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Forest greenhouse gas emissions estimates in major forest tenure instruments in the Philippines from 2001–2020

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ABSTRACT. Forest carbon loss from land use and land cover change is among the major greenhouse gas (GHG) emissions sources, second only to fossil fuel combustion. Determination of updated and spatially consistent forest GHG emissions is vital for countries like the Philippines participating in Reducing Emissions from Deforestation and Forest Degradation Plus (REDD+). This study aims to provide estimates and analyze the trends of forest GHG emissions in three major forest tenure instrument areas in the country, namely the Community Based Forest Management Agreement (CBFMA), Integrated Forest Management Agreement (IFMA), and Mineral Production Sharing Agreement (MPSA). Results showed that these tenure instruments' total forest GHG emissions had a significant and increasing linear trend on a national scale ($r_{ghg}e$ = 0.77, p-value< 0.05), amounting to 29.73 Mt of CO_2e from 2001 to 2020. CARAGA and Zamboanga region provinces exhibited significant forest GHG emissions owing to the vast extent of their concessions and probably forest loss and tree harvesting occurring in their tenure jurisdictions. Interestingly, nickel mining was the only mineral commodity with a linear and robust association with national forest GHG emissions ($r_{ghg}e$ = 0.74, p-value< 0.05). Nonetheless, remote sensing data quality and modeling limitations, overlapping tenure boundaries, inherent data flaws, and various starting and ending dates of tenure holders' activities should guide the users in interpreting our results. The implications of this study could serve as a basis for reviewing and re-evaluating the tenure instrument agreements and their contribution to forest conservation and climate change mitigation because some agreements are either expiring (*e.g.*, CBFMA) or are open for new tenure applications (*e.g.*, MPSA).

Keywords: carbon sequestration, climate change, deforestation, forest carbon, forest loss

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INTRODUCTION

The Philippines has undergone extensive deforestation and forest degradation towards other land uses from the latter half of the 20th century (Kummer, 1992; Vitug, 1993; ESSC, 1999) up to the recent years of the 21st century (Apan *et al*., 2017; Perez *et al*., 2020; Araza *et al*., 2021; Fallarcuna *et al*., 2021). These issues were later addressed via nationwide reforestation and forest rehabilitation programs often implemented in tenured forest lands or those having tenure instruments (Chokkalingam *et al*., 2006). These instruments are leases, permits, agreements, joint venture or production-sharing agreements, and licenses concerning developing, exploring, and utilizing the country's natural resources (DENR–AO, 2020). These tenure instruments, mainly situated in forestlands, brushlands, and untenured upland areas, have a 25-year agreement and are renewable for another 25 years. Tenure instruments, such as the CBFMA (EO 263, 1995), the Integrated Forest Management Agreement (IFMA) (DENR–AO, 1999), and the MPSA (RA 7942, 1995) are among the major tenure instruments located in the forested areas of the country (**Appendix Figure 1**). CBFMA caters to people's organizations, while IFMA is for corporate entities. Lastly, MPSA is a tenure instrument that enables mining companies to extract minerals from their concessions. IFMA replaced the Timber License Agreements (TLA), a tenure instrument used in the heyday of logging years during the dictatorship of former president Ferdinand E. Marcos, Sr.

Studies on Philippine forest GHG emissions and carbon stock assessments and sequestration rates showed that there is a huge potential source of carbon credits and financing through either the Clean Development Mechanism (CDM) or REDD+ (Lasco & Pulhin, 2003; Lasco *et al*., 2012) and found it to be a cost-effective alternative in reducing the country's emissions (Sheeran, 2006). There have been several studies on forest carbon stock, rates of sequestration, and emissions conducted at national (Lasco & Pulhin, 2000; Lasco & Pulhin, 2003; Lasco *et al*., 2009) and sub-national scales (Lasco *et al*., 2002; Camacho *et al*., 2009; Mukul *et al*., 2016; Veridiano *et al*., 2020). Other studies incorporate remote sensing and field data to estimate carbon stocks and sequestration on their sites (De Alban *et al*., 2015; Monzon *et al*., 2015; Veridiano *et al*., 2015; De Alban *et al*., 2021). However, no studies solely focused on tenure instruments at a national scale, thus possibly undermining the forestry, silvicultural, and extractive activities in these concessions that could contribute significantly to GHG emissions and sequestration. The main aim of this study is to provide estimates and analyze the trends of gross forest GHG emissions from three tenurial instruments on a national level, identify where those emissions occur, and possibly provide an interpretation of why those patterns are exhibited during the study period.

With the availability of global and satellite-derived forest GHG emissions (Harris *et al*., 2021), annual forest GHG emissions can be estimated on a national scale for the Philippines. Nevertheless, data misinterpretation is still possible, and making sense of it should be practiced with caution for the following reasons. Firstly, outputs from Harris *et al*. (2021) primarily depend on forest activity data from forest loss years (Hansen *et al*., 2013). Significant improvements are apparent in the 2011–2020 period compared to 2001–2010 due to improved data quality, increased data acquisition, and enhanced algorithm implementation (Weise & Potapov, 2021). This could result in increased forest GHG emissions detected from 2010 onward. Secondly, the study did not take into account the carbon removal (sequestration) to get the net forest carbon flux as data artifacts (defined as inherent data flaws and deviation caused by algorithm processing errors or conditions) were found during the initial data checking and visual inspection; thus, it was assumed that all forest emissions were equal to a full stand replacement disturbance, discounting the possibility of carbon being stored in harvested wood products and sequestered in forest growth. Thirdly, there were overlapping tenure boundaries used by the Forest Management Bureau (FMB) and Mines and Geosciences Bureau (MGB) in determining the exact municipality or group of municipalities covered by specific tenure polygon features. This is common in a country where various overlapping claims are seen on the map and on the ground. Fourthly, different starting years (approved) and ending years (expiry) could mean that any forest GHG emission detected beyond those years cannot be fully attributed to tenure holders' management operations alone. Lastly, this study's estimated forest GHG emissions are conservative as the forest definition is equal to or greater than half hectares, implying that emission values could be higher.

