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Artikel Penelitian

Assessing Carbon Carrying Capacity of Forest Ecosystem: A Case Study in West Sumatera Province

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ABSTRACT

All attempts have been taken by majority nations to reduce and invent the greenhouse gases (GHG) emission, but none of them provide any quantitative framework to assess ecosystem capacity for carrying carbon. To measure ecosystem boundaries to offset carbon and how far the emission has exceeded beyond them, this paper aims to calculate the carbon carrying capacity and evaluate its availability to sequester CO₂ emission in a certain area. Considering forests, the major carbon reservoir to be the key ecosystem and taking West Sumatera Province in Indonesia as the case study, the Carbon Carrying Capacity (CCC) assessment is conducted with ecological footprint concept through carbon capacity surplus-deficit. The results show the forest CCC was fluctuated which were the highest 3.9 million ton in 2016 and the lowest 2.4 million ton in 2019, and primary mangrove land cover was the biggest carbon sequesters for 114 ton C/ha every year. The forest CCC was dominantly deficit which interpreted as limited and unavailable forest capacity to offset carbon emission. To improve forest CCC, forest area needs to be conserved, also develop low-carbon and green economic transformation to reduce GHG emission. The local society can take role to conserve the forest through customary laws application, then the government ought to plan spatial strategies through limiting land use for the primary forest and prohibiting mangrove and swamp forest conversion, also monitor, control and make legal approach to achieve national targets on reducing CO₂ emission.

Keyword: Carbon Carrying Capacity, Carbon Sequestration, Ecological Footprint, Forest Ecosystem, Carbon Emission

ABSTRAK

Setiap negara telah mengupayakan berbagai kebijakan dan program untuk menginventarisasi dan menurunkan emisi gas rumah kaca, tetapi belum terdapat framework khusus untuk mengetahui kapasitas ekosistem dalam menyerap dan menyeimbangi emisi tersebut. Penelitian ini bertujuan untuk menghitung daya dukung dan mengevaluasi batas kemampuan ekosistem dalam mereduksi emisi CO₂ di suatu wilayah dengan mempertimbangkan hutan yang merupakan ‘reservoir’ utama karbon menjadi ekosistem kunci. Evaluasi daya dukung karbon ini menggunakan konsep *ecological footprint* melalui perhitungan *surplus-deficit* kapasitas karbon dan menjadikan Provinsi Sumatera Barat sebagai wilayah studi. Hasil penelitian menunjukkan bahwa daya dukung karbon ekosistem hutan berfluktuasi dari tahun 2016-2020 dengan kapasitas penyerapan emisi CO₂ tertinggi 3,9 juta ton pada 2016 dan terendah 2,4 juta ton pada 2019, dimana tutupan lahan *mangrove* primer menjadi penyerap karbon terbesar sebanyak 114 ton/ha setiap tahunnya. Daya dukung karbon tersebut didominasi hasil *deficit* atau kemampuan penyerapan lebih kecil dibandingkan emisinya. Rekomendasi penelitian ini untuk meningkatkan kapasitas penyerapan karbon, yaitu melakukan konservasi tutupan lahan hutan serta mengembangkan transformasi ekonomi hijau dan rendah karbon untuk mengurangi emisi gas rumah kaca. Komunitas masyarakat juga dapat berperan dalam melestarikan ekosistem hutan melalui kearifan lokal dan pemerintah perlu merencanakan strategi spasial dengan membatasi penggunaan lahan pada tutupan lahan primer, konversi hutan mangrove dan rawa, serta melakukan pemantauan dan pengendalian emisi untuk mencapai target nasional pengurangan emisi CO₂.

Kata Kunci: Daya Dukung Karbon, *Ecological Footprint*, Ekosistem Hutan, Emisi Karbon, Penyerapan Karbon

1. INTRODUCTION

Climate change and warmer temperature are recently occurring in every continent as the consequences of greenhouse gases (GHG) emission. The Earth's surface average temperature in 2011-2020 was the warmest on record, which has been affecting the melting polar iceberg, rising sea level, intense drought and other phenomenon that will have irreversible affects to the ecosystem (UN, 2020). In 2015, approximately 195 countries committed to reduce GHG emission by signing up the United Nations Framework Convention on Climate Change-Conference of the Parties (UNFCCC-COP) 21 in Paris. Indonesia in particular, through the Nationally Determined Contribution (NDC) document, committed to reduce 29% (own funding) and 41% (international funding) of GHG emission under business as usual by 2030 (PPID KLHK, 2016). The targets have upgraded to respectively 31.89% and 43.20% through Indonesia's Enhanced NDC (ENDC) document in 2022, in order to prevent more than 1.5°C of global temperature rise and achieve net zero emission in 2060 (PPID KLHK, 2022).

