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Abstract

Tropical deforestation is mainly driven by agricultural expansion, land grabbing, illegal logging, urbanization, cattle ranching as well as mining. However, extraction of minerals and its impacts in high biodiversity regions are still poorly known, particularly in Colombia, a tropical megadiverse hotspot. Here, using high-resolution datasets of forest cover changes and detailed geospatial mining data for Colombia, we show a growing contribution of legal mining to national deforestation: 3.4% over the 2001–2018 period, with a peak at 5.6% in 2017. During this period, around 121 819 ha have been deforested inside legal mining concessions, and an estimation of over 400 000 ha deforested by both legal and illegal. Gold and coal are the most important legally-mined materials in Colombia associated to deforestation, particularly in the recent years with 511% and 257% tree cover loss increases respectively (average over 2016–2018 compared to 2001–2015 average of mined material deforestation average). Three Colombian departments summed out ∼70% of the national deforestation occurring in legal concessions: in 2018, up to 23% of deforestation in Antioquia was taking place in legal mines (gold producer). Finally, we found that only 1% (respectively, 3%) of the concessions contribute to 60% (>90%) of the legal mining-related deforestation, mainly driven by large clearings to agriculture. Environmental law enforcement, monitoring activities and engaging the mining industry in effective forest conservation and landscape restoration strategies are urgently needed in Colombia for preserving biodiversity and ecosystem services.

1. Introduction

Deforestation in the tropics is a key threat to biodiversity conservation, climate, and people well-being (Malhi *et al* 2008, Lawrence and Vandecar 2015, Giam 2017). Loss and degradation of forest has a detrimental effect on a wide array of ecosystem services, such as water provision, climate regulation, and soil formation, which in turn undermines the sustainable provision of goods and services that nature provides to mankind (MEA 2005, Foley *et al* 2007). Despite this, deforestation in the tropics is widespread; recent numbers reports about 12 million ha of tree loss in 2018 (Global Forest Watch 2019). Conversion of forested ecosystems in tropical regions has been mainly discussed in relation to extensive livestock activities, agricultural expansion, and illegal logging (Geist and Lambin 2001, Gibbs *et al* 2010, Hosonuma *et al* 2012, Curtis *et al* 2018). These drivers of change are also dominant in Colombia, a megadiversity hotspot, where forest loss and degradation are mainly associated to informal agricultural expansion, land grabbing, land speculation, and illicit cropping (Armenteras *et al* 2006, 2018, Etter *et al* 2006, Dávalos *et al* 2011).

Apart from important water use, chemical pollution of water and soils, health and human rights impacts (Rudas and Hawkins 2014, Betancur 2019, Comptroller General of Colombia 2013, Pérez-Escobar *et al* 2018), mining is also a relevant driver behind loss of tree cover in the tropics (Alvarez-Berríos and Aide 2015, Sonter *et al* 2017, Bebbington *et al* 2018). Nevertheless, comprehensive information on deforestation associated to both legal and illegal

mining is very little present in tropical regions. In Peru, an exception in this sense, several efforts have been produced to study illegal gold mining and loss of forest (Swenson *et al* 2011, Asner *et al* 2013, Asner and Tupayachi 2016, Weisse and Naughton-Treves 2016, Caballero Espejo *et al* 2018). Dezécache *et al* (2017) found a strong relationship between deforestation associated to gold mining and gold-prices in Guyana, Suriname, French Guiana and the Brazilian State of Amapá. Generally, studies focus on illegal mining activities, while few discuss the role of legal mining concessions in loss of forested ecosystems. However, Colombia is a large producer of mining materials: 1st coal and 5th gold producer in Latin America. In 2018, the mining sector represented 1.66% of the Colombian GDP where coal and metallic minerals represented 1.09% and 0.35%, respectively (Minenergia 2019).

Nowadays, no multiannual quantitative information has been provided about deforestation associated to legal mining for Colombia, although representing key information to understand the magnitude and impact that the extraction of mineral resources have on forested ecosystem in such a megadiverse country.

Therefore, the main objective of this work is to disentangle the role of legal mining towards deforestation using the Colombian case study. Specific objectives of this work are:

(a) Quantify the spatial and temporal dynamics of deforestation occurring in legal mining concessions in Colombia.
(b) Identify deforestation associated to specific concessions and mined materials.
(c) Discuss challenges and provide recommendations on mining-related policies to control deforestation.

2. Methods

2.1. Study area

Colombia is the 2nd most biodiverse country in the world, with recent estimates of 51 330 species on its territory (SIB 2019). The country hosts a large variety of ecosystems, the majority dominated by treed cover: in 2017 about the 52% of its terrestrial surface, corresponding to 593 113 km^2, was categorized as forest (IDEAM 2018). The large majority of this belongs to tropical moist broadleaf forests (Olson *et al* 2001), while dry broadleaf forests currently represent just 8% (7200 km^2) of their original coverage due to the intensive agricultural transformation that historically took place in Northern Colombia (González *et al* 2018).

