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Extreme citizens science for climate justice: linking pixel to people for mapping gas flaring in Amazon rainforest

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Supplementary material for this article is available [online](#)

Abstract

In the Ecuadorian Amazon—one of Earth’s last high-biodiversity wilderness areas and home to uncontacted indigenous populations—50 years of widespread oil development is jeopardizing biodiversity and feeding environmental conflicts. In 2019, a campaign to eliminate oil-related gas flaring, led by Amazonian communities impacted by fossil fuel production, resulted in an injunction against the Ecuadorian Ministry of Energy and Non-Renewable Natural Resources and the Ministry of Environment and Water. On 26 January 2021 the Court of Nueva Loja issued a historical order to ban gas flaring in the Ecuadorian Amazon. The present citizen science project played an important role in this process, enabling the production of independent spatial information through participatory mapping with indigenous and farmer communities. Globally, lack of independent information about oil activities has led to the monitoring of gas flaring by satellite imagery, achieving remarkable results. However, apart from institutional and remotely sensed data, reliable spatial information on gas flaring in the Ecuadorian Amazon is not available. Therefore, we adopted the community-based participatory action research approach to develop a participatory GIS process, aiming both to provide reliable data and to support social campaigns for environmental and climate justice. This work presents the first participatory mapping initiative of gas flaring at a regional scale, carried out completely through open source data and software. Having identified 295 previously unmapped gas flaring sites through participatory mapping, we highlight that the extent of gas flaring activities is well beyond the official data provided by the Ecuadorian Ministry of Environment and National Oceanic and Atmospheric Administration Nightfire annual datasets, which map only 24% and 33% of the sites, respectively. Seventy five of the detected sites were in the Yasuní Biosphere Reserve. Moreover, 39 of the identified sites were venting instead of flaring, a phenomenon never before documented in the Ecuadorian Amazon.

This study demonstrates that, because official datasets and satellite imagery underestimate the extent of gas flaring in the Ecuadorian Amazon, community-based mapping offers a promising alternative for producing trusted, community-based scientific data. This community-produced data can support campaigns for legal recognition of human rights and environmental justice in the Ecuadorian Amazon. Finally, this study shows how local environmental conflicts can foster policy transformations that promote climate justice.

1. Introduction

1.1. Leaving fossil fuel underground: unburnable and unleakable carbon

Climate change is happening everywhere. Despite this fact, the ‘carbon model’, based on fossil fuel energy production, firmly remains the dominant global economic paradigm (Allen *et al* 2018, Rhodes 2019, Newell and Simms 2020).

To limit global warming to 1.5 °C by 2050, recent studies based on an updated baseline scenario suggest that about 81% of oil, 86% of natural gas and 97% of coal must remain ‘locked underground’ (Welsby *et al* 2021).

These predictions have led to the ‘unburnable carbon’ framework, steering the global agenda toward more effective climate policies that focus on transitions to clean energy, as well as decarbonization processes (Jakob and Hilaire 2015, van der Ploeg and Rezai 2017, Erickson *et al* 2018, Green 2018, Piggot *et al* 2018). The ‘Yasuni-ITT Initiative’ embodies an inclusive approach to unburnable carbon, combining conservation priorities with human rights protection to keep fossil fuels underground in a crucial sector of the Amazon rainforest (Martinez-Alier *et al* 2014, Vallejo *et al* 2015, Fierro 2017, Macintosh and Constable 2017). This comprehensive ecosystem-based approach is at present spreading in the international scientific debate about geographical criteria and institutional mechanisms to define unburnable carbon policies for very high biologically and culturally diverse areas (Codato *et al* 2019, Facchinelli *et al* 2020, Pellegrini *et al* 2021). While much of the climate discussion focuses on highly visible, industrial combustion of fossil fuels, a less investigated issue is the ‘fugitive’, ‘leaked’, ‘vented’ or ‘flared’ emissions related to fossil fuel extraction and production. Such unintended ‘unleakable carbon’ is mainly produced by gas flaring activities, which are also sources of direct and indirect environmental and social impacts (Hendrick *et al* 2017).

1.2. Oil-related gas flaring and socio-environmental impacts

Gas flaring is related to *in situ* combustion of unused gases (mostly CH₄) along with fossil fuel extraction and production processes. It is recognized as an irrational industrial practice, representing not only a leak of usable energy, but also a major source

of greenhouse gas and local pollution (Ismail and Umukoro 2012, Emam 2015).

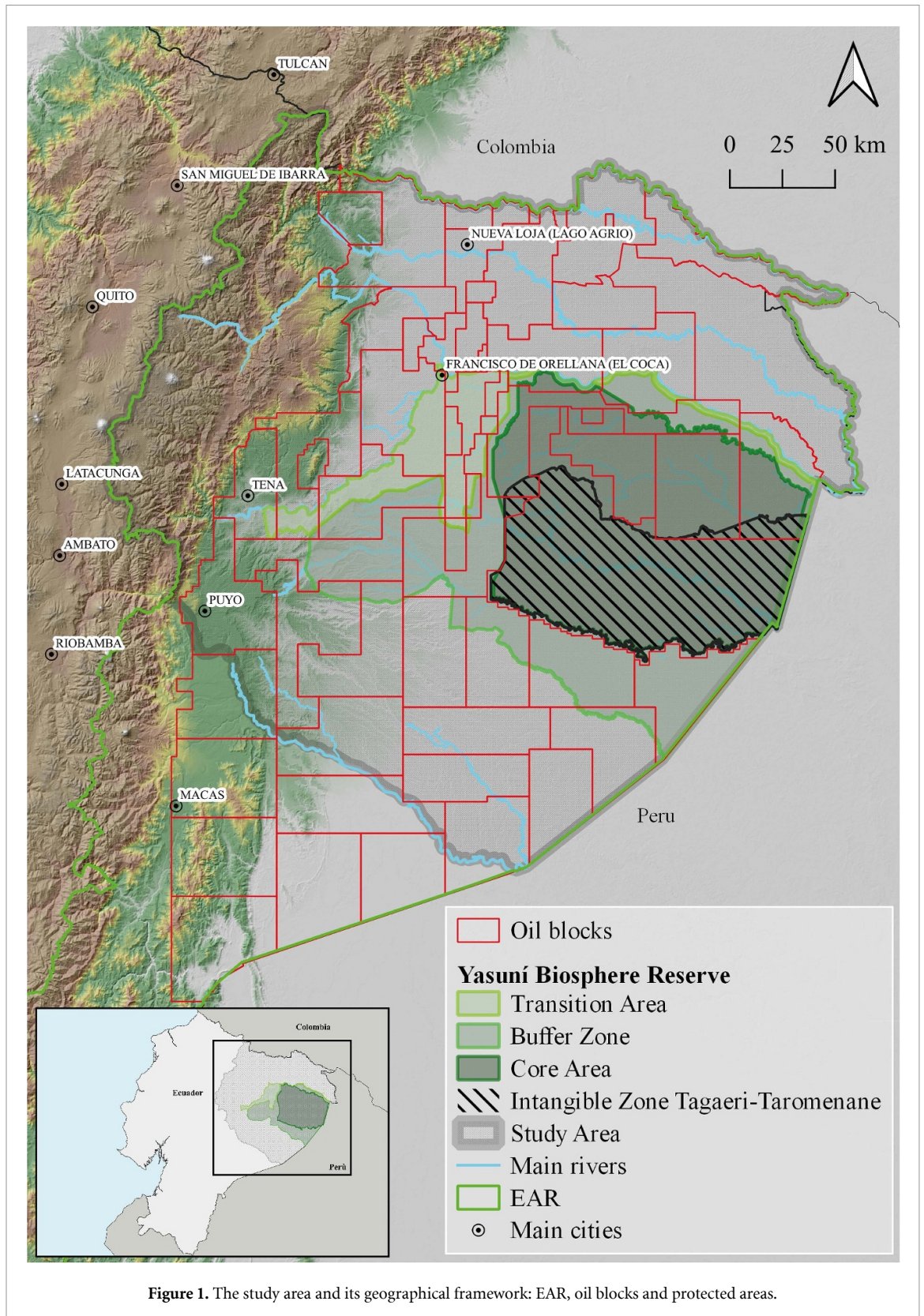
In 2019, the reported amount of flared gas worldwide was 150 billion cubic metres (BCM), the highest level over 10 years (World Bank 2020). Moreover, estimated gas flaring emissions include about 400 Mt yr⁻¹ of CO₂ equivalent and 230 Mt yr⁻¹ of black carbon, representing about 1% and 4% of global anthropogenic emissions, respectively (Weyant *et al* 2016, Quéré *et al* 2018, Caseiro *et al* 2020, World Bank 2020).