National policies, program and tools have been created to estimate the potential reduction and invent the GHG emission in the form of carbon dioxide (CO₂ equivalent). Ministry of Environment and Forestry (2018) reported that Indonesia's CO₂ emission decreased 8.7% during 2016, which needed more efforts to reach the ENDC target. However, all those approaches are not intended yet to assess the capacity of ecosystem to carry carbon emission from population's activities as Rockström et al. (2009) stated that sustainable development cannot be accomplished outside of the limits of the planet. The majority of assessment tools for environmental sustainability do not contain any quantitative framework in terms of measuring the idea of "Carbon-neutral"- the balance, uptakes, and offsetting of carbon emissions (Lee and Lee, 2013). Moreover, Intergovernmental Panel on Climate Change (IPCC), that is the United Nations body for assessing the science related to climate change, does not deliver any guideline regarding to assess ecosystem capacity for carrying carbon. Consequently, there is a necessity to measure and analyze the specific carbon carrying capacity of the ecosystem in order to sustain it within continuous development. By assessing certain ecological carrying capacity offers a framework for establishing objectives, determining actions, and monitoring progress toward predetermined objectives (Borucke et al., 2013), in this case are the ENDC targets.

The concept of carrying capacity is commonly used to figuring out the limit of earth's regenerative capacity for supporting human consumption of natural resources, and natural assimilative capacity for carrying waste emission (Khanna et al., 1999). There are various carrying capacity methods and approaches have been developed by scholars and experts over time. The one Carbon Carrying Capacity (CCC) can be a potential tool to measure ecosystem boundaries to offset carbon and how far the emission has exceeded beyond them. It is interpreted as the amount of carbon held in an ecosystem at a state of dynamic equilibrium under prevailing environmental conditions and natural disturbance regimes, but excluding anthropogenic disturbance (Gupta and Rao, 1994; Keith et al., 2009). The term of CCC for offsetting emission was first introduced by Keith et al. (2010) that stated by calculating the gap between CCC and carbon stocks resulted carbon sequestration potential as it could provide baseline against the current carbon stocks. This measurement is landscape-scale based offering method for calculating the amount of carbon lost or gained from human land use activities, simply put as the quantity of CO₂ absorbed in a specific area for photosynthesis (Keith et al., 2010; Fu et al., 2020).

The highest carbon carrying and sequestration capacity is owned by forest as the greatest carbon reservoir in terrestrial ecosystems (Liu et al., 2014). Forest can sequester 67% of the total CO₂ removed from the atmosphere, also hold 90% of plant biomass carbon and 80% of carbon contained in soil in all terrestrial ecosystems (Landsberg and Gower, 1997). The total amount of carbon stored in all the pools within a forest is described as CCC by taking into account the effects of natural disturbance events (especially fire) on carbon dynamics and environmental heterogeneity when the ecosystem is in a state of dynamic equilibrium with climate forcing factors (Keith et al., 2010). Thus, I consider forest as the key ecosystem to offset carbon emission in this study.

Regarding to meet the need of sustainable environment assessment related to GHG emission, this paper is curious about to what extent the forest ecosystem capacity carrying the carbon emission in a certain area. The assessment of CCC in this paper will be delivered with an approach adopted from ecological footprint framework that quantifying key ecosystem services by two measures which are (i) ecological footprint as the demand of activities put on biosphere in a certain year, and (ii) biocapacity as the ecological regenerative capacity (Wackernagel et al.,

2002). The different between those two measures provides the ecological deficit or surplus representing the status of forest carbon carrying capacity that leads to take advanced actions for reducing carbon emission and forest degradation. The same study with different approach had been done by Xiao et al. (2013) who calculated carbon carrying capacity of Shandong Province in China and Wei et al. (2017) analyzed the vegetation carbon carrying capacity of Xinjiang Province in China that was increasing continuously. In 2020, Fu et al. evaluated the carbon footprint and vegetation carbon carrying capacity of Yunnan Province also in China through similar ecological footprint concept that showed increasing carbon carrying capacity from 2008 to 2017 and growing carbon surplus. Most of the study related to this field was conducted in China, but none identical one that have been done in Indonesia.

