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Oil production, biodiversity conservation and indigenous territories: Towards geographical criteria for unburnable carbon areas in the Amazon rainforest

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ABSTRACT

Climate change currently represents the tip of the iceberg of the human footprint on the Biosphere, showing social and environmental impacts both on local and global scales. McGlade and Ekins (2015) argued that to keep the temperature from increasing by 2 °C, more than 80% of coal, 50% of gas and 30% of oil reserves must remain "unburnable" underground. Within such a global scenario, the Amazon Biome presently plays a crucial role both as a carbon sink and as a fossil fuel reserve. Secondly, the Amazon Biome, - a key region in terms of provisioning ecosystem services and biological and cultural diversity - is endangered by several threats and pressures from oil and gas activities.

In this study, the first Amazon-scale integrated spatial analysis was performed, quantifying interactions between oil operations, protected areas, and indigenous territories, and focusing on the issue of leaving fossil fuels untapped.

The general aim of the present research is to provide a spatial tool useful for geographical criteria to define potential unburnable carbon areas in highly sensitive cultural and biological areas. Specific aims are identifying and quantifying overlaps between oil exploitation elements (blocks, wells, seismic lines, pipelines) and Protected Areas for biodiversity conservation, and indigenous territories.

The results show that 10.47% of the Amazon study area is currently involved in oil and gas activities. In particular, oil blocks overlap 59.26% of the Ecuadorian Amazon, 34% of the Bolivian Amazon, and 35.77% of the Colombian Amazon. The overlaps could have a stronger effect on policymakers decisions if we consider that: a) 10.47% of the Amazon study area means that oil and gas concessions cover about 620,679 km^2 of tropical ecosystems, i.e. the 6% of US territory or more than the double of UK.

1. Introduction

Climate change currently represents the tip of the iceberg of the human footprint on the Biosphere, showing social and environmental impacts both on local and global scales. Policy makers have set 2 °C above the average global temperature of pre-industrial times as the threshold that should not be crossed by 2100 in order to avoid drastic environmental consequences (COP21, 2015; IPCC, 2014; Jakob & Hilaire, 2015; Steffen, 2015). At present, more than 100 countries have adopted such a limit as a driving principle for mitigation efforts. In order to keep the temperature from increasing by 2 °C in the period 2011–2050, the CO_2 emissions must remain between 870 and 1240 Gt (Clarke et al., 2014; McGlade & Ekins, 2015). To reach this goal, McGlade and Ekins (2015) argued that more than 80% of coal, 50% of gas and 30% of oil reserves must remain "unburnable" underground. The reserves quantities to be kept unburnable are modeled using TIAM-UCL for market allocation and energy flow optimization, and BUEGO (Bottom Up Economic and Geological Oil field production model), considering capital and operating costs, and geological factors (natural decline rate). The geographical distribution of unused fossil fuels is presented for ten world regional areas resulting from the aggregation of country reserves. McGlade and Ekins's paper (2015) supply a standard reference for the management of the carbon budget, combining climate science with 2P reserves (proved and probable). Within this framework,

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two scientific issues remain unexplored: i) the spatial explicit location of reserves to be kept unburnable, ii) the definition of geographical criteria overcoming current economic and technical approach.

Coined in 2011 by the Carbon Tracker Initiative, the concept of “unburnable carbon” (or “unburnable reserves”, or “unburnable fuels”) increased in use both in scientific literature and in international meetings, introducing a policy-relevant paradigm to discuss climate change mitigation/compensation strategies associated with fossil fuel reserves that should remain untouched (Hendrick, Cleveland, & Phillips, 2017).

The actual energy and climatic global scenarios is giving to the Amazon Biome a crucial role both as a carbon sink and as a fossil fuel reserve. In fact, the Amazon rainforest represents a paradigmatic icon in the framework of the “unburnable carbon” concept since many hydrocarbon activities are actually ongoing and many others are planned at the basin scale (Finer et al., 2015). Moreover, it is a key region in provisioning a set of crucial ecosystem services worldwide, particularly with regard to carbon sequestration and to water resources. Due to the expansion of productive and communication infrastructures, such as roads and pipelines on one side, and industrial structures on the other, its conservation and sustainable management is at present an important challenge (Finer, Jenkins, Pimm, Keane, & Ross, 2008; Oakleaf et al., 2015; RAISG, 2012). The Amazon Biome also hosts important centres of biological and cultural diversity that should be preserved and protected (Finer et al., 2015); it hosts a great diversity and complexity of taxa both in fauna (insects, amphibians, birds and mammals) and flora aspects, with about 30,000 known endemic plant species (Bass et al., 2010; Mittermeier et al., 2003). The wide presence of various protected areas (hereafter PAs) and measures for sustainable management of natural resources witnesses the importance of Amazon thanks to its exceptional biological diversity (Charity, Dudley, Oliveira, & Stolton, 2016; RAISG, 2012). Even if environmental legislation and policies on biodiversity conservation are different in each country, most PAs are recognized by the International Union for the Conservation of Nature (IUCN) and then organized according to the classification adopted by the international convention.

In addition, the Amazon Biome is home to a great diversity of cultures: about 300 of indigenous populations are currently living in Amazonian tropical forests. The indigenous populations generally live within constituted territories (formally or not yet formally recognized as indigenous territories), while some of these groups are in the so-called “voluntary isolation” from oil and agricultural colonisations or they are still uncontacted (Chirif & Hierro, 2007; Pappalardo, De Marchi, & Ferrarese, 2013; RAISG, 2012; Shelton et al., 2012).

The overlap of different plans to use natural resources often leads to frictions between the different stakeholders: oil development and production projects often fuel environmental conflicts, especially in and around indigenous territories (Cuba, Bebbington, Rogan, & Millones, 2014; De Marchi, Pappalardo, & Codato, 2017; De Marchi, Pappalardo, Codato, & Ferrarese, 2015; Jaramillo, 2011; Messina, Walsh, Mena, & Delamater, 2006; Pappalardo et al., 2013; Reyes-García et al., 2012).

Apart from the effects on the climate change, oil-related socio-environmental impacts are widely documented: biodiversity loss due to ecosystem degradation and habitat fragmentation; water bodies contamination; changes in indigenous culture and in the use of the territory. It is also widely recognized that oil and gas operations, including agriculture frontier expansion, are highly threatening to the indigenous people, causing many changes in their traditional livelihood, that is small-scale agriculture, hunting, and fishing (Bozigar, Gray, & Bilsborrow, 2016; Vasquez, 2014).