Local impacts of gas flaring affect ecosystems, biodiversity, and local communities, and include changes in microclimate, acid rains, alteration of physiochemical properties of soil, rainwater and air, direct emission of more than 250 identified toxins, and decrease in crop yields (Ismail and Umukoro 2012, Obi and Osang 2015, Onuoma *et al* 2015, Ozabor and Obisesan 2015, Uyigwe and Enujekwu 2017).

1.3. Oil production in the Ecuadorian Amazon: environmental conflicts, social campaigns and legal action

This study is based in the Ecuadorian Amazon region (EAR), specifically the provinces of Sucumbios, Orellana, Napo and Pastaza, for a geographical extension of 82 608 km². At present day, the EAR is characterized by the operation of different, and often conflicting natural resource management projects, including biodiversity conservation, indigenous territory protection, and fossil fuel production (Bass *et al* 2010, Finer *et al* 2015, Codato *et al* 2019, Qin *et al* 2019). This territorial complexity is demonstrated by the spatial overlap of the different projects showed in figure 1: oil blocks for fossil fuel development, important protected areas such as the Yasuni Biosphere Reserve (YBR) and the Intangible Zone for uncontacted indigenous people (Tagaeri and Taromenane).

The socio-environmental impacts of fossil fuel production in the EAR have been widely documented (Finer *et al* 2008, Butt *et al* 2013, Kimerling 2013, Pappalardo *et al* 2013, Azevedo-Santos *et al* 2016), as have been the limitations of the existing natural resource regulatory framework, both in terms of effective application (Finer *et al* 2014, Facchinelli *et al* 2020) and effective capacity to reduce impacts, particularly on local indigenous communities (Cabodevilla and Aguirre 2013, Diantini *et al* 2020). It is important



to highlight that even if the EAR is the centre of a national economy based on fossil fuel extractivism (Larrea 2017), local communities are disproportionately paying the ecological, cultural and social costs of oil production, which feeds various socio-environmental conflicts in the area (Cabodevilla and Aguirre 2013, Molina et al 2016, El Universo 2019b).

After over 30 years of ongoing environmental conflicts, local organizations, whose previous demands were primarily remediation and compensation for the socio-environmental impacts of the oil industry, are now expanding their demands to include meaningful actions against climate change and greenhouse gases emissions. From a theoretical

point of view, this could be interpreted as the incorporation of relevant elements of the global climate justice movement into local environmental movements. Notably, this shift is happening at the local scale throughout the world—while struggling for a cleaner and healthier environment in their territories, communities, particularly those living in oil extraction areas, have begun to develop an increasing awareness of the global impacts of climate change and the crucial role they can play in the shift toward a more climate just world (Widener 2013, Schlosberg and Collins 2014).

For instance, in the EAR, local communities of the association Union de Los Afectados Por Texaco (UDAPT) have gained international visibility in their longstanding class action suit demanding remediation of the extensive pollution produced by the Chevron-Texaco oil company in the 1990s (Kimerling 2013, El Comercio 2018). Influenced by grassroots social movements for environmental justice, the Ecuadorian government launched the global Yasuní-ITT Initiative in 2007 to prevent oil extraction in the ITT oil block of the YBR with the goal of protecting biodiversity and indigenous communities in voluntary isolation. The Yasuní-Initiative was based on a global climate justice framework, highlighting the international community's responsibility to compensate Ecuador for lost oil profits in exchange for the climatic benefits the global community would reap as a result of forest conservation (Larrea and Warnars 2009). Although the presidential Initiative failed due to lack of international contributions and political issues, grassroots movements, including indigenous ones, continue to campaign for environmental protection, land rights, and climate justice (Lu *et al* 2017). The collective Yasunidos is one such group promoting environmental campaigns and demanding a national referendum on environmental issues (Coryat 2015).

In the past five years, grassroots environmental demands concerning gas flaring activities have highlighted the connection between local environmental concerns and global climate justice (Unión de Los Afectados por Texaco 2019, Accion Ecologica 2020). It should be noted that oil-related gas flaring emissions in Ecuador amount for approximately 1 BCM yr⁻¹ comprising 8% of Ecuador's total nationally determined contributions, the country's target level emissions agreed upon through the Paris Climate Agreement (Elvidge *et al* 2018). Moreover, recent studies showed ten indigenous communities, 18 small towns, and ten schools located within a radius of 650 m from detected gas flaring sites, suggesting exposure to pollutants and potential health impacts (Facchinelli *et al* 2020).

Previous research, fieldwork, and engagement with local actors, as well as knowledge of the territory, allowed the authors to design and develop

this study in this social context. The present research coalesces with the campaign 'Apáguen los mecheros' led by a network of national and international non-governmental organizations, indigenous organizations, and sectors of civil society, demanding a moratorium on all gas flaring stacks in the EAR (Unión de Los Afectados por Texaco 2019).

1.4. Gas flaring monitoring from satellite data: opportunities and constraints

Over the past decade, the lack of independent and reliable information on gas flaring activities has led to the development of various remote-sensing methods to identify locations of gas flaring sites, as well as estimating flared volumes and emissions. These methods have achieved remarkable results (Anejionu 2019, Faruolo *et al* 2020).

Elvidge *et al* created the first open worldwide dataset on gas flaring, available both as raw daily detections and as an annual dataset (Elvidge *et al* 2013, 2015), developed through the Nightfire algorithm used on night-time imagery from the visible infrared imaging radiometer suite sensor on the National Oceanic and Atmospheric Administration (NOAA) satellite Suomi-National Polar-orbiting Partnership.

