km^2 more land). However, considerably greater opportunity costs are incurred by the spatially optimised solution compared to the cost optimised solution. In the cost optimised solution, foregoing 5% of total annual profits of the entire study region (approximately US$ 221 million) accommodates the protection of an average of 65% of each conservation feature and includes 65% of total land available for conservation. For the spatially optimised solution, an equivalent sacrifice of oil profits only allows for the protection of an average of only 27.5% of each conservation feature and the coverage of just 26% of the conservable land. To achieve an equivalent level of protection, spatial optimisation requires forgoing approximately 40% of total oil profits (US$ 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-optimised solution demonstrates the importance of considering variations in the productive value of land when designing efficient reserve networks. The performance by taxonomic group is given in Appendix S4.

The heterogeneity of costs across the region caused some significant differences in the two outputs (Figure 3). Several blocks across the north and centre of the landscape feature prominently in the spatially optimised solution, but not in the cost optimised prioritisation due to the high opportunity cost. The cost optimised solution relied more on the relatively low-cost southern oil blocks and Block 59 (Vinita) to preserve conservation features. Both solutions rank 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 optimised prioritisation was robust to fluctuations in oil price, with the spatial arrangement of priority areas across the different oil price scenarios broadly remaining consistent (see Appendix

S4). In the reduced cost scenario, affordable protection of some conservation features can found in the 'deactivated' Block 20 and less emphasis is placed on protecting areas around the existing protected areas. Were price to be reduced further, more of the oil blocks would become deactivated and, as opportunity cost across the region becomes more homogenous, the prioritisation would begin to resemble that of the spatially optimised solution. A lasting reduction in oil price would reduce the threat to the forest from oil extraction, making such a prioritisation less urgent. In the scenarios of higher oil prices, a greater emphasis is placed on conservation in the remaining agricultural areas due to their relative affordability.

The ecological-economic trade-off curve (Figure 2b) is equivalent to a production possibility frontier (PPF, pareto frontier) with oil and ecological protection as the two goods produced (see Appendix S4). 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 presented here 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. the rights of indigenous communities).

The solutions presented are inherently static, but inputs are affected by dynamic processes (e.g. oil price, varying production rates, changing climate) and involve evolving uncertainties (e.g. size and location of deposits). The prioritisations should be recognised as a snapshot and used cautiously when informing future reserve networks. The oil price sensitivity analysis provides reassurance that the plans are robust to one of the more volatile uncertainties of the system. The analysis should be updated and refined when new information becomes available.

It should also be noted that habitat fragmentation has not been addressed directly in the prioritisation but could have an impact on the quality of the suggested reserve networks. An additional tool to assess and optimise 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 paper.

To consider the dynamics of deforestation in system we developed the emerging hotspot analysis, described below.

Emergency Conservation Targets: prioritising threatened land

From the start of 2001 to the end of 2015, the Ecuadorian Amazon lost 1,833 km^2 of forest, 2.3% of total cover, at an average rate of 122 $km^2 \cdot yr^{-1}$, with an upward trend in the rate of loss (see Appendix S4).

Over 20% of the study region intersects with a loss hotspot, half of them being new, intensifying or persistent hotspot areas (see Fig. 4a; see Appendix S5 for definitions of the categories). The analysis reveals that the most acute forest loss is close to the historic oil centre of the Ecuadorian Amazon and that this loss is intensifying. Fourteen oil blocks have more than 90% of their areas covered in hotspots, and ten blocks are entirely covered. Three blocks (46, 54 and 60), have their entire extents covered by intensifying hotspots, and three more (50, 51 and 56), have their entire extents covered by intensifying or persistent hotspots.

Additionally, there is an area of new hotspots in Block 43 (ITT) at the Tiputini oil field. Extraction has only recently commenced there and been subject to controversy due its potential impacts on pristine habitats and voluntary uncontacted communities (Vallejo et al. 2015). The presence of hotspots here demonstrates that the recent expansion of oil extraction in Ecuador is resulting in perceptible declines in forest cover. Loss is also occurring inside and close to the boundaries of protected areas. For example, some of Cuyabeno Wildlife Reserve to the north east of the region is affected by new, intensifying and sporadic hotspots that coincide with oil wells. Unsurprisingly, hotspot coverage tends 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-optimised solution that retains an average of 60% of conservation features (see Appendix S4), 12% is covered by a hotspot. We highlight blocks with more than 15% of their extent categorised as Emergency Conservation Targets (ECTs), providing a platform for identifying administrative regions where efforts should be focused to prevent further oil exploitation and establish protected areas that prevent further encroachment (see Appendix S3). As these blocks are away from the highest value known oil reserves, protected area status may be feasible.