Each phase of the hydrocarbon exploration, extraction and production have significant impact on the environment (Anejionu, Ahiarammunnah, & Nri-ezedi, 2015; Diantini, 2016). In particular, the main impacts are land cover changes, habitat fragmentation, and surface and underground water contamination. Deforestation and habitat fragmentation processes are mainly related to exploration (seismic prospection and “wildcat wells”) and expansion of oil development infrastructures. This leads to the opening of new roads which are required to structure pipeline networks to construct drilling platforms, heliports and wells (Bravo, 2007; Pappalardo et al., 2013). Contamination of aquifers and superficial water bodies can lead to cascade effects: alteration of aquatic organisms and an increase in congenital disorders (Kazlauskienė & Taujanskis, 2010), with high risks also for humans (San Sebastián & Karin Hurtig, 2004). Other oil-related impacts are the acoustic pollution (well-drilling phase, seismic surveys) and the release of toxic gasses (H_2S, SO_2) caused by gas venting and gas flaring (Mall, Buccino, & Nichols, 2007; NETL, 2009).

All these aspects highlight the importance of a first definition of geographical criteria to identify potential unburnable carbon areas within the Amazon Biome. McGlade and Ekins's study (2015) suggests to keep unburnable about the 73% of coal, 56% of gas and 42% of oil reserves for Central and South America, without any Carbon Capture and Storage Policies (CCS) (2015).

An emblematic study case on fossil fuels operations at Amazon scale together with the climate debate is needed, going beyond the current framework, which is based only on considering economic and geological criteria. By using a geographical approach the present study case put the pathway towards a spatial explicit definition of “unburnable carbon areas”, in order to develop the remaining reserves in the face of global climate change (Butt et al., 2013; McGlade & Ekins, 2015; Rezai & Van der Ploeg, 2016; Seto et al., 2016). This pathway comprises different steps: spatial data collection and validation, including the definition of methodologies and criteria, combined with the expert consultation and the public debate as part of the decision-making process.

Overlaps and spatial analyses between onshore oil operations and Amazonian ecosystems were previously performed in different studies, but only at country or regional scales (the Western Amazon). Many adopted ecological or biology conservation approaches never focused on the issues of leaving fossil fuels untapped (Cuba et al., 2014; Finer et al., 2008, 2015; Lessmann, Fajardo, Muñoz, & Bonaccorso, 2016; Zurita-Arthos & Mulligan, 2013). For the first time other important elements of oil exploitation were estimated and geo-visualized in this study: gas and oil wells, and seismic lines for geophysical prospection.

In this paper we performed the first Amazon-scale integrated spatial analysis about interactions between oil operations, protected areas, and indigenous territories. All nine Amazon countries were analysed with a focus on five countries (Brazil, Colombia, Ecuador, Peru and Bolivia) which cover the 87.5% of the entire Biome. We excluded from the spatial analysis Guyana, French Guyana (oversea department of France), Suriname and the Amazon regions of Venezuela, since there is no oil and gas operations in these countries (RAISG, 2012; The Petroleum Economist, 2012). An updated geodatabase was built by collecting, analysing and aggregating country-based and regional spatial data; it was used as a baseline to define geographical criteria for unburnable carbon areas in important priority areas for biodiversity conservation and human right protection.

The general aim of the present research is to provide a spatial tool useful for geographical criteria in order to define potential unburnable carbon areas in highly sensitive cultural and biological areas. By using open source Geographical Information Systems (GIS) and remote sensing technologies we specifically aim: i) to identify and quantify overlaps between oil development projects with PAs and indigenous territories; ii) to analyse the spatial relationships between oil production and culturally and ecologically sensitive areas; iii) to spatially validate the dimension of oil development and production; iv) to prepare a geodatabase of oil & gas activities, ecological, conservation and socio-cultural features of the study area.

2. Data and methods

Methodology comprises successive and complementary steps. First,

Table 1
Spatial data used in the analysis and their sources.

Category	Data	Sources
Ecological boundary	Amazon Biome boundary	WWF Amazon Ecoregion from ARCGIS online
Oil and Gas	Oil blocks divided into exploration, exploitation and promotion, oil and gas wells, 2D seismic lines, pipelines	Agencia Nacional de Hidrocarburos Colombia (ANH Colombia); Agência Nacional do Petróleo, Gás Natural e Biocombustíveis (ANP, Brazil); Yacimientos Petrolíferos Fiscales Bolivianos (YPFB, Bolivia), Agencia Nacional de Hidrocarburos Bolivia (ANH Bolivia); Perupetro S.A. (Perú); Ministerio del Ambiente Ecuador (MAE Ecuador), Secretaria de Hidrocarburos Ecuador (SHE, Ecuador)
Cultural diversity	Indigenous territories (ITs)	Red Ambiental de Información Georreferenciada (RAISG); Shelton et al., 2012; CIDH, 2013
Biodiversity conservation	Protected areas (PAs)	Protected Planet: The World Database on Protected Areas (WDPA, UNEP-WCM and IUCN)
Administrative boundaries	Country boundaries	GADM

Table 2
Spatial analysis of the Amazon study area: dimension of protected areas (PAs) and indigenous territories (ITs) for each country.

Features	Bolivia	Brazil	Colombia	Peru	Ecuador	Amazon study area
Amazon region (km^2)	446,500.24	4,081,977.74	503,808.62	786,723.53	114,679.26	5,933,689.39
% of the Amazon in the total Amazon study area	7.52	68.79	8.49	13.26	1.93	100.00
% of the Amazon region in the total area of each Country	40.76	46.77	43.97	60.82	44.09	46.87
PAs in the Amazon region (km^2)	119,038.74	1,094,342.87	96,542.83	192,578.39	30,128.22	1,532,631.06
% of PAs in the Amazon region	26.66	26.81	19.16	24.48	26.27	25.83
FRITs (km^2)	87,665.83	1,068,836.27	254,817.34	127,823.00	61,751.98	1,600,894.42
% of FRITs in the Amazon region	19.63	26.18	50.58	16.25	53.85	26.98
NFRITs (km^2)	39,454.51	0.00	0.00	11,389.12	2681.10	53,524.73
% of NFRITs in the Amazon region	8.84	0.00	0.00	1.45	2.34	0.90
PVITs (km^2)	No data	583,279.39	9869.77	71,186.43	7572.75	671,908.33
% of PVITs in the Amazon region	No data	14.29	1.96	9.05	6.60	11.32

we performed a literature review and data mining to research, collect and select spatial and non-spatial data concerning the ongoing and future oil and gas activities for each country. This data was related to ecological, conservation and cultural features. The list of the data used in the analysis and their sources is presented in Table 1. We selected the most updated available information, up to 2016 for oil and gas activities and to 2017 for cultural and conservation elements. We privileged official information from international and national Geoportal, websites or WebGIS, in a georeferenced vector or raster format when possible, or PDF maps and Excel databases prepared to be used in the GIS environment.

The study area was defined by clipping the borders of the five countries (Bolivia, Brazil, Colombia, Ecuador, Peru) with the Amazon Biome boundary, based on the Terrestrial Ecoregions of the World base map (Olson & Dinerstein, 1998 in WWF, 2013). The Amazon study area is marked on the maps by a blue line (Figs. 1–3).