This dataset is widely used as the primary source of independent data on gas flaring distribution and volume, as well as for estimating emissions (Anejionu *et al* 2015, Elvidge *et al* 2018, World Bank 2020). Moreover, most studies have performed spatial data validation only for remotely detected sites, presenting uncertainty about possible undetected gas flaring stacks (Anejionu *et al* 2014, Elvidge *et al* 2015). Generally, different satellite-derived datasets are cross-referenced to validate one another (Casadio *et al* 2012, Fisher and Wooster 2019, Caseiro *et al* 2020). There is wide use of high-resolution imagery available from Google Earth, both for data validation and comparison (Casadio *et al* 2012, Anejionu *et al* 2015, Elvidge *et al* 2015). However, this methodology presents distinct limitations and constraints, particularly due to lack of high-resolution imagery for large geographical regions and historical images.

For some studies, data validation is only performed for data reported from oil companies (Faruolo *et al* 2018, Durango-Cordero *et al* 2019).

Often, studies do not ground truth remotely sensed datasets with independent, locally validated sources likely due to elevated costs, logistical and safety issues, or inaccessibility of the sites (Anejionu *et al* 2014, Duncan *et al* 2014).

Hence, as far as is documented in the literature, this is the first large-scale, ground-based data validation project of pixel-derived data and collection of unmapped gas flaring sites data at the regional scale.

1.5. Participatory mapping for extreme citizen science: environmental monitoring and local community empowerment

As reported by Haklay, in the last decade, lower costs to access, create, and modify spatial data has allowed community organizations to become even more involved in environmental decision-making processes, an area of knowledge previously difficult to access due to technological and economic barriers (2018). As a result, research institutions have better been able to support local communities in highlighting environmental injustices in their territories through ‘citizen science’ (2013). This is particularly true for what Haklay defines as ‘extreme citizen science’, a higher level of citizen involvement, participation, and engagement in projects, in which citizens define problems, collect, and analyse data (2013).

In the field of geography, as geospatial technologies such as GPS, mobile Geographical Information Systems (GIS) and GeoApp become more accessible, community-based mapping and participatory geography approaches to scientific research have been adopted worldwide (Brown and Fagerholm 2015, Radil and Anderson 2019). Participatory geographic information systems (PGISs) uses participatory mapping processes and local engagement as tools to promote social justice and equality, to reinforce community identity, and to support geographical knowledge (Brown and Kytta 2014). Pedregal *et al* (2020) state that PGIS ‘engage and empower marginalized groups in society through the use of spatial technologies, which have become a useful tool for environmental justice movements to transmit and report environmental conflicts, and uneven socio-ecological damage’. Local knowledge can also provide information not included in official datasets, which otherwise would be difficult, if not impossible, for international researchers to acquire (Radil and Anderson 2019). In this light, community-based mapping and PGIS currently represent important tools both for data acquisition and to empower local actors affected by the socio-environmental impacts of fossil fuel production.

This research utilizes a community-based participatory action research (CBPAR) approach, with the goal of promoting positive social change, and centering the needs and objectives of the local communities (Bacon *et al* 2013). The creation of long-term relationships with local populations is crucial to achieving democratic, egalitarian, and inclusive collaborations, beginning with the first phases of the project, including the design of the study and identification of objectives (Garzà *et al* 2013, Rickenbacker *et al* 2019).

CBPAR is a promising framework for achieving tangible results that promote environmental justice in the form of policy change, reduction of

environmental disparities, heightened environmental awareness, and empowerment of local communities in decision-making processes (McKay 2011, Balazs and Morello-Frosch 2013, Garcia *et al* 2013, Johnston *et al* 2020).

1.6. Aims of the work

Presently, the only available data on gas flaring in the EAR are from satellite monitoring, oil companies and the Ecuadorian Ministry of Environment (EME) (Durango-Cordero *et al* 2019, Facchinelli *et al* 2020). The latter, last being updated into 2012, cannot be considered an independent dataset as such since most of oil extraction in the EAR is carried out from the state-owned company Petroamazonas. In this context, there is currently no reliable and ground-validated dataset regarding gas flaring activities in the EAR.

The present research aims to fill this gap by integrating pixel-based approaches with participatory processes developed with local communities, aiming to support their efforts toward the climate justice.

The specific aims of the study are: (a) mapping all gas flaring sites in the EAR; (b) validating the existing datasets on gas flaring sites; (c) carrying out CBPAR and PGIS to support local communities in their lawsuit demanding a moratorium on gas flaring activities in the EAR.

2. Data and methods

2.1. Participatory process

The research, which initially aimed to map gas flaring sites detected from the Nightfire algorithm in the YBR, was restructured to meet the needs of local communities and organizations by providing reliable data that will support a lawsuit demanding a moratorium on gas flaring in the EAR.

The process of participatory mapping of gas flaring sites was developed and carried out in collaboration with the local organizations UDAPT (Nueva Loja, Province of Sucumbíos) and the Fundación Alejandro Labaka—FAL (Puerto Francisco de Orellana, Province of Orellana). Two local indigenous communities joined the participatory mapping sessions as well.

The participatory process was characterized by the aspects from the approaches described in ‘participatory framework’, with table 1 providing an overview of how these aspects relate to theory and led to increase the quality of the research. An extensive description of the participatory process, as well as of the ways in which it strengthens the present research, is outlined in supplementary materials 1.1 (available online at stacks.iop.org/ERL/17/024003/mmedia).

In addition, the participatory mapping process designed by researchers and members of local organizations is reported in supplementary materials 1.2.

Table 1. Phases and benefits of the participatory approach.

Phase of the work	Results of the involvement	Participatory approach	Actor involved
Definition of research goals	Study area extension Mapped flares beyond those in the official datasets.	CZ CBPAR	Campaign Apaguen Los Mecheros
Design of the fieldwork	Participation in data collection of fields for non-active gas flaring sites, including number of active stacks.	CZ	UDAPT
Data collection	Possibility of finding and accessing gas flaring sites not detected by satellites. Ability to discover activity in previously inactive sites thank to the possibility of revisiting.	PGIS	UDAPT Local communities involved in participatory mapping. FAL
Data analysis	Identification of gas flaring sites which were active but venting.	PGIS CZ	UDAPT
Dissemination of the results	Publication of the results in different national and international media.	CBPAR	UDAPT FAL Campaign Apaguen los Mecheros
Informing action to prompt social change	Inclusion of the data in technical materials for a lawsuit.	CBPAR PGIS	Campaign Apaguen Los Mecheros



Data was collected from geophotos, spatial data, and ancillary information (number and status of stacks) as showed in figure 2. To ensure long-term sustainability of the mapping project, were employed only open access data and open-source applications and software.

