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# Spatial inventory of selected atmospheric emissions from oil industry in Ecuadorian Amazon: Insights from comparisons among satellite and institutional datasets



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## ABSTRACT

Atmospheric emissions from oil activities impact human health, socioeconomic status and exacerbate global warming. This study was conducted in the North-eastern Ecuadorian Amazon, a rich biodiverse and cultural area. This study aimed to show the benefits of public institutional data to advance hazard mapping knowledge for comprehensible risk evaluation. A spatial inventory was built from publicly disclosed reports spanning ten years (2003–2012). Emissions were estimated for gas flaring, associated black carbon (BC) and greenhouse gases (i.e., CO<sub>2</sub> and CH<sub>4</sub>). To assess the quality of publicly available data, the calculated emissions were compared with satellite observations and historical energy statistics from the United Nations (UN). Results indicate total gas flared for this period of 7.6 Gm<sup>3</sup>, corresponding to 782 Mm<sup>3</sup> yr<sup>-1</sup>, and equivalent to a 3.7–4.5 kt yr<sup>-1</sup> of BC. These values were in agreement with the UN estimates, suggesting that publicly available data are of acceptable quality. In contrast, the results from energy censuses diverged from satellite observation data, which might be explained by a poor calibration of satellite sensors. Study results enabled emissions mapping at a higher spatial scale than previous studies. Black carbon presented the highest results with 29.4–148.0 kg m<sup>-2</sup> yr<sup>-1</sup> in the cities of Shushufindi and Joya de Los Sachas. Greenhouse gases were up to twenty-fold higher than previous estimates. Publicly disclosed data estimates were discussed in terms of their potential on evaluations for climate, local health and economic impacts, to raise environmental monitoring and accountability in governmental institutions.

## 1. Introduction

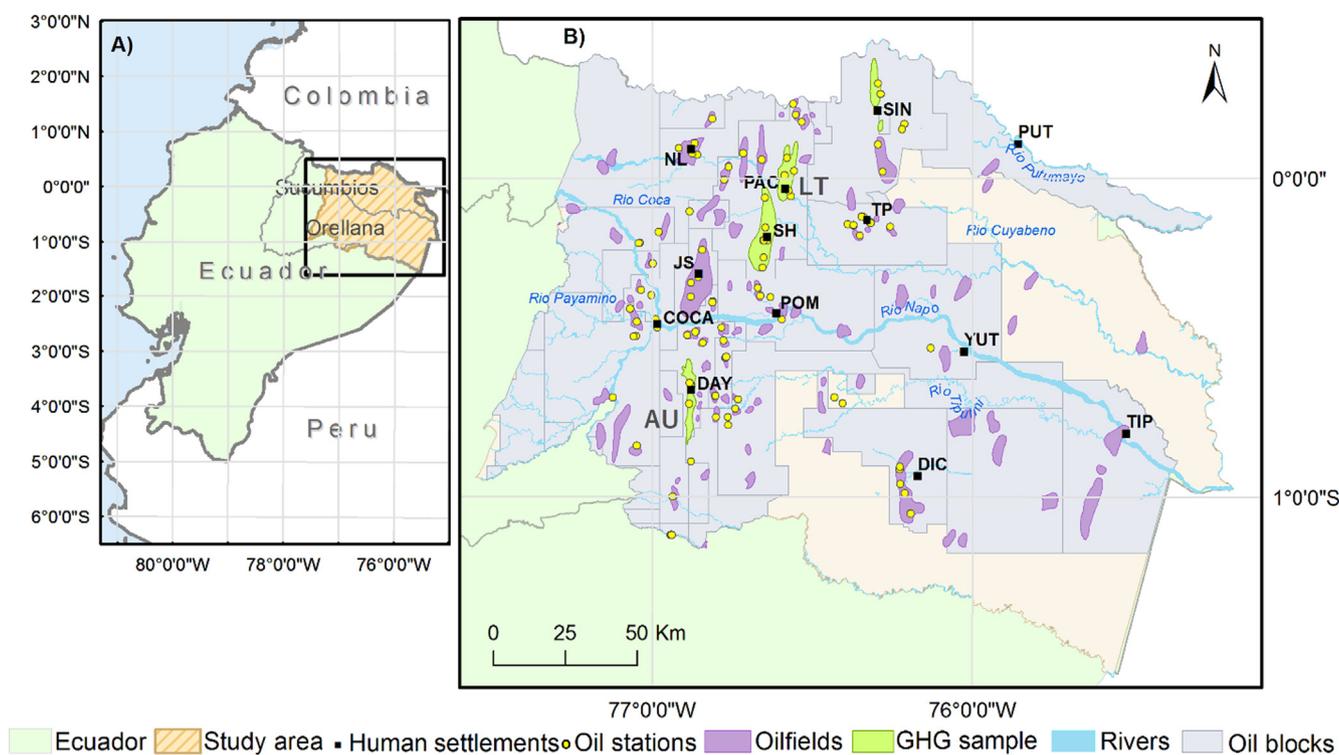
The North-eastern Ecuadorian Amazon (NEA) is considered a worldwide biodiversity hotspot, encompassing a large number of endemic flora and fauna (Bass et al., 2010; Myers et al., 2000). Rich oil reserves have increased national economic growth, supporting improvements of education and health services in Ecuador (Larrea, 2006). However, local communities within the NEA allege negligible benefits, conversely enduring decades of related oil pollution, conveying health and environmental degradation (Baynard et al., 2013; Butt et al., 2013; Finer et al., 2008). Oil-related contamination has exacerbated the negative effects of human settlement including: decline in livestock health (Waldner et al., 2001); reduced yields in crops (Dung et al., 2008); reduced human health (Chang et al., 2014; San Sebastián and Hurtig, 2005; Sebastián et al., 2001); degraded environmental amenities;

reduced rural land values (Boxall et al., 2005); and reduced biodiversity richness (Finer et al., 2008; Jernelöv, 2010). These claims have resulted in twenty five years international legal challenges between local communities and Chevron (Buccina et al., 2013; San Sebastián and Hurtig, 2005). In 2018, an international court ruled in favour of Chevron, while the pollution remains in the NEA (BBC News, 2018).

Oil and gas extraction releases hazardous emissions attributed to several routine safety and security operations (Jernelöv, 2010). The atmosphere is affected by long-term venting and flaring of associated petroleum gas (APG) at separation batteries. Venting and flaring are necessary processes that occur when gas and water are separated from crude oil. They occur for pipeline security and safety reasons when means of transportation are lacking and re-injection to improve oil production in mature oil wells or electricity generation is not possible (Huang and Fu, 2016).