In recent years Colombia has experienced extensive deforestation, with the highest number of 2199 km^2 deforested in 2017 as calculated by the Colombian Institute of Hydrology, Meteorology and Environmental Studies (IDEAM 2018), being the biogeographical Amazon the most affected region. In this work we analyzed the Colombian terrestrial area overlapping the legal mining concessions obtained from the Colombia's Mining Cadaster (figure 1), corresponding to about 3.2% of the Colombia continental area in 2018 i.e. a total of 36872.6 km^2 (supplementary figure S1 (available online at stacks.iop.org/ERL/16/064046/mmedia)).

2.2. Data

Localization and extent of legal mining concessions were obtained from the Colombia's Mining Cadaster, covering in this study the years 2001–2018. The dataset is also available from the global forest watch portal (http://data.globalforestwatch.org/datasets/colombia-mining-titles) and includes geographical information of the concession, dates of start and end of the concession lease, category of mineral(s) extracted, and other ancillary information. Forest data were obtained from the global forest change dataset v.1.6 (Hansen *et al* 2013), derived from multitemporal multispectral Landsat data at 30 × 30 m spatial resolution. The information layers used were related to: (a) forest loss, defined as a change from a forest to non-forest state (available from 2001 to 2018), and (b) accumulated forest gain, as the inverse transition of forest loss, over the period available in the dataset: 2000–2012. No year is associated to pixels in the forest gain layer. In this work, the tree canopy cover density information carried at the pixel level within the global forest change dataset, was used to filter pixels with a percentage of tree cover $\geqslant$60% to define the forest class, following similar criteria of e.g. Potapov *et al* (2012) and Hirota *et al* (2011). Additionally, we also considered the deforestation data from the Colombia's National Forest and Carbon Monitoring System—SMBYC (IDEAM 2018) to compare the estimates of forest loss inside mining concessions derived from the Hansen's *et al* (2013) dataset. The SMBYC data correspond to governmental reports of the estimation of the area and change of forest cover in Colombia for the following periods: 1990–2000, two 5 year periods (2000–2005, 2005–2010), one biannual (2010–2012) and annual statistics for years 2013–2018. To make an annual comparison between both dataset, we estimated annual deforestation as a simple average for the *n*-period of deforestation data covered by the SMBYC dataset (e.g. for a quinquennial statistics we divided by 5 years to get the annual deforestation estimate).

2.3. Statistics extraction

Using the $\geqslant$60% tree cover density threshold to define our class forest, we extracted the number of forest to non-forest events for each year inside each mining concessions from the forest loss layer of Hansen *et al* (2013) dataset. The extraction of statistics covered the period of time between the year of beginning and the year of end of the lease of each concession.