A significant portion of the northern blocks that have ceased producing oil (11, 48 and 51) is categorised as an ECT. Is contains high value conservation areas that are threatened by imminent forest loss. Their *exhausted* status means that they now have low opportunity cost of conservation and therefore could provide cost-effective reserve land in an otherwise problematic part of the landscape. 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 contains a substantial region of new hotspot targets. The proximate cause of the forest loss should be identified addressed 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. The percentage of each block covered by ECT is given in Appendix S3. By identifying administrative regions that contain a large proportion of ECT it is possible to precisely target conservation resources and adapt extractive development plans to fulfil both conservation and economic goals.

In other analyses, biodiversity hotspots are defined broadly, often extending over several countries or vast ocean extents (Myers et al. 2000). The combination of spatial conservation prioritisation and emerging forest loss hotspot analysis presented here identified ecologically important regions that are under imminent threat of habitat loss, defined with high spatial resolution (~2.25 km), thus enabling local level intervention. We have identified local “hotspots” in terms of their relative importance for cost-effective biodiversity conservation, accounting for the imminence and anticipated severity of forest loss.

However, targeted local interventions may, in effect, lead to damage being displaced elsewhere (*spillover*). This further highlights the need to update plans dynamically, in this case, as new remote sensing data becomes available. Additionally, while 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 an adequate, long-term ecological protection, the remaining priority regions in the cost-optimised network need to be protected once the ECTs are secure.

Previous conservation prioritisation 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. The approach presented here 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.

Discussion

This article presents a new, adaptive approach for cost-effective conservation planning in regions of high ecological and economic value, accounting for the imminence of threats. It recognises that the conservation values of some areas of high economic value may not feasibly be protected, so instead seeks complementary areas to achieve ecological goals. The analysis demonstrates that integrating the spatial heterogeneity of extractive opportunity costs across a landscape significantly increases the performance and viability of conservation prioritisations. It shows that substantial ecological protection can 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. It further demonstrates that dynamic threats, identified remotely from satellite data, can be integrated into the spatial prioritisation process enhancing its precision and effectiveness. By focusing conservation resources in areas where ecological objectives can be cost-effectively achieved, and that are under imminent threat of degradation, proactive conservation strategies can be developed for forest regions where resources extraction conflicts with biodiversity.

The techniques were used to design pragmatic conservation networks for the Ecuadorian Amazon, a region of exceptional ecological value and harbouring 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 that our innovative solutions can help to balance the needs of stakeholders and provide a way forward in a high-stakes situation. The Ecuadorian government could use this study to inform its decisions on the boundaries of extractive concessions/permits and 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.

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 for the future. Unfortunately, consistent, spatially resolved data on reserves is 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 prioritisations presented here.

However, the *time course* of oil productivity will vary across the landscape (e.g. as reserves are depleted), while 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 upon this analysis by including potential future values.

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.

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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 (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 used in this study are available on Harvard Dataverse with the 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 prioritisations and run information are available on figshare at https://figshare.com/projects/Ecuador_oil_fields_prioritisations/37217. Spatially (area) optimised prioritisation outputs (https://doi.org/10.6084/m9.figshare.6958595) and cost optimised prioritisation output (https://doi.org/10.6084/m9.figshare.6958580) are available on figshare. The emerging hot spot analysis outputs are available from figshare with identifier https://doi.org/10.6084/m9.figshare.6981485. The Python code used in the emerging hot spot 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.

Literature cited

Alroy J. 2017. Effects of habitat disturbance on tropical forest biodiversity. Proceedings of the National Academy of Sciences **114**:6056–6061. Available from http://www.pnas.org/content/114/23/6056.abstract DOI: 10.1073/pnas.1611855114.

Ardron JA, Possingham HP, Klein CJ. 2010. Marxan Good Practices Handbook, Version 2. Pacific Marine Analysis and Research Association, Victoria, BC, Canada. Available from www.pacmara.org.

Arellano P, Tansey K, Balzter H, Boyd DS. 2015. Detecting the effects of hydrocarbon pollution in the Amazon forest using hyperspectral satellite images. Environmental Pollution **205**:225–239. DOI: 10.1016/j.envpol.2015.05.041.