METHODOLOGY

The forest GHG emissions data used were primarily based on the study of Harris *et al*. (2021), with its outputs downloadable from the Global Forest Watch (2021) website. It developed a spatially explicit global system of estimating forest carbon fluxes using large-area vegetation models, national GHG inventories, and Earth observation data, which follows the Intergovernmental Panel on Climate Change's (IPCC's) guidelines on national GHG inventories (IPCC, 2019). It used the improved and updated Hansen *et al*. (2013) global forest change as its activity data similar to what was done in other studies (Zarin *et al*., 2016; Bebber & Butt, 2017) and co-located these with various carbon emission and removal factors developed from incorporating ground and earth observation monitoring data about land use and management type, forest type, forest age class, fire history and biomass, and soil carbon stocks (Harris *et al*., 2021). However, the Harris *et al*. (2021) forest GHG emission data is not validated in the Philippines, thus making it the study's main limitation. The forests tenure instrument vector files (shapefiles) of CBFMA and IFMA (DENR–FMB, 2014) were used, while MPSA vector polygons were digitized and georeferenced from MGB mining tenement maps per region (DENR–MGB, 2021). The vector file attribute tables contain pertinent information such as tenure holder names, approval and expiry dates, municipalities, and provinces covered by those tenure polygons. The 2002 forest cover data of ESSC (2010) was used to delineate the forest cover baseline for 2000 (**Appendix Table 1**).

The ESSC forest as 2000 baseline forest (ESSC, 2010) to clip Hansen *et al*. (2013) 2000 tree canopy cover data were used. This forest cover baseline addresses the forest definition issues encountered compared to official government forest cover statistics, including plantations and non-forest vegetation (ESSC, 2010). Then, 80–100% tree canopy cover pixel values were extracted to ensure that only dense forest trees were included. This range represents more than 90% of ESSC forest coverage and is in line with other findings that this threshold covers most of the broadleaf evergreen forests (Tang *et al*., 2019; Fallarcuna *et al*., 2021) and excludes young regenerating trees that can be classified as shrubs and saplings. Annual forest gross GHG emissions were then computed per tenure instrument type (CBFMA, IFMA, and MPSA) by overlaying with the modified ESSC 2000 forest cover and clipping with tenure polygon features per individual municipality or groups of municipalities and presenting through a graph (**Appendix Figure 2**). This study did not incorporate the forest carbon removal/sequestration data because it contained data artifacts upon quick visual inspection; thus, net forest GHG flux computations were excluded. Also, contiguous forest GHG emission pixels ≤ 0.5 ha were the only ones used in the processing, as the pixels below this threshold could be modeling artifacts. This aligns with the internationally accepted 0.5 ha minimum forest area definition (UN–FAO, 2000). National and the top five groups of municipalities were ranked based on total forest GHG emissions. Instead of using the tenure holder's name, the study adopted the municipality names from the 'MUNICIPAL' attribute column of polygon features to anonymize identity. If several tenure polygons are single-part features, they are dissolved or grouped to avoid double counting. Trend analyses were then carried out to determine whether there are significantly increasing and decreasing patterns of GHG emissions against the study period (2001–2020) using the Pearson correlation coefficient (r) (Hansen *et al*., 2013; Zarin *et al*., 2016). Finally, the annual emissions derived from this step were correlated with relevant forestry and mineral statistics available annually from 2001–2020. Google Earth Engine was used for all the data processing, except for trend analyses where R statistical programming was used.

RESULTS AND DISCUSSION

National forest GHG emissions of tenure instruments

CBFMA and IFMA had almost the same values for total forest GHG emissions, amounting to 12.96 Mt of CO_2e and 12.81 Mt of CO_2e, respectively. These result in almost similar annual mean forest GHG emissions for the tenure types (CBFMA: 0.65 Mt of CO_2e; IFMA: 0.65 Mt of CO_2e). MPSA had a total forest GHG emission of 3.89 Mt of CO_2e and an annual mean forest GHG emission of 0.19 Mt of CO_2e. Regarding their contribution to national forest GHG emissions, CBFMA, IFMA, and MPSA had 9.15%, 9.10%, and 2.75%, respectively. These percentages represent 21.01% of national forest GHG emissions. The national forest GHG emissions amounted to about 141.51 Mt of CO_2e from 2001–2020.

In **Table 1**, various parameters per tenure parcel are shown. A parcel refers to distinct individuals or groups of polygons that cover a single or several municipalities. CBFMA had the greatest number of parcels (594), followed by MPSA (86) and IFMA (83). The percentage of parcels with detected forest GHG emissions is 80% for MPSA, 72% for IFMA, and 38% for CBFMA. The mean area of parcels is highest for IFMA (9,443.4 ha), followed by MPSA (3,487.5 ha) and CBFMA (2,639.2 ha). In this case, directly attributing the forest emissions to a specific deforestation or

Table 1. Various parcel and forest statistics per tenure type.

Tenure	Total distinct parcels	Total parcels with detected emissions	Parcels with detected emissions (%)	Mean area of parcels	Area with forest (ha)	Total parcel area (ha)	Area with forest (%)
CBFMA	594	226	38	2,639.2	573,533.5	1,567,726.0	36.52
IFMA	83	60	72	9,443.7	514,430.6	783,834.5	65.63
MPSA	86	69	80	3,487.5	60,893.8	299,929.8	22.97

forest degradation driver like logging, slash-and-burn farming, landslides, and fires per parcel is impossible. However, by analyzing the purpose and nature of the said tenure types, it can be generally infered that forest GHG emissions in CBFMA are perhaps caused by small-scale tree plantation harvesting, illegal logging, and/or uncontrolled burning (Gauld, 2000; Suh, 2012); industrial tree plantation or secondary forest timber harvesting in IFMA (Makinano *et al*., 2010; Salvador & Ibanez, 2006), and also logging in MPSA (mining operations requires timber harvesting to extract belowground ore deposits) (Mag-usara & Japitana, 2015).

Figure 1a illustrates the yearly forest GHG emissions of each forest tenure instrument. 2016 and 2017 were the peak periods of forest GHG emissions, with values of 2.72 and 2.90 Mt of CO_2e, respectively, while the lowest forest GHG emissions were recorded in 2001 (0.34 Mt of CO_2e). Regarding relative contribution (**Figure 1b**), CBFMA and IFMA contributed 43% on average and did not exceed 55%. Meanwhile, MPSA had the smallest percentage contribution, ranging from 5% (2008) to almost 22% (2011). CBFMA and IFMA had a strong and increasing linear trend of forest GHG emissions, with correlation coefficients of $r_{ghg}e$ = 0.75 and $r_{ghg}e$ = 0.75, respectively, at $p < 0.05$, while MPSA had a moderately increasing linear trend ($r_{ghg}e$ = 0.51, $p < 0.05$). The total forest GHG emissions of all tenure types had an r-value of 0.77, at p-value < 0.05, denoting a strong and positive linear trend from 2001–2020.