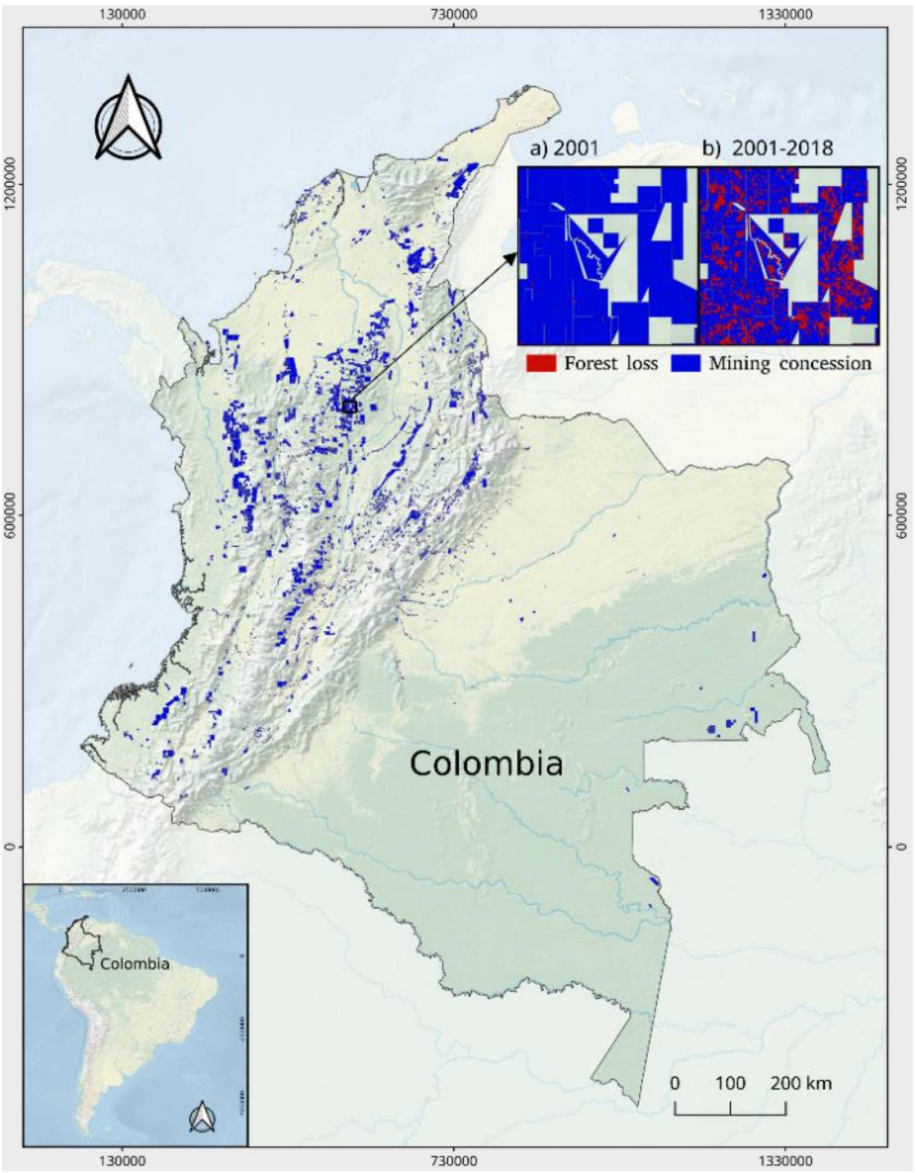

Figure 1. Map of Colombia and granted mining concessions (blue polygons). Panels in the top-right corner show an example of forest loss extension in 2001 (a), and from 2001 to 2018 (b), (red; according to Hansen *et al* 2013); municipalities of Remedios and Segovia, Antioquia Department.

Further, to identify whether the extent in mining-related deforestation is due to large-scale or small-scale deforestation (Austin *et al* 2017), we calculated yearly deforestation in mining concessions by grouping them in classes of small, medium, medium-to-large and large-scale deforestation (cut-offs at <1 ha, 1–10 ha, 10–100 ha and >100 ha, respectively).

To gain insights into: (a) if mines are preferably installed in forested areas or not, and (b) the influence of the tree cover density threshold selected, we derived for year 2018 the variation in forest extent and the 2001–2018 accumulated forest loss statistics in mining concessions using four additional tree canopy cover thresholds, i.e. >10%, >30%, >50% and >70% in the Hansen *et al* (2013) dataset.

Additionally, as deforestation events can be also represented by timber logging, we used the 2012 CORINE land use-land cover datasets (C-LULC) for Colombia (IDEAM 2020) to derive: (a) an indication of the proportion of forest to non-forest transitions involving industrial plantations inside concessions. Being the C-LULC processed using generalization and an 1 ha minimal mapping unit, we also calculated the proportion of forest cover in Hansen *et al* (2013) inside the timber plantation boundaries. And (b) we derived an estimation of the relative extent of natural forests, industrial plantations, built land and agricultural activities, to gain insights into the predominance of major land cover and land use taking place in the concessions.

In a further step, we calculated the forest loss extent associated to each material extracted for all concessions. We grouped all material information (>200 types of materials) into eight different categories: (a) gold, (b) platinum, (c) silver, (d) coal, (e) building materials, (f) emeralds and other

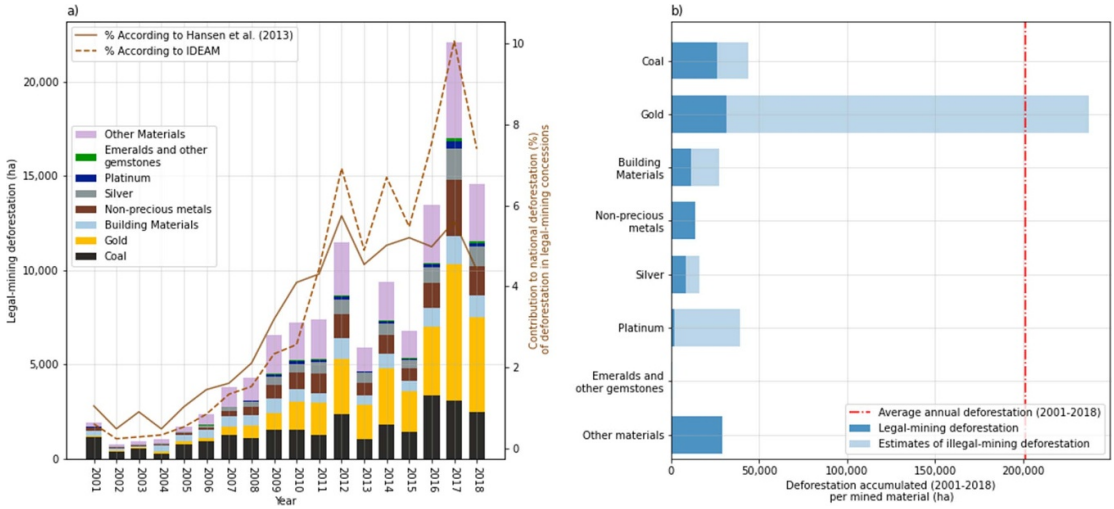

Figure 2. (a) Annual deforestation occurring in Colombian legal mining concessions from 2001 to 2018 (left *Y*-axis, units: ha) by type of mined material (color bars). Superimposed the contribution of annual deforestation to the Colombian national deforestation with respect to Hansen *et al* (2013) (filled brown line; right *Y*-axis, units: %) and interpolated IDEAM SMBYC data (dotted brown line, units: %). (b) Accumulated deforestation (2001–2018) in Colombia per mined material in legal concessions (dark blue) and the extrapolated estimates due to illegal mining (light blue). The red dotted line indicates the annual average Colombian national deforestation over the 2001–2018 period. See section 2 for a description of each mined material category.