This paper intends to analyze forest carbon carrying capacity Indonesia taking West Sumatera as the case study. West Sumatera is one of provinces in Indonesia that has huge total forest area about 2.284.807 hectares, approximately 54% of total province land area (BPS-Statistics of West Sumatera, 2023). However, Forestry Agency of West Sumatera Provincial Government (2018) reported about 630.694 ha of forest area was in the critical and very critical level due to the land use changes. In landscapes with a dominance of natural forests, CCC is the most appropriate baseline to utilize for carbon accounting and serve a basis for tracking changes in land management or land use activities that either enhance or decrease carbon stocks as a result of forest development (Keith et al., 2010). Moreover, this region is prone to ecological environment vulnerability as located in two tectonic plates' collision, namely the Indo-Australia and Eurasia, and traversed by the Great Sumatran Fault. The IPCC defines vulnerability as the propensity of human and ecological systems to suffer harm and their ability to respond to stresses imposed as a result of climate change effects (Frigerio and De Amicis, 2016). This study aims (i) to calculate the forest CCC and (ii) evaluate the dynamics of forest CCC to sequester given CO₂ emission in the study area. Eventually, this study provides a reference for decision makers to consider the forest carbon carrying capacity for taking actions and policies to achieve NDC target and future development.

2. METHODOLOGY

2.1 Study Area

West Sumatera is a province of Sumatera Island located between 98°36'-101°53' East Longitude and 0°54' North Latitude - 3°30' South Latitude. This province consists of low plains in the west coast and volcanic high plains created by Barisan Hills with 42.12 thousand km² land area. In term of geographic position, West Sumatera Province border to North Sumatera and Riau in the north, Indian Ocean in the south and west, also Jambi and Bengkulu in the east. There are 19 regencies/municipalities in West Sumatera Province, where 7 of them are occupied by 218 islands (BPS-Statistics of West Sumatera, 2023).

The characteristic of climate in this province is wet tropical climate because it lies on the equator line at 0° latitude line. During 2022, the average temperature of West Sumatera was 17.4°C-34.8°C in range with average humidity was 81.2%. At the same period of time, most of 734 mm³ rainfall occurred in November that was monitored at the Minangkabau Pariaman Maritime Meteorological Station. Furthermore, the air quality index in 2022 was 90.65 classified as very good category, and environmental index was 74.98 which increased from previous year (BPS-Statistics of West Sumatera, 2023).

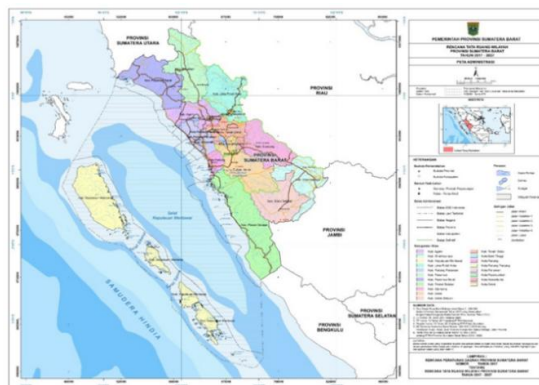


Figure 1. Administrative Map of West Sumatera Province

Source: Regional Spatial Planning of West Sumatera Province 2017-2037

The total 2.28 hectares forest area consist of 20% of nature reserve forest, 22% of protected forest, 6% of limited production forest, 10% of production forest, 4% of conversion production forest, and 39% of other uses area. Forest Watch Indonesia (FWI) monitored the deforestation rate in the outside of protected and conservation area reaching 50,446 ha/year. The extensive forest brings this region as one of the highest provinces in Sumatera which supports the ecosystem services in providing fuel, timber and genetic resources as the energy resources for domestic activities. In addition, 60.13% of the forest lands are highly potential for climate regulation services in the province (Environmental Agency of West Sumatera, 2017).

2.2 Forest Carbon Carrying Capacity Calculation

Critical components of carbon cycle are the stock of total ecosystem carbon and the flux of annual net ecosystem exchange (Keith et al., 2010). According to the IPCC Method (IPCC, 2006), Net Forest Production (NFP) is used to account for the CO₂ fluxes between forest ecosystems and the atmosphere as net exchange in C stocks over time. NFP was calculated here as the net sequestered carbon in all the significant pools of forest ecosystems per hectare per year. Thus, forest CCC was formulated as follows (Fu et al., 2020):

$$C_{\text{forest}} = A_{\text{forest}} \times C_{\text{NFP}} \times \frac{44}{12} \quad (1)$$

Where,

C_{forest} = the carbon sequestration as the forest CCC (unit t)

A_{forest} = the forestry area (unit ha)

C_{NFP} = the average net ecosystem productivity of the forest (unit t/ha)

44/12 = the ratio of molecular weight of CO₂ and C

The NFP calculated by stock different method provided by IPCC (2006):

$$NFP = \frac{C_2 - C_1}{N_2 - N_1} / \Delta A \quad (2)$$

Where,

C_2 = the latest carbon stock of every pool (unit t)

C_1 = the initial carbon stock of every pool (unit t)

N_2 = the latest year of the carbon calculation

N_1 = the initial year of the carbon calculation

ΔA = the land use changes through selection year (ha)