Municipal-level forest GHG emissions ranking

Figure 2 shows the top five municipality groups by total forest GHG emissions per tenure type. It is important to note that a particular tenure parcel might have a vast area, often covering several municipalities simultaneously. For example, tenure parcels that were in the top spot for both CBFMA (Lianga, San Agustin, San Miguel, Tago, and Marihatag in Surigao del Sur (SdS)) and IFMA (Carmen, Lanuza, San Miguel, Cortes, and Tandag, SdS) cover five municipalities (**Figure 3b**). MPSA's tenure parcel with the most forest GHG emissions covers only a single municipality (Carrascal, SdS). In CBFMA, SdS municipalities (Lianga, San Agustin, San Miguel, Tago, and Marihatag) had the highest forest GHG emission total (1.04 Mt of CO_2e) which is almost twice of Esperanza, Agusan del Sur (AdS) (0.59 Mt of CO_2e) and Aborlan, Palawan (0.52 Mt of CO_2e) tenure parcels, which placed second and third, respectively. IFMA's contiguous tenure parcels in Carmen, Lanuza, San Miguel, Cortes, and Tandag in SdS had the highest forest GHG emissions (1.99 Mt of CO_2e). This was followed by Sirawai, Siocon, and Sibuco of Zamboanga del Norte (ZdN) (1.81 Mt of CO_2e) and Talacogon and San Luis of AdS (0.86 Mt of CO_2e). For MPSA, Carrascal, SdS had the most forest GHG emissions, totaling (0.58 Mt of CO_2e), followed by Diplahan and Bayog in Zamboanga del Sur (ZdS) (0.46 Mt of CO_2e), and Lianga, Barobo, and San Francisco in AdS (0.34 Mt of CO_2e).

Figure 4 shows the percentage contribution of the top five municipality groups by tenure instrument type from 2001–2020. This helps determine the relative contribution of the top five municipality groups in GHG forest emissions compared to other municipal tenure parcels excluded from the top five.

In CBFMA (**Figure 4a**), SdS municipalities (Lianga, San Agustin, San Miguel, Tago, and Marihatag) had a mean percentage contribution of 8.33%, followed by Esperanza, AdS with 4.74%, and La Paz and Loreto, AdS with 4.20% for the whole study period. Other CBFMA tenure parcels not in the top five list had an annual mean percentage contribution of 75.86%. IFMA and MPSA's top five municipalities had a much higher mean percentage contribution pattern than CBFMA. In IFMA (**Figure 4b**), the top municipalities of

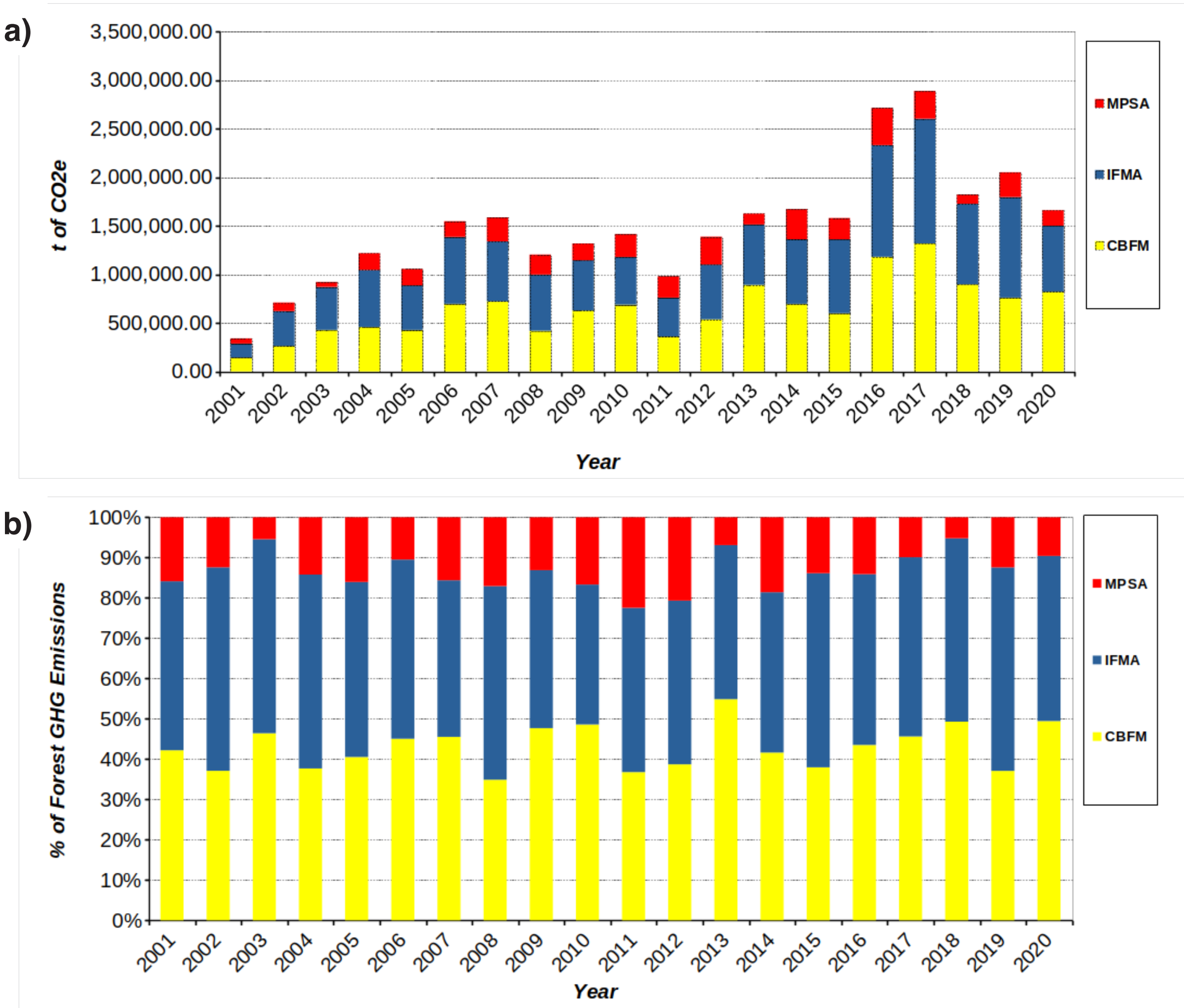

Figure 1. Yearly forest (a) GHG emissions and (b) relative contribution of MPSA, IFMA, and CBFMA.

SdS (Carmen, Lanuza, San Miguel, Cortes, and Tandag) contributed about 15.49% of total mean forest GHG emissions of the study period (almost twice of CBFMA's top one SdS municipalities). Next are the Sirawai, Siocon, and Sibuco municipalities in ZdN and San Luis and La Paz in AdS, with 14.05% and 6.88%, respectively.