Argus Media. 2014. Ecuador to grant Ishpingo oil field permit. Available from http://www.argusmedia.com/pages/NewsBody.aspx?id=931445 (accessed September 25, 2018).

Arponen A, Cabeza M, Eklund J, Kujala H, Lehtomäki J. 2010. Costs of integrating economics and conservation planning. Conservation Biology **24**:1198–1204. DOI: 10.1111/j.1523-1739.2010.01539.x.

Ban NC, Klein CJ. 2009. Spatial socioeconomic data as a cost in systematic marine conservation planning. Conservation Letters **2**:206–215. Available from http://doi.wiley.com/10.1111/j.1755-263X.2009.00071.x DOI: 10.1111/j.1755-263X.2009.00071.x.

Bardi U. 2014. Extracted: How the quest for mineral wealth is plundering the planet. Chelsea Green Publishing, New York.

Barlow J et al. 2016. Anthropogenic disturbance in tropical forests can double biodiversity loss from deforestation. Nature **535**:144–147. Available from http://www.nature.com/doifinder/10.1038/nature18326 DOI: 10.1038/nature18326.

Bass MS et al. 2010. Global conservation significance of Ecuador's Yasuní National Park. PLoS ONE **5**. DOI: 10.1371/journal.pone.0008767.

Bicknell JE, Collins MB, Pickles RSA, McCann NP, Bernard CR, Fernandes DJ, Miller MGR, James SM, Williams AU, Struebig MJ. 2017. Designing protected area networks that translate international conservation commitments into national action. Biological Conservation **214**:168–175. DOI: 10.1016/j.biocon.2017.08.024.

BP. 2017. BP Energy Outlook: 2017 edition. Available from http://www.bp.com/en/global/corporate/energy-economics/energy-outlook.html.

Butt N, Beyer HL, Bennett JR, Biggs D, Maggini R, Mills M, Renwick AR, Seabrook LM, Possingham HP. 2013. Biodiversity Risks from Fossil Fuel Extraction. Science **342**:425–426. Available from http://www.sciencemag.org/cgi/doi/10.1126/science.1237261 DOI: 10.1126/science.1237261.

Cameron SE, Williams KJ, Mitchell DK. 2008. Efficiency and concordance of alternative methods for minimizing opportunity costs in conservation planning. Conservation Biology **22**:886–896. DOI: 10.1111/j.1523-1739.2008.00982.x.

Cardinale B, Duffy J, Gonzalez A. 2012. Biodiversity loss and its impact on humanity. Nature **486**:59–67. DOI: 10.1038/nature11148.

Carwardine J, Wilson KA, Watts M, Etter A, Klein CJ, Possingham HP. 2008. Avoiding costly conservation mistakes: The importance of defining actions and costs in spatial priority settings. PLoS ONE **3**. DOI: 10.1371/journal.pone.0002586.

Columba Zárate K. 2013. Manual para la Gestión Operativa de las Áreas Protegidas de Ecuador. Quito, Ecuador. Available from http://www.ambiente.gob.ec/wp-content/uploads/downloads/2014/02/04-Manual-para-la-Gestión-Operativa-de-las-Áreas-Protegidas-de-Ecuador.pdf.

Constitución del Ecuador. 2008. Artículo 407, Título VII.

Espinosa S, Branch LC, Cueva R. 2014. Road development and the geography of hunting by an amazonian indigenous group: Consequences for wildlife conservation. PLoS ONE **9**. DOI: 10.1371/journal.pone.0114916.

Finer M, Babbitt B, Novoa S, Ferrarese F, Pappalardo SE, Marchi M De, Saucedo M, Kumar A. 2015. Future of oil and gas development in the western Amazon. Environmental Research Letters

10:024003. Available from http://dx.doi.org/10.1088/1748-9326/10/2/024003 DOI: 10.1088/1748-9326/10/2/024003.

Finer M, Jenkins CN, Pimm SL, Keane B, Ross C. 2008. Oil and gas projects in the Western Amazon: Threats to wilderness, biodiversity, and indigenous peoples. PLoS ONE **3**:e2932. DOI: 10.1371/journal.pone.0002932.

Finer M, Vijay V, Ponce F, Jenkins CN, Kahn TR. 2009. Ecuador's Yasuní Biosphere Reserve: a brief modern history and conservation challenges. Environmental Research Letters **4**:034005. DOI: 10.1088/1748-9326/4/3/034005.

Hansen MC et al. 2013. High-Resolution Global Maps of 21st-Century Forest Cover Change. Science **342**:850–853. Available from http://www.sciencemag.org/cgi/doi/10.1126/science.1244693 DOI: 10.1126/science.1244693.