precious stones, (g) non-precious metals and (h) other materials (see annex 1 in supplementary material). A single concession could contain exploitation permits for the extraction of more than one mineral/material; in this case, the amount of forest loss attributed to each mineral was divided by the number of mineral permits owned by the concession.

Additionally, for each of the 32 administrative departments of Colombia, we calculated the ratio between the extent of deforestation inside the total of the concessions belonging to the department over the overall deforestation in the department.

Afforestation and reforestation can be also present in the concessions. To provide a broad indication of the magnitude of forest loss versus forest gain, we calculated the total accumulated tree cover loss and total accumulated tree cover gain for the years for which this information is available in both datasets, i.e. for the time overlap between the forest loss and forest gain layers (2001–2012). To derive an estimate of the deforestation associated to illegal mining, we used Colombian Mining Census 2011 data (Minenergia 2012), calculating for each material category and at national level, the ratio between the number of illegal mining production units vs the number of legal mining production units, multiplying it by the well-constrained deforestation associated to legal mining.

3. Results

3.1. Deforestation in mining concessions

In the last two decades, mining leases in Colombia have been growing (1316 legal titles in 2001 and 6952 in 2018; 8590 in total across the 2001–2018 period), particularly in neighboring areas of the three Colombian Andean cordilleras (figure 1). Using a $\geqslant$60% tree cover density threshold, we estimated forest loss in Colombian legal mines reached overall 121 819 ha between 2001 and 2018, with a national accumulated deforestation estimated at 3 652 464 ha during the same period. Hence, deforestation inside legal mine concessions contributed to about 3.3% of the Colombian deforestation extent from 2001 to 2018. Temporally, a steep increase in deforestation associated to legal mines is observed: from less than 2400 ha annually before 2006 to more than 13 000 ha after 2015 (figure 2(a), left axis). This translates into a legal mining contribution growth to national deforestation from ~1% before 2006 to ~5%–6% after 2015 according to our consistent dataset (Hansen *et al* 2013) but ~7%–10% after 2015 according to SMBYC national deforestation estimates (IDEAM 2018). Year 2017 shows the highest extent of deforested land in legal concessions: about 22 000 ha, i.e. 5.6% or 10.1% of national deforestation using Hansen *et al* (2013) or SMBYC national deforestation estimates (IDEAM 2018), respectively (figure 2(a), right axis).

The choice of the canopy cover density to define the forest class have an influence on these numbers. First, for lower tree cover thresholds (from >10% to >30%), in 2018 the amount of forest extent in the concessions varies by 4%, while for higher tree cover thresholds (from >50% to >70%) of about 7% (table S1). Second, the accumulated tree loss (2001–2018) in mining concessions varies of +11.4% using >10% tree cover threshold, to a −3.3% (>70%), with respect to the >60% tree cover threshold adopted in this study. However, the contribution of mining to national deforestation

(2001–2018) varies to small extents as a function of the choice of tree cover threshold (see supplementary figure S2).

Inside active mining concessions, timber plantations increased from 2373 ha to 5225 ha in the period covered by the two C-LULC datasets used; as an example, 5225 ha corresponds to 0.15% of the extent of mining concessions in 2012. Interestingly, only 29 ha of timber plantations overlap with tree loss events in the same period (0.3% of accumulated deforestation in 2006–2012).

Moreover, more than half of the conversions in highly-deforested mines (>400 ha) are from forests towards agricultural areas and to a lesser extent towards secondary vegetation (supplementary figure S3). Moreover, more than 80% of the recent mining-related deforestation occurs in medium and large forest clearings (>10 ha each). Small and small-to-medium clearings have negligible effects on deforestation trends (pink and grey pink bars in supplementary figure S4). Steep increase in large clearings (from less than 1000 ha before 2016, to more than 3000 ha yr^{-1} after 2016) occurs after the peace agreement ratification with the FARC-EP in 2016.

Based on the 2011 Colombian mining census (Minenergia 2012) (see section 2), we estimated the deforestation due to illegal mining to be of ∼284 000 ha over the 2001–2018 period, i.e. a factor of 2.3 more than the deforestation associated to legal mining (figure 2(b)). Consequently, we estimated the overall mining contribution (legal and illegal) to deforestation in Colombia to be of ∼11% (2001–2018), according to our consistent dataset (Hansen *et al* 2013). Assuming this factor to be the same in the last years (2016–2018), ∼17% of the Colombian deforestation could be associated to mining activities in this recent period.