Relative contribution of top five municipalities to total GHG emissions

The remaining tenure parcels of IFMA contributed 51.05%. Five municipalities in Surigao del Sur (Carmen, Lanuza, San Miguel, Cortes, and Tandag, SDS) and two municipalities in Zamboanga del Norte (Sirawai, Siocon, and Sibuco in ZdN) dominated the annual forest GHG emission contribution with 15.49% and 15.05%, respectively. For MPSA (**Figure 4c**), Carrascal, SdS had a total percentage contribution of 14.85%, followed by Bayog and Diplahan ZdS with 11.93%, and Lianga, Barobo, and San Francisco in AdS with 8.82%. The overall contribution of other municipalities outside these top municipalities is 55.03%. Municipalities of ZdS (Diplahan and Bayog) had the highest emission proportion from 2001 to 2007 and were eventually replaced by Carrascal, SdS for most of the succeeding years. Annual forest GHG emissions in MPSA were also grouped per mineral to determine which commodity had the most emissions during the study period (**Figure 5**).

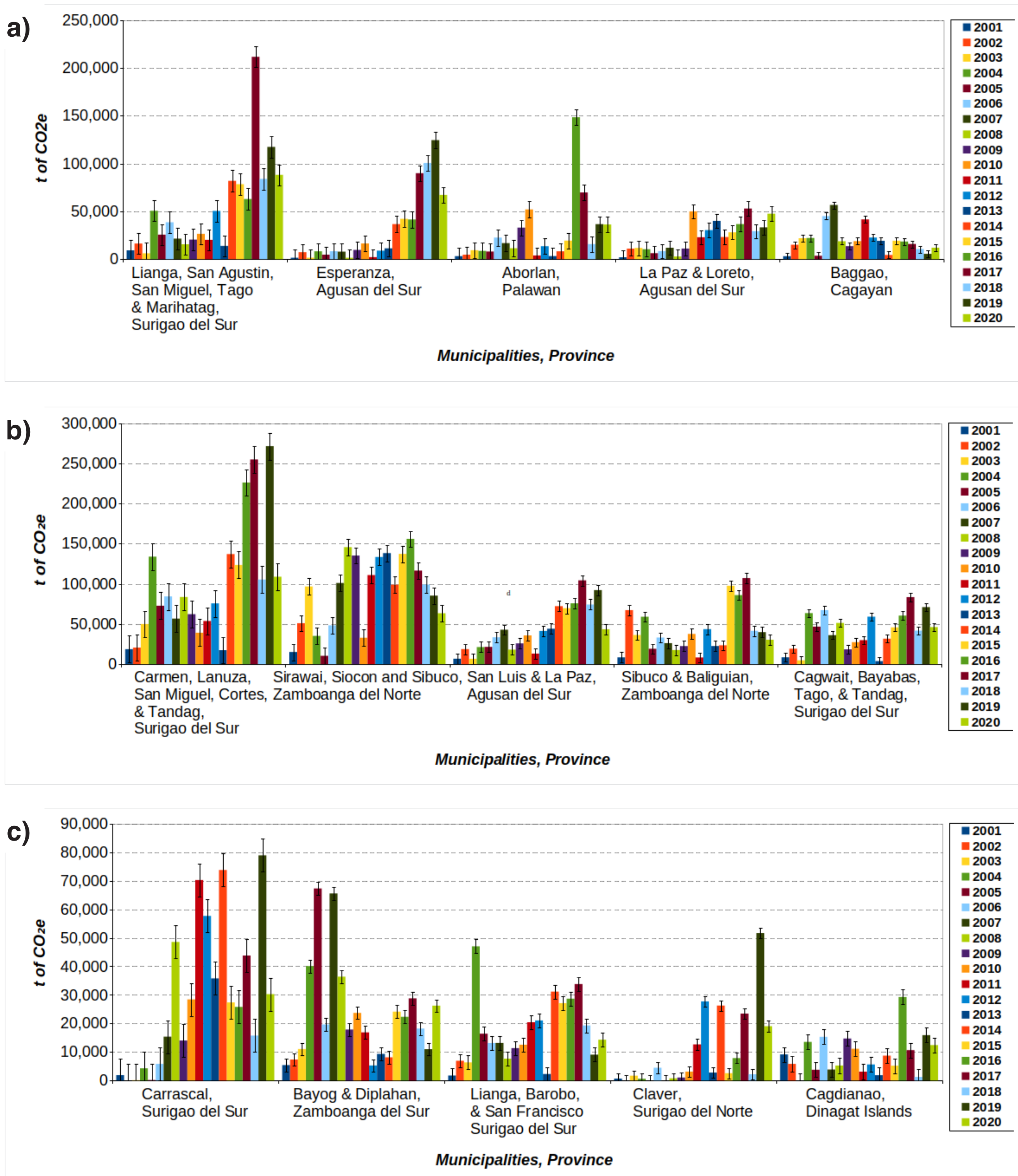

Figure 2. Yearly forest GHG emissions of the top five municipalities in (a) CBFMA, (b) IFMA, and (c) MPSA tenure instruments (Error bars represent standard error).