We included these features in the analysis: oil and gas blocks, divided into areas promoted for leasing (promotion blocks), concession areas for the exploration phase (exploration blocks) and concession areas for exploitation activities (exploitation blocks) (Finer et al., 2015), pipelines, 2D seismic lines and oil and gas wells. In relation to PAs, we used the dataset World Database of Protected Areas (WDPA) available through the ProtectedPlanet.net website (UNEP-WCMC & IUCN, 2017). In particular, the WDPA dataset was used after its comparison with information derived from geoportals of each country: in the case of Brazil and Bolivia we erased from the WDPA dataset the polygons with designation "Indigenous Area", to avoid double counting with Indigenous Territories. Considering the indigenous territories (hereafter ITs), the reference was the shapefile available on the website of "Red Ambiental de Información Georreferenciada" (RAISG), adopting three categories for the different polygons, i.e. 1) areas formally recognized as indigenous territories by the national government (hereafter FRITs); 2) areas not formally recognized or in process of recognition by the national government (hereafter NFRITs); 3) intangible zones or areas proposed to be territorial reserve for volunteered isolated/uncontacted indigenous people (hereafter all considered as territories for populations in volunteer isolation, or PVITs). As regards the PVITs, the dataset of RAISG was integrated with other information, in order to better analyse their situation: for Colombia we considered the polygon area of the Rio Pure Natural National Park extracted by WDPA, because it was created to protect the Yuri - Arojes uncontacted indigenous people's territory (CIDH, 2013); for Brazil we selected and extracted from the Shapefile of RAISG all the polygons shown as "indigenous territories with people in isolation" reported in Shelton et al.'s work (2012); for Bolivia, we used the information and georeferenced the maps of the PVITs presented in Shelton et al.'s work (2012). In this last case we used the digitalized shapefile only as a reference in the output maps, without considering it in the analysis, due to the low quality of the pdf. Second, the selected features were stored in a geodatabase, converting all data in a defined planimetric reference system for each country (UTM WGS 84 Zone 18S for Peru, Zone 19N for Colombia, Zone 20S for Bolivia and 21S for Brazil) to perform spatial analysis and setting it in a geographic system (WGS84) to prepare cartographic output for the whole Amazon study area. Once the GIS project for each country was ready, we performed spatial analysis using a GIS open source software program: QGIS, LTR 2.18 version. The logical steps followed for the analysis were 1) clipping all data collected at the level of each country and its Amazon region; 2) erasing possible overlaps between polygons in the oil and gas blocks shapefiles and in the PAs shapefiles, avoiding double counting; 3) calculating spatial geometries in a different way according to the vector data type, i.e. the total of elements for data point (wells), area in km^2 for polygon features, such as PAs, blocks, ITs and kilometers length for seismic lines and pipelines; 4) performing a spatial overlay operation with the geo algorithm "intersect", which enables us to highlight where oil and gas activities, ITs and PAs overlap the same zone and to calculate the related geometries. In conclusion, all outputs were presented in maps, graphs and tables showing spatial relationships for the Amazon study area and absolute and relative frequencies of each feature for each country's Amazon, the total of Amazon regions in the study area and related to the total area of each country.

For the Amazon regions of each country and for the Amazon study

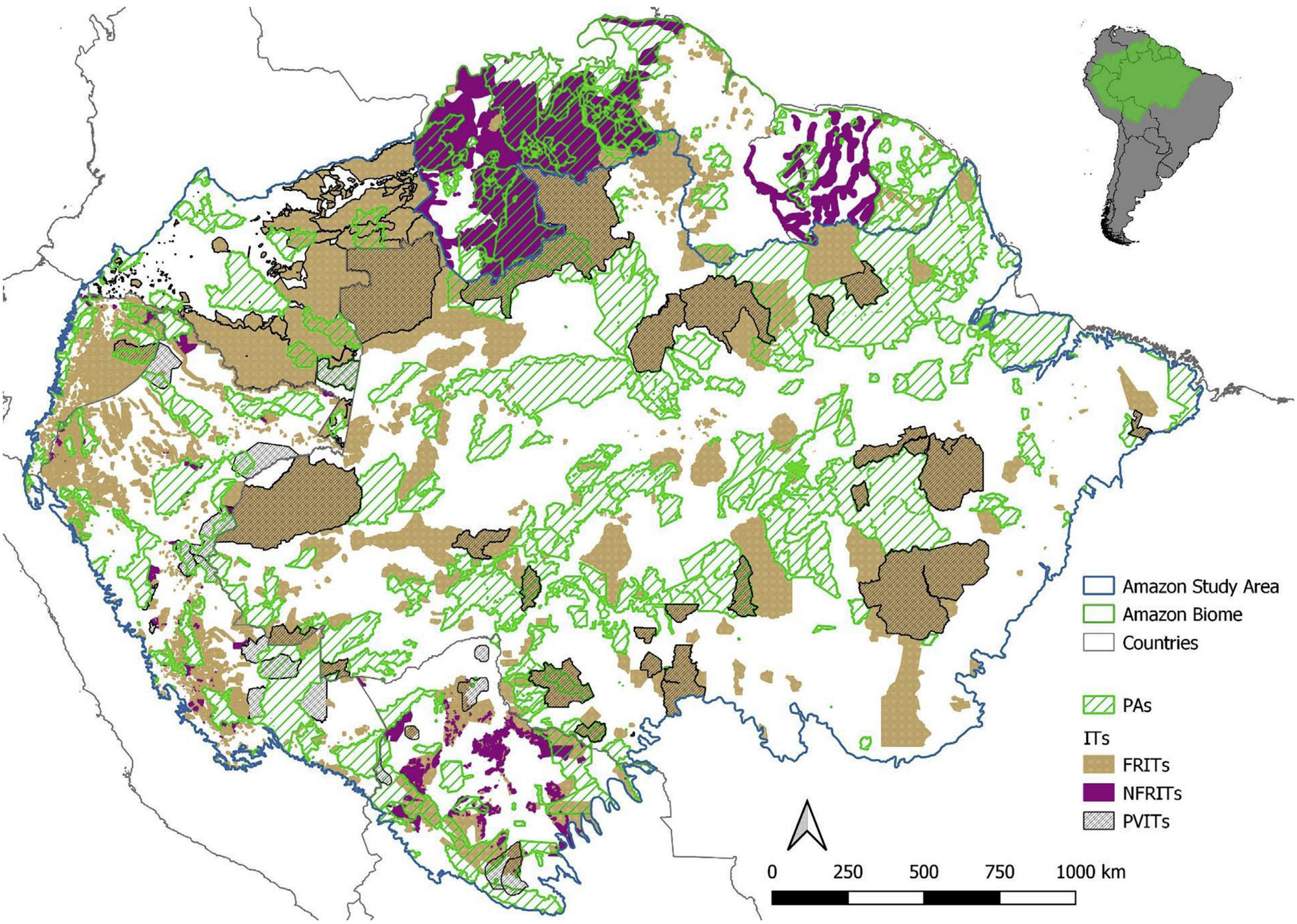

Fig. 1. Map of Protected Areas (PAs) and Indigenous Territories (ITs) in all the Amazon Biome showing different categories: FRITs (Formally Recognized Indigenous Territories), NFRITs (No Formally Recognized Indigenous Territories), PVITs (People in Voluntary Isolation Territories).