3.2. Mined materials associated to deforestation

Over the 2001–2018 period, coal (26 267 ha), gold (31 554 ha), and other materials (28 824 ha) in legal concessions have been associated with most forest clearing, i.e. 71% of the overall legal mining-related deforestation. During those years, substantial increase in deforestation extent related to gold, coal and other materials are observed: +511%, +257% and +320%, respectively (average over the years 2016–2018 compared to 2001–2015 average).

Before 2010, coal was the legal mined material with most deforestation associated (60% of legal-mining deforestation in 2001 to 21% in 2010), but since 2011, forest loss due to gold mining is predominating (23% of legal-mining deforestation in 2011 to 34% in 2018, supplementary figure S5).

According to (SIMCO 2020), 805.4 t of gold and 1209.3 Mt of coal were legally extracted in Colombia from 2001 to 2018. This means that each megaton of coal is associated with 21.7 ha of deforestation extent and each ton of gold with 39.2 ha. Assuming a rough estimate of 500 (300–700) trees per hectare (based on the number of stems per hectare in tropical dry and moist biomes of Crowther *et al* 2015), ∼11 (6–15) trees are cut for each kiloton of coal and ∼20 (11–27) trees are cut for each kilogram of gold in Colombia.

Finally, we can estimate the carbon emissions due to the legal-mining deforestation, using average carbon content per land cover in Colombia (Yepes *et al* 2011). Given the difference between average carbon content in Colombian forests (84.4 tC ha^{-1}, a conservative estimate compared to other worldwide studies, e.g. ∼122–141 tC ha^{-1}; (Saatchi *et al* 2011)) and, based on final land cover after deforestation given by data shown in supplementary figure S3 (∼85% heterogeneous agricultural areas −5.8 tC ha^{-1} and ∼15% secondary vegetation −19.6 tC ha^{-1}), we estimate the loss of carbon stored in forests cleared in Colombian legal mines to be 9.3 MtC over the 2001–2018 period, i.e. a +34.3 $MtCO_{2,eq}$ emissions release due to the cleared forests in the mining ceases.

3.3. Spatial variability linked to legal-mining deforestation

From 2001 to 2018, three departments in Colombia concentrated 70% of deforestation in legal-mining concessions: Antioquia (44%, ∼1/2 due to gold and ∼1/5 due to other materials), Bolivar (19%, ∼1/3 due to gold) and Norte de Santander (7%, >2/3 due to coal). Departmental annual statistics are reported in supplementary table S2.

About half of the legal mining leases deforest less than 1 ha and ∼29% do not show substantial deforestation (<0.09 ha, our minimal mapping unit; figure 3). However, half of all the legal mining leases deforest more than 1 ha with a large variability across concessions: for instance, in each of 99 concessions, more than 400 ha of forested land were cleared (figure 3), mostly concentrated in the north of the country (supplementary figure S6). Moreover, only 1% (respectively, 3%) of the concessions contribute to ∼60% (>90%) of the legal mining-related deforestation.

4. Discussion

4.1. Mining: a complex growing threat for forests?

We reveal here an understudied and underestimated driver of forest loss in Colombia, particularly in the last years. From 2001 to 2012, the number of mining concessions increased by a factor of 6 (supplementary figure S1), which caused an increasing pressure on forests without constraining changes in the legal framework to protect forests inside mines. In the last years (2016–2018), we clearly show a growing contribution of mining to deforestation that as far as we know has not been thoroughly discussed or reported in Colombia. During the latter period, 5%–6% of national deforestation occurred in mining leases, a number difficult to compare