2.3 Forest Carbon Carrying Capacity Assessment

Assessing the dynamic balance of forest CCC was based on ecological footprint method that measures ecological footprint referring to the amount of activity subjected to biosphere and ecological regeneration as biocapacity. In this case, the yearly CO₂ emission of a region accounted as the ecological footprint and the forest CCC of the same region at the same period was the biocapacity. The ecological deficit or surplus from the difference between the two components was the result for CCC assessment. The calculation formula of carbon capacity surplus and carbon deficit as follows (Fu et al., 2020):

$$CD = C_{\text{Forest}} - C_{\text{Emission}} \quad (3)$$

Where,

CD = carbon capacity surplus or carbon capacity deficit (unit t)

$CD > 0$ represents the capacity surplus and $CD < 0$ represents the capacity deficit.

2.4 Data Collection

Data for calculating forest CCC were the spatial data of forest area based on West Sumatera land covers from 2016 to 2020 (**Table 1**) collected from Ministry of Forestry online geoportal and Forestry Agency of West Sumatera Provincial Government, and then analyzed by ArcMap software. Forest land covers involved in this calculation were primary and secondary dry land forests, primary and secondary mangrove land forests, primary and secondary swamp forest, also planted forest.

Table 1. Forest Land Cover of West Sumatera from 2016 to 2020

Year	2016	2017	2018	2019	2020
Forest Land Covers (ha)	1,922,146	1,863,538	1,897,911	1,189,447	1,744,549

Sources: Ministry of Forestry online geoportal and Forestry Agency of West Sumatera Provincial Government

CO₂ emission between 2016 and 2020 for assessing the forest CCC were gathered from West Sumatera GHG inventory data which were available online at SIGN-SMART (**Table 2**), a GHG inventory system developed by Indonesia Environmental Ministry.

Table 2. GHG Inventory of West Sumatera from 2016 to 2020

Sectors	Emission (10 ³ ton CO ₂)				
	2016	2017	2018	2019	2020
Energy	2,540.12	2,014.05	2,179.03	N/A	1,763.41
Agriculture	3,500.54	3,477.09	3,438.91	3,432.39	3,396.56
Forestry	1,214.82	294.71	-12,499.54	890.13	-513.41
Waste	902.21	833.94	826.17	833.32	851.04
TOTAL	8,157.68	6,619.79	-6,055.43	5,155.84	5,470.60

Source: <https://signsmart.menlhk.go.id/>

2.4 Data Analysis

Spatial data of forested area in West Sumatera involving the area of each forest land covers were analyzed using ArcGIS to obtain the gain and loss of carbon stock as the changes of forest land area. Carbon gain stock means the improving of forested area, while the loss stock is the opposite condition. The value of gain stock was included in calculating the NFP as Equation (2), then the average of NFP during 2016-2020 was determined. Next, the annual CCC of each forest covers were calculated as Equation (1). The differences of annual CCC value and the yearly CO₂ emission presented the forest ecosystem capacity surplus/deficit on sequestering CO₂ emission. The analytical framework as follows.

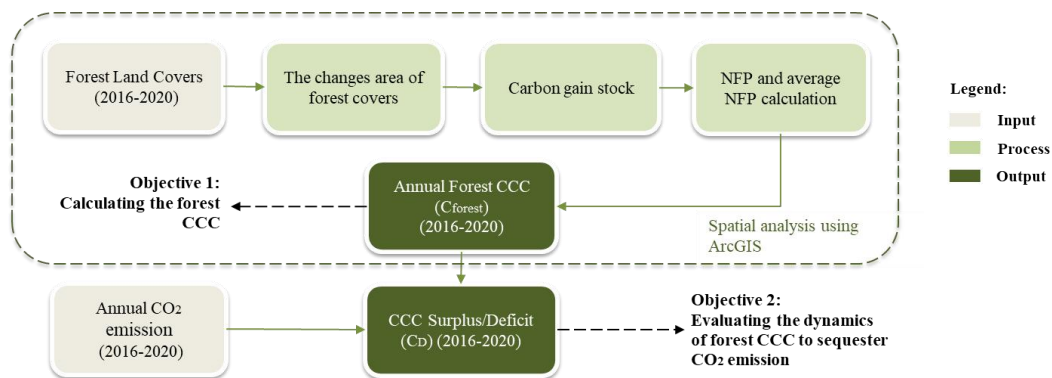


Figure 2. Analytical Framework

3. RESULTS AND DISCUSSION

3.1. Forest Carbon Carrying Capacity

As the formula for NFP calculation above, **Figure 3** shows the NFP in all forest pools of study area that represents the annual net sequestered carbon or CO₂ fluxes between forest ecosystems and the atmosphere in 5 years period. Primary mangrove land cover had the highest NFP that sequesters 114 ton/ha carbons every year and it accounted for 30% CO₂ fluxes proportion of all calculated forest pools. The next sequesters were primary dry land forest, primary swamp land forest and secondary dry land forest which have NFP of 67 ton/ha, 55 ton/ha and 46 ton/ha respectively. Secondary swamp land forest and planted forest shared the same proportion for sequestering carbon annually in 38 ton/ha. Land covers owning the smallest NFP was the secondary mangrove land forest that sequesters carbon for 26 ton/ha each year.