Table 3
GIS analysis of the spatial relationships between oil and gas activities, protected areas (PAs), and indigenous territories (ITs) in the Amazon regions for Brazil and Bolivia.

Features	Brazil			Bolivia		
	Total	Relative Frequency	% of feature in the Amazon out of the entire country	Total	Relative Frequency	% of feature in the Amazon out of the entire country
Wells (num.)	607.00	–	3.25%	757.00	–	31.52%
Exploration blocks (km^2)	48,528.09	1.19%	24.28%	24,989.86	5.60%	52.95%
Exploitation blocks (km^2)	1064.87	0.03%	13.27%	1107.31	0.25%	14.53%
Promotion blocks (km^2)	19,805.48	0.49%	22.37%	125,758.37	28.17%	53.21%
Total blocks (km^2)	69,398.44	1.70%	23.41%	151,855.54	34.01%	52.16%
Seismic (km)	308,262.79	–	58.12%	24,273.94	–	28.41%
Pipelines (km)	1010.03	–	4.33%	662.78	–	11.18%
PAs within blocks (km^2)	0.00	0.00% [a]	–	36,517.01	30.68%[a]	79.95%
FRITs within blocks (km^2)	6.94	0.01%[a]	100.00%	35,981.65	41.04%[a]	75.80%
NFRITs within blocks (km^2)	–	-[a]	–	11,695.08	29.64%[a]	39.68%
PVITs within blocks (km^2)	0.00	0.00%[a]	–	no data	-[a]	–
Seismic in PAs (km)	49,107.32	15.93%[b]	91.24%	8212.14	33.83%[b]	44.33%
Seismic in FRITs & NFRITs (km)	18,081.08	5.87%[b]	98.18%	5967.04	24.58%[b]	28.83%
Seismic in PVITs (km)	7012.17	2.27%[b]	100.00%	No data	-[b]	–
Wells in PAs	69.00	11.37%[b]	20.35%	33.00	4.36%[b]	9.32%
Wells in FRITs & NFRITs	17.00	2.80% [b]	94.44%	4.00	0.53%[b]	0.84%
Wells in PVITs	4.00	0.66%[b]	100.00%	No data	-[b]	–
Pipelines in PAs	92.58	9.16% [b]	5.15%	0.00	0.00%[b]	–
Pipelines in FRITs & NFRITs	8.50	0.84%[b]	100.00%	0.00	0.00%[b]	–
Pipelines in PVITs	0.00	0.00%[b]	–	No data	-[b]	–

[a] % of the feature area within blocks on the total feature in Amazon.
[b] % of the count of the feature in PAs and ITs on the total feature in Amazon.

Table 4
GIS analysis of the spatial relationships between oil and gas activities, protected areas (PAs), and indigenous territories (ITs) in the Amazon regions for Colombia and Ecuador.

Features	Colombia			Ecuador		
	Total	Relative Frequency	% of feature in the Amazon out of the entire country	Total	Relative Frequency	% of feature in the Amazon out of the entire country
Wells (num.)	788.00	–	3.89%	2299.00	–	43.96%
Exploration blocks (km^2)	72,889.61	14.47%	26.33%	1089.97	0.95%	18.28%
Exploitation blocks (km^2)	2295.18	0.46%	10.41%	31,530.00	27.49%	96.46%
Promotion blocks (km^2)	105,005.44	20.84%	35.09%	35,337.43	30.81%	100.00%
Total blocks (km^2)	180,190.23	35.77%	30.13%	67,957.39	59.26%	91.30%
Seismic (km)	33,894.08	–	14.67%	no data	–	–
Pipelines (km)	323.36	–	2.36%	1367.89	–	53.80%
PAs within blocks (km^2)	131.12	2.60% [a]	1.43%	6510.87	21.61% [a]	99.06%
FRITs within blocks (km^2)	51,623.58	20.26%[a]	–	44,310.92	71.76%[a]	–
NFRITs within blocks (km^2)	–	-[a]	–	606.75	22.63%[a]	–
PVITs within blocks (km^2)	0.00	0.00%[a]	–	400.85	5.29%[a]	–
Seismic in PAs (km)	623.76	1.84%[b]	9.32%	no data	-[b]	–
Seismic in FRITs & NFRITs (km)	3383.22	9.98%[b]	–	no data	-[b]	–
Seismic in PVITs (km)	0.00	0.00%[b]	–	no data	-[b]	–
Wells in PAs	1.00	0.13%[b]	0.18%	107.00	4.65%[b]	100.00%
Wells in FRITs & NFRITs	19.00	2.41%[b]	–	706.00	30.71%[b]	–
Wells in PVITs	0.00	0.00%[b]	–	7.00	0.64%[b]	–
Pipelines in PAs	0.00	0.00%[b]	–	137.93	10.08%[b]	81.79%
Pipelines in FRITs & NFRITs	0.00	0.00%[b]	–	308.60	22.56%[b]	–
Pipelines in PVITs	0.00	0.00%[b]	–	0.00	0.00%[b]	–

[a] % of the feature area within blocks on the total feature in the Amazon.
[b] % of the count of the feature in PAs and ITs on the total feature in the Amazon.

Table 5
GIS analysis of the spatial relationships between oil and gas activities, protected areas (PAs), and indigenous territories (ITs) in the Amazon region for Peru and for the total Amazon study area.