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**Fig. 1.** Location of the study area. (A) The North-eastern Ecuadorian Amazon (NEA) in Ecuador. (B) The study area within the two NEA provinces of Sucumbios and Orellana including oilfields and oil stations. Represented human settlements are abbreviated: DAY = Dayuma; NL = Nueva Loja (aka Lago Agrio); SH = Shushufindi; TP = Tarapoa; PAC = Pacayacu; POM = Pompeya; PUT = Putumayo; COCA = Puerto Francisco de Orellana; JS = Joya de Los Sachas; YUT = Yuturi; DI = Dícaro; SIN = Singue; TP = Tiputini. GHG sample refers to greenhouse gases sampled oilfields, which are: SH = Shushufindi; LT = Libertador; AU = Auca; SIN = Singue.

Venting and flaring produce atmospheric pollutants, comprising aerosol particulate matter (PM), including black carbon (BC), and greenhouse gases (GHG) such as methane or carbon dioxide. Gas flaring has the potential to acidify rainwater (Anejionu et al., 2015b). Black carbon (BC) is released during gas flaring and acts at a local level, resulting in soil calcination, degradation and destruction of vegetation (Solov, 2011). BC is a major light absorbing fraction of PM aerosols (Bond and Bergstrom, 2006) formed from incomplete combustion. Their radiative heating properties (Jacobson, 2001) transform it into a short-lived climate forcer with potential adverse effects on health (McEwen and Johnson, 2012) such as cardiopulmonary morbidity and mortality (Anejionu et al., 2015a; Giwa et al., 2014; Huang and Fu, 2016; Janssen et al., 2011). BC is classified as carcinogenic to humans by the International Agency for Research on Cancer (IARC, 2012). On the other hand, carbon dioxide (CO<sub>2</sub>) and methane (CH<sub>4</sub>) are climate change forcers with significant warming potentials (Soltanieh et al., 2016) and methane has energy generation capabilities, misused by venting or flaring (Anenberg et al., 2012; Boden et al., 2012; Dlugokencky, 2003; Robalino-López et al., 2014; Simpson et al., 2012). Besides, reduction of BC and methane emissions provide co-benefits in reducing specific vulnerability to heat waves, to droughts and flooding, to changes in the distribution of vector-borne diseases (Haines et al., 2006) and to agricultural losses (Shindell et al., 2012), since it improves air quality, economy, and human health altogether (Anenberg et al., 2012; Haines et al., 2006; Shindell et al., 2012).

Until 2006, Ecuador flared most of its APG (Peláez-Samaniego et al., 2007) resulting in energy and economic losses as well as atmospheric emissions to the environment (Ite and Ibok, 2013). The Ministry of Energy and Mines (MEM) and the Amazon Defence Front (ADF) have attempted to estimate these emissions in the NEA. Three distinct periods of management activities in Ecuador have been identified (Juteau et al., 2014):

- T1 (1972–1991): Foreign Texaco and National Petroleum

Corporation (CEPE) engaged in oil activities;

- T2 (1992–2001): the State-owned Petro-Ecuador company assumed oil production and data compilation on gas produced was requisite;
- T3 (2001–2012): the State-owned Petro-Ecuador company assumed oil production and APG data reporting to Ministry of Environment (MAE) is mandatory.

Spatial gridding allocation of disaggregated emissions is useful for several purposes, such as pollution hotspot analysis, trajectory modeling, hazard and exposure mapping, multiple-pollutant and risk assessments (Andreo et al., 2006; Guttikunda and Calori, 2013; Lahr et al., 2010; Lahr and Kooistra, 2010). Oil emission sources and present perception on contamination potential have been spatially interpreted for oil spills, from long-term datasets (Durango-Cordero et al., 2018), and from local population surveys (Maestripietri and Saqalli, 2016) but not for atmospheric contaminants. The present study was undertaken as a part of the transdisciplinary MONOIL research program focused on environmental monitoring, health, society and oil in Ecuador (MONOIL, 2017).

This study first aimed to examine data quality acceptability, specifically determination on whether sufficient disclosure of energy data from the Ecuadorian government occurs, for the calculation of reliable estimates of APG flared at a regional scale. This was done using data extending over the T3 management period, supposedly characterized by improved monitoring (SENPLADES, 2013). In order to assess the available data's quality, our estimates were compared to United Nation data and to satellite observations provided by the National Oceanographic and Atmospheric Association (NOAA).

This study's second objective was to map airborne emissions using the Ecuadorian publicly available dataset, as long as their estimates were reasonably accurate to undertake mapping and to provide atmospheric local emissions at flare stacks. These evaluations and maps may support future hazard mapping and the improvement of security and safety planning.

## 2. Materials and methods

### 2.1. Study area

The study area (Fig. 1) was restricted to the provinces of Sucumbíos and Orellana in the NEA (~144–900 m.a.s.l., Amazon lowlands), representing a 35,051 km<sup>2</sup> area (Fig. 1B). this area includes upstream and midstream oil and gas production infrastructure which are related to potentially polluting activities, likely to impact forests, rivers and streams but also cities, villages and extensive farming land. This study excluded rivers with high flow rates (i.e. Napo, Tiputini, Coca, Payamino, Putumayo, Cuyabeno and Aguatico) where the dynamic surface and groundwater interactions are poorly understood. The study area is characterized by a warm climate with a temperature range of 24°C to 35°C, and an average annual rainfall of 2900 mm yr<sup>-1</sup> (INAMHI, 2018). The hydrology regime is irregular with 1000–5000 m<sup>3</sup> s<sup>-1</sup> daily discharges, and characterized by flash floods, due to extreme sensitivity to rain events (Laraque et al., 2007). The Intertropical Convergence Zone (ITCZ) is responsible for complex atmospheric processes in the NEA, which is influenced by trade winds with changing direction throughout the year (Palermo and Parra, 2014).

### 2.2. Data for atmospheric emissions and comparisons

Energy bulletins and long-term reports of APG were compiled by the National Board of Hydrocarbons' website (NBH, 2018). Most of the historical energy reports are produced by the current Agency of Hydrocarbons Regulation Agency (ARCH) and the former National Hydrocarbons Directive (DNH) retrieved during compulsory environmental impact assessments. Several bulletins from the relatively new (created in 2008) Ministry of Strategic Sectors (MSS, 2015, 2014, 2013) were also integrated into several parts of the methodological process. These reports were disaggregated and categorized on a yearly basis for the 2003–2012 period. Institutional spatial data layers of oil infrastructure, including oil fields, flare stacks and stations, were obtained during the 2014–2017 partnership between ANR-MONOIL research Programme and the Ecuadorian Ministry of Environment Programme of Socio-environmental Remediation (MAE-PRAS). Data used in this study is summarized in Table 1.