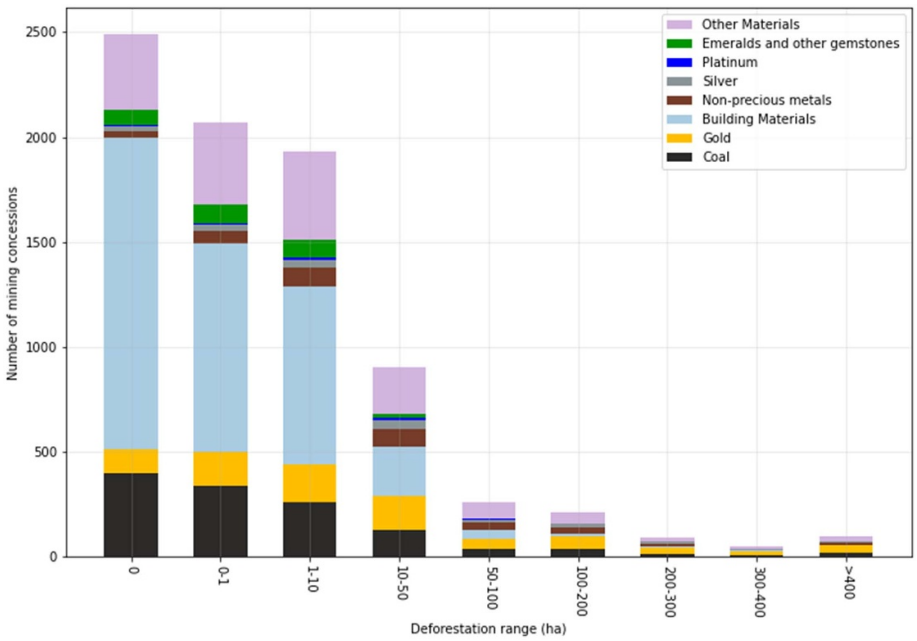

Figure 3. Histogram with the number of concessions where no deforestation was found (zero on the *X*-axis), along with those with deforestation extent ranging from 0–1, 1–10, 10–50, 50–100, 100–200, 200–300, 300–400, >400 ha. For each range, the proportion of deforestation for each mined material is reported (eight colors for each range).

to national estimates because the Colombian official institute in charge of monitoring deforestation (IDEAM-SMBYC) does not report information on legal mining-related deforestation.

Our best mining estimate contribution (legal + illegal) to national deforestation in the last years (∼17%) contrasts with smaller estimates previously put forward elsewhere: mining accounts for 7% of the deforestation across 100 developing countries from 2000 to 2010 (Hosonuma *et al* 2012) and no case studies report mining as a substantial 'driver of change associated with deforestation' in Colombia (Armenteras and Rodríguez Eraso 2014). Almost no exhaustive statistics of deforestation associated to national illegal mining (Cabrera *et al* 2019, Negret *et al* 2019) nor land use inside mining sites are currently provided. The sole estimate we found in Colombia (Ombudsman Office 2015) indicates: 'the integrated system for monitoring illicit crops, in the 2013–2014 observations, reported 16 701 ha deforested by illegal mining, i.e. this activity is responsible for 13.8% of the country's deforestation in that period' (highlighted and translated by the authors), is consistent with our estimates of illegal mining-related deforestation over the same period (11%, i.e. ∼19 000 ha due to illegal mining compared to the ∼170 000 ha for the national deforestation, according to figure 2(b) during this period. Note that the attribution of deforestation to the sole illegal mining is very difficult because of other superimposed land uses, particularly illicit crops (Office of the Comptroller General of Colombia 2013, Massé and Le Billon 2018). Moreover, in the last two decades, gold and coal were clearly identified as the minerals with most intensive exploration and exploitation (SIMCO 2020), which is consistent with the most important damages to forest cover (figure 2 and supplementary figure S5).

In the following paragraphs, we provide hypotheses about why mining operations in Colombia are generating more deforestation over time. The growing trend in legal mining-related deforestation from 2001 to 2012 (figure 2) can be explained by the growing trend in mining concessions' area granted (supplementary figure S1), which both showed an increase by a factor 6 throughout this specific period.

However, less clear are the reasons behind the deforestation increase in mining sites after 2013, when the number of existing mining leases stagnated between 2013 and 2018. After 2013, the increased deforestation in mining areas are driven by gold in two northern departments (yellow color in pie charts of Antioquia and Bolivar, see supplementary figure S7) and by coal in northeastern departments (black color in pie charts of Santanderes and Cesar).

Some hypotheses can be discussed. First, wood is commonly used to construct buildings for workers, mining tunnels, stabilize unpaved roads, and as a material to support several other operations. More sophisticated and extensive mining infrastructure (for mineral extraction, processing and transportation) within leases can be also put forward to explain higher legal-mining deforestation after 2013 (Alvarez-Berríos and Aide 2015, Sonter *et al* 2017, Bebbington *et al* 2018); although, gold and coal production since then show no or decreasing trend in

Colombia (SIMCO 2020), which tends to reduce the importance of this specific driver. Second, in several reported cases, local people in mining municipalities cut trees for timber extraction and their own use within mining concessions (Ombudsman Office 2015). Those aspects could have increased in the last years. Third, it is envisageable that after the peace-agreement signature between the Colombian State and FARC-EP guerilla (2016), vacui of territorial power were left, leading several groups (armed or not) to intervene in those old-conflictual zones, including some legal mining sites. Lack of law enforcement and protection could have led to an increase of forest loss inside mine concessions. As revealed by two recent studies in Colombia, this is typically the case after peace agreement, e.g. in protected areas (Clerici *et al* 2020) and in the Andes–Amazon transition belt (Murillo-Sandoval *et al* 2020). Fourth and importantly, in Colombia several illegal armed and non-armed groups, were and are still operating (Murillo-Sandoval *et al* 2020). It is not uncommon that informal agreements are made between these groups and the concessions' owners to let those groups perform mining activities (Massé and Camargo 2012, Massé and Le Billon 2018, Betancur 2019). Criminal dimensions in the mining sector have necessarily to be considered, as Massé and Le Billon (2018) summarize through the following Pax Mafiosa scheme: 'instead of directly extort mining companies through threats of violence, illegal groups have also arranged a qui pro quo whereby companies do not complain to the government about illegal mining taking place within or close to their concession in exchange for a relative peace'. Besides, although it is fewly reported, we cannot discount the possibilities for other increases in land-use in recent years (urbanization, infrastructures) within mining sites. In this respect, across the 99 concessions deforesting more than 400 ha, we found that for more than half of the deforested areas, the land is used for agricultural purposes (supplementary figure S3).

