Modelling for Estimation Carbon Stocks in Land Cover Using A System Dynamic Approach (Case Study: Prabumulih City, South Sumatera, Indonesia)

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Abstract

Human activities, which have interfered with the ecological system, have led to global warming. This has led to the release of carbon stocks into the atmosphere, thereby reducing the function of carbon sinks in places with vegetated land. With increased human activities, vegetated land will soon become non-vegetated. This is because the increased human activities have led to the absorption of higher amounts of carbon in the atmosphere than the required level. Therefore, this study aimed to estimate land cover on carbon stocks in Prabumulih City, South Sumatera Province, Indonesia. The study employed a random field survey using a dynamic system, with the results showing that land cover consisted of oil palm plantations, mixed plantations, grass, swamp shrubs, and rivers. However, the area was dominated by rubber plantations, and as a result, the carbon stocks continued to decline. For instance, in 2008, the level of carbon stock was 2,438.72 Gg and fell to 2,190.85 Gg in 2020, indicating a 4.8% decrease. It is projected that by 2030, the carbon stock in land cover will be 1,988.07 Gg.

Keywords: global warming, emissions, simulation, environment

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Introduction

The main cause of global warming has been attributed to an increase in the concentration of various atmospheric greenhouse gases, including carbon dioxide (CO₂), methane (CH₄), nitrous oxide (NO), and chloro fluoro carbon (CFC), which are emitted directly to the environment (Prasad et al., 2017). Human activities disrupt this balance by producing an increase in CO₂ from fossil fuels such as coal, gas, petroleum products and combustion in power plants, transportation, and industry (Rahman & Hasan, 2017). In addition, according to Hairiah and Rahayu (2007), human activities such as burning forests and agricultural vegetation in protected areas have resulted in environmental damage. As a result, this affects the amount of carbon stock and causes climate change. The higher the level of GHG and carbon dioxide (CO₂) emission in the atmosphere, the greater the urgency in adopting carbon sequestration measures to mitigate the effects of climate change (Betts et al., 2016).

High demand for land to be used for infrastructure, settlement, and economic support facilities such as offices, roads, buying and selling centers, and industry has caused a decrease in the amount of vegetation cover, specifically in cities, as a result of the increasing urban population (Pratiwi et al., 2017). Further, rapid changes in land-use patterns have resulted in forest degradation negatively impacting the global climate due to the GHGs from terrestrial and aquatic systems (Kumar & Sharma, 2015). Emissions of carbon dioxide equivalent (CO₂eq) have continued to increase along with human activities such as land conversion, increased vehicle use, improper waste disposal, and other harmful activities (Pratiwi et al., 2021a).

Tropical forests in Indonesia have the most extensive natural and biological species in the world. However, most of them have been degraded and made distinct, thus, it is crucial to scrutinize the impact in relation to the role of storing carbon (Astiani et al., 2017). Sutaryo (2009) stated that one of the roles of tropical rain forests on the environment is their ability to absorb CO₂ due to the variety of plant species that grow in the area. Plants are naturally able to absorb CO₂ and convert it into oxygen through the process of photosynthesis. So tropical rain forests are the best carbon dioxide absorbers compared to other ecosystems. Changing vegetation land to non-vegetated land can cause the release of carbon stocks into the atmosphere, reducing the function of carbon sinks in places with vegetated land leading to increased CO₂ emissions. Each type of land cover has a different ability to
absorb carbon, for instance, forests in the tropics serve as significant carbon sinks and store up to 40% carbon stocks compared to other ecosystems (Maxwell et al., 2019). The changes in carbon stocks occur due to natural processes in forests, indirect human influences, forest regeneration and harvesting, conversion of forests to agricultural land, wetlands, grasslands, settlements, and others (IPCC, 2003). Based on this, it is necessary to predict the carbon stock in land cover, which will likely decrease yearly, using a dynamic system approach.

System dynamics is a computerized approach to policy analysis and design used for dynamic problems that arise in complex social, managerial, economic, or ecological systems, literally any dynamic system characterized by interdependence, reciprocal interactions, information feedback, and circular causality. This approach starts with defining the problem dynamically, then carries out the mapping and modelling stage, to the steps to build confidence in the model and its policy implications. A system design based on a dynamic model approach was necessary to understand the behavior changes and perform a simple simulation in providing alternative control and management strategies that were more effective and integrated (Mandra, 2013). Modeling system is a simple method to describe the real situation in nature (Musi et al., 2017). Forrester (2016) states that after the modelling is complete, the logic and accuracy of the computer model simulation is determined by assumptions as input from the model.