Features	Peru			Total Amazon study area	
	Total	Relative Frequency	% of feature in the Amazon out of the entire country	Total	Relative Frequency
Wells (num.)	614.00	–	4.93%	5065	–
Exploration blocks (km^2)	90,830.28	11.55%	79.35%	238,327.81	4.02%
Exploitation blocks (km^2)	26,210.52	3.33%	85.22%	62,207.88	1.05%
Promotion blocks (km^2)	34,237.19	4.35%	78.63%	320,143.90	5.40%
Total blocks (km^2)	151,277.99	19.23%	80.14%	620,679.59	10.47%
Seismic (km)	95,355.97	–	97.51%	461,786.78	–
Pipelines (km)	1481.06	–	61.95%	4845.12	–
PAs within blocks (km^2)	24,248.17	12.59%[a]	89.97%	67,407.17	4.40%[a]
FRITs within blocks (km^2)	34,889.15	27.29%[a]	–	166,812.242	10.42%[a]
NFRITs within blocks (km^2)	2084.13	18.30%[a]	–	14,385.96	26.88%[a]
PVITs within blocks (km^2)	12,001.45	16.86%[a]	–	12,402.30	1.85%[a]
Seismic in PAs (km)	15,667.80	16.43%[b]	97.55%	73,611.02	15.94%[b]
Seismic in FRITs & NFRITs (km)	20,156.35	21.14%[b]	–	47,587.69	10.31%[b]
Seismic in PVITs (km)	5795.19	6.08%[b]	–	12,807.36	2.77%[b]
Wells in PAs	27.00	4.40%[b]	50.00%	237.00	4.68%[b]
Wells in FRITs & NFRITs	55.00	8.96%[b]	–	801.00	15.81%[b]
Wells in PVITs	12.00	1.95%[b]	–	23.00	0.45%[b]
Pipelines in PAs	47.56	3.21%[b]	100.00%	278.07	5.74%[b]
Pipelines in FRITs & NFRITs	422.66	28.54%[b]	–	739.76	15.27%[b]
Pipelines in PVITs	0.00	0.00%[b]	–	0.00	0.00%[b]

[a] % of the feature area within blocks on the total feature in the Amazon.
[b] % of the count of the feature in PAs and ITs on the total feature in the Amazon.

area we calculated: 1) the absolute total; 2) the relative frequency related to the Amazon study area or the area of a given feature within blocks on that total feature in Amazon (see * in Tables 3–5), or to the percentage of the count of the feature in PAs and ITs on the total feature in Amazon (see ** in Tables 3–5); 3) the percentage of the feature in Amazon out of the total feature in the whole country. Graphs in Fig. 5 highlight some of these results, while maps in Fig. 2 show the spatial distribution of oil and gas activities in the Amazon study area, and Fig. 3 highlights only the overlaps between oil and gas activities, conservation and socio-cultural features. Finally, a special focus on the Amazon regions of Bolivia, Colombia, Ecuador, and Peru is presented in Fig. 4.

3. Results

The Amazon study area considered corresponds to 5,933,689 km^2, about 87.46% of the entire Amazon Biome (approximately 6,784,388 km^2). In particular, 68.79% of the study area belongs to Brazil, while the remaining 31.21% belongs to Bolivia, Colombia, Peru and Ecuador, by the 7.52%, 8.49%, 13.26% and 1.93% respectively. Moreover, 25.83% of Amazon study area is covered by PAs, with about 24–26% of each country's Amazon area under biodiversity conservation

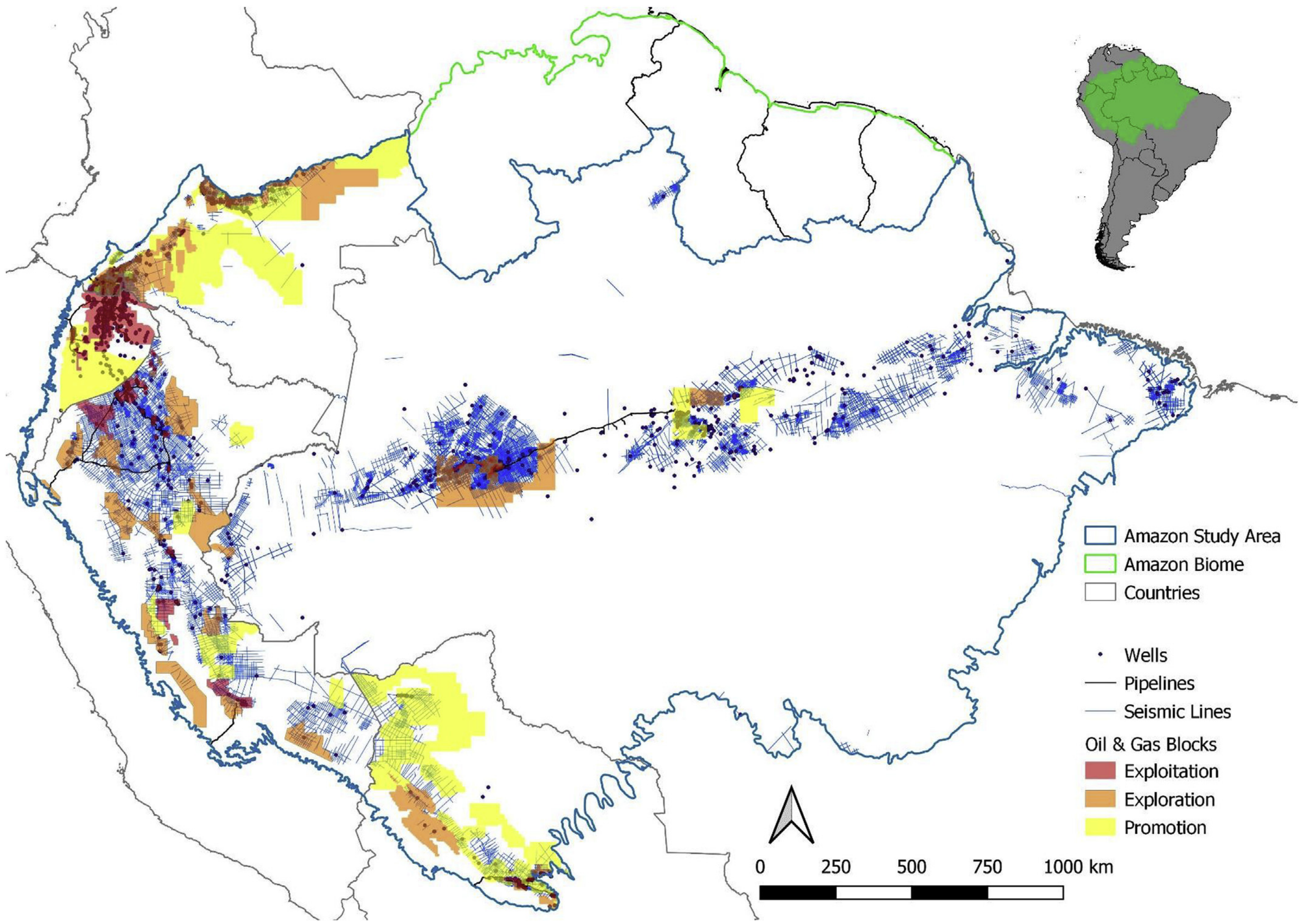

Fig. 2. Map of oil and gas elements in the Amazon Biome: wells, pipelines, seismic lines and blocks by category (exploitation, exploration, promotion). Amazon regions of Venezuela, Guyana, French Guyana and Suriname have not oil and gas operations.

measures, except Colombia with 19.63%. Concerning the protection measures for indigenous communities, the three different categories of ITs can be found in the Bolivian, Ecuadorian and Peruvian Amazon, while in Colombia and Brazil there is no NFRIT data. It is worth noting that 26.98% of the Amazon area is occupied by FRITs, 0.90% by NFRITs, and 11.32% by PVITs. In addition, in Colombia more than 50% of its Amazon region is occupied by FRITs, while 6.60% and 9.05% of the Ecuadorian and Peruvian Amazon regions respectively, are recognized or proposed as PVITs; in Brazil the PVITs correspond to 14.29% (Fig. 1 and Table 2).