Harris NL et al. 2017. Using spatial statistics to identify emerging hot spots of forest loss. Environmental Research Letters **12**:024012. Available from http://stacks.iop.org/1748-9326/12/i=2/a=024012?key=crossref.1d8d003a7cd09e614cb9c335a67862b9 DOI: 10.1088/1748-9326/aa5a2f.

Isbell F et al. 2011. High plant diversity is needed to maintain ecosystem services. Nature **477**:199–202. Available from http://www.nature.com/doifinder/10.1038/nature10282 DOI: 10.1038/nature10282.

Jenkins CN, Pimm SL, Joppa LN. 2013. Global patterns of terrestrial vertebrate diversity and conservation. Proceedings of the National Academy of Sciences **110**:E2602–E2610. DOI: 10.1073/pnas.1302251110.

Kendall MG, Gibbons JD. 1990. Rank Correlation Methods.

Kim D-H, Sexton JO, Townshend JR. 2015. Accelerated deforestation in the humid tropics from the 1990s to the 2000s. Geophysical Research Letters **42**:3495–3501. Available from http://doi.wiley.com/10.1002/2014GL062777 DOI: 10.1002/2014GL062777.

Kimerling J. 1991. Amazon Crude. Washington DC: Natural Resources Defense Council.

Laurance WF, Goosem M, Laurance SGW. 2009. Impacts of roads and linear clearings on tropical forests. DOI: 10.1016/j.tree.2009.06.009.

Lessmann J, Fajardo J, Muñoz J, Bonaccorso E. 2016. Large expansion of oil industry in the Ecuadorian Amazon: biodiversity vulnerability and conservation alternatives. Ecology and Evolution **6**:4997–5012. DOI: 10.1002/ece3.2099.

Mann HB. 1945. Nonparametric Tests Against Trend. Econometrica **13**:245–259. Available from http://www.jstor.org/stable/1907187%5Cnhttp://www.jstor.org/%5Cnhttp://www.jstor.org/action/showPublisher?publisherCode=econosoc.%5Cnhttp://www.jstor.org DOI: 10.1017/CBO9781107415324.004.

Margules CR, Pressey RL. 2000. Systematic conservation planning. Nature **405**:243–253. Available from http://www.nature.com/doifinder/10.1038/35012251 DOI: 10.1038/35012251.

McCracken SF, Forstner MRJ. 2014. Oil road effects on the anuran community of a high canopy tank bromeliad (Aechmea zebrina) in the upper Amazon Basin, Ecuador. PLoS ONE **9**. DOI: 10.1371/journal.pone.0085470.

McShane TO et al. 2011. Hard choices: Making trade-offs between biodiversity conservation and human well-being. Biological Conservation **144**:966–972. DOI: 10.1016/j.biocon.2010.04.038.

Ministerio de Ambiente del Ecuador. 2012. Sistema de clasificación de los Ecosistemas del Ecuador Continental. Available from http://www.ambiente.gob.ec/wp-content/uploads/downloads/2012/09/LEYENDA-ECOSISTEMAS_ECUADOR_2.pdf DOI: 10.1017/CBO9781107415324.004.

Moilanen A, Franco AMA, Early RI, Fox R, Wintle B, Thomas CD. 2005. Prioritizing multiple-use landscapes for conservation: methods for large multi-species planning problems. Proceedings of the Royal Society B-Biological Sciences **272**:1885–1891. DOI: DOI 10.1098/rspb.2005.3164.

Mönkkönen M, Juutinen A, Mazziotta A, Miettinen K, Podkopaev D, Reunanen P, Salminen H, Tikkanen OP. 2014. Spatially dynamic forest management to sustain biodiversity and economic returns. Journal of Environmental Management **134**:80–89. DOI: 10.1016/j.jenvman.2013.12.021.

Moore CH et al. 2016. Improving spatial prioritisation for remote marine regions: optimising biodiversity conservation and sustainable development trade-offs. Scientific Reports **6**:32029. Available from http://www.nature.com/articles/srep32029 DOI: 10.1038/srep32029.

Moss RL, Tzimas E, Willis P, Arendorf J, Thompson P, Chapman A, Morley N, Sims E, Bryson R, Peason J. 2013. Critical metals in the path towards the decarbonisation of the EU energy sector: Assessing rare metals as supply-chain bottlenecks in low-carbon energy technologies. Luxembourg. Available from https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/critical-metals-path-towards-decarbonisation-eu-energy-sector-assessing-rare-metals-supply DOI: 10.2790/46338.