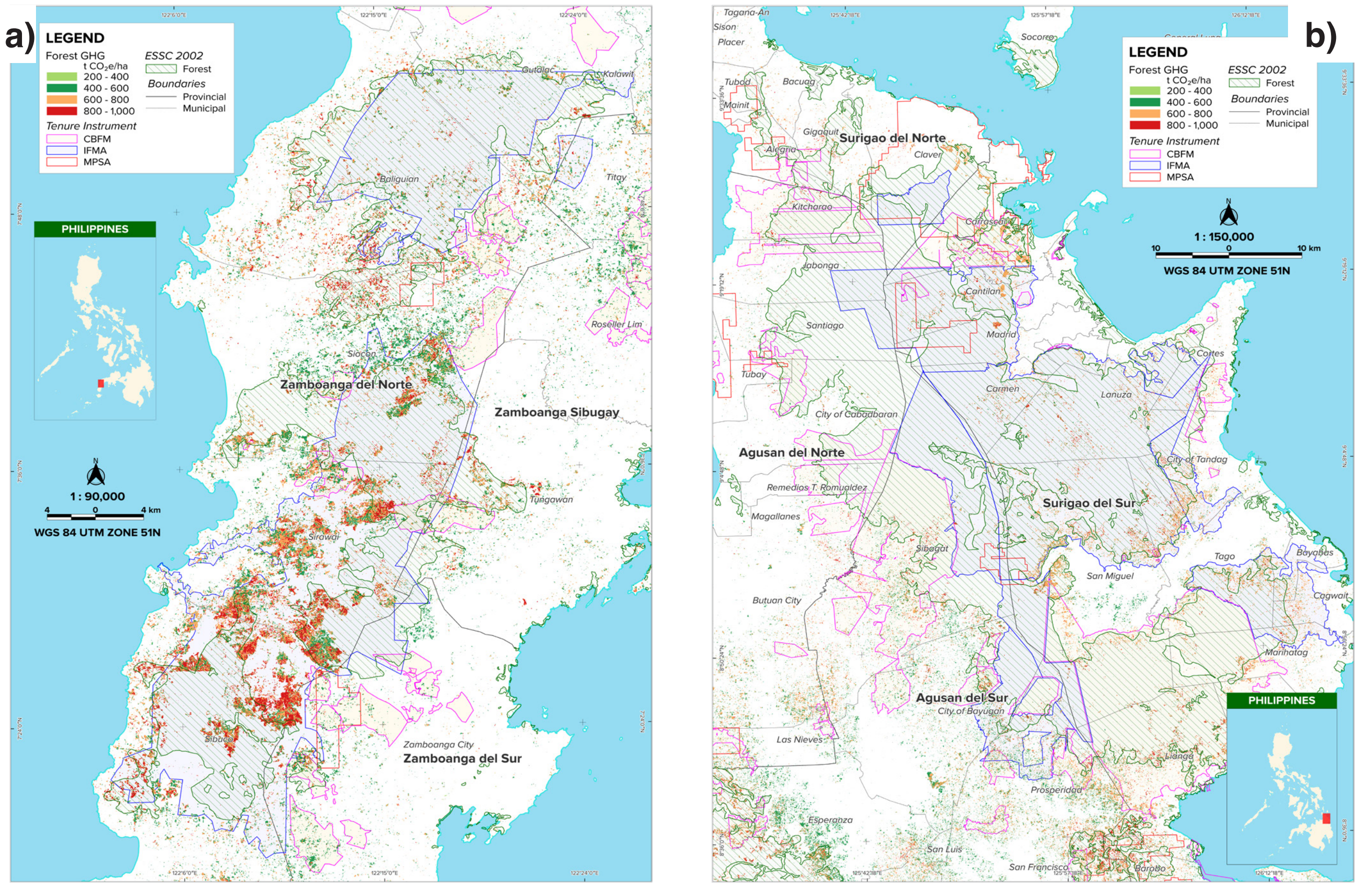

Figure 3. Forest GHG maps of selected tenure municipalities in a) Region 9 and b) Region 13.

The year 2016 had the highest estimate of forest GHG emission (0.38 Mt of CO_2e), while 2003 had the lowest (50,120.25 t of CO_2e). Nickel had the biggest total percent contribution (48.72%) compared to gold (19.98%), gold and copper (16.01%), chromite (4.16%), iron (3.7%), and others (7.42%).

Correlation results per municipality groups

In **Table 2**, significant trend values are presented per forest tenure type. Municipalities from CBFMA had r values ranging from 0.45 to 0.73, suggesting a moderate to a high degree of increasing linear trend of forest GHG emissions in the study period. This is also true for IFMA with r values of 0.60 to 0.79. In other words, the pattern of CBFMA's and IFMA's forest greenhouse emissions significantly rose from 2001 up to 2020. Meanwhile, MPSA had slightly lower r values than CBFMA and IFMA, ranging from 0.47 to 0.65.

Correlation to forestry and mineral statistics

CBFMA and IFMA forest GHG emissions were strongly and negatively associated with the number of tenure holders (r = 0.53, r = 0.71, significant at p-value < 0.05), respectively from 2001-2020. On the other hand, no significant relationship was found between the annual log and roundwood production compared to forest GHG emissions for both CBFMA and IFMA. In MPSA, the only mineral commodity that had a strong and positive association with mineral statistics, such as production volume (r_{vol} = 0.74, p-value< 0.05) and estimated value (r_{val} = 0.74, p-value< 0.05), was nickel.

Forest GHG emission patterns of tenure instruments

On the national scale, CBFMA and IFMA had almost the same statistics for forest GHG emissions. However, it is important to note that the percent of detected emissions in CBFMA was almost twice as low as IFMA and MPSA (**Table 1**).

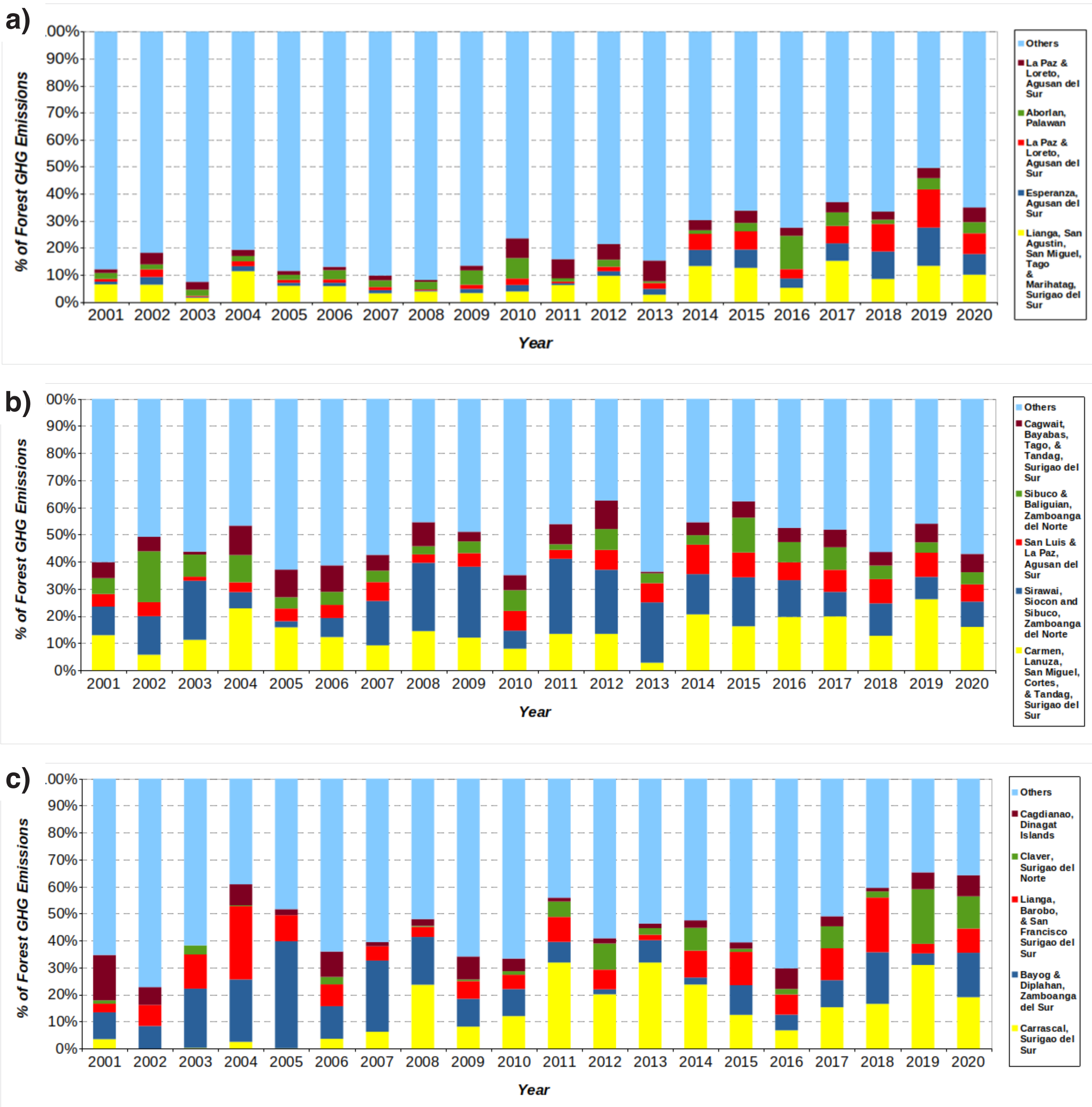

Figure 4. Percentage contribution of top five municipalities by forest GHG emissions in (a) CBFMA, (b) IFMA, and (c) MPSA.