Table 2. indicates the multiple datasets used for comparison of the results obtained in this study. Comparison analysis considered the materials, methods and type of analysis implemented to estimate airborne emissions. Other estimates of APG flared volumes were retrieved from night-time satellite observations of gas flares provided by the National Geophysical Data Centre (NOAA) and from historical energy statistics compiled by the United Nations (UNDATA). Thus, the emission factors (EFs) used in this study were applied to BC calculations. CO<sub>2</sub> estimates were directly retrieved from the Carbon Dioxide

Information Analysis Center (CDIAC). The methods used in this study are described in Section 2.3.

### 2.3. Emission processing and calculations

#### 2.3.1. Gas flaring

In Ecuador, data on flared or vented gas emissions are not readily available. Institutional technical reports and bulletins were analysed for T2 and T3 periods to facilitate a description of the technology and infrastructure implemented and to derive emission estimates. In general, the analysis followed the upstream production process, which includes extraction, transportation to refining and final export (Foss, 2012). Except for the proportion of gas leaked or used, APG is assumed to be flared. Data is disaggregated on an annual basis to calculate potentially flared gas at each oilfield. The general procedure to obtain total gas flared is described in the following equation:

$$\text{Gas flared (m}^3\text{)} = \sum_{i=1}^{50} \text{APG}_{nu_i} - (\text{APG}_{e_i} + \text{APG}_{f_i}) \tag{1}$$

where,

i = the index of the oilfield considered (50 oilfields in total)

APG<sub>nu</sub> = unused APG in each single oilfield.

APG<sub>e</sub> = input for electricity generation at Shushufindi Gas Plant, only reported for years 2005 to 2012, and representing 8.3% of total APG<sub>nu</sub> (MSS, 2014, 2013)

APG<sub>f</sub> = leaked fugitive emissions, representing 3% of total APG<sub>nu</sub> (Larsen et al., 2015; MSS, 2013).

#### 2.3.2. Black carbon

BC emissions were obtained using emission factors (EFs) which were measured from the heating capacity of gas burning at flare stacks (McEwen and Johnson, 2012). In Ecuador, no official EFs for BC have been defined, hence estimates were calculated using the regional baseline emission factors (EF = 0.5) and upper bound values (EF = 0.75) (Huang and Fu, 2016; McEwen and Johnson, 2012), following the equation (Giwa et al., 2014):

$$\text{BC}(t) = \text{EF} \left( \frac{t \text{ of BC}}{10^3 \text{ m}^3} \right) \times \text{Vol. gas flared } 10^3 \text{ m}^3 \tag{2}$$

In addition, BC emissions were calculated from gas flaring estimates from the United Nations at the national level (which was relevant as virtually all gas flaring in Ecuador occurs within the study area), and from the National Geophysical Data Centre (NOAA-NGDC) long-term inventories of satellite products, in order to compare with our estimates. Emissions were expressed as the sum of emissions per oilfield, average emissions per single oil-field and flaring infrastructure, i.e. flare stacks and batteries, and total emissions for the study area.

**Table 1**  
Database compilation used in this study for emission estimates and spatial allocation.

Spatial data	Description	Sources
Populations	Point	SENPLADES (2017)
Flare stacks	Point	NOAA (2015) MAE-PRAS (2014)
Oilfields	Polygons, 1:250.000	National Board of Hydrocarbons (2014) Petro-Ecuador (2013)
Refineries and batteries	Point	MAE-PRAS (1972–2014)
<b>Non spatial data</b>		
Associated gas	Gas exploited at oil fields	National Board of Hydrocarbons (2003–2014)
Gas composition	Molar fraction	National Board of Hydrocarbons (2016) Guerra del Hierro (2014)
Oil production	Records of monthly production	PetroEcuador (2001–2012)
Utilized gas	Historical data (2003–2012)	National Energetic Balance (2013)
Transportation	Historical data (2007–2012)	Ministry of Strategic Sectors Bulletins (2013–2014) National Institute of Statistics and Census (INEC)

**Table 2**  
 Datasets and calculations used for airborne emission comparisons (APG: associated petroleum gas; BC: black carbon; EF: emission factor).

Data source	Material	Type of analysis	Pollutant estimated
NOAA	Satellite observations (2003–2012)	Estimated APG flared was multiplied by EFs used for this study	BC
UNDATA	Historical energy statistics (2003–2012)	Estimated APG flared was multiplied by EFs used for this study	BC
CDIAC	Historical energy statistics (2003–2012)	Estimates retrieved were directly used	CO <sub>2</sub>
This study	See Table 1	Production equations and upper and lower EFs	BC
		Production and mass balance equations for carbon dioxide and methane	CO <sub>2</sub> , CH <sub>4</sub>

2.3.2.1. *Atmospheric emission mapping.* Individual and battery-associated flare stacks identified from NOAA satellite data and MAE-PRAS were regrouped in a single spatial layer. Total gas flared in each oilfield, computed as described in Section 2.3.1, was divided equally to corresponding flaring points following a four-step hierarchical approach:

- (1) if a flare stack was inside an oilfield, it was assigned directly to its corresponding oilfield (n = 143);
- (2) if a flare stack was outside oilfields, it was attributed to oilfield by nearest distance method (n = 38). Some flares were not found to occur with a specific oilfield (1) or occur in close proximity to an oilfield (2). In this case,
- (3) flared gas was attributed to north-western flare stacks based on the production process from reservoir to export (Foss, 2012). This indicates APG flows from secondary pipelines to north-western Ecuador, connecting with processing facilities to two core pipelines: Pipeline System of Trans Ecuadorian (SOTE) and Heavy Crudes Pipeline (OCP).
- (4) Fictitious flaring stacks were allocated to oilfields lacking flaring infrastructure but with registered APG and crude oil production.

The number of fictitious flare stacks added to each oilfield would ideally have been estimated through the correlation between number of flare stacks and quantity of APG. However, the weak coefficient of determination ( $r^2 = 0.22$ ) hindered the estimation of the number of flare stacks to be placed within or in proximity to an oilfield, hence a centroid was created for each oilfield, as often implemented in spatial gridding allocation studies (Benkovitz et al., 1996; Rehr et al., 2010). In every aforementioned case, the assignment of BC emissions to a single flare stack was expressed using total min-max BC values at each oilfield divided equally to the corresponding number of flare stacks.