Myers N, Mittermeier RA, Mittermeier CG, da Fonseca GAB, Kent J. 2000. Biodiversity hotspots for conservation priorities. Nature **403**:853–858. Available from http://www.ncbi.nlm.nih.gov/pubmed/10706275%5Cnhttp://www.nature.com/doifinder/10.1038/35002501 DOI: 10.1038/35002501.

Naidoo R, Iwamura T. 2007. Global-scale mapping of economic benefits from agricultural lands: Implications for conservation priorities. Biological Conservation **140**:40–49. DOI: 10.1016/j.biocon.2007.07.025.

Ord JK, Getis A. 1995. Local Spatial Autocorrelation Statistics: Distributional Issues and an Application. Geographical Analysis **27**:286–306. DOI: 10.1111/j.1538-4632.1995.tb00912.x.

Polasky S, Camm JD, Garber-Yonts B. 2001. Selecting biological reserves cost-effectively: An application to terrestrial vertebrate conservation in Oregon. Land Economics **77**:68–78. DOI:

10.3368/le.77.1.68.

Polasky S, Nelson E, Lonsdorf E, Fackler P, Starfield A. 2005. Conserving species in a working landscape: Land use with biological and economic objectives. Ecological Applications **15**:1387–1401. DOI: 10.1890/03-5423.

Rosell-Melé A, Moraleda-Cibrián N, Cartró-Sabaté M, Colomer-Ventura F, Mayor P, Orta-Martínez M. 2017. Oil pollution in soils and sediments from the Northern Peruvian Amazon. Science of The Total Environment **610**:1010–1019. DOI: 10.1016/j.scitotenv.2017.07.208.

Sarkar S, Illoldi-Range P. 2010. Systematic conservation planning: An updated protocol. Natureza & Conservação **8**:19–26. DOI: 10.4322/natcon.00801003.

Secretaría de Hidrocarburos del Ecuador. 2017. Mapa de Bloques Petroleros. Available from http://www.secretariahidrocarburos.gob.ec/mapa-de-bloques-petroleros/ (accessed December 1, 2019).

Sonter LJ, Herrera D, Barrett DJ, Galford GL, Moran CJ, Soares-Filho BS. 2017. Mining drives extensive deforestation in the Brazilian Amazon. Nature Communications **8**:1013. DOI: 10.1038/s41467-017-00557-w.

Stewart RR, Possingham HP. 2005. Efficiency, costs and trade-offs in marine reserve system design. Environmental Modeling and Assessment **10**:203–213. DOI: 10.1007/s10666-005-9001-y.

Suárez E, Morales M, Cueva R, Bucheli U V., Zapata-Ríos G, Toral E, Torres J, Prado W, Olalla VJ. 2009. Oil industry, wild meat trade and roads: Indirect effects of oil extraction activities in a protected area in north-eastern Ecuador. Animal Conservation **12**:364–373. DOI: 10.1111/j.1469-1795.2009.00262.x.

Vallejo MC, Burbano R, Falconí F, Larrea C. 2015. Leaving oil underground in Ecuador: The Yasuní-ITT initiative from a multi-criteria perspective. Ecological Economics **109**:175–185. DOI: 10.1016/j.ecolecon.2014.11.013.

Wunder S. 2003. Oil wealth and the fate of the forest: a comparative study of eight tropical countries. Routledge.

WWF. 2018. Living Planet Report - 2018: Aiming Higher. Gland, Switzerland.