Oil and gas activities cover 10.47% of the study area by concessions. More precisely, 4.02% is occupied by exploration blocks, 1.05% by exploitation blocks, and the remaining 5.40% by blocks in promotion. It is important to underline that excluding the Brazilian Amazon (it represents 69% of the total study area, but only 1.70% is overlapped by blocks), the percentage considerably rises up: 59.26% in Ecuador, 34% in Bolivia, 35.77% in Colombia, 19.23% in Peru (Figs. 2 and 4 and Tables 3–5). GIS analyses show that Peru and Bolivia seem to be investing in the oil frontier expansion within their own Amazon region; in fact, the percentage of Amazon exploration blocks on the total exploration surface area of the countries is 79.35% and 52.95%, respectively. In Ecuador, a country with a long history of oil development, 91.30% of onshore oil and gas activities are in the Amazon; in fact, the Northern sector is widely covered by blocks in exploitation, while the Southern is under promotion since 2012 (De Marchi et al., 2017). In absolute terms, promotion blocks cover more than 320,000 km^2 of the Amazon Biome, mainly located in Bolivia and Colombia; exploration blocks reach 238,327 km^2, due to the contribution of Peru and Colombia; the largest Amazon region under exploitation activities is located in Ecuador (31,530 km^2) and Peru (26,210 km^2) (chart in Fig. 5a).

In relation to the oil infrastructures within Amazon study area, the highest oil and gas well distribution is in Ecuador, with 2999 points, while in the other countries is quite similar, varying between 600 and 800 points. The 31.52% and 43.96% of the total wells of Bolivia and Ecuador respectively are located in their Amazon region; in the remaining three countries, most wells are located outside the Amazon regions (Fig. 2, Tables 3–5 and Fig. 5c).

Concerning the linear development of the pipelines, it is predominant in Ecuadorian and Peruvian Amazon, with 1368 and 1481 km respectively. On the other side, pipelines have an extent of 663 km in Bolivia and 323 km in Colombia (Fig. 2, Tables 3–5 an Fig. 5d). These results are probably related to the high development of exploitation activities in Ecuador and Peru. The overall length of the 2D seismic is 461,787 km in the whole Amazon study area, with the exception of Ecuador, whose data is not available. The largest extent is in the Brazilian Amazon, with 308,263 km, while Peruvian seismic lines (95,356 km) are three times the Colombian's (33,894 km), with a presence of the 97,51% of this feature in relation to the total of the country (Fig. 2, Tables 2–5 and Fig. 5e).

Another interesting result is the overlapping between hydrocarbon blocks with PAs and ITs (Tables 3–5, Figs. 3 and 5b). For the whole study area, 4.40% of the PA total surface in the Amazon is overlapped by blocks: in Colombia and Brazil overlaps are very limited or absent, while in Peru it is 12.59%, greater in Ecuador (21.61%) and in Bolivia

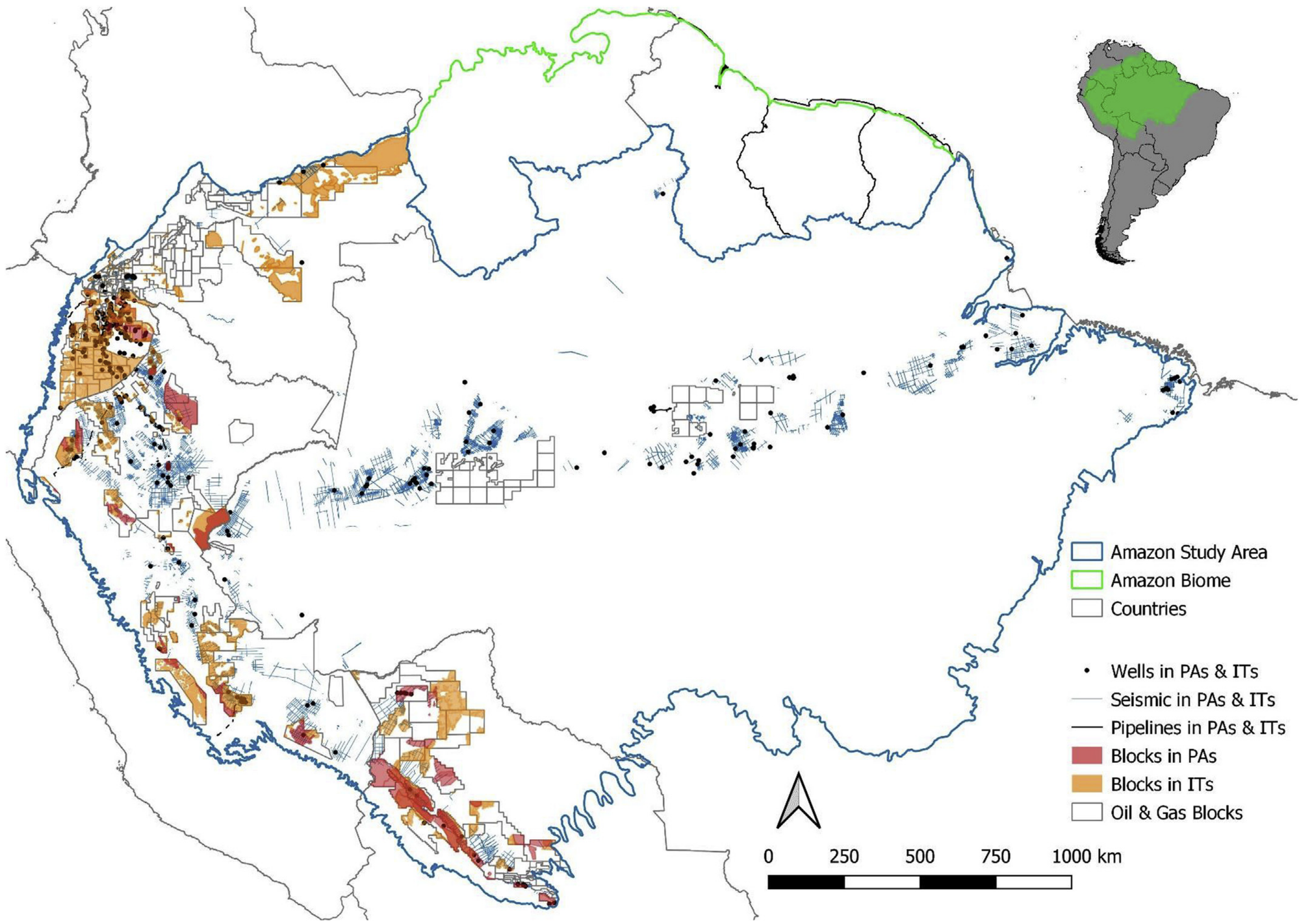

Fig. 3. Synthesis map of overlap among oil operations, protected areas (PAs), and indigenous territories (ITs) in the Amazon study area.