2.2. Data validation of existing dataset on gas flaring distribution

Spatial data from the participatory mapping process were used to conduct ground truth validation of existing datasets, including: (a) the annual dataset produced by the NOAA Nightfire algorithm for

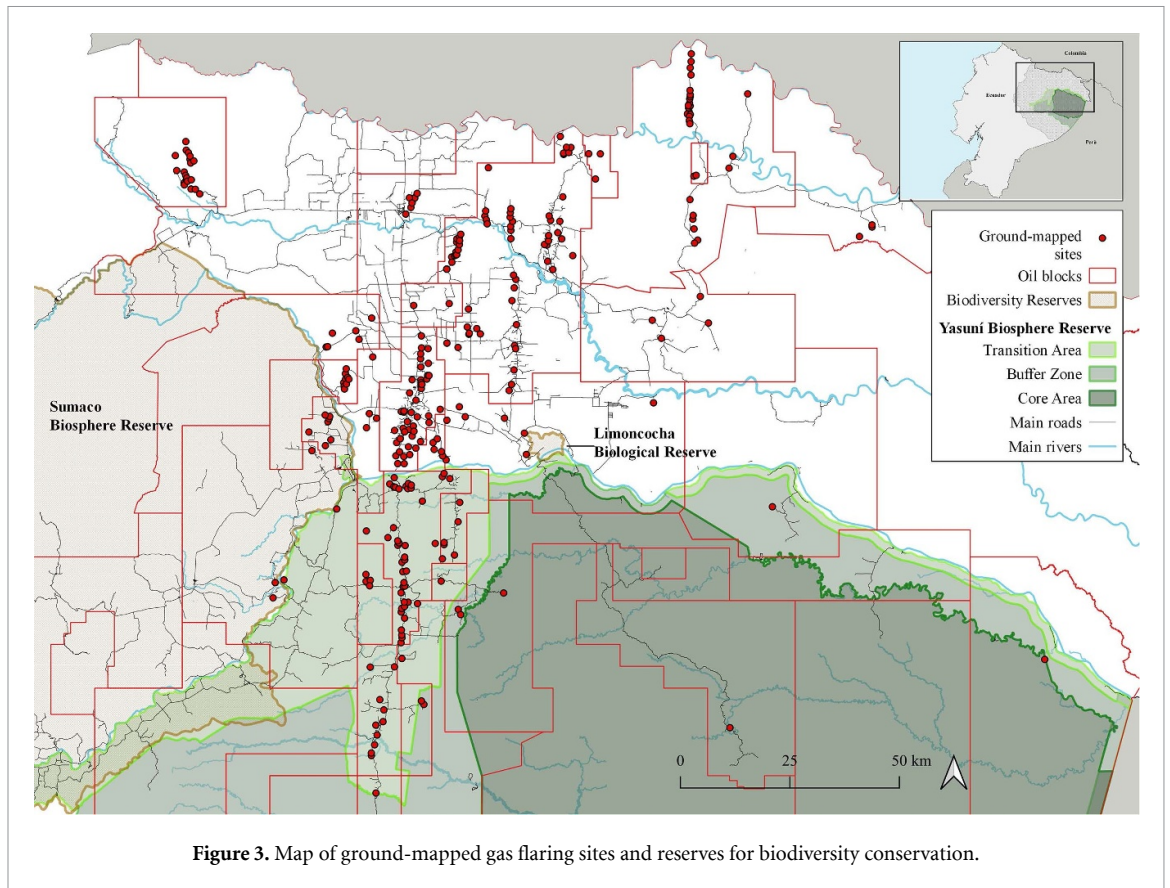


Figure 3. Map of ground-mapped gas flaring sites and reserves for biodiversity conservation.

2019; (b) daily detections from 1 January 2019 to 11 May 2020; and (c) the official data from the EME. For the first two datasets, which are currently hosted from the Earth Observation Group of the Colorado School of Mines (EOG 2021a, 2021b) a buffer of 530 m was adopted as minimum distance from ground-truth mapped sites to consider the point as validated, representing half of the diagonal length of the square pixel of 750 m from derived data (Elvidge *et al* 2013). For the dataset of daily detections, only clusters of three detections in a radius of 423 m were considered, as was done in Facchinelli *et al* (2020). In order to minimize potential omissions caused by event-specific factors (i.e. cloud cover or intermittence), we expanded our analysis of the daily detections dataset to include a wider timeframe than the one of the fieldwork which was carried out in May and June 2019. Using this methodology, we aimed to ensure that missed flares are due to the limitations of the Nightfire algorithm.

The EME dataset was validated by performing a precautionary buffer of 300 m, which includes possible spatial errors in the collected data.

Data validation was performed on 164 out of 180 flaring sites from EME, 63 from the NOAA annual dataset, and 109 clusters out of 117 of the NOAA daily detection.

Table 2. Gas flaring sites identified in the EAR during the participatory mapping campaign. The number of sites is divided by Province.

	Gas flaring sites	Stacks	Active stacks
EAR	295	437	280
Sucumbíos Province	135	204	115
Orellana Province	155	228	162
Napo Province	2	2	2
Pastaza Province	3	3	1

3. Results

3.1. Participative cartography of gas flaring sites in EAR

The participatory mapping campaign resulted in the mapping of 295 gas flaring sites, for a total of 437 single stacks. Two hundred and eighty stacks were active at the time of the survey (see figure 3 and table 2).

75 of the identified sites were within the YBR, and three in the core area (table 3). Additionally, 25% of the mapped gas flaring sites are in the YBR. Notably, gas flaring activity was identified and mapped

Table 3. Gas flaring sites identified in the Yasuni Biosphere Reserve.

	Gas flaring sites	Stacks	Active stacks
RBV—total	75	103	69
RBV—core area	3	3	3
RBV—buffer zone	5	5	4
RBV—transition	67	95	62

Table 4. Gas flaring sites by oil company.

Oil company	Number of flares
Petroamazonas EP	231
Tecpecuador	20
Enap Sipec	16
Consorcio Petrosud Petroriva	7
Andes Petroleum	4
Consorcio Pegaso	4
Petroriental	4
Consorcio Interpec	3
Consorcio Dgc	2
Consorcio Marañon	2
Petrobell	1

within the Sumaco Biosphere Reserve (ten sites) and just outside the borders of the Limoncocha Biological Reserve (two sites). Spatial analysis demonstrates that most of the gas flaring sites (230 of 295, or 78% of the total) were in state-owned oil blocks operated by Petroamazonas EP (table 4).

3.2. Comparative analysis between ground-based data and the existent gas flaring datasets

Results of the comparative analysis between field-collected data and other datasets shows a high user accuracy (% of ground-validated sites between the ones identified from the satellite) of the NOAA Nightfire dataset, both for the annual data (63 sites, 100% user accuracy) and daily detection data (109 surveyed cluster, 94% user accuracy). In contrast, EME data seem to be less reliable (164 surveyed sites, 59% user accuracy). However, all the datasets showed a high number of missing flares: 223 for the NOAA annual dataset, 179 for daily detection, and 247 for EME data (respectively 76%, 61% and 77% of the mapped sites) (see figure 4 and table 5). Both satellite datasets in some cases converged multiple real world sites into a single site detection within the dataset due to the coarse spatial resolution of the sensor.

3.3. Empowering people and data for gas flaring monitoring

Results of the participatory mapping were shared with local communities while spatial data are publicly available through the Ona platform (Amazonya Project 2020b). Additional materials produced for community use included a Storymap and WebGIS

implemented in Lizmap with cartographic representation of gas flaring sites (Amazonya Project 2019, 2020a). The data and report produced were adopted as technical supports for the coalition demanding a moratorium on gas flaring activities in the EAR. In February 2020, the campaign ‘Apaguen los mecheros’ presented a ‘protection action’ to the Court of Nueva Loja to demand the end of gas flaring activity (El Universo 2019a, Mongabay Latam 2020). The request was initially rejected in May 2020, then appealed and accepted in January 2021 (El Comercio 2021). The decision gave oil companies 18 months to close all gas flaring sites near populated centres and until 2030 to close all other sites (El Universo 2021). This legal victory underscores the role that scientific research can play in supporting the needs of local communities, centring and facilitating extreme citizen science approaches that can benefit multiple stakeholders. As research goals become linked to the real needs of local communities, communities can gain access to tools that support their struggles for local environmental justice, while making concrete advances toward the achievement of climate justice. Notably, the Court of Nueva Loja’s decision has inspired other communities to take action in similar ways (Acción Ecológica 2020).