Figures

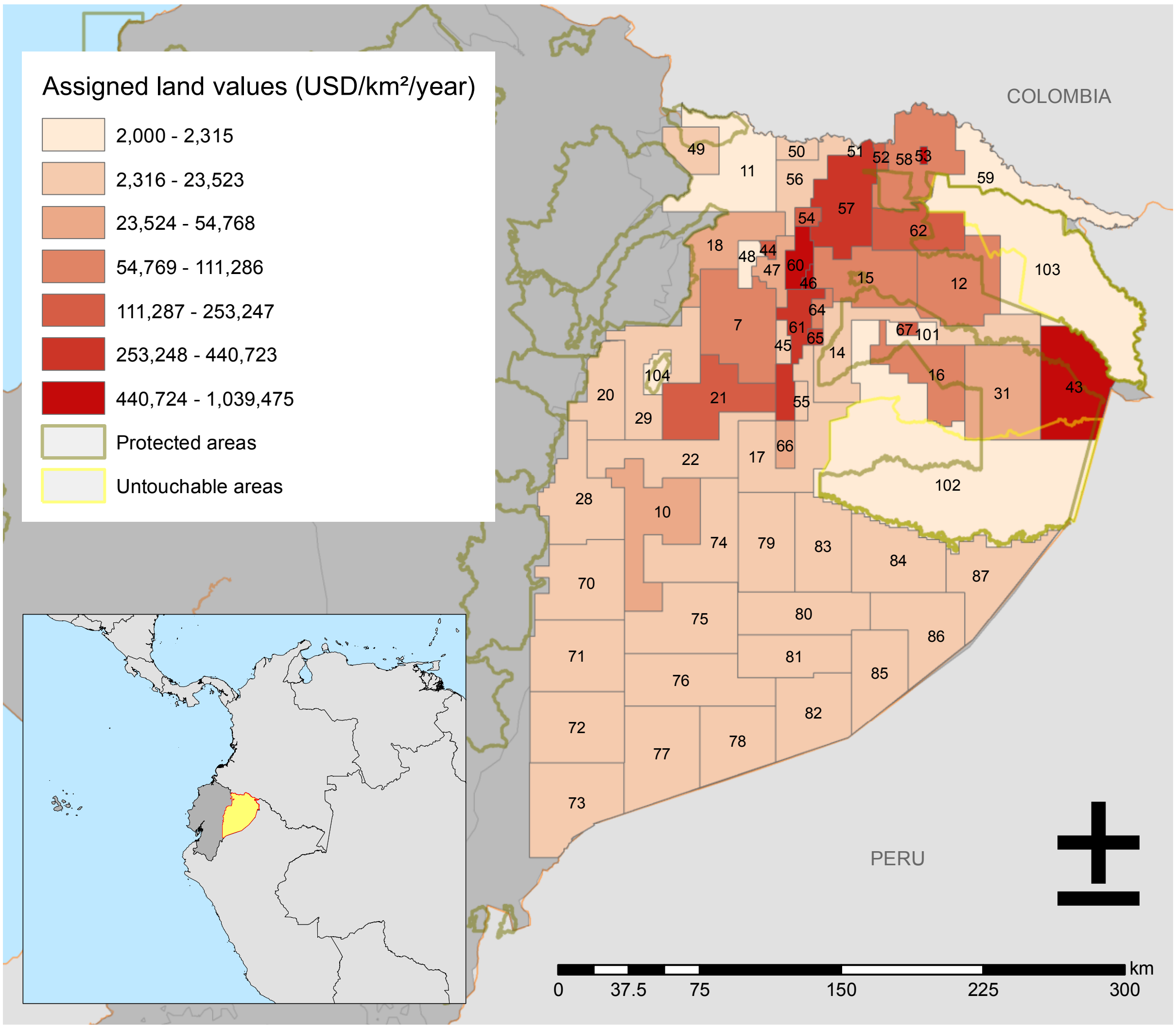

Figure 1 | Ecuadorian oil block study region with assigned land values. Values are equal to the profit one would expect to receive from the land if it were exploited instead of conserved. Values are derived from oil production and reserve data, and a minimum agricultural threshold of 2000 USD/km^2/yr is assigned to *non-oil* regions and exhausted oil blocks. Labels numbered below 100 refer to oil blocks and above 100 represent *non-oil* regions.