A cell-grid layer was created to sum-up BC emission of each flaring facility. Cell size can be determined according to the study area size and spacing of observed emissions (Bertazzon et al., 2014). The spacing between single flare stacks was considered too large to use a symbol to represent quantity. Representation of emissions was considered to be more informative when presented in 25 km<sup>2</sup> grid-cell for the time period considered (also mapped in 9 km<sup>2</sup> and 16 km<sup>2</sup> grid-cells, but not shown; and the data can be rescaled to 1x1 km also as needed to input in transport models). The grid-cell size seemed well adapted to the spatial scale considered in this study, as dispersion plumes have previously been simulated in regional models such as the CCATT-BRAMS (in the Brazilian Amazon) using 15 and 30 km<sup>2</sup> grid-cells (Freitas et al., 2009) and global models such as the MEGAN V.2.1. of 3025 km<sup>2</sup> grid-cells (Sindelarova et al., 2014). Besides, this spatial resolution could be evaluated in terms of cumulative, added or synergistic effects with other hazardous substances (Lahr et al., 2010), i.e., particulate aerosols (PM<sub>2.5,10</sub>), spilled hydrocarbons, oilpit brines that could probably be within a similar or lower dispersion ranges, also analysed within the framework of the transdisciplinary ANR-MONOIL research program (MONOIL, 2017). Spatial treatments were performed in ArcGIS® system. Values were mapped via Jenk natural breaks.

2.3.3. *Carbon dioxide and methane*

CO<sub>2</sub> and CH<sub>4</sub> were calculated using the Intergovernmental Panel on

Climate Change (IPCC) – Tier 2 method which denotes a combination of production and mass balance equations (IPCC, 2006a). The calculation procedure incorporated several data on chemical properties of gases, as shown in Eqs. (3) and (4). Estimates were made for four major oilfields because data was complete and available (n = 22 oil wells in total): Auca, Shushufindi, Singue and Libertador, see Fig. 1B.

$$E_{CO_2, oilprod, flaring} = GORxQ_{oil}(1 - CE)X_{flared}M_{CO_2} [y_{CO_2} + (N_{CCH_4}xy_{CH_4} + N_{CNMVO}xy_{NMVO}) (1 - X_{soot})]x \text{ kmol} \quad (3)$$

$$E_{CH_4, oilprod, flaring} = GORxQ_{oil}(1 - CE)X_{flared}(1 - FE)xM_{CH_4}x \text{ kmol} \quad (4)$$

Where,

$E_{k, oil prod, flaring}$  = direct amount (Gg yr<sup>-1</sup>) of GHG *k* emitted due to flaring at oil production facilities.

GOR = average gas to oil ratio (m<sup>3</sup> m<sup>-3</sup>) referenced at 15 °C and 101.325 kPa.

Q<sub>oil</sub> = total annual oil production (10<sup>3</sup> m<sup>3</sup> y<sup>-1</sup>).

M<sub>gas</sub> = molecular weight of gas of interest (e.g. 16.043 for CH<sub>4</sub> and 44.011 for CO<sub>2</sub>).

NMVO = non-methane volatile organic compounds.

N<sub>ci</sub> = number of moles of carbon per mole of compound (e.g. 1 for both CH<sub>4</sub> and CO<sub>2</sub>, 4.6 for NMVO).

y<sub>i</sub> = mol or volume fraction of the associated gas that is composed of substance.

CE = gas conservation efficiency factor.

X<sub>flared</sub> = fraction of the waste gas that is flared, using estimates from UNDATA.

FE = flaring destruction efficiency (i.e., fraction of the gas that leaves the flare partially or fully burnt, typical a value of 0.98 assumed for flares at production and processing facilities).

X<sub>soot</sub> = fraction of non CO<sub>2</sub> carbon in the input waste gas stream that is converted to soot or particulate matter during flaring.

kmol = is the number of kmol per m<sup>3</sup> of gas referenced at 101.325 kPa and 15 °C (i.e. 42.3 × 10<sup>-3</sup> kmol m<sup>-3</sup> for CH<sub>4</sub> and 4.23 × 10<sup>-3</sup> kmol m<sup>-3</sup> for CO<sub>2</sub>) multiplied by a unit conversion factor of 10<sup>-3</sup> Gg t<sup>-1</sup> which brings the result of each applicable equation to units of Gg y<sup>-1</sup>.

2.3.3.1. *Estimating variations based on percentile change in key parameters.* The required data to implement Eqs. (3) and (4) should be site specific, however the IPCC guidelines propose default values if no site specific information is available. All input parameters could be obtained or defined using suggested defaults, except the conservation efficiency (CE) and X<sub>flared</sub> (IPCC, 2006a). The CE factor expresses the amount of produced gas and vapour that is used for fuel, produced into gas gathering systems or re-injected, using a value of +1 if all gas is conserved and value of 0 if all gas is flared. CE values may fluctuate between these two values depending on the technology implemented at a specific site, while X<sub>flared</sub> expresses the fraction of gas that is rather flared than vented (IPCC, 2006a).

Sensitivity analysis is recommended for variables to prioritize efforts to develop good estimates (IPCC, 2006b). CE and X<sub>flared</sub> depend on expert knowledge-based assumptions on the type of technology implemented. A simple sensitivity analysis through percentile variation

– in 10% increments (Sala et al., 2000; Sax and Isakov, 2003) was performed for CE and Xflared. The range of values were calculated for the potential minimum (10% flared 90% conserved) to the maximum values (90% all gas is flared 10% conserved), assuming values of less than 10% for gas flared to be an unlikely outcome because at least 8.3% APG is used for energy generation (MSS, 2014, 2013) and 3% APG is leaked (Larsen et al., 2015). Likewise, the gas flared fraction used as input parameter was also varied in percentiles from 10th to 90th since these values are more likely to occur. Subsequently, a range of possible min and max values for every oilfield in year-on-year basis were created using this approach to Xflared and CE values.

### 3. Results

#### 3.1. Gas flaring and black carbon emissions according to publicly available data

Gas flares for the T3 period totalled 7.6 Gm<sup>3</sup> for 53% of oilfields (n = 50/94). Estimated BC emissions during 2003–2012 ranged from 3.7 to 4.5 Mt. Fifty oil fields had APG data associated with them and eleven did not have flare stacks. Fictitious stacks were allocated (centroids) to oilfields where no flare stack was evident. At least, 52.8% of APG (4.3 Gm<sup>3</sup>) was flared at four out of fifty oilfields operated in the NEA: Shushufindi, la Joya de Los Sachas, Libertador, south from Putumayo River and Yuturi. Estimates were described using median (interquartile range). The gas burnt per oilfield was 39.3 Mm<sup>3</sup> (5.7–100 Mm<sup>3</sup>) and 15.2 Mm<sup>3</sup> (5.7–35.1 Mm<sup>3</sup>) per flare stack (n = 181). All selected emissions, including GHG were displayed in Table 3. These allows a comparison between all selected hazardous emissions, simultaneously. Resulting GHG emissions were explained in Section 3.3.