(30.68%). The high value in Bolivia probably depends on the presence of a Law Decree (Decreto Supremo 2366, 20th of May 2015), which allows this type of activity within PAs. Regarding the FRITs, in the whole study area, the percentage of the overlaps with blocks is greater than for PAs, (10.42%). In Brazil, the overlapping is absent, whereas in Ecuador, Bolivia, Peru and Colombia is 71.76%, 41,04%, 27.29% and 20.26% respectively. Furthermore, the Bolivian, Ecuadorian and Peruvian proportion of NFRITs within blocks should be also taken into account since it represents 29.64%, 22.63% and 18.30% of this total feature in the Amazon, respectively. Overlaps with NFRITs is particularly important, since these ancestral territories are more vulnerable to external pressures because they are not considered (yet) in any legal protection measure. Other very sensitive areas, such as the PVITs, show an overlapping with blocks that is 12,402 km^2 in the whole Amazon, in particular 401 km^2 in Ecuador and 12,001 km^2 in Peru. In addition, the Ecuadorian oil blocks which overlap the PVITs (5.29% of this protected area), recently shifted to the exploitation phase (De Marchi et al., 2017). It is worth noting together that we have no data for PVITs in Bolivia.

Regarding the presence of oil and gas wells in PAs and ITs (Tables 3–5 and Figs. 3 and 5c), there are 237 and 801 drilled wells respectively, corresponding to 4.68% and more than 16% of all wells in the Amazon (the largest contribution is Ecuador with 107 wells in PAs and 706 in ITs). Furthermore, the GIS analysis shows the presence of about 48 km of pipelines in Peruvian PAs and 138 km in Ecuadorian PAs, and 423 km and 309 km in ITs respectively (Tables 3–5). The monitoring of this kind of infrastructures is very important in sensitive areas, because of their possible impacts on socio-ecological systems.

The intersections of seismic exploration lines with PAs and ITs were analysed as well (Tables 3–5 and Figs. 3 and 5e). In both cases, countries with higher values are Brazil (49,107 km of the seismic within PAs and 18,081 km within ITs) and Peru (15,668 km of the seismic inside of PAs and 25,951 km within ITs). We were unable to find date information of these linear clearings, so we could not analyse whether they are prior to the constitution of PAs and ITs. Anyway, it is important to mention that a more in-depth analysis should be performed because of the potential negative effects in these sensitive areas (habitat fragmentation, edge effect, the use of these lines as a path for hunting).

The synthesis map in Fig. 3, which show only the relationships between oil and gas activities, and conservation and cultural features, well represent the overall scenario: the Andean-Amazon countries (Colombia, Ecuador, Peru and Bolivia) show the largest block overlaps, while in Brazil there are seismic lines and wells mainly in the West-Est axis of its Central Amazon. In Fig. 4 we present a synthesis maps of the four Andean-Amazon countries with the overlap among oil operations, PAs, and ITs. Figs. 2–4, show for the first time the geographical implications of oil and gas industry: the combination of a spatio-temporal system of seismic lines, oil blocks, point features (wells), pipelines. Extremely interesting is the situation in Brazil, where seismic lines produce a large invasion of space despite the lower presence of blocks. Ecuador is another case with the large presence of seismic lines, but it was not possible to acquire high resolution data.