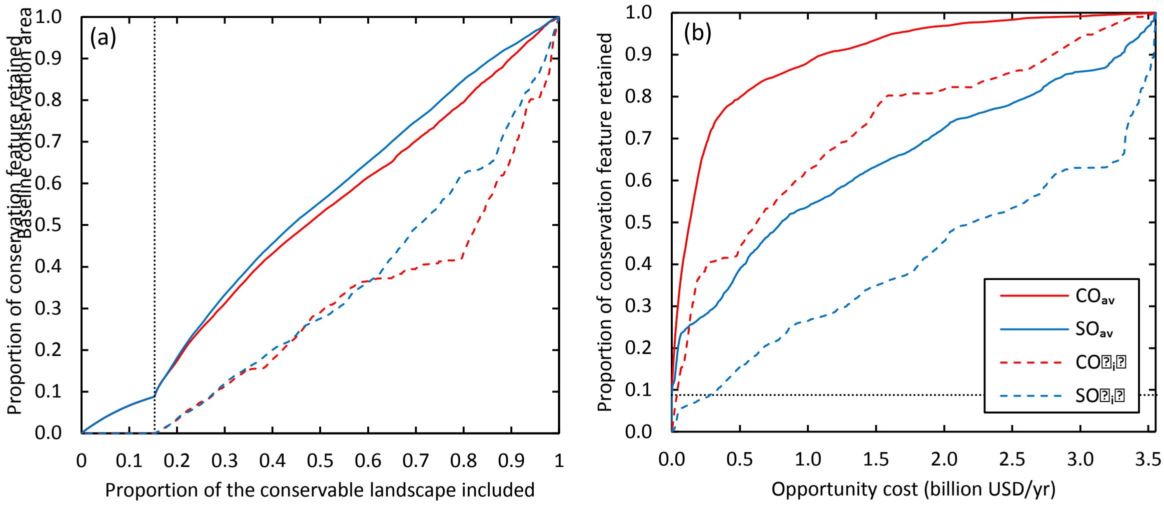

Figure 2 | The (a) spatial and (b) financial efficiency of ecological protection of the cost-optimised (CO) and spatially-optimised (SO) prioritisations. The solid lines represent the average proportion of conservation feature distributions retained and the dashed lines the proportion retained of the least represented conservation feature (minimum). The vertical (in a) and horizontal (in b) dotted lines represent threshold for the baseline conservation scenarios (i.e. when only the strictly protected areas are included).