The average of given NFP is used to calculate forest CCC of West Sumatera between 2016 and 2020 as the result in the following **Table 3**. The forest CCC was fluctuated over the period which started from 3.9 million ton in 2016 and went down to 3.7 million ton in 2017, followed by escalation to 3.8 million ton in 2018. The lowest forest CCC was in 2019 dropped to 2.4 million ton losing 1.4 million ton capacity from previous year. Then, it rose in 2020 to 3.5 million ton forest CCC.

Table 3. Forest Carbon Carrying Capacity of West Sumatera from 2016 to 2020

Average NFP/CNFP (ton/ha)	Forest CCC/Cforest (ton)				
	2016	2017	2018	2019	2020
55.43	3,906,532.92	3,787,419.14	3,857,278.17	2,417,409.43	3,545,588.16

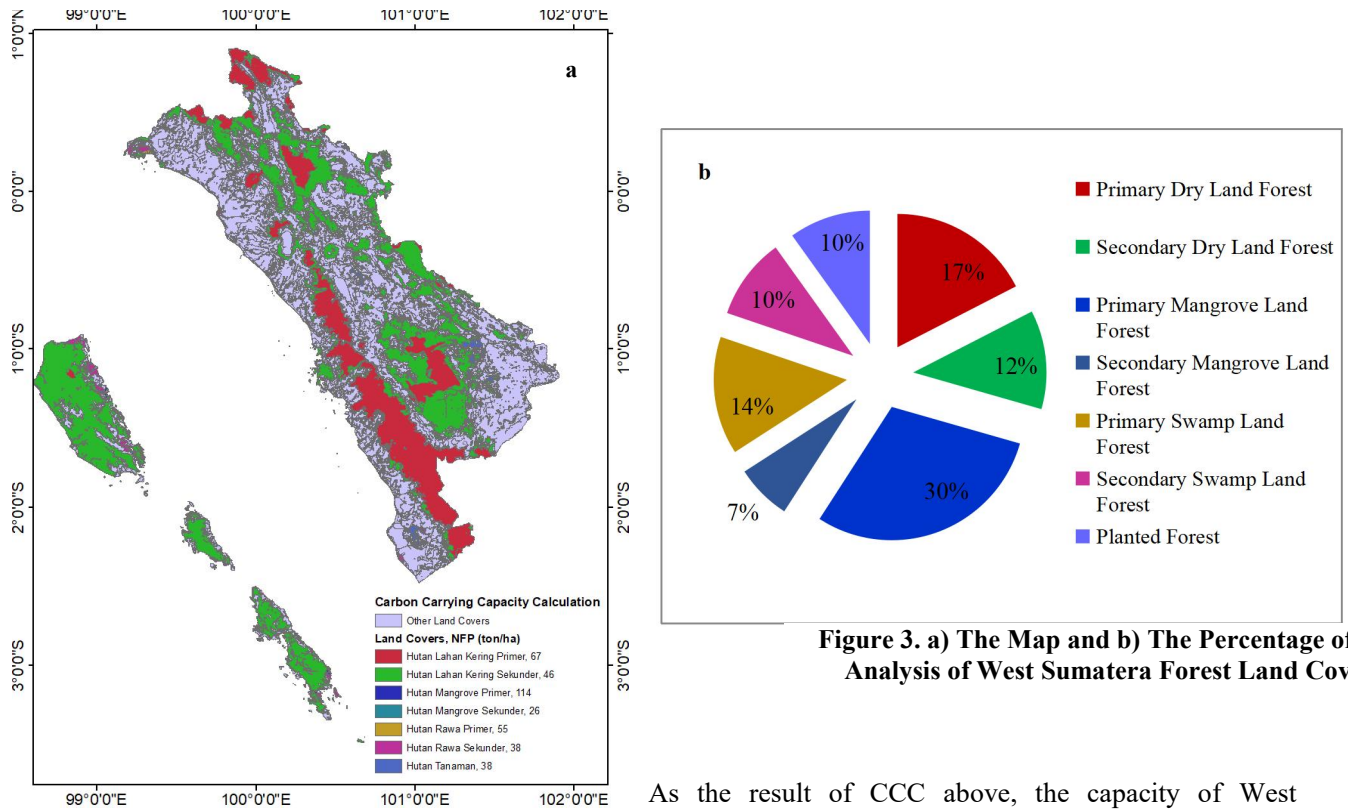


Figure 3. a) The Map and b) The Percentage of NFP Analysis of West Sumatra Forest Land Covers