#### 3.2. Estimates of this study compared to other datasets

UNDATA emissions, although estimated at the national level, reported fluctuating estimates on a year-on-year basis compared to this study from 2004 to 2005 and from 2009 to 2012. Overall, UNDATA estimates were very close to this study's estimates from publicly available data, and those were highly correlated (r = 0.84). Thus, to effectively compare data from satellite observations to other datasets, an average curve for APG flared and BC was calculated from historical energy statistics data. All these institutional datasets are referred hereafter as Energy Census Data (ECD).

Fig. 2 shows that calculated emissions from NOAA satellite data

**Table 3**

Total and annual median gas flared and BC emissions in the T3 managerial period. BC is expressed in tons with base (EF = 0.5) and upper bound (EF = 0.75) emission factors. Average (± SD) values for GHG estimates. Only the four highest oilfields are shown (gas flare and BC). Flare stack values exclude oilfields with no declared flare stacks.

Oilfields (n = 50)	Gas flared		BC		CO <sub>2</sub>		CH <sub>4</sub>		Contribution <sup>b</sup> (%)
	Total (Mm <sup>3</sup> )	Median <sup>d</sup> (Mm <sup>3</sup> yr <sup>-1</sup> )	Total (t)	Min-Max (t yr <sup>-1</sup> )	Total (kt)	Average (kt yr <sup>-1</sup> )	Total (kt)	Average (kt yr <sup>-1</sup> )	
Shushufindi (SH)	1479.2	147.7 (0–176)	646–891	80–121	53289.67	5921.1 ± 756	474.28	158 ± 15	17%
Libertador (LT) <sup>c</sup>	928.6	92.4 (50–109)	378–500	48–62	24586.10	2731.8 ± 1428	318.61	106.2 ± 11	12%
Sacha (SC)	859.1	83.2 (75–92)	340–496	42–61	–	–	–	–	11%
Yuturi (YT)	704.8	74.6 (23–78)	277–469	32–58	–	–	–	–	9%
Auca	213.0	17.3 (13–21)	89–111	11–14	9874.57	1097.2 ± 1775	193.24	64.4 ± 5	3%
Singue	71.1	6.3 (1–10)	31–43	4–5	2968.46	329.8 ± 201	22.15	7.4 ± 0.5	1%
Single oilfield	39.3 (5.7–100)	4.1 (0.4–13)	62–91	7–10	4833	537.1	17.9	2	–
Flare stacks	15.17 (5.7–35.1)	1.89 (0.7–4.4)	190–278	5.1–7.5	1362	151.4	5.1	0.6	–
Total T3	7600	782 (732–816)	3735–4583	373–572	82,144 <sup>a</sup>	6106 ± 4.6	304.64 <sup>a</sup>	25.3 ± 36.4	100%

<sup>a</sup> GHG estimations for total NEA based on key (n = 4; 36.8% of total) sampled oilfields. Totals were calculated using a 2.72 factor.

<sup>b</sup> The contribution column is calculated based on gas flared and BC only.

<sup>c</sup> Corresponds to a group of 5 oilfields where GHG emissions are calculated using data from top flaring oilfield: Pacayacu.

<sup>d</sup> Median and interquartile ranges at 25th and 75th percentiles.

observations contrasted with ECD average estimates. Annual variations (2003–2012) indicate a widening gap from 1.2 to 2.5 fold between satellite observations and ECD average, showcasing the strong negative correlation between the two datasets (r = -0.90). According to this study the highest BC emissions occurred in 2003 (516 t). Emissions in subsequent years decreased to reach 401 t in 2012.

The higher NOAA satellite estimates indicate an increasing trend, reaching up to 945 t in 2012. Overall, gas flaring and BC emissions were weakly correlated to oil production (Fig. 2). Annual oil production seemed to be globally stable during T3, with year-to-year fluctuations between 17 and 22 Gm<sup>3</sup>.

#### 3.3. Mapping of airborne black carbon emissions at a regional scale

BC estimates ranged between 2.7 and 1153.5 kg km<sup>-2</sup> yr<sup>-1</sup> (lower EF) and 4–1730 (upper EF) across grid cells. The visual display was the same for both EF because the values are proportional. Highest emissions were located at Libertador oilfield, crossing north to south from Shushufindi to Pompeya, west to east from Joya de Los Sachas to Yuturi oilfield, and at Dícaro. Medium to low emissions were found from Tarapoa to Putumayo (Fig. 3B).

#### 3.4. Greenhouse gas estimates

Carbon dioxide and methane emissions were estimated for three years, in four out of fifty oilfields with reported APG. Fig. 3A indicates where these oilfields are located. Fig. 4. and Table 4 show total and average GHG emissions for three representative years per oilfield. Variability across oil fields was slightly higher for methane emissions than carbon dioxide. Annual average reported per flare stack (country-specific data) accounted for 271 ± 98 kt CO<sub>2</sub> yr<sup>-1</sup> and 1 ± 0.7 kt CH<sub>4</sub> yr<sup>-1</sup> within the oilfields sampled.

This estimate represents 36.8% of the total GHG emissions resulting from APG flared. These estimates should thus be multiplied by a factor of 2.72, to obtain GHG corresponding approximately to the total APG flared for the entire NEA in T3. Therefore, the NEA would totalize 82.1 Mt CO<sub>2</sub> and 304.6 kt CH<sub>4</sub> during this period, equivalent to an annual average of 6.1 Mt yr<sup>-1</sup> CO<sub>2</sub> and 25.3 kt yr<sup>-1</sup> CH<sub>4</sub> (Table 2). Fig. 4. presents estimates and variations for the four oilfields.

GHG estimates can only be compared to other datasets for CO<sub>2</sub>, because CH<sub>4</sub> has not been previously evaluated in the NEA. CO<sub>2</sub> has been previously estimated in a disaggregated manner by the Carbon Dioxide Information Analysis Center (CDIAC) enabling gas flaring to be compared only for years 2003, 2007 and 2012. The approach used in