Land cover in Indonesia is diverse, ranging from plantations to built-up land with the ability to absorb different types of carbon. Therefore, with these differences, it is necessary to calculate the stored carbon stock to determine changes in the land cover area on the existing carbon stock by utilizing a system dynamic approach. This study aimed at analyzing estimation land cover on carbon stocks in Prabumulih City, South Sumatera Province, Indonesia using a system dynamic approach.

Methods
Research site
The study was conducted in Prabumulih City, South Sumatera Province, Indonesia, which is between S3°20'09.01"–S3°34'24.7" latitude and E104°07'50.4"–E104°19'41.6" longitude with an average altitude of 5154 m above sea level. It covers 434.50 km² of land with over 60% of rubber plantations around it. However, due to the increasing urban population, the area is developing rapidly, with the city government committed to improving infrastructure for office facilities, entertainment, and modernized roads. This development has led to changes in land cover types, such as plantation patterns. In the long run, these changes are likely to affect the ecosystem in Prabumulih City negatively. The research site is shown in Figure 1.

Land cover data
Land cover data were obtained from Pratiwi et al. (2021b) (Table 1), where the analysis was carried out using supervised classification from Landsat satellite imagery. They included area statistics of five different land cover types for 2008, 2014, and 2020. To analyze the type of land cover in the primary data, using a field survey by determining several sampling points that were carried out randomly representing each type of land cover according to the actual conditions using GPS (Table 2), which is used to confirm the results of Pratiwi et al. (2021b).
listed in Table 1 and what types of land cover exist in Prabumulih City. Field survey data in the form of descriptions and documentation indicate the condition of land cover types in Prabumulih City.

### Table 1 Land cover area Prabumulih City in 2008, 2014, and 2020

| Land cover              | 2008 Area (ha) | Proportion (%) | 2014 Area (ha) | Proportion (%) | 2020 Area (ha) | Proportion (%) |
|------------------------|----------------|----------------|----------------|----------------|----------------|----------------|
| Cloud                  | 37.8           | 0.08           | 496.11         | 1.08           | 786            | 1.71           |
| No data                | 3.7            | 0.43           | 265.28         | 0.58           | 398.80         | 0.87           |
| River                  | 198.57         | 0.01           | 801.53         | 1.75           | 1,245.89       | 2.72           |
| Swamp scrub            | 2,008.44       | 4.38           | 2,062.74       | 4.50           | 1,746.06       | 3.81           |
| Built-up land          | 1,856.15       | 4.05           | 4,967.23       | 10.83          | 5,398.55       | 11.77          |
| Open field             | 4,263.52       | 9.30           | 4,232.37       | 9.23           | 2,529.71       | 5.52           |
| Mixed plantation       | 36,329.52      | 79.22          | 31,937.94      | 69.64          | 32,716.35      | 71.34          |
| Palm plantations       | 1,135.33       | 2.48           | 852.80         | 1.86           | 764.12         | 1.67           |
| Grass                  | 25.62          | 0.06           | 244            | 0.53           | 274.46         | 0.60           |
| Total                  | 45,859         | 100            | 45,859         | 100            | 45,859         | 100            |

Source: Pratiwi et al. (2021a)

### Table 2 Sampling points of land cover types in Prabumulih City

| No | X coordinate | Y coordinate | Existing land cover               |
|----|--------------|--------------|-----------------------------------|
| 1  | 420,888      | 9,619,901    | Open field                        |
| 2  | 413,825      | 9,621,271    | Open field                        |
| 3  | 419,212      | 9,626,004    | Open field                        |
| 4  | 415,218      | 9,620,375    | Built-up                          |
| 5  | 415,960      | 9,622,216    | Land built                        |
| 6  | 421,525      | 9,626,691    | Land built                        |
| 7  | 417,658      | 9,623,354    | Land built                        |
| 8  | 423,101      | 9,619,308    | Pineapple + rubber plantation     |
| 9  | 423,302      | 9,619,211    | Pineapple + rubber plantation     |
| 10 | 423,099      | 9,619,287    | Pineapple + rubber plantation     |
| 11 | 405,787      | 9,613,023    | Palm plantation                   |
| 12 | 405,439      | 9,612,646    | Palm plantation                   |
| 13 | 405,636      | 9,612,815    | Palm plantation                   |
| 14 | 408,165      | 9,614,875    | Rubber plantation                 |
| 15 | 409,501      | 9,613,326    | Rubber plantation                 |
| 16 | 407,828      | 9,609,873    | Rubber plantation                 |
| 17 | 425,670      | 9,626,147    | Rubber plantation                 |
| 18 | 415,935      | 9,621,237    | Swamp scrub                       |
| 19 | 409,513      | 9,613,176    | Swamp scrub                       |
| 20 | 412,796      | 9,620,302    | Grass                             |
| 21 | 419,342      | 9,622,181    | River                             |
| 22 | 418,513      | 9,621,404    | River                             |
| 23 | 419,433      | 9,622,876    | River                             |