Thus, as suggested predominant driver for the Colombian legal mining-related deforestation, we suggest that illegal deforestation taking place within legal concessions boundaries might explain the growing deforestation in mining concessions after 2013. Despite of the crucial lack of local data, of systematic complaints or reports, this can be highlighted by information requested to Colombian authorities. Two rights of petition, with communication number 'ANLA 2019198213-2-000' and 'Minambiente 8201-2-126324' sent by us on 17 December 2019 and on 18 May 2020 to the National Authority for Environmental Licenses (ANLA in Spanish) and the Ministry of Environment respectively, report only 64 legal forest exploitation permits ('permiso de aprovechamiento forestal') in 35 Colombian mining concessions and only 22 legal removals of forest area in 22 Colombian mining concessions ('Sustracción de Áreas de Reserva Forestal') between 2001 and 2018. Comparing to the thousands of legal mines existing in Colombia during this period (supplementary figure S1), this tends to indicate that less than 2% of Colombian mining concessions request such permits to cut trees. Thus, illegal deforestation in the great majority of legal Colombian mines appears as one plausible hypothesis for legal mining-related deforestation.

Finally, accumulated reforestation/afforestation estimated inside the mining concessions (2001–2012) represents a 21% of the correspondent deforestation figure (not shown). These numbers witness the smaller presence of non forest-to-forest transitions inside the concessions, which are currently far to compensate the growing deforestation dynamics. These transitions are likely due to natural regrowth and less likely to restoration activities: at the national level some studies in fact observed in several Colombian regions forest recovery trends, especially in mountainous areas (Sánchez-Cuervo *et al* 2012, Rubiano *et al* 2017). In this sense, there is regional evidence that after closing mines, the common pattern is not to reforest in a substantial and resilient manner (Fierro 2012, Comptroller General of Colombia 2013, Mosquera *et al* 2019).

4.2. Moving forward

Several observations and recommendations can be drawn based on the results of our deforestation analysis for the Colombian mining concessions.

4.2.1. Law enforcement on mining sector environmental compliance

According to article 80 of the Political Constitution of the Republic of Colombia adopted in 1991: 'The State will plan the handling and use of natural resources in order to guarantee their sustainable development, conservation, restoration, or replacement. Additionally, it will have to caution and control the factors of environmental deterioration, impose legal sanctions, and demand the repair of any damage caused. (…)', but the legal framework to impose sanctions against massive tree loss is clearly not effective (Comptroller General of Colombia 2013, Rudas and Hawkins 2014, Alzate Gómez 2015). For instance, more than 90% of the mining leases did not request a forest exploitation permit, while our study clearly shows that in ∼80% of the Colombian mining leases deforestation occurred. This illustrates the large breach between the legal obligations and the reality of legal mining-related deforestation.

4.2.2. Monitoring forest protection compliance

The Colombian Institute of Hydrology, Meteorology and Environmental Studies (IDEAM), a governmental institution in charge of monitoring land cover change in Colombia, would benefit from a more systematic monitoring of forest loss occurring

in mining leases, which would help to achieve a better quantification of deforestation drivers, and make early alerts on strong deforestation trends inside mining boundaries. The report ordered by the Supreme Court to the Colombian State in 2016, and compiled by the Colombian Institute Alexander von Humboldt (Mosquera *et al* 2019), clearly states that 'very few cases of successful closing mines are found in the country', adding that: 'In short, measures are applied that are not sufficiently effective and sustainable for the problem being addressed, but that generate other environmental impacts and socio-natural risks'. This further highlights a clear lack of monitoring activities to verify mining compliance with environmental standards, particularly in the mine closing process.

4.2.3. Adopt best landscape planning practices in the mining sector

Without actions to counteract deforestation in mining leases, supposing that all newly requested mining titles would be granted (at February 2019, corresponding to 8.56% of the Colombian land territory, according to the National Mining Agency, 2019), they would add up approximately ∼400 000 ha of new legal mining zones over two decades, all other things equal. Furthermore, note that almost 30% of the legal mines do not cause substantial deforestation (see section 3.3), and any material category studied is concerned by both massive deforestation (figure 3, >400 ha deforested/mine; all colors—i.e. material categories—are present) or none (figure 3, 0 ha deforested/mine; ibid). This highlights the fact that any extraction of material in Colombia is concerned and has the potential to reduce its deforestation footprint. For instance, by generalizing practices of deforesting less than 1 ha for each mining lease (8590 in total) across a similar period (18 years), this would reduce the deforestation associated to legal mining by more than 113 000 ha, i.e. reducing by more than 93% the legal mining sector deforestation footprint. Moreover, reforestation should be systematic if deforestation cannot be avoided in agreements with national institutes and regional environmental institutions. Review mining fiscal treatment to evaluate whether environmental externalities are efficiently fought would reinforce the adoption of best practices.