As the result of CCC above, the capacity of West Sumatra forest to carry carbon emission was up and down according to the area of forest land. The area of forest in 2016 was 1.9 million hectares, which was the widest during the selected years, led to the biggest carbon carrying capacity. It also happened to the narrowest 1.1 million hectares forest area in 2019 that had 2.4 million ton carbon carrying capacity. As Keith et al. (2010) stated that critical components of the forest carbon cycle include the living and dead biomass and soil covering the land. The huge gap between 2016 and 2019 forest CCC might be caused by the increase of forest land conversion activities as FWI recorded in 2017 that about 20,457 ha of West Sumatra forest converted to non-forest land each year. However, spatial analysis errors also can influence the significant different of those land covers area, because the base map of the analysis was taken from online geoportal.

Regarding to NFP calculation outcomes, primary mangrove land forest was the major carbon sequestration pool among other land covers. It took for 30% of the total CO₂ fluxes of the forest ecosystem although the land area was not prominent and remarkable, about 12,628 hectares in latest year. It took the same account for primary swamp land forest which offset for 14% carbon with its 1.096 hectares area in 2020. Primary land forest is the forest as its natural condition without human and anthropogenic disturbances, also the standing stock of biomass carbon depends on the forest rates of production, turnover, and decomposition (Keith et al. 2010). Mangroves is the most carbon-rich biomes that as coastal habitats account for 14% of carbon sequestration by the global ocean and containing an average of 937 ton carbon/ha (Alongi, 2012). Moreover, Indonesian swamp forests can sequester between 0.01-0.03 gigatonnes of carbon annually (Worm et al., 1993). Forest land covers in West Sumatra were dominated by secondary and primary dry land forest, but their proportions to sequester carbon were only 12% and 17% respectively.

3.2. Forest Carbon Carrying Capacity Assessment

As shown in **Figure 4.**, most of West Sumatra forest CCC was deficit during five years started from 4.2 million ton in 2016 which was the highest CCC deficit, then declined to 2.8 million ton deficit in 2017. The only forest CCC surplus was in 2018 reaching 9.9 million ton, but the capacity dropped to 2.7 million ton CCC deficit in 2019 and ended in 1.9 million ton deficit in 2020.

Forest CCC assessment showed that the carbon emission seriously exceeds the fixed carbon absorption amount of forest ecosystem, thus the emission reduction capacity was very weak during the great carbon emission reduction pressure (Zhao et al., 2007). In other words, there were limited or no more available forest areas to sequester carbon emission and needed quick responses to balance the carrying capacity and emission pressure. Even though

the emission trend declined between 2016 and 2020, the forest ability to offset the emission was not enough. Moreover, the major contributors of CO₂ emission in West Sumatera were agriculture as the primary economic structure and industrial sector as the higher fuel consumption. Forest CCC in 2018 was the only capacity surplus because the CO₂ sequestration of forestry sector (the minus sign of emission value means sequestration), due to the increase of peatland and mineral land covers, which was bigger than other sectors emission values. This emission figure linked to the slight rise of forest land area from 2017 to 2018.

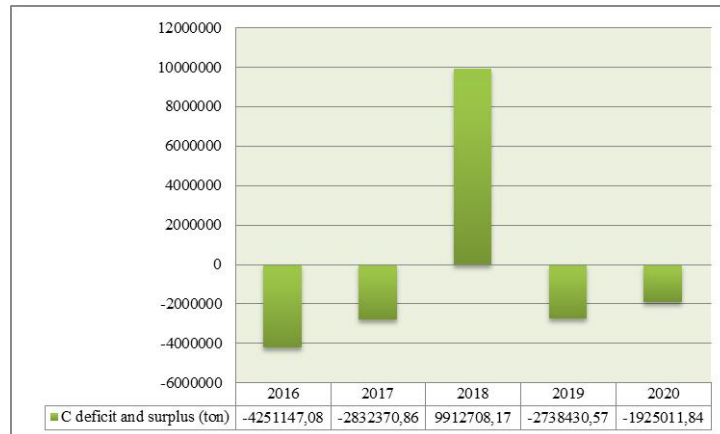


Figure 4. Forest CCC Deficit and Surplus

Deficit of forest CCC impacts to ecological process, especially carbon cycle in reducing and offsetting the GHG emission. Inadequate capacity of forest ecosystem for sequestering carbon represents the significant degradation and land use changes of forested area in West Sumatera. If the condition continues, the global warming and climate issues still exist affecting the other forest ecosystem services, including provisioning and supporting services, that influence every sectors of the region public's welfare, such as food security, agricultural activities, and genetic resources. Additionally, the climate changes cause drought, groundwater reduction, and various natural disasters.