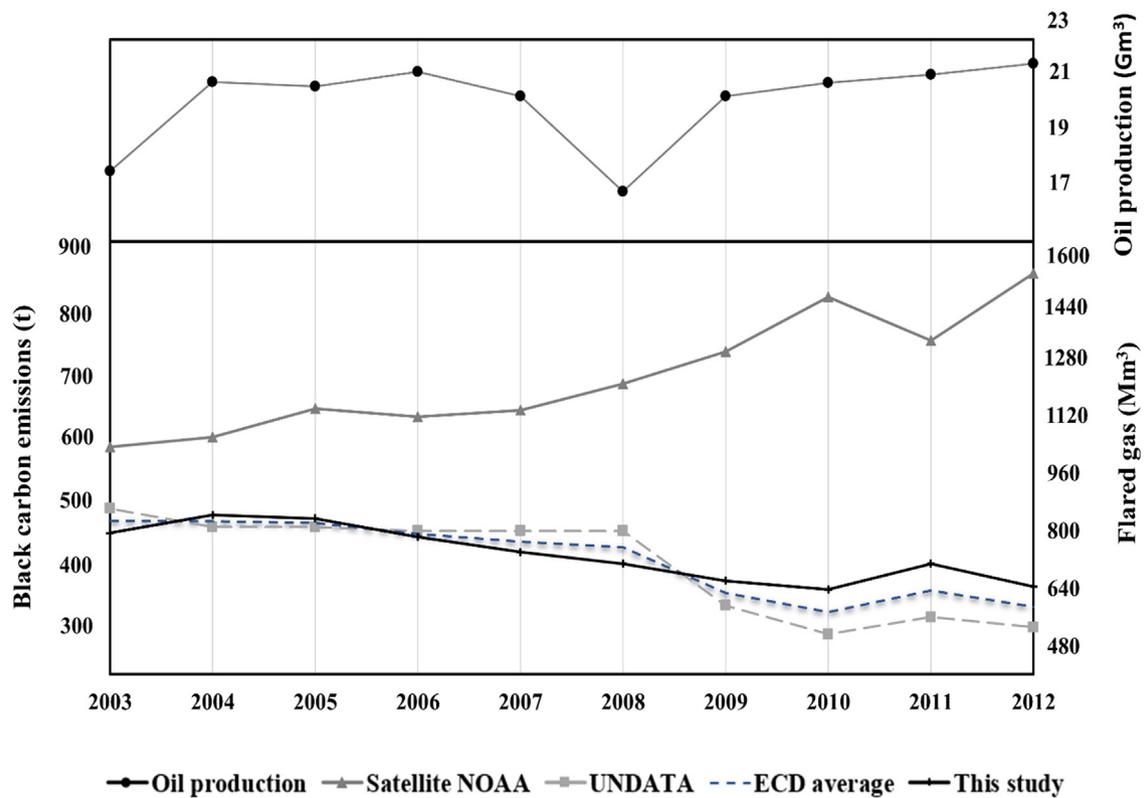


Fig. 2. Temporal patterns of flared gas volumes and corresponding BC emissions in tons. Total oil production from all Ecuadorian fields is also plotted for comparison. Correlation coefficients between flared gas and oil produced were:  $r = 0.39$  for NOAA satellite data;  $r = -0.30$  for ECD average. Data is disaggregated for oil production from Bulletins of the National Board of Hydrocarbons’ website, by oil field, restricted to the study area.

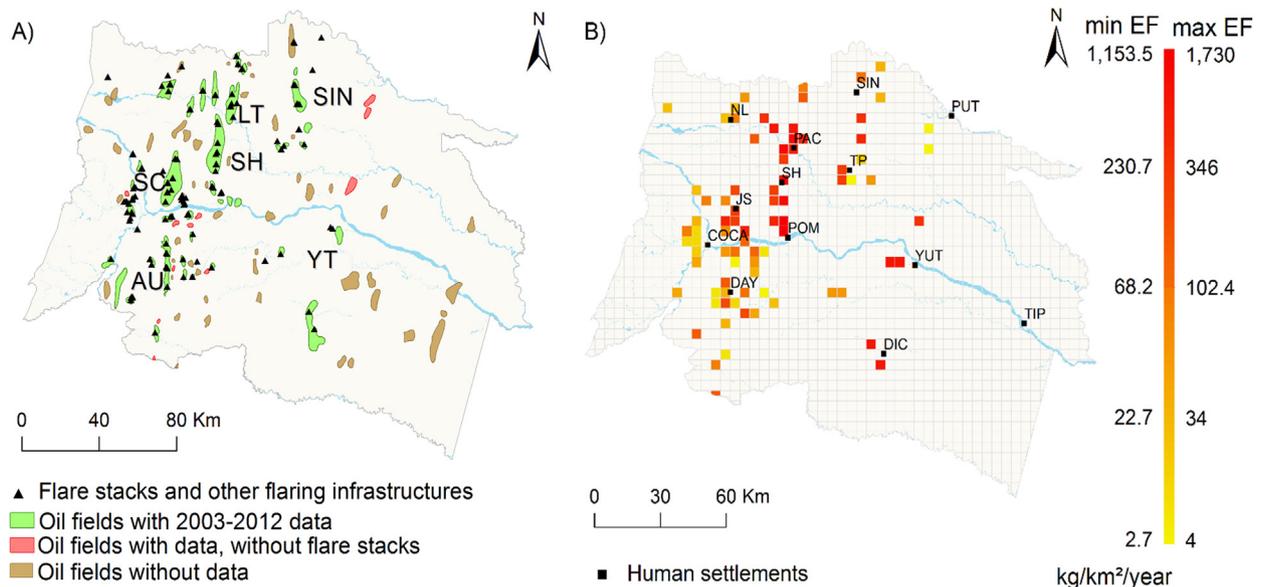


Fig. 3. Spatial variations of airborne emissions within the North-eastern Ecuadorian Amazon (NEA) from 2003 to 2012. (A) Air pollution related infrastructures: flare stacks, batteries or refineries and main oilfields (AU: Auca; SH: Shushufindi, SC: Sacha, SIN: Singue; LT: Libertador, YT: Yuturi). (B) Black Carbon emissions reported at upper and lower bound average values. The values scale show lower and upper EF emissions.

this study showed twentyfold higher emissions than CDIAC estimates.

#### 4. Discussion

##### 4.1. Data reporting

Higher levels of disclosure, and improvement in statistical analysis

and collection methods may increase inventory reliability and value in supporting safety and security decisions. Public disclosure benefits environmental accounting. Constraints in information access hampers proper estimations. This is especially true in oil industry, whose accidental emissions or discharges are seldom reported (Jerne $\ddot{a}$ l $\ddot{o}$ v, 2010). In the NEA, APG data reported for 2005 and 2008 is incomplete for some oilfields, e.g. APG has not even been reported for Yasun $\acute{ı}$ -ITT in Fig. 3 a