This could mean that CBFMA's tenure parcels, which are smaller in area per polygon feature than the other two tenure instruments, had less extensive forestry activities, such as limited tree harvesting (smallholder forestry) (Herbohn, 2006; Lasco & Pulhin, 2006; Pulhin & Ramirez, 2016), and were more inclined to forest protection, conservation, and rehabilitation (Lasco & Pulhin, 2006). Since the country has a ratio of a single forest guard to 4,000–7,000 ha of forest patrolled (Domingo & Manejar, 2018), activities such as illegal forest clearing, and fires can be significant forest sources of GHG emissions from all tenure instruments. Also, it cannot be discounted that soil erosion and landslides could be detected as forest loss pixels, hence registering as forest GHG emissions (Araza *et al.*, 2021). Another observation illustrates that most larger tenure

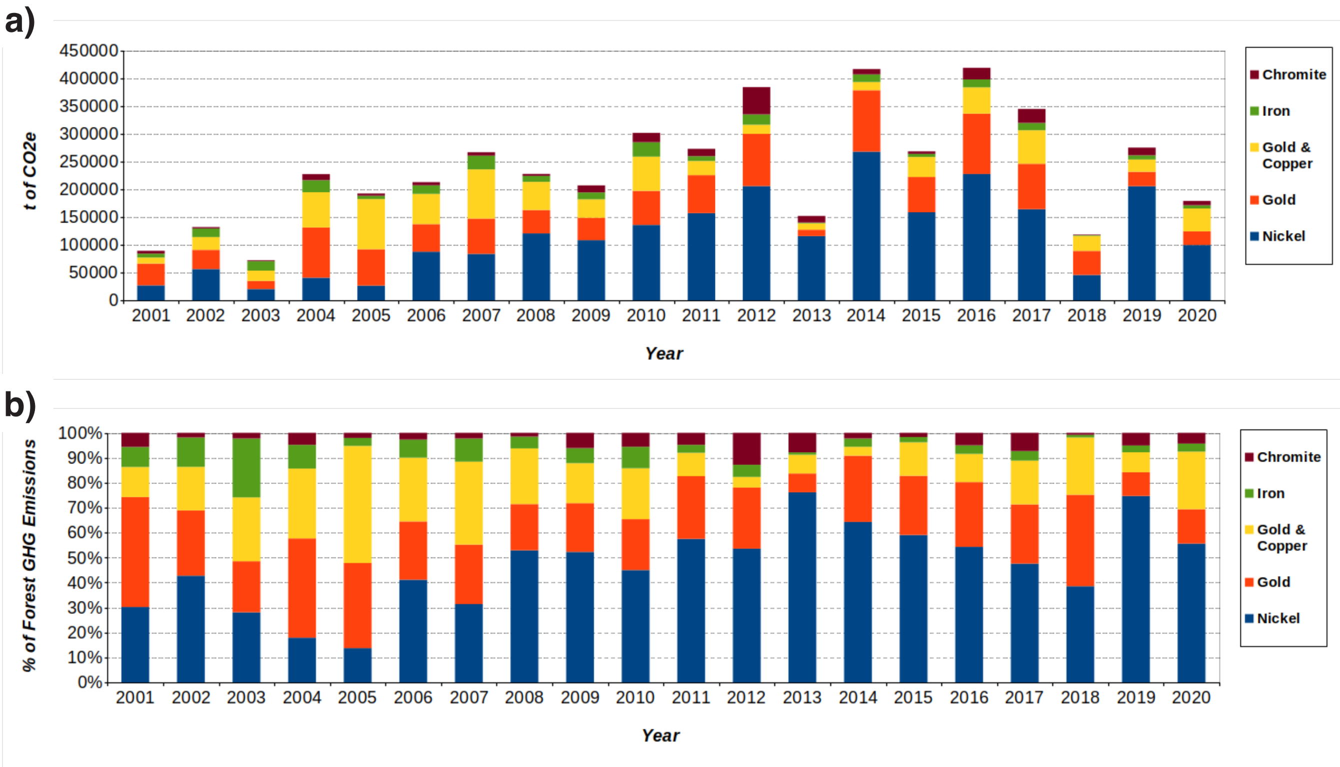

Figure 5. MPSA's (a) annual GHG forest emission and (b) percent contribution by mineral commodity.

Table 2. Municipality groups with increasingly linear trends of forest GHG emissions from 2001–2020 (all are significant at p-value < 0.05).

CBFMA		IFMA		MPSA	
Municipality, Province	($r_{ghg}e$)	Municipality, Province	($r_{ghg}e$)	Municipality, Province	($r_{ghg}e$)
La Paz & Loreto, AdS*	0.73	Talacogon & San Luis, AdS	0.79	Libjo, Dinagat Islands	0.65
Lianga, San Agustin, San Manuel, Tago & Marihatag SdS*	0.65	San Luis, AdS	0.76	Matuguinao, San Jorge, San Jose de Abuan, & Gandara, Samar	0.61
Sibagat, AdS	0.63	San Luis and La Paz, AdS*	0.74	Claver, Surigao del Norte	0.51
Esperanza, AdS*	0.62	Cantilan, Madrid, Lanuza & Carrascal, SdS	0.73	Narra & Quezon, Palawan	0.49
Aborlan, Palawan	0.48	Cateel, Davao Oriental	0.71	Brooke's Pt., Palawan	0.47
Carrascal, Cantilan, and Lanuza, SdS	0.47	Isulan, Sultan Kudarat	0.71		
Impasug-ong, Bukidnon	0.45	Sibagat & San Miguel, SdS	0.65		
		La Paz, AdS	0.64		
		Manay, Davao Oriental	0.60		
		Carmen, Lanuza, San Miguel, Cortes, & Tandang, SdS*	0.60		

Municipalities present in **Figures 3 and 4.*

parcels are in mainland Mindanao. This supports that Mindanao has many major extractive forest industries (Serrano, 2005) and contains over 50% of commercial forestlands (Mangahas, 2010). These might include logging in natural secondary forests or tree plantations.