Land cover types in carbon stock using system dynamic

Analysis of carbon stock on the land cover using dynamic systems approaches by Sterman (2002), as for the stage carried out such needs analysis, problem formulation,
system identification, model validation, and modeling. The initial step was needs analysis of model development with a dynamic systems approach that identified the demands of each stakeholder during the interviews. Additionally, the problem formulation stage was developed based on the needs of each stakeholder, where the identified differences prompted the problem of controlling CO$_2$eq emissions. The third stage involved system identification, which was carried out to provide an overview of the causal relationship represented by a positive (+) or negative (-) sign. The fourth stage was model validation, which ensured that the model described the actual system condition by statistical tests of absolute mean error (AME) and absolute variation error (AVE). According to Hartrisari (2007), AME was the difference between the average value of the simulation results and the actual value, while AVE was the deviation of the variation (variance) between the simulation value and the actual variation, while the acceptable deviation limit was between 110%. Finally, the Modeling stage was based on the model structure of the land cover diversity on carbon stocks. For the modeling stage, each land cover type has different carbon stocks (Table 3) absorption capacity of each type of land cover is described as follows in Equation [1]. The total carbon stock is obtained by multiplying the area of the land cover type by the carbon stock so that the total carbon stock is received.

$$C = L \times \text{stock carbon (ton C ha}^{-1}))$$  

[1]

note: $C =$ stock carbon total (ton C); $L =$ landcover area (ha). The dynamic system approach stages are mathematically defined in a computer language using Powersim 10 software.

Results and Discussion

Land cover type Based on the results of the field survey, several types of land cover were identified in Prabumulih City, such as rubber, pineapple, oil palm plantations, open land, built-up land, swamp scrub, grass, and rivers. Based on observations, Prabumulih City was dominated by rubber plantations, which are spread throughout the city, reaching 60% of the area because some people still use rubber farmers as a source of livelihood and most of the rubber plantations in Prabumulih City are smallholder rubber plantations. Prabumulih city has a characteristic called the "pineapple city" because pineapples have a delightful taste compared to other pineapples, and pineapple plants are mostly used as intercrops in rubber plantations. The area was centrally located with rubber plantations managed by the community as pictured in (Figure 2A, Figure 2B).

Results from the study indicated a lot of shifts in the land covers where oil palm plantations were being replaced with rubber plantations as shown in (Figures 3A, Figure 3B). The study area was considered an oil-producing city. Therefore, the available open land was due to conversion to residential land and oil wells (Figure 4A).

Prabumulih city is one of the national oil and gas barns and the operating base and mainstay of production where the natural gas network supplies almost 100% for households. The city was traversed by the Kelekar river, the Rambang river, and other small rivers (Figure 4B). Built-up land was centrally located in the city area (Figure 4C), with swamp shrubs that consisted of stagnant water (Figure 4D). Furthermore, grassland cover was in the form of football fields and golf courses (Figure 4E).

System dynamic model Analysis of land cover diversity on carbon stock analysis was carried out using a dynamic system approach with the aid of Powersim 10 software with the following stages discussed below:

Table 3  Carbon stocks by land cover type

| Land cover type       | Carbon stocks C (ton ha$^{-1}$) | Source                                                                 |
|----------------------|---------------------------------|------------------------------------------------------------------------|
| Mixed plantation     | 63                               | Technical guidelines for calculating baseline greenhouse gas emissions and removals for the land-based sector, 2014 |
| Palm plantations     | 63                               |                                                                       |
| Shrubs               | 30                               |                                                                       |
| Settlement/Built up  | 4                                |                                                                       |
| Cloud                | 0                                |                                                                       |
| Water body           | 0                                |                                                                       |
| Open field           | 2.5                              |                                                                       |
| Grass                | 4                                |                                                                       |

Figure 2  Rubber plantation land cover (2A), pineapple used as intercrops in rubber plantations (2B).
Need analysis The interview results showed the need for the government, academics, and the community to analyze carbon stocks since each stakeholder had different needs as illustrated in Table 4. In general, stakeholders want a healthy and pollution-free environment.