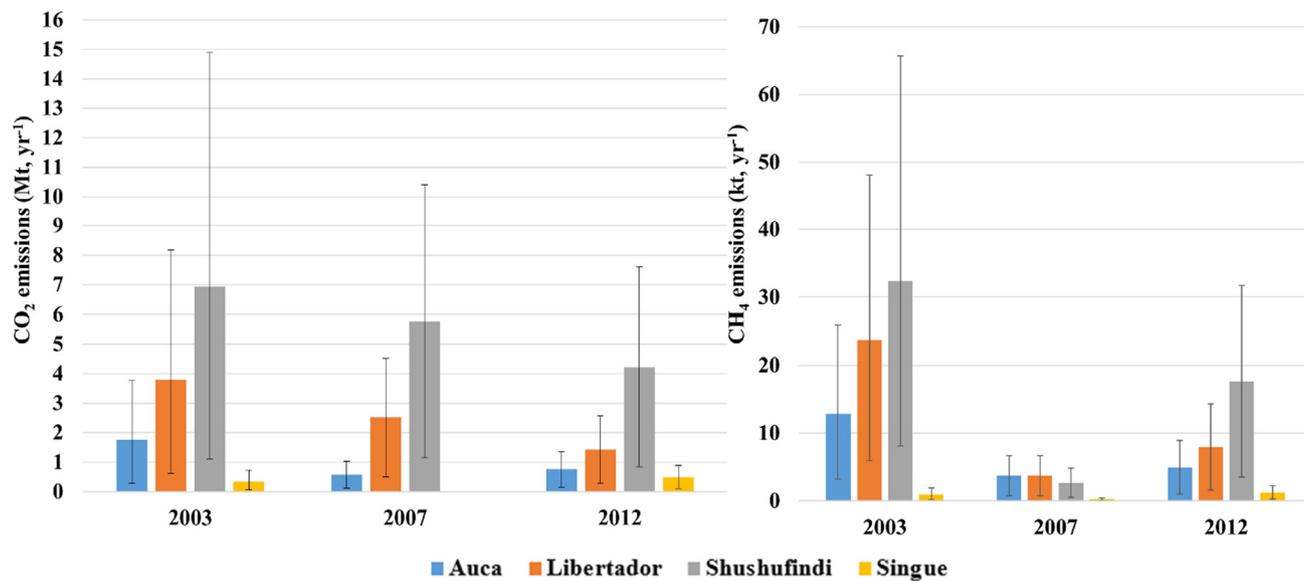


Fig. 4. Coloured bars illustrate CH<sub>4</sub> and CO<sub>2</sub> estimates with percentiles of CE and Xflared at 0.5. Error bars represent estimate variation with percentiles of CE and Xflared between 0.1 and 0.9. Estimates were derived for 3 years and 4 oil fields where data was complete. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

**Table 4**  
Total and average annual GHG emissions for four oilfields from sampled data collected in 2003, 2007 and 2012 (n = 22 oil wells).

Oilfield	CO <sub>2</sub>		CH <sub>4</sub>	
	Total (Mt)	Annual average (± SD) (Mt yr <sup>-1</sup> )	Total (kt)	Annual average (± SD) (kt yr <sup>-1</sup> )
Auca	3.3	1 ± 0.7	21.5	7 ± 5
Libertador	8.2	2,731 ± 1.4	35.4	12 ± 11
Shushufindi	17.8	5921 ± 1.8	52.7	18 ± 15
Singue	0.88	329 ± 0.2	2.5	0.8 ± 0.5
Total (n = 4)	30.2	2245 ± 0.5a	112	9.3 ± 4.5 <sup>a</sup>

<sup>a</sup> ± SD calculated using pooled estimators. Rounded data.

famous oil field for its conservation initiative aiming in keeping oil underground (Larrea and Warnars, 2009; Vallejo et al., 2015). Similarly, there is incomplete and limited data available for flaring infrastructure in some oilfields, such as Vinta, Yuca Sur or Pañacocha.

Ecuador had signed the Kyoto Protocol (1992) but during T3 had no flaring and venting targeted policies (WorldBank, 2004). The protocol established that regulating institutions and producing companies should be independent entities. Both tasks were in charge by the same institution in Ecuador. In most developing countries, institutional responsibilities for gas flaring and venting are often nontransparent, conflicting, and ineffective (WorldBank, 2004). This lesson was later recognized and, in 2008, institutional changes were made (Rwengabo, 2018), which is probably reflected by the sudden drop in APG flared from 2008 onwards, as shown by the ECD trend lines in Fig. 2. This suggests that the drop in APG flared would be related more to an increase of gas use efficiency than to a moderate decrease in data disclosure. It is possible that some quantities of APG were unreported, as the satellite calibration problems at that time (see Section 4.2.2.) obviously not explain the full gap between estimates from the NOAA and from energy census data. One third of the data in our study comes from open government data, which is well in conformity with the Ecuadorian Transparency and Access to Public Information Law (LOTAIP). Ecuador ranked 58th out of 93 countries in e-government data disclosure and open data, especially for airborne pollutant emissions (Open Knowledge International, 2015) and has 44% of open data implementation, indicating an important level of disclosure from public institutions, still

this is 10% less than the South American average (Triviño 2016). Other countries improve disclosure as a way to better control their emissions, which is an important step to meet zero-emission goals defined within the Global Gas Flaring Reduction Partnership (GFFR) (World Bank Group, 2018), e.g. Nigeria openly reports total gas flared (Giwa et al., 2014). The Ecuadorian government does not formally belong to this partnership (World Bank Group, 2018) but the state company has engaged in voluntarily attempts to meet these targets.

#### 4.2. Emission estimates

##### 4.2.1. Black carbon

In Ecuador, EFs and standardized measurements for heating values are in infancy stages. Upper bound EF had previously been extrapolated from Venezuela, assuming similar technology was implemented (Huang and Fu, 2016), and lower EF are also based on general estimates from heat values emissions (McEwen and Johnson, 2012). BC emission is an important fraction of PM with global warming and cancerigenous properties (Bond et al., 2004; Conrad and Johnson, 2015; De Miranda et al., 2012). Most recently, Conrad and Johnson, (2017), measured EFs for BC at four single flare stacks in Libertador oil field. The result they obtained was that BC emission rates are highly variable and underestimated worldwide. Using the resulted EFs, average emissions in the NEA were estimated at 8.3–23.9 t BC yr<sup>-1</sup> per flare stack. These values were slightly higher than our 5.1–7.5 t BC yr<sup>-1</sup> estimates, using reference EFs described in Section 2.3.2. These differences highlight the importance of increasing the sampling effort to properly define average EFs for the study area.

##### 4.2.2. Greenhouse gases

The site-specific databases and derived estimates seemed to be a representative fraction of emissions from the oil sector. CO<sub>2</sub> emission estimates in this study were up to twenty fold of those estimated by the CDIAC (Boden et al., 2012). To obtain similar yields estimated in this study, CE (conservation efficiency) and Xflared (fraction of flared APG) values need to be set at 90% and 30% respectively. Those values are unlikely to occur considering the used and leaked APG fractions. On the other hand, Ecuador is ranked 49th in CH<sub>4</sub> emissions from fossil fuel use. However, an annual ranking may not be the relevant way to present inter-countries comparisons

as Ecuador reports illustrate a high inter-annual variability in APG

production (Simpson et al., 2012); integrating longer term data (e.g. 2–4 years) would probably be better.