With the support of organizations with local knowledge, the participatory mapping process allowed for the identification of gas flaring sites otherwise ‘invisible’ to satellite sensors. These organizations were able to identify sites with gas venting (which is not detectable from the satellite and can easily be confused with inactive stacks during data collection) As a result of these ground-truthing efforts, 39 stacks (Ten in the Transition area of the YBR), showed in figure 5, were recorded as venting gas directly in the air.

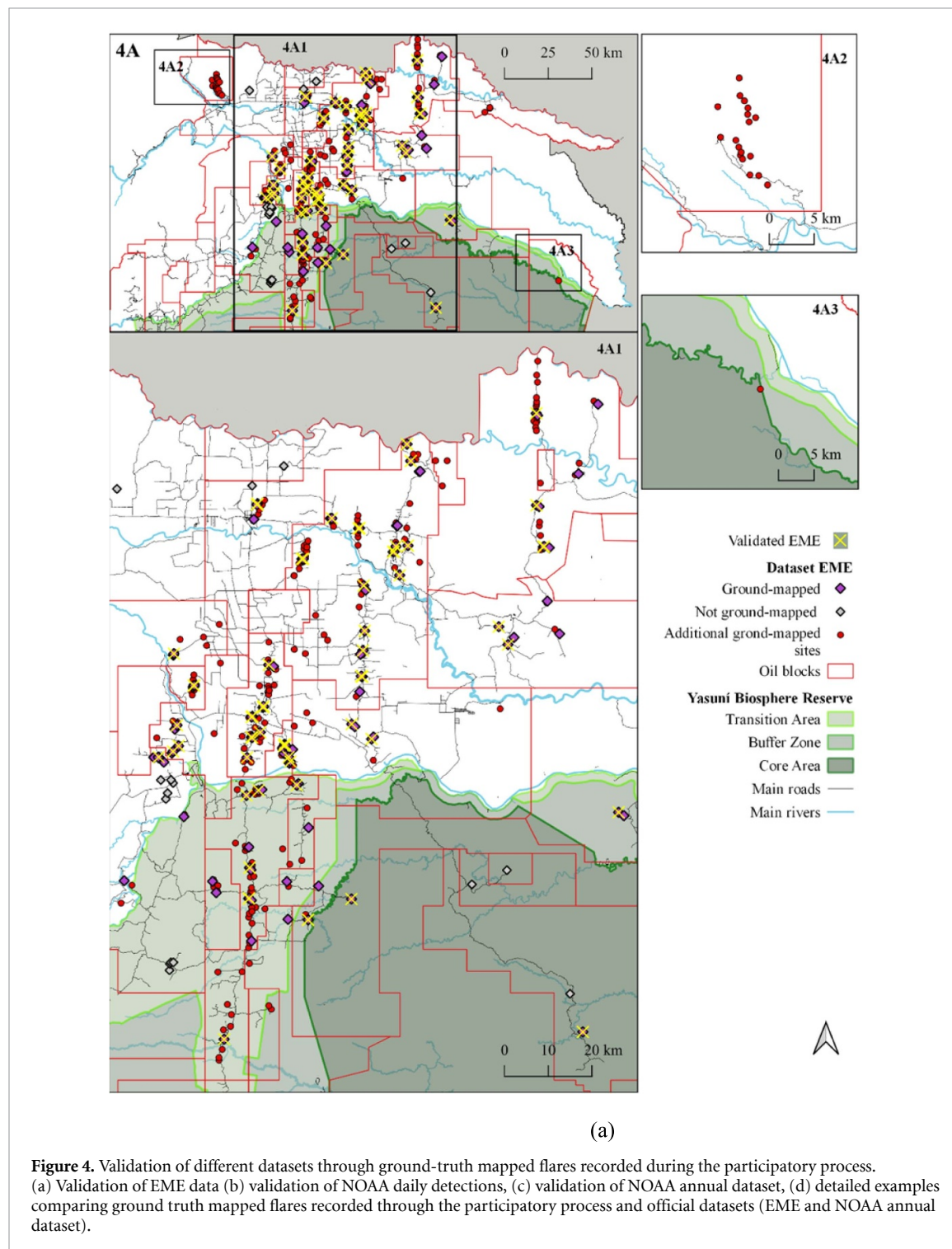
4. Discussion

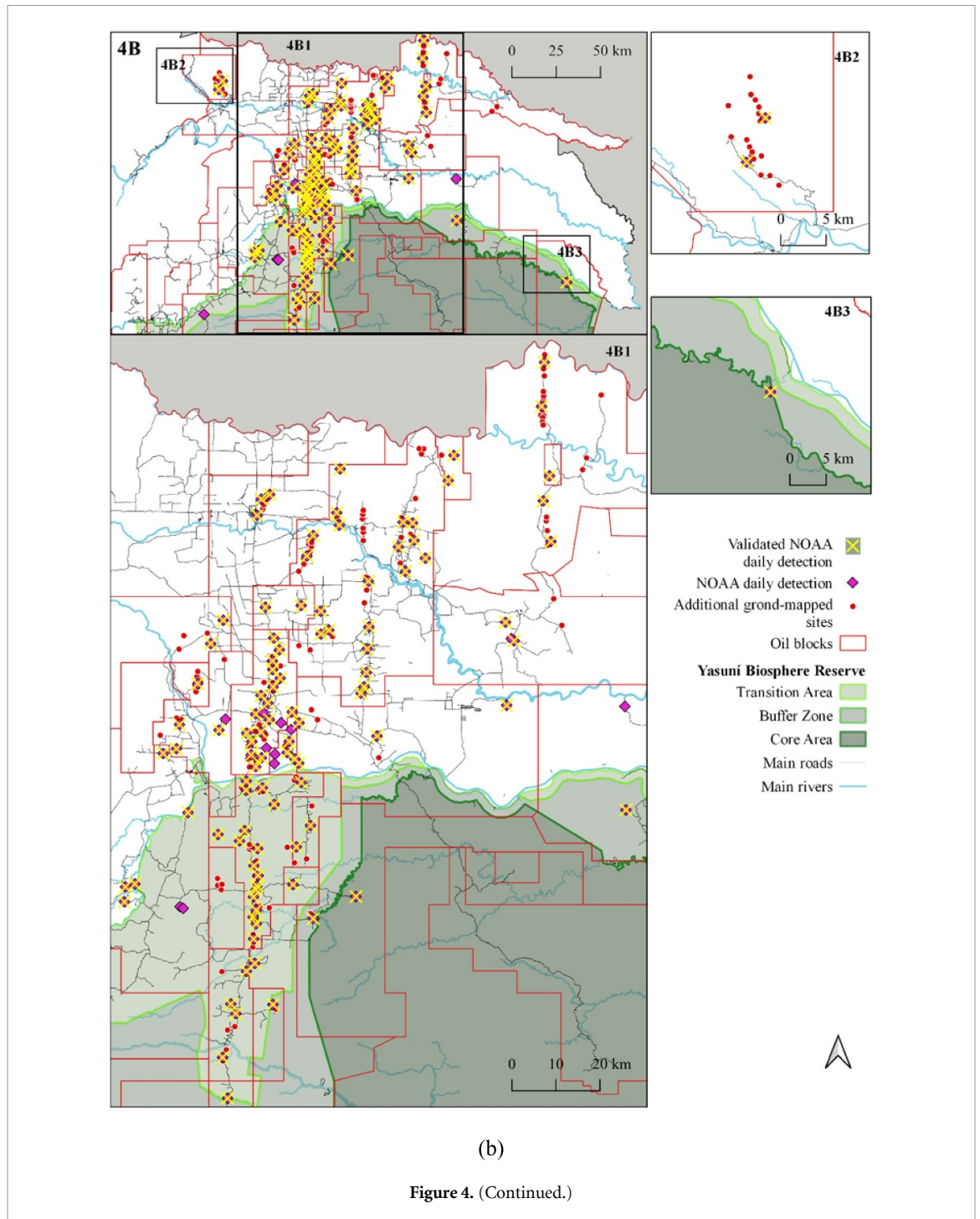
By adopting a participatory approach, this study provides the first reliable, ground-validated and independent dataset on gas flaring, confirming that gas flaring activities are widespread in the EAR, with implications for biodiversity conservation, human rights protection, and policymaking. Local partners played a key role throughout all phases of the project, ultimately expanding the study area for gas flaring, initially set as the YBR, to cover most blocks with oil activity, as well as the identifying flaring sites not detected by satellite.