The identified municipalities (Lianga, San Agustin, San Miguel, and Marihatag, Surigao del Sur of CBFM; Carmen, Lanuza, San Miguel, Cortes, and Tandag, Surigao del Sur for IFMA; and Carrascal, Surigao del Sur of MPSA) and their trends of forest GHG emissions (**Figure 2**) could give some overview of forest management implications for a particular forest tenure type at the local level. Looking at the top five municipality groups per percentage contribution (**Figure 2**) revealed that the biggest contributor of forest GHG emissions occurring in IFMA was geographically concentrated in a few municipalities with a total contribution of more than 50%, compared to CBFMA's 24%. This is supported by the fact that IFMA is geared towards timber production through industrial tree plantation establishment (DENR–AO, 1999–53, Makinano *et al*., 2010), while CBFMA emphasizes limited timber extraction with more focus on forest protection, conservation, and poverty alleviation (EO 263, 1995; Lasco & Pulhin, 2006; Suh, 2012). Likewise, MPSA had a total contribution of 55% from its top five municipality parcels. The fact that CBFMA had the lowest mean area per parcel suggests that this type of forest management was usually practiced by smaller and local groups such as people's organizations.

The cumulative forest GHG emissions from CBFMA's small parcels are tied with that of IFMA, as the former had the biggest total area and number of tenure holders. The top municipality groups for all tenure types are in Surigao del Sur. This corroborates that Surigao del Sur, belonging to CARAGA (Region 13), is where most forestry operations, such as tree harvesting, are found (CARAGA Watch, 2009; PSA 2018b; DENR–FMB, 2020). This was enabled by the policies declaring Region 13 as a "Timber Corridor" (PSA, 2018b) and the former undivided Surigao province as a mineral reservation (Proclamation No. 391 series of 1935). Furthermore, Surigao del Sur was dubbed the mining capital of the country (PSA, 2018a) as supported by findings for top forest GHG emissions in Carrascal, Surigao del Sur's MPSA. Zamboanga Peninsula (Region 9) had emissions that largely came from IFMA (**Figure 4b**), where a logging ban was imposed due to destructive floods and typhoons (Mendez, 2018). In addition, Zamboanga Peninsula's municipalities with IFMA and MPSA were identified as emerging forest loss hot spots, as evident in GFW's online interactive map (Harris *et al*., 2017). Some tenure instrument parcels are adjacent to each other, implying that there could be some leakage effects (Meyfroidt & Lambin, 2009; Ford *et al*., 2020). For example, municipalities adjacent to Surigao del Sur's big chunks of CBFMA, IFMA, and MPSA (**Figure 3a**) suggest probable deforestation leakage.

Results of correlated forestry statistics to emissions show a negative association between the number of tenure holders and forest GHG emissions for both CBFMA and IFMA. This trend illustrates that decreasing the number of tenure holders might contribute to the increase in forest GHG emissions. Since GHG emissions are related to deforestation, the said assumption is based on the research that regardless of tenure types, land tenure security is linked with less deforestation (Robinson *et al*., 2011; Robinson *et al*., 2014), though tenures that are mainly for production and extraction purposes are less effective in reducing deforestation than the ones which promote forest production and conservation (Pacheco & Meyer, 2022). However, this should be interpreted carefully because the tenure types had different starting dates, although most were within the study period. For the mineral statistics, we could ascertain that a sole mineral commodity, nickel, is responsible for the increasing trend of forest GHG emissions in MPSA, as supported by its production volume and estimated value. This is supported by the fact that the majority of MPSA holders that operated during the study period applied for nickel as their mineral commodity, allocating more forested lands for nickel open pit ore extraction (Camba, 2021; GlobalData, 2022), thus resulting in higher forest GHG emissions. In terms of nickel production, the Philippines is second to Indonesia (USGS, 2020), and by continuing to extract this mineral commodity, MPSA's economic gains might result in forest reduction as illustrated in Carrascal, SdS (Mag-usara & Japitana, 2015), canceling the growth from mineral exports. This growing contribution of mining to forest loss and eventual forest GHG emissions is also happening globally, as illustrated in South American countries (Csillik & Asner, 2020; González-González *et al*., 2021). This warrants a comprehensive review in line with the lifting of the ban on applying for new mining agreements in the country (Cabico, 2021; DENR AO, 2021) in light of the current administration's push for mine processing (Dumlao-Abadilla, 2023).

CONCLUSIONS

A globally and spatially consistent forest GHG product was used to map and find trends in three major forest tenure instruments in the Philippines. Results showed that CBFMA, IFMA, and MPSA had significant and increasing trends of gross forest GHG emissions from 2001–2020 at the national level. CBFM had near total and average forest GHG emission values to IFMA's due to their vast expanse and coverage. The relative forest GHG emissions contribution from the tenure instruments' top five municipality groups came from Mindanao, except for CBFMA. The computed GHG emissions per tenure type signify the possible intensive or extensive forestry practices that result in such emissions. The significant amounts and increasing trends of forest GHG emissions from this study imply a need to improve further or modify existing forest management and conservation strategies to effectively attain the envisioned goals of the said tenure instruments, like the promotion of community-led sustainable forest governance that is socially equitable (CBFM), ensuring mainly the continuous supply of sustainable wood products through industrial forest plantations without compromising future forest stocks (IFMA), utilization and conservation of mineral resources for national growth that safeguards the environment and respects community rights (MPSA). Remote sensing data and modeling limitations, overlapping tenure boundaries, data artifacts, and different starting and ending dates of tenure holders' activities should caution the users in interpreting our results. Validation could be made by collating and assessing further the various forestry and mineral statistics from specific municipalities and creating a probability-based sampling approach in conjunction with other reference data to verify the estimated forest GHG emissions. Finally, the data presented here may serve as a reference for evaluating forest tenure instruments since most are nearing their agreement expiry dates.