#### 4.3. Comparison of emission sources

##### 4.3.1. Single flare stacks from various countries

Estimates at single flaring facilities indicate Ecuador, specifically the study area, remained a low global contributor to gas flaring for the period considered, with a total amount of 7.6 Gm<sup>3</sup> during the T3 managerial period, equivalent to an average of 4.19 Mm<sup>3</sup>.yr<sup>-1</sup> per flare stack. Comparatively, in the Niger Delta, 350 Gm<sup>3</sup> of total APG was flared for a similar period (2000–2013), corresponding to 80 Mm<sup>3</sup>.yr<sup>-1</sup> for each single flare stack (Anejionu et al., 2015a). In Alberta, the median value for individual stacks reported was 0.03 Mm<sup>3</sup>.yr<sup>-1</sup> APG flared (Johnson and Coderre, 2011). The reported amount of flared APG per flare stack thus differs significantly, i.e., nine times lower emissions in Alberta than in the study area, and 19.5 times higher in Nigeria.

##### 4.3.2. Institutional and satellite datasets

Instrument calibrations, data collection or calculations can result in errors portraying under or overestimation of emissions. For instance, estimates from the NOAA satellite sensor, prior to 2012, might reflect similar spectral responses with other important sources, i.e., cloud coverage, biomass burning, and be prone to overestimates, compared to the previous DMSP-OLS calibration technique. Approximately 25% higher APG flared was estimated from satellite data in Nigeria and in Bolivia, where overestimates were due to biomass burning (Anejionu et al., 2015b). In subsequent years (2013, 2014 and 2015) the superior, calibrated sensor, VIIRS, indicated 800, 1000 and 1100 Mm<sup>3</sup> gas flared respectively in Ecuador (World Bank Group, 2018), to be compared to the 1500 Mm<sup>3</sup> in 2012 according to the former sensor (this study). This suggests an overestimation until 2012 for Ecuador as well, although it was not possible to assess its extent to provide a correction for the satellite imagery estimates. Conversely, the lowest UNDATA estimates (particularly for the 2009–2012 time period) consider gas flaring at the national level, possibly underestimating emissions due to missing discharges. Comparative analysis of airborne emissions suggests using several data sources is an asset in the evaluation of hazardous emissions. Long term estimates by satellite observations have also been prone to errors (Elvidge et al., 2009). Historical energy data and other methods of estimation are suitable for determining the activity sector specific emissions and for comparative analysis with independent non-governmental and satellite product reported estimations.

##### 4.3.3. Across activity sectors

Oil production is key contributor of BC emissions in Ecuador, yet other potentially important anthropogenic emissions cannot be neglected, i.e., biomass burning (Fearnside, 2000; Ramanathan and Carmichael, 2008) and vehicle fossil fuel combustion (Gramsch et al., 2013). Data was insufficient to compare gas flaring with biomass burning, alleged to be an important source of contaminants (sulphur, nitrogen, carbon, and metals), due to long trajectories and depositions within the Ecuadorian Amazon (Barraza et al., 2018; Fabian et al., 2005). Nonetheless, available reports from the National Institute of Statistics and Census of Ecuador (INEC) enable comparisons with transportation emissions in the NEA. INEC reported the number of diesel vehicles ( $\Sigma = 6780$  buses in 2012) has increased during 2007–2012 (INEC, 2017). With an estimated EF for diesel vehicles of 0.15 t BC bus<sup>-1</sup>.yr<sup>-1</sup> (Conrad and Johnson, 2015) this results in an average of  $264 \pm 64$  t BC yr<sup>-1</sup> discharged during T3 period. These emissions arise from 20.5% of total vehicles. For the remaining 79.5%, corresponding to gasoline vehicles, a 0.03-fold factor may be applied to the emissions from diesel vehicles (Streets et al., 2001). Average vehicle emissions account for  $485 \pm 76$  t BC yr<sup>-1</sup>, comparable to 388–568 t BC yr<sup>-1</sup> from flaring APG. In fact, this is in agreement with a local study which suggests that the concentrations of particulate aerosols

from flared APG may be similar to urban sites (Barraza et al., 2018).

#### 4.4. Potential economic, health, and environmental losses

Direct economic losses associated to gas flaring represent potentially important economic revenues for Ecuador. Considering our total estimates, and the conversion factor from thermal units (a unit commonly used for calculating the monetary value to generate electricity) of 0.24 US\$ m<sup>3</sup> if sold in the United States (US Department of Energy, 2017), the main potential Ecuadorian commercial partner, would result in a US\$182.4 million yr<sup>-1</sup> economic losses. A partial estimate that should integrate monetary values of environmental and health costs, yet to be quantified. Inhalation is the main exposure pathway for local populations to airborne pollution in the NEA (Barraza et al., 2018). Black carbon is a carcinogen (IARC, 2012), having also short-term health effects (Janssen et al., 2011), and may serve as a carrier for toxic chemicals passing through the blood system, and cause cardiopulmonary diseases (Janssen et al., 2011). Hence, forthcoming hydrocarbon regulations could include BC and methane emissions.

## 5. Conclusion

This study presents a “bottom-up approach” to process and visually represent APG datasets in gridded form for specific activities (i.e. type of infrastructure) in oil and gas production of selected pollutants. Emission estimates and subsequent homogenized spatial distribution of pollutants in the NEA are needed for future transport modelling and hazard mapping. Willingness of institutions and operators to disclose data is key to enhance security and safety decision making, towards improved health, economic, and environmental conditions. During this study period (2003–2012) Ecuadorian institutions started to implement recovery technology. Institution reports and bulletins do not always provide appropriate data detailed or accurate data for emission estimation. This study has proposed an emission estimation approach that uses government data rather than the variable institutional datasets, and relies less on satellite products. Having several data sources for estimation is found to be useful. Finally, public access to gas flaring data from Ecuadorian institutions was found to be within acceptable levels (two-fold lower estimates than satellite observations), which is an important step towards accomplishing environmental monitoring and accountability objectives.

Future research aims to combine maps on oil spills and BC to address cumulative impacts, including other potential pollutants (e.g. total hydrocarbons, heavy metals) and source types (i.e. mud drilling pits). Hazard maps could assist decision making, when overlapping environmental (e.g. biodiversity values, surface waters, groundwater, etc.) and socioeconomic (poverty, medical service access, education, etc.) vulnerability maps. This study is a comprehensive first step to provide emission maps that could be used as input to assess atmospheric dispersion together with previous inventories and subsequently overlaid with vulnerability maps.

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