4.2.4. Increase knowledge on structural socio-economic drivers of deforestation inside mining concessions

Deforestation in mining concessions has indeed multifactorial explanations: internal, i.e. due to mining industries decisions, and external, i.e. mining lease in conflict zones, with potential undesired entrance of illegal groups. A better knowledge of these mechanisms in such complex social-ecological systems would greatly benefit strategies to counteract forest clearance.

4.3. Limitations and perspectives

Our study does not take into account severe environmental impacts that mining could indirectly have on the forest health and its resilience, and thus on lagged forest loss: forest fragmentation, water acidification, slope instability, loss of species habitat and ecological connectivity, pollution of water and soils, sedimentation and effects on the dynamics of water bodies (Fierro 2012, Office of the Comptroller General of Colombia 2013).

Moreover, offsite impacts of mining industries are likely to be high (e.g. Sonter *et al* 2017): moving extracted minerals from mines to the exploitation centers requires building transportation infrastructure, i.e. rails, roads, and ports, which also incentivize new settlements along the way, as well as demand for firewood and croplands—all of which usually take place at the expense of forests. Thus, the methodological framework adopted in this study can in some case under/overestimate deforestation. For example, accounting also for off-site roads, rails and other infrastructure linked to legal mining activities would likely increase the overall deforestation associated to legal mining.

Besides, data available about illegal mining sites and their associated deforestation in Colombia are poor. Our illegal-mining related deforestation estimates are approximative because they are based on the number of illegal/legal mines ratio as measured by the mining census (Minenergia 2012). However, the Colombian mining census more probably did not witness all illegal mining sites that seek to be hidden or in insecure zones. Moreover, we did not implement such ratio for other materials and non-metallic categories where no or very few information was collected. This likely implies an underestimation of our illegal-mining related deforestation estimate. We thus acknowledge here that although legal mines has substantial environmental impact, illegal mining activities are considerable threats to environmental protection and social protection. A recent report of the Office of the Comptroller General of Colombia remarks that 'public institutionality (in extensive and long-term mining municipalities), as well as deforestation rates, are significantly worse than in municipalities with coca production', adding: 'It can be claimed, beyond any doubt, that the municipalities where mining exploitation is concentrated has an institutionality (i.e. game rules) much worse (…) than the one observed for one of the most harmful activities for the development: the illicit crops' (Office of the Comptroller General of Colombia 2013).

In other means, our estimates both for legal-mining related and illegal mining related deforestation are likely conservative.

5. Conclusion

For the first time, we provide estimates of spatio-temporal deforestation dynamics at high resolution inside legal mining concessions in Colombia in the last two decades, together with information on mined materials associated to such deforestation. Overall, legal mining is a substantial and growing but not predominant driver of deforestation in Colombia: only 3.3% of the total Colombian deforestation extent over the 2001–2018 period. However, in some departments such as Antioquia (gold producer) and La Guajira (coal), legal mining can account for up to about one fifth of the departmental deforestation in some years, which does represent a worrying fact from an ecological and ecosystem services perspective. Furthermore, in recent years we report a rapid growth of legal mining-related deforestation, mostly driven (>90%) by a few hundreds of the mining leases (3%, $n = 258$) and by gold and coal extraction.

Our study suggests many important environmental consequences, being deforestation an important proxy for loss of terrestrial biodiversity and ecosystem services, which has in turn potential negative impacts on socio-economic systems and human welfare (IPBES 2019). For instance, in Colombia, we estimate that accounting for carbon emissions due to deforestation in legal mines (see calculation in section 3.2) would add up ∼1/3 to the greenhouse gases emissions of the mining industry sector over the entire 2001–2018 period (IDEAM 2016), an important topic for climate change. Worse still, accounting for those carbon emissions in legal mines in year 2017, this would likely double the greenhouse gases emissions of the mining industry sector in 2017. To fight climate change efficiently, Colombia should crucially address this matter in the framework of its recently updated National Determined Contribution which aims for a 51% emissions reduction by 2030 (MinAmbiente 2020).

Finally, we stress that it is of paramount importance to systematically monitor and transparently report land cover change inside mining concessions, and that law enforcement agencies should take effective action when mining firms do not comply with normatives about forest management. Efficient law enforcement mechanisms to increase public institutionality and reduction of the illegal mining sector in mining municipalities are necessary and urgent.

Data availability statement

The data that support the findings of this study are available from the corresponding authors upon reasonable request.

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Conflict of interest

The authors declare no competing financial interests.

Graphic softwares

All analysis were performed using Python v.3.7.3 (Oliphant 2007) and the panda v.0.25.1) (McKinney 2010), geopandas v.0.5.1 (Jordhal 2014), numpy v.1.16 (Oliphant 2006; van der Walt *et al* 2011) and matplotlib v.3.1 (Hunter 2007) packages. Other minor analyses and cartographic outputs were carried out using QGIS v.3.6 (QGIS Development Team 2019).

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