Based on the assessment of forest CCC, there are necessary actions to stabilize and neutralize the CO₂ emission and carbon carrying capacity in West Sumatera both through forest conservation-reforestation and GHG emission reduction. The forested area ought to be maintained and reduced the forest conversion, particularly for the primary land forests, mangrove and swamp forest, in order to improve forest carbon sequestration pools and carrying capacity. Furthermore, emission mitigation activities should to be taken especially for agricultural and industrial sectors through low-carbon development, technology utilization, and green economic transformation.

4. CONCLUSION

Forest CCC is a tool to assess ecosystem boundaries to sequester carbon emission and how far the emission has exceeded beyond them. In this paper, forest CCC of West Sumatera Province is calculated by IPCC NFP method, while the assessment is conducted with ecological footprint concept through carbon capacity surplus-deficit. The forest CCC was fluctuated over the period which were 3.9 million ton in 2016, 3.7 million ton in 2017, 3.8 million ton in 2018, 2.4 million ton in 2019 as the lowest CCC, and 3.5 million ton in 2020. Then, the highest NFP that sequesters 114 ton/ha carbon every year was primary mangrove land cover accounted for 30% CO₂ fluxes proportion of all calculated forest pools. The assessment results show the forest CCC was dominantly deficit interpreted as limited and unavailable forest capacity to offset CO₂ emission. The only forest CCC surplus was in 2018 because of the increasing of peatland and mineral land covers. To improve forest CCC, forest area especially the primary land forests, mangrove and swamp forest need to be sustained and conserved, also develop low-carbon and green economic transformation to reduce GHG emission.

The local society and the government could collaborate for forest conservation and mitigation actions. West Sumatera is famous for the unified custom society which has their own tradition rules including forest protection such as "hutan adat" (custom forest) and "hutan larangan" (prohibited forest). They consider the forest around their village as the ancestral legacy and they punish anyone who damaging the area with the agreed sanctions. This society can be encouraged and empowered to protect the surrounding forest land area as they still respect the

customary laws. In addition, the provincial and regional government should make appropriate strategies related to land use-land cover or the spatial plan and forest conservation. The spatial plan could limit land use for the primary forest and prohibit conversion of mangrove and swamp forest. For the emission reduction, government should develop organic agriculture application, renewable energy use, waste reduction and recycle and other mitigation actions. Monitoring, control and legal approach are also needed to support the strategies to achieve ENDC target in 2030.

This study can guide related stakeholders in determining actions and monitoring progress toward objectives of reducing GHG emission. Nevertheless, because of the limitation of this study, I recommend further study to assess Indonesia's forest CCC in long period and forecast the forest CCC ENDC target year to evaluate greater impact.