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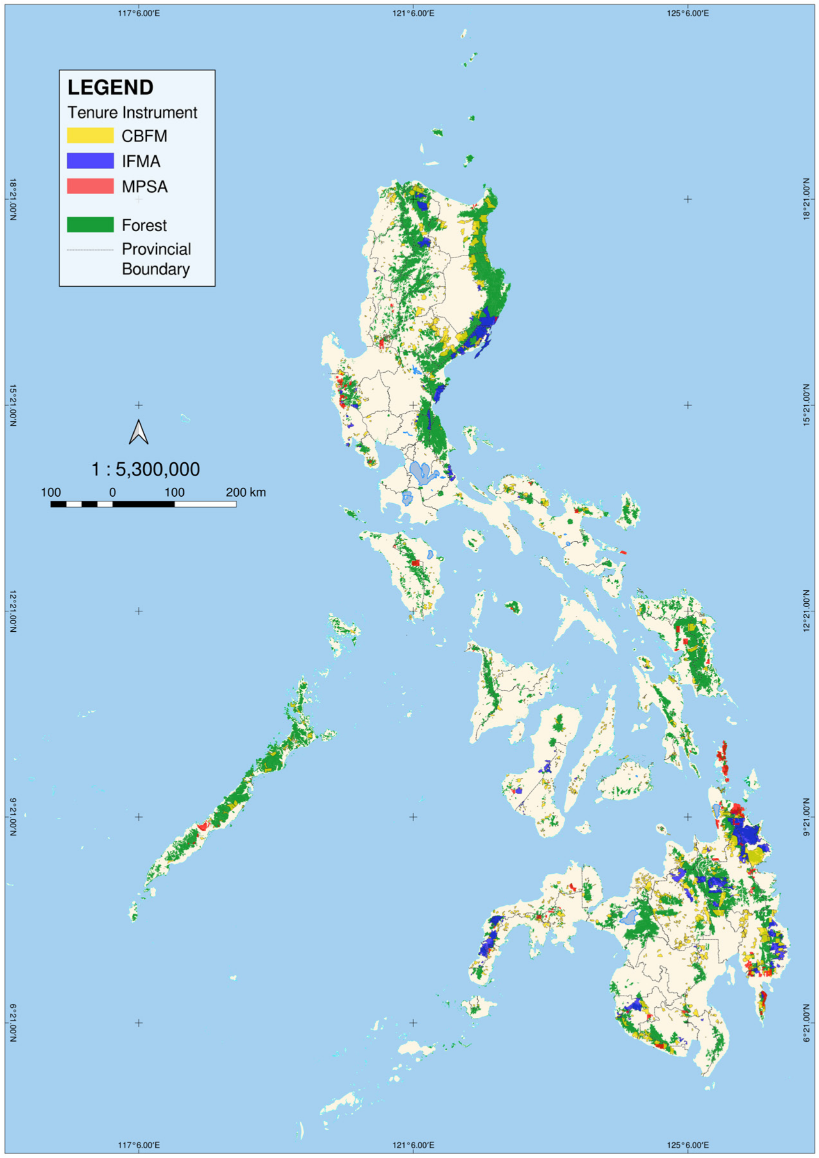
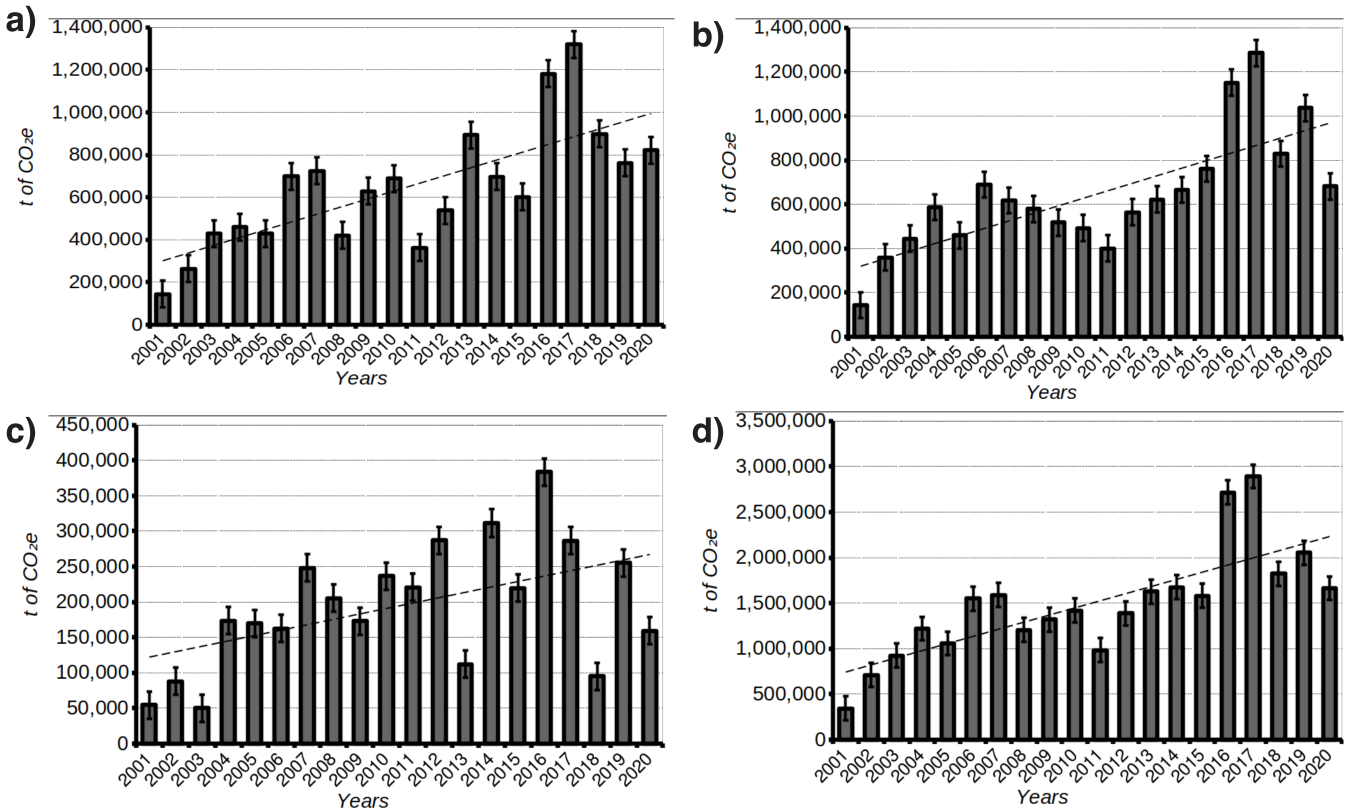


Appendix Figure 1. CBFM, IFMA, and MPSA geographic distribution overlaid with ESSC 2002 forest.

Appendix Table 1. Proportion (%) of forest types where GHG emissions occurred per tenure.

Tenure type	Open	Closed	Mangroves	Coniferous	Mossy
CBFM	80.83	16.38	0.22	0.08	2.50
IFMA	90.26	9.47	-	-	0.27
MPSA	62.12	37.07	-	0.46	0.36



Appendix Figure 2. Annual gross forest GHG emissions for (a) CBFM, r = 0.75; (b) IFMA, r = 0.75; (c) MPSA, 0.51; and (d) all tenure instruments combined, r = 0.77; all are significant at $p < 0.05$. (Error bars represent SE).