By using the lens adopted from Balazs and Morello-Frosch, these community contributions enhanced the rigor and the relevance of the research (2013). The ground-truthing validation process of the NOAA Nightfire dataset highlighted the problem of remote sensed data potentially omitting real world gas

Table 5. Results of the validation of different gas flaring datasets, ‘additional ground-mapped sites’ represent previously unmapped sites captured during field data collection, ‘identified flares’ represents the percentage of the total mapped flares (295 sites) identified by the corresponding dataset.

Dataset	Total sites	Surveyed	Validated sites	Additional ground-mapped sites	Identified flare
NOAA annual dataset	63	63	63	223	24%
NOAA daily detection	117	109	103	179	39%
Ecuadorian Ministry of Environment (EME)	180	164	97	198	33%

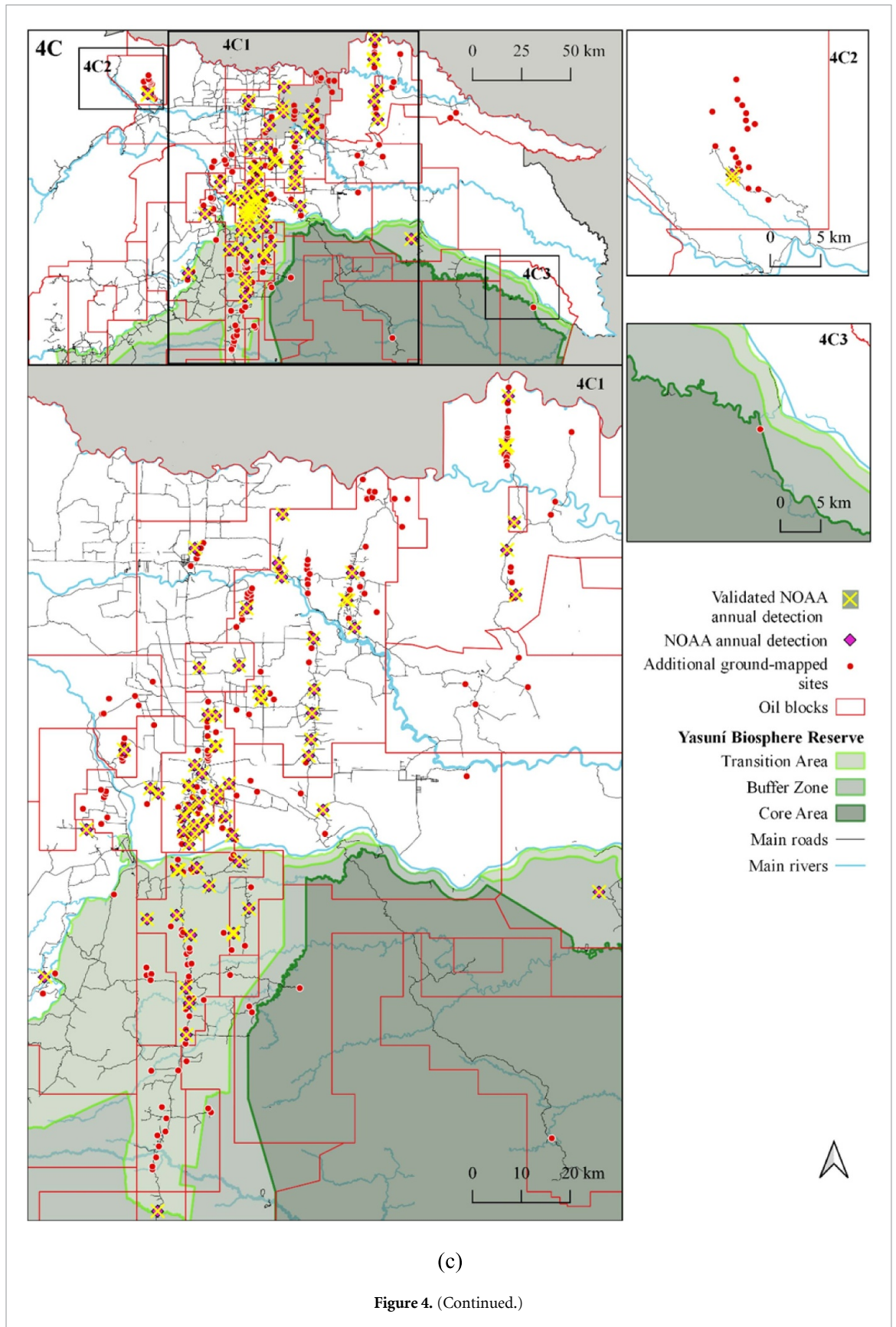




flaring sites, though this issue is not often addressed in the scientific literature on satellite monitoring of gas flaring activities (Faruolo *et al* 2020). This potential data gap is particularly important to consider in geographical contexts characterized by the presence of small facilities in large, dense territories, like that of the Amazon rainforest. Data issues contributing to this problem include: (a) low spatial resolution in night-time imagery, (b) low temporal resolution, (c) effects of solar irradiance in daytime imagery, (d) effect of cloud coverage, and (e) challenges in detecting small or intermittent flares (Elvidge *et al* 2015, Anejionu 2019, Facchinelli *et al* 2020). In this