REFERENCES

- Alongi, D. M. (2012). Carbon sequestration in mangrove forests. In *Carbon Management* (Vol. 3, Issue 3, pp. 313–322). <https://doi.org/10.4155/cmt.12.20>
- Borucke, M., Moore, D., Cranston, G., Gracey, K., Iha, K., Larson, J., Lazarus, E., Morales, J. C., Wackernagel, M., & Galli, A. (2013). Accounting for demand and supply of the biosphere's regenerative capacity: The National Footprint Accounts' underlying methodology and framework. In *Ecological Indicators* (Vol. 24, pp. 518–533). Elsevier B.V. <https://doi.org/10.1016/j.ecolind.2012.08.005>
- BPS-Statistics of Sumatera Barat Province. (2023). Provinsi Sumatera Barat dalam Angka. BPS Provinsi Sumatera Barat ISSN: 0303-5328
- Dinas Kehutanan Prov. Sumatera Barat. (2018). Sekilas Hutan Sumbar. <https://dishut.sumbarprov.go.id/>
- Dinas Lingkungan Hidup Provinsi Sumatera Barat. (2017). Daya Dukung dan Daya Tampung Lingkungan Hidup (DDDTLH) Provinsi Sumatera Barat.
- Dinas Pekerjaan Umum dan Penataan Ruang Provinsi Sumatera Barat. (2018). Penyempurnaan Materi Teknis Proses Legalisasi Revisi RTRW Provinsi Sumatera Barat 2018.
- Frigerio, I., De Amicis, M. (2016). Mapping social vulnerability to natural hazards in Italy: a suitable tool for risk mitigation strategies. *Environ. Sci. Pol.* 63, 187–196.
- Fu, W., Luo, M., Chen, J., & Udimal, T. B. (2020). Carbon footprint and carbon carrying capacity of vegetation in ecologically fragile areas: A case study of Yunnan. *Physics and Chemistry of the Earth*, 120. <https://doi.org/10.1016/j.pce.2020.102904>
- Geoportal Kementerian Lingkungan Hidup dan Kehutanan (online). <https://geoportal.menlhk.go.id/portal/home/>
- Gupta RK and Rao DL. (1994). Potential of wastelands for sequestering carbon by reforestation. *Current Science*, 66, 378–380.
- IPCC. (2006). IPCC Guidelines for National Greenhouse Gas Inventories. Intergovernmental Panel on Climate Change.
- Keith, H., Mackey, B., Berry, S., Lindenmayer, D., & Gibbons, P. (2010). Estimating carbon carrying capacity in natural forest ecosystems across heterogeneous landscapes: addressing sources of error. *Global Change Biology*, 16(11), 2971–2989. <https://doi.org/10.1111/j.1365-2486.2009.02146.x>
- Khanna P, Babu P R and George M S. (1999) *Prog. Plann.* 52 101–166
- Landsberg JJ, Gower ST. *Applications of Physiological Ecology to Forest Management*. San Diego, CA: Academic Press; 1997.
- Lee, B., & Lee, K. (2013). Environmental sustainability assessment based on the concept of carbon carrying capacity. *Applied Mechanics and Materials*, 284–287, 1511–1517. <https://doi.org/10.4028/www.scientific.net/AMM.284-287.1511>
- Liu, Y. C., Yu, G. R., Wang, Q. F., Zhang, Y. J., & Xu, Z. H. (2014). Carbon carry capacity and carbon sequestration potential in China based on an integrated analysis of mature forest biomass. *Science China Life Sciences*, 57(12), 1218–1229. <https://doi.org/10.1007/s11427-014-4776-1>
- Pejabat Pengelola Informasi dan Dokumentasi Kementerian Lingkungan Hidup dan Kehutanan RI. (2016). Indonesia Menandatangani Perjanjian Paris Tentang Perubahan Iklim. https://ppid.menlhk.go.id/siaran_pers/browse/298.
- Pejabat Pengelola Informasi dan Dokumentasi Kementerian Lingkungan Hidup dan Kehutanan RI. 2018. Indonesia Telah Berhasil Turunkan Emisi Karbon 8,7% Dari Target 29%. https://ppid.menlhk.go.id/siaran_pers/browse/1357.
- Pejabat Pengelola Informasi dan Dokumentasi Kementerian Lingkungan Hidup dan Kehutanan RI. (2020). Enhanced NDC: Komitmen Indonesia Untuk Makin Berkontribusi Dalam Menjaga Suhu

- Global.<https://ppid.menlhk.go.id/berita/siaran-pers/6836/enhanced-ndc-komitmen-indonesia-untuk-makin-berkontribusi-dalam-menjaga-suhu-global>.
- Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S., Lambin, E., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H. J., Nykvist, B., De Wit, C. A., Hughes, T., Van Der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P. K., Costanza, R., Svedin, U., ... Walker, B. (2009). *Planetary Boundaries: Exploring the Safe Operating Space for Humanity* (Vol. 14, Issue 2). <https://about.jstor.org/terms>
- SIGN-SMART Sistem Informasi Inventarisasi Gas Ruma Kaca Nasional (online). <https://signsmart.menlhk.go.id/v2.1/app/dashboard>
- United Nation. 2020. What is Climate Change. <https://www.un.org/en/climatechange/what-is-climate-change>.
- Wackernagel, M., Schulz, B., Deumling, D., Linares, A.C., Jenkins, M., Kapos, V., Monfreda, C., Loh, J., Myers, N., Norgaard, R., Randers, J., 2002. Tracking the ecological overshoot of the human economy. *Proc. Natl. Acad. Sci U.S.A.* 99 (14), 9266–9271.
- Wei, L., Lin, N., Ju, M. (2017). Carbon safety assessment based on carbon footprint and carbon capacity in Xinjiang Uygur Autonomous Region. *Bull. Soil Water Conserv.* 37 (281–285), 291.
- Worm, K., Unesco, S., & Rostsea. (1993). *INDONESIAN PEAT SWAMP FORESTS AND THEIR ROLE AS A CARBON SINK*. In *Chemosphere* (Vol. 27, Issue 6).
- Xiao, L., Zhao, X., Xu, H. (2013). Dynamics of carbon footprint and carbon carrying capacity of Shandong Province. *J. Ecol. Rural Environ.* 29 (2), 152–157.
- Zhao, X., Ma, C., Gao, L. (2007). Assessment of ecological safety under different scales based on ecological tension index. *Chin. J. Eco-Agric.* 6, 135–138.