4. Discussion and conclusions

Where to leave fossil fuel unburnable is a completely new research

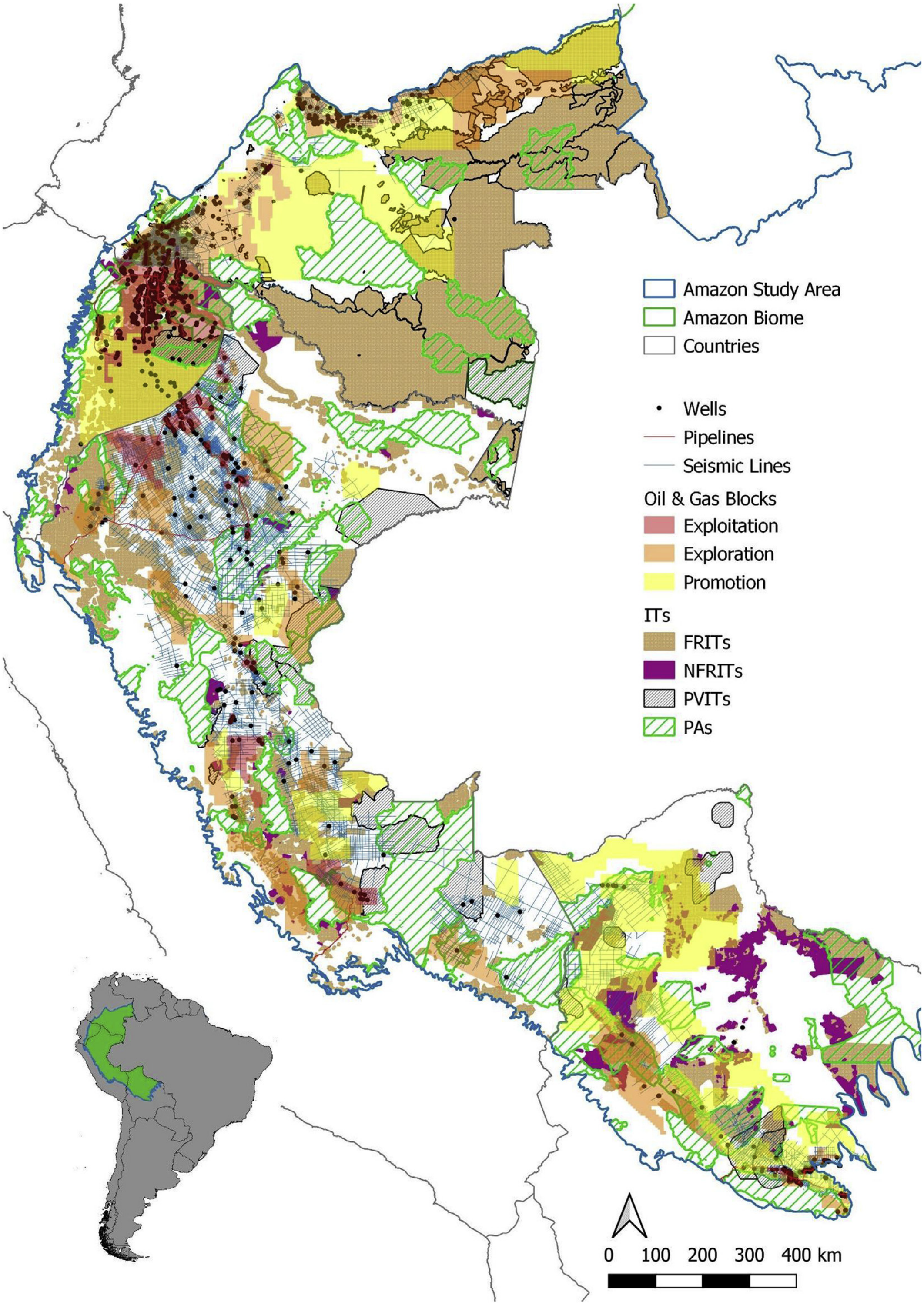

Fig. 4. Synthesis map of overlap among oil operations, protected areas (PAs), and indigenous territories (ITs) in the four Andean Amazon countries (Colombia, Ecuador, Peru, Bolivia).

challenge. Landscape spatialization of the Earth global carbon budget is not an easy task for many reasons: from the concept and the use of spatial approach, the need of adopting geographical criteria, the availability of open and free data, the uncertainty about reserves and resources.

Despite climate and physical quantification of unburnable carbon, criteria for choosing specifically which reserves must remain underground have not been addressed yet, in particular in relation to the implementation of effective policies for emission reduction. At the moment, climate change research suggests general targets for regional or national levels without any spatially explicit localization for untapped fossil fuel reserves. Moreover, parameters for the selection of specific reservoir are mainly based on the extraction costs and reserves depletion.

Analysis based on aggregating contextual data around countries, companies and international organizations does not allow display

Fig. 5. Main results of spatial analysis in the Amazon regions of the 5 countries: km^2 of blocks divided by categories (a), % of protected areas (PAs) and indigenous territories (TIs) overlapped by blocks (b), number of wells in Amazon, PAs and TIs (c), km of pipelines in Amazon, PAs and TIs (d), km of seismic lines in Amazon, PAs and TIs (e).

whether a fossil fuel reserve is under a desert or a river delta, overlaps with indigenous territories or protected natural areas. Hence, this lack of spatial thinking and geographical perspective of climate change research demands a strong commitment in developing inclusive territorial policies for unused fossil reserves, strengthening the reproducibility of the complex territorial systems overlapped by carbon reserves.

Impacts of fossil fuels on climate change for the next decades are well detailed by scientific literature; however, fossil hydrocarbons are key drivers not only for future climate change but also for past and current social and environmental impacts. The ecological footprint of fossil fuel production is increasing as accessible reserves are depleted due to greater use of water, energy, and diluents, limiting the positive effect of energy efficiency and consumption reduction. Impacts on health, social texture, water and biodiversity of conventional and unconventional oil and gas operations in different geographical contexts are widely reported in scientific literature.

However, despite the international call for a low carbon economy, fossil fuels exploitation is still based on an economic perspective of resource availability. Countries and companies mainly focus on few indicators: 2P reserves, km of seismic lines (2D or 3D), drilled wells, pipelines and refineries. No mention about the place in which oil and gas are extracted, and no communication about the overlapping with biologically and culturally sensitive areas. The World Energy Atlas (The Petroleum Economist, 2012) standard reference for oil and gas industry just maps oil related features, without giving any other information.

The definition of criteria for leaving fossil fuel reserves untapped asks for a wide consideration of geographical parameters both at international and national level. At the same time the percentage of reserves to keep unburnable around the world cannot be applied on the basis of a common regional "flat value" but it demands for an intergenerational justice considering the historical contribution of each country to cumulative carbon emissions (Botzen, Gowdy, & van den Bergh, 2008; Höhne et al., 2011; Rocha et al., 2015; Ward & Mahowald, 2014).

Criteria based on economy and technology of fossil fuel resources need to be debunked considering from one side the uncertainty of reserves figures and, on the other side, the commitment of countries and companies to updating the accounting of gas and oil reserves. For all these reasons, criteria evaluating what is over the soil should be stand above the criteria of resources, adopting a territorial suitability approach in which (especially for Amazon regions) cultural and ecological diversity represents priorities.

However, adopting a geographical approach asks for a large availability of data for an open and transparent research, and policy process based on a spatially-explicit information system, incorporating interactions among territorial diversities and fossil fuels reserves. At present, the available information about oil and gas sector is fragmentary, not well organized by countries or owned by business intelligence companies selling information to private enterprises operating in conventional or unconventional markets of oil, and gas. Despite higher prices (also for research institutions) or such private information is not completely updated and, when available to research institution, does not allow a transparent scientific communication process. Hence, the approach of data mining and crowd sourcing of geographical data is essential for developing new transparent climate research and policies.

In this study, we focused on the overlap between oil and gas exploration and exploitation, and culturally and ecologically sensitive areas, such as environmentally protected areas and indigenous territories, defining geographical criteria for unburnable carbon areas. The main results show that 10.47% of the Amazon study area is involved in oil and gas activities. In particular, blocks overlap the 59.26% of Ecuadorian Amazon, the 34.01% of Bolivian Amazon, and the, 35.77% of Colombian Amazon. The overlaps could have a stronger effect on policy makers decisions if we consider that: a) the 10.47% of Amazon study area means that oil and gas concessions cover about 620,679 km^2 of tropical ecosystems, equal to the 6% of US territory or more than the double of UK; b) despite probably only a small part of the concession area is or will be directly used for oil production, the territorial control by transnational companies and sub-contractors is or will be maintained all over the oil blocks with implication on relationships with local communities and national policies; c) possible oil spills or gas flaring from a source could affect huge areas or rivers outside the overlaps, reaching and affecting other countries; d) seismic lines and pipelines could create habitat fragmentations and could be used as paths by settlers and indigenous people; indeed, indirect impacts, such as the edge effect or the increase of hunting, could have stronger effects than direct impacts.

Future investigations can be implemented, such as spatial multicriteria analysis to support the decision-making process to develop unburnable carbon policies.

Spatial analysis of wells, seismic and pipelines not taken into account in previous investigations unveiled the necessity of further in-depth studies, in order to expand the data collection and the database creation to consider other aspects, such as economic and normative issues.

We need a new approach in spatialization of climate policies exploring the "space" between the geology and economy of fossil fuel resources and the climatology of atmosphere concentration and temperature. We should bridge the gap, remembering that between the subsoil and the atmosphere there is the landscape: the climate is something on the earth not just in the sky (Farinelli, 2018).

Declarations of interest

None.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apgeog.2018.12.001.

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