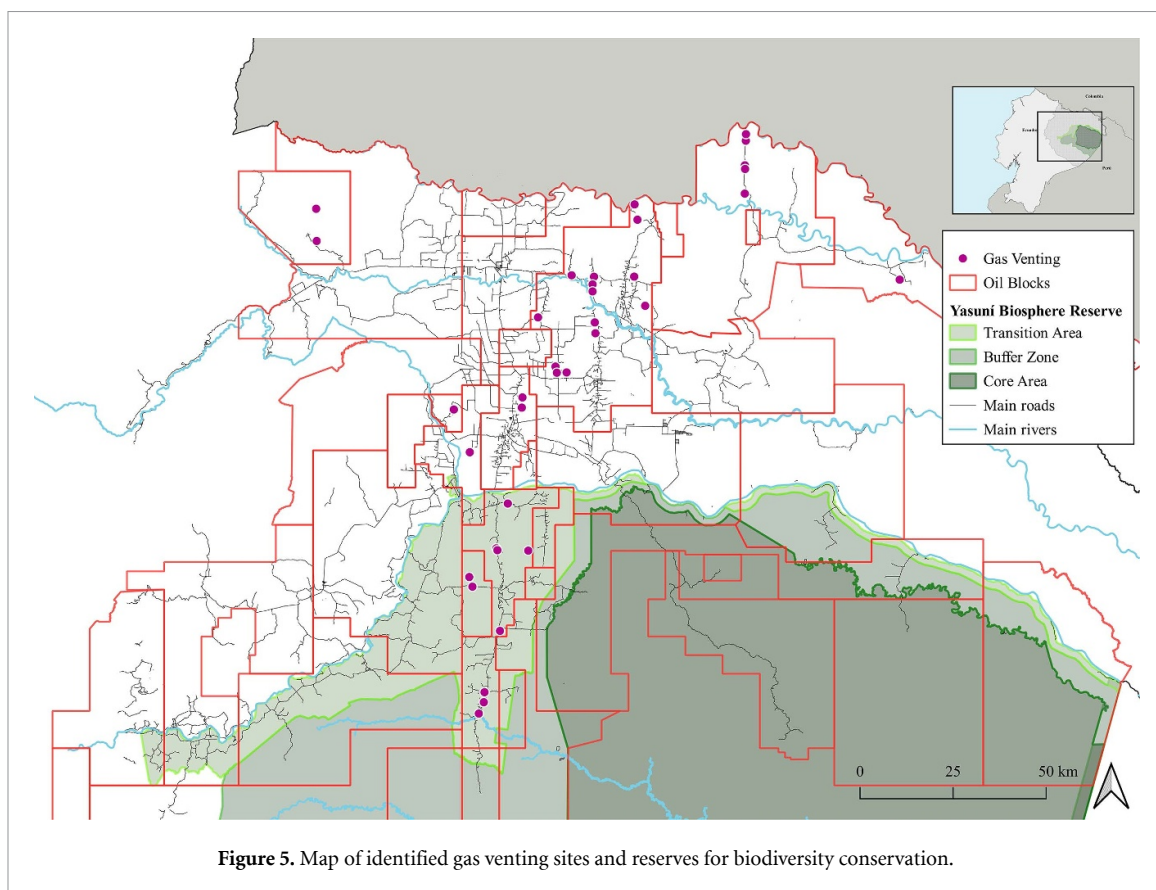
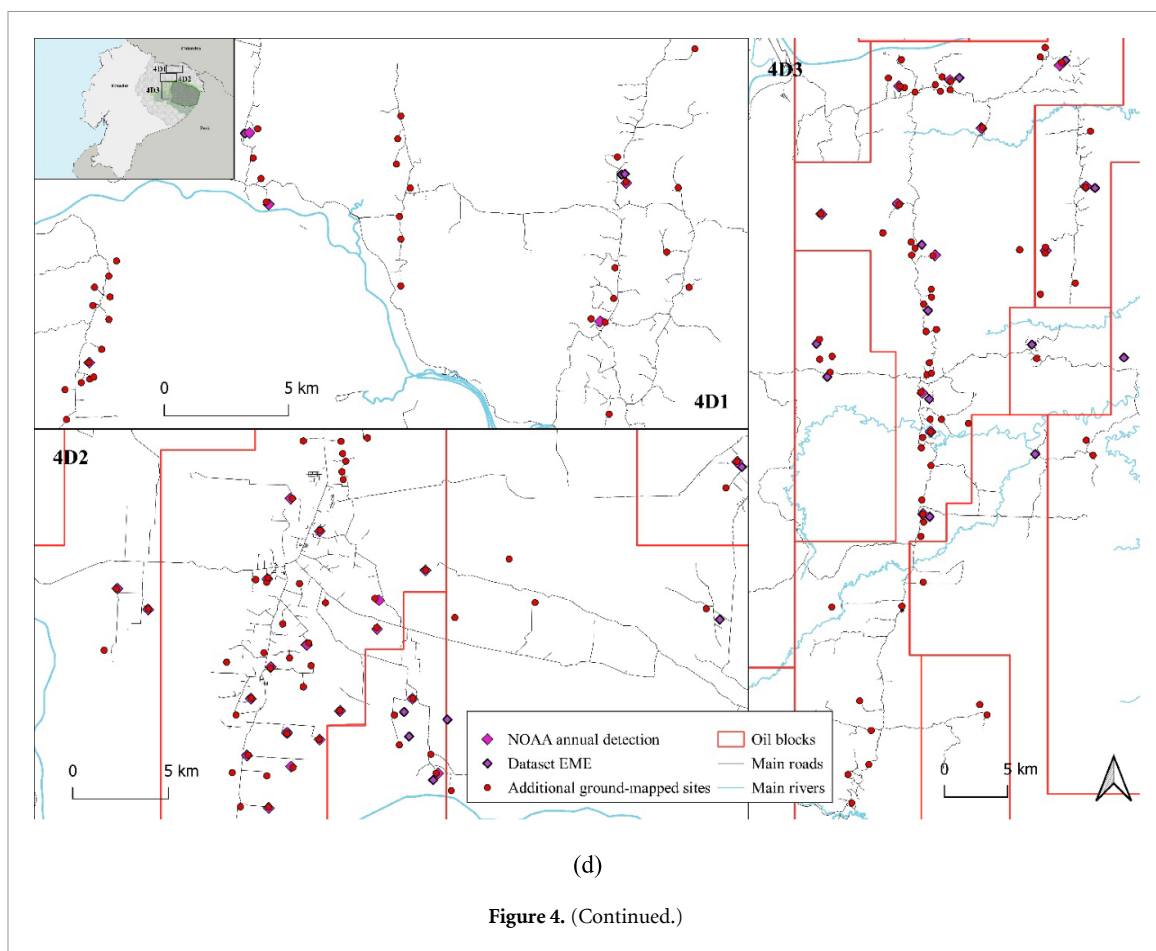
context, data collected on the ground can greatly support remote-sensing methods, providing a large-scale, ground validated dataset. The results of this study suggest that most current satellite-based studies assessing gas flaring may underestimate activity and, therefore, its impacts on the environment and local communities.

This study also confirms that CBPAR and PGIS processes can support the empowerment of local communities by systemizing and formalizing their knowledge into datasets, which otherwise may remain in anecdotal form, thus increasing its readability and recognition from other actors (Mena *et al* 2020).