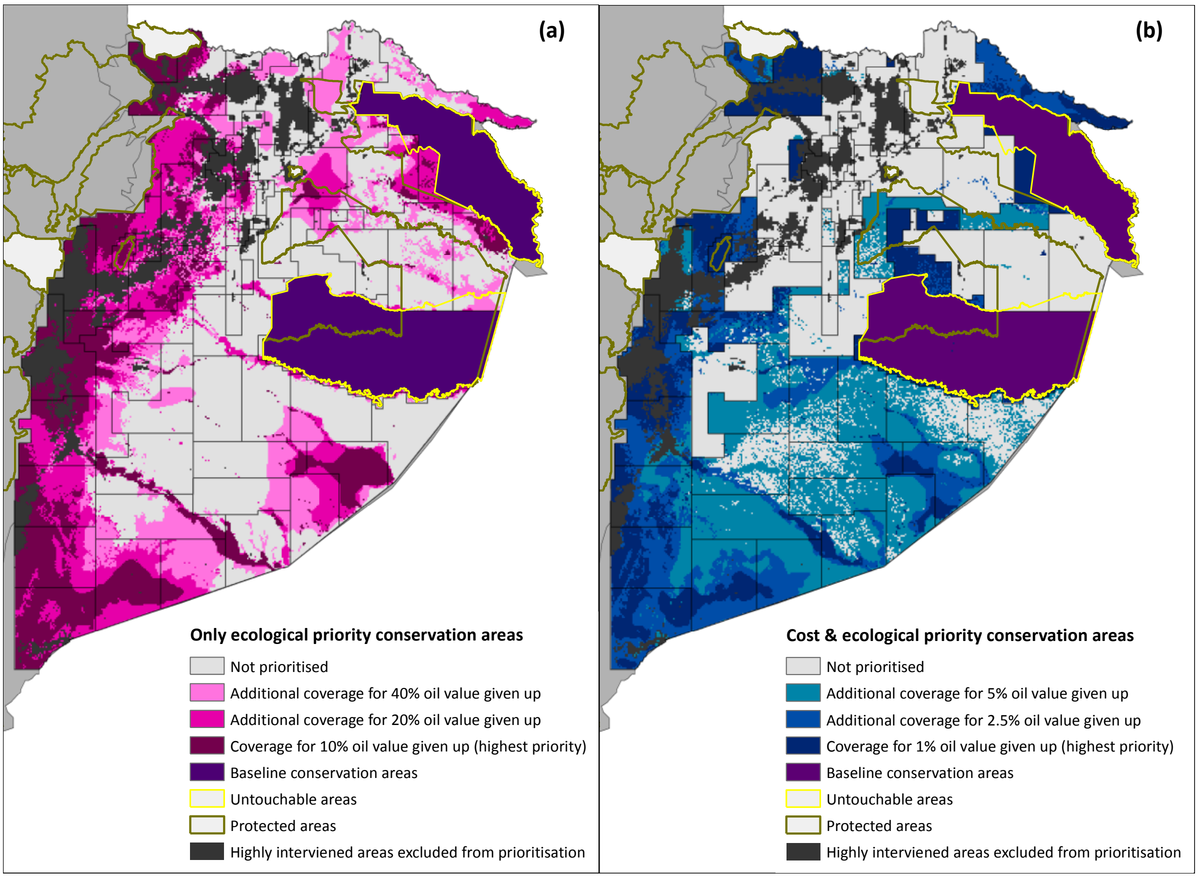

Figure 3 | Priority conservation areas in the Ecuadorian Amazon oil block region that become available at various opportunity costs levels. In (a) the prioritisation was optimised to achieve maximum retention of conservation features for a given area of land included in the conservation network and shows scenarios of forgoing 10%, 20% and 40% of annual oil profits. In (b) the prioritisation was optimised to achieve maximum coverage of conservation features for a given opportunity cost and shows scenarios of forgoing 1%, 2.5% and 5% of annual oil profits.

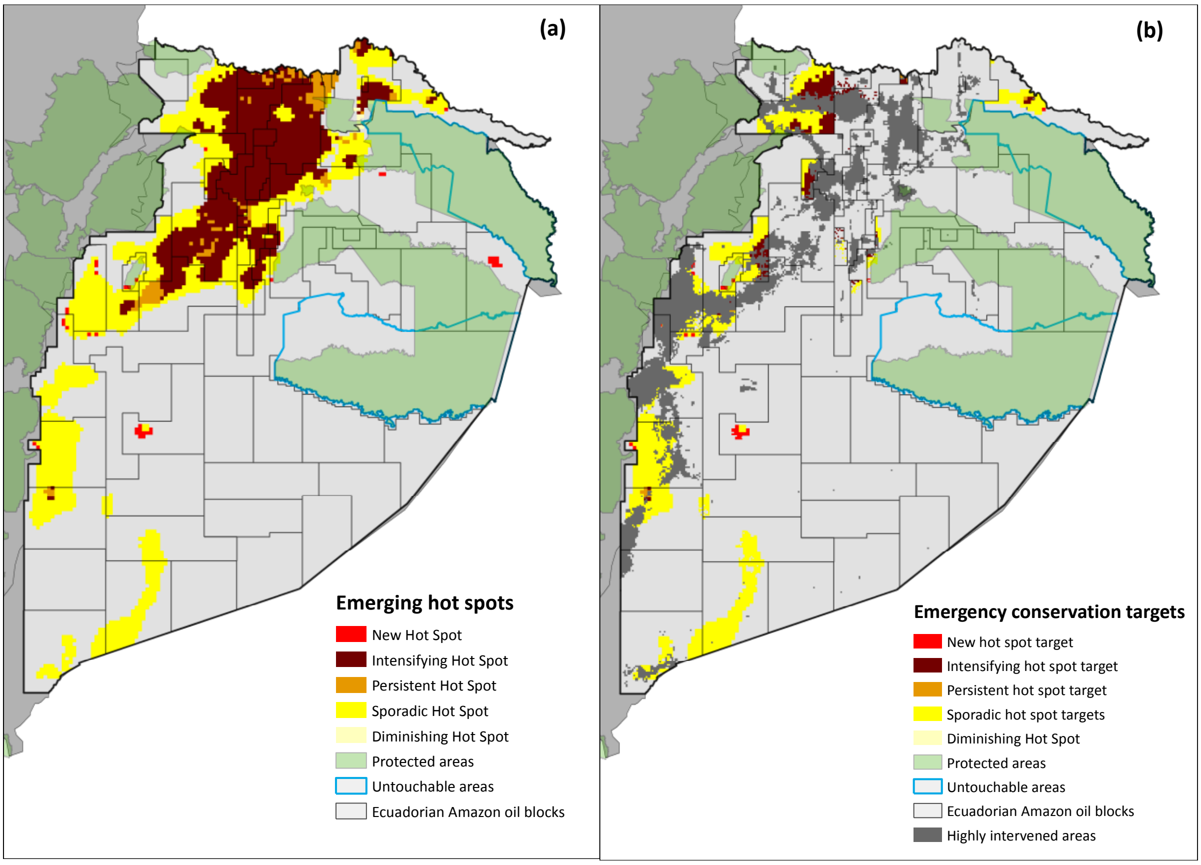

Figure 4. (a) Emerging hotspot analysis of the Ecuadorian Amazon oil block region; (b) Emergency Conservation Targets showing areas that are essential for a reserve network that protects at least 60% of conservation features and imminently threatened by forest loss.