Formalizing local knowledge through citizen science approaches in fossil fuel extraction areas can also prompt policy changes toward a more climate just world.

Additionally, this study confirms another central concept of PGIS and CBPAR: local communities are the experts of their territory; their participation greatly enhanced both the amount of data collected,



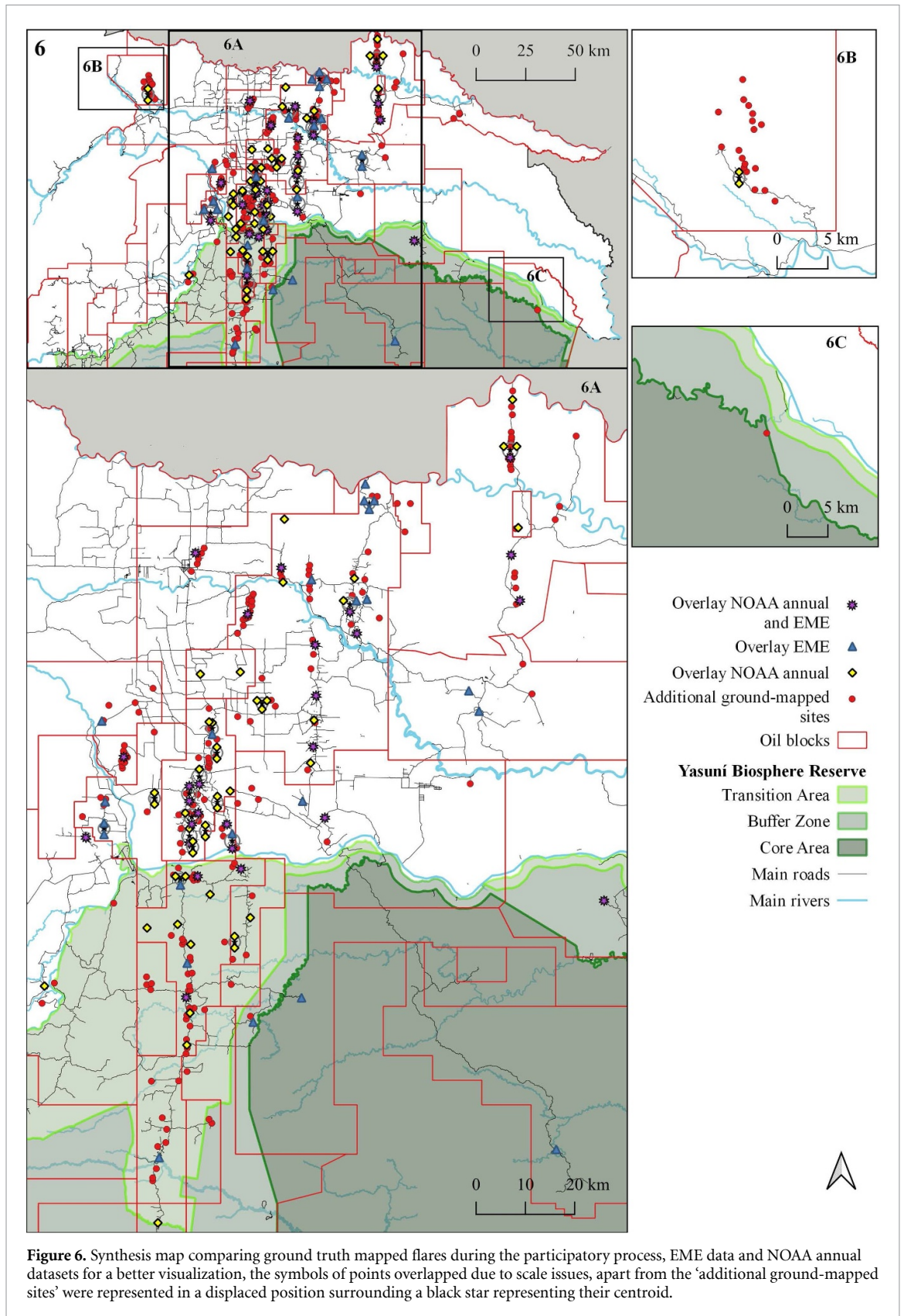


Figure 6. Synthesis map comparing ground truth mapped flares during the participatory process, EME data and NOAA annual datasets for a better visualization, the symbols of points overlapped due to scale issues, apart from the 'additional ground-mapped sites' were represented in a displaced position surrounding a black star representing their centroid.

as well as its quality (Williams and Dunn 2003, Balazs and Morello-Frosch 2013, Mena *et al* 2020).

For example, communities were able to identify sites with gas venting activities, a phenomenon completely unreported in existing datasets, as well as in previous literature on oil activities in the EAR, despite

venting activities having more significant environmental, social, and health impacts than gas flaring, (Ismail and Umukoro 2012, Durango-Cordero *et al* 2019, Velázquez-Gómez and Lacorte 2020).

Finally, it is worth noting that around flare stacks, particularly the largest ones, a significant number

of dead insects were detected. This causes particular concern, given that the region is a global diversity hot-spot for insects (Bass *et al* 2010). Because this particular impact has never been reported nor estimated in the literature, it is an important area for further research (Ologunorisa 2001, Solov'yanov 2011, Ismail and Umukoro 2012). Moreover, it highlights the importance of studying all impacts of oil activities and how this may create chains of additional, unexpected impacts (Orta-Martínez *et al* 2018).

5. Conclusions

This work represents the first attempt to monitor gas flaring activities by combining remote sensing-based methods with a participatory, citizen science approach to develop a ground validated dataset at the regional scale. Moreover, it empowered local communities through the creation of data to support a lawsuit demanding a ban of gas flaring activities in the EAR.

Thus, it shows how citizen science processes can, by supporting local communities in areas of fossil fuel extraction in the formalization of their knowledge, stimulate the implementation of climate justice policies.

Through mapping 295 gas flaring sites on the ground, this study highlights that the extent of gas flaring activities in the EAR exceeds what is reported in official data from EME and NOAA (figure 6).

The data validation process confirmed high reliability of the NOAA Nightfire annual datasets (100%). However, the high number of missing flare sites in both satellite-derived datasets (223 and 179 sites not detected for the annual dataset and daily detections, respectively) highlights an important area in need of improvement in satellite monitoring.

This study highlights the great potential of PGIS and CBPAR approaches to enhance the quality of data in environmental monitoring. By showing additional sources of impacts (e.g. 39 gas venting sites), it confirmed that local communities are often the most reliable source of knowledge about the territory in comparison to official knowledge or external observers (Williams and Dunn 2003, Balazs and Morello-Frosch 2013, Mena *et al* 2020).

Furthermore, this study describes a PGIS process based entirely on open-source GIS technologies for the implementation of low-cost environmental monitoring that is economically sustainable for non-governmental organizations and researchers.

Finally, further research is needed to identify and quantify the impacts of gas flaring in the Ecuadorian Amazon, and in other Amazonian sectors. Future research should focus on the development of a continuous monitoring system and field studies to measure chemical emissions, and to identify place-specific impacts that account for local, social, and environmental conditions.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: <https://climate-justice.earth/gas-flaring-sites-in-the-ecuadorian-amazon-region/>.

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