Identified problems The following needs were identified from each stakeholder interviewed. First, lack of public awareness on the importance of vegetated land cover and carbon stocks. Second, lack of government socialization to the community to maintain the existing plants in the home...
Contributed by the changes in land cover from vegetated to non-vegetated, leading to loss of biodiversity, thereby affecting carbon stocks and CO₂ emissions. For instance, in 2008, it was 45,619 ha, and in 2020, it was 43,433 ha indicating a 4.8% decrease (Table 1). In 2030, it is estimated that vegetated land cover will continue to decline to 39,167 ha showing an alarming trend that needs intervention. According to Feng et al. (2020), land-use change was attributed to the rapid urban expansion and loss of forests and grasslands, causing substantial carbon emissions that contributed to greenhouse warming as indicated in Figure 7.

The study also indicated that human and climatic factors contributed to land use/cover changes, where decisions were based on short-term economic factors such as globalization, policy, and technological innovation (USGCRP, 2018). For vegetated land (forest), the risk of conversion to other land uses was related to environmental, social, cultural, economic, and political factors (Puhlick et al., 2017; USGCRP, 2018). Several other factors led to land conversions, such as urban expansion (Shifley et al., 2014), demographic variables (Woodall et al., 2015), and distance to the nearest road (Puhlick et al., 2017). Therefore, it was feared that these factors affected vegetated areas and threatened carbon stocks and CO₂ emissions.

The graph in Figure 8 shows the projected carbon stock in Prabumulih City for 2008-2030, which is above ground carbon stock. Carbon stocks in 2008 were 2,438.72 Gg, and there was a decrease in carbon stocks in 2020 to 2,190.85 Gg. In 2030 it is predicted that the carbon stock in land cover will be 1,988.07 Gg.

Table 6 shows the trend of carbon stocks from each land cover type that tends to decrease, such as mixed plantations, oil palm plantations, swamp shrubs and open land. Meanwhile, those that have increased are built-up land and grass. The increase in carbon stocks in built-up land is due to an increase in built-up land area, where the assumption is that the built-up land still contributes 4 ton ha⁻¹ of carbon stocks from home yards or private green open spaces. Compared to other land cover types, carbon stocks from open land are smaller than different types of land cover, especially woody land cover.

Mixed plantations have the highest carbon stocks from year to year compared to other land covers, followed by swamp shrubs, mixed plantations, built-up land, open land.
Table 5  Validation of AME and AVE values

| Year | Mixed plantation | Oil palm | Open land | Built-up land | Swamp shrubs | Grassland |
|------|------------------|----------|-----------|--------------|--------------|-----------|
|      | A (ha)           | S (ha)   | A (ha)    | S (ha)       | A (ha)       | S (ha)    |
| 2008 | 36,329.52        | 36,329.52| 1,135.33  | 1,135.33     | 4,263.52     | 4,263.52  |
| 2014 | 31,937.94        | 31,939.92| 852.79    | 852.79       | 4,232.37     | 4,232.91  |
| 2020 | 32,716.35        | 32,719.23| 764.12    | 764.12       | 2,529.71     | 2,530.21  |
| Average | 33,661.27 | 33,662.89| 917.42    | 917.12       | 3,675.2      | 3,675.55  |
| AME  | 0.005            | 0.00039  | 0.0108    | 0.006        | 0.0108       | 0.0032    |
| AVE  | 0.111            | 0.0017   | 0.0276    | 0.033        | 0.0432       | 0.0084    |
| Status | Valid            | Valid    | Valid     | Valid        | Valid        | Valid     |

Figure 5  Causal loop diagram of area and carbon stock in Prabumulih.

Figure 6  Land cover area and carbon stock sub model.
Grassland is open land that is not covered by vegetation. Mixing plantation is a combination of plantation and vegetation. Grassland is an area with low vegetation cover, which is turned into other types of land cover, such as settlements. Therefore, carbon emissions are released as the ability to store carbon stocks decreases, impacting environmental sustainability.

Each type of land cover that turns into other land covers, especially non-vegetated land covers, can release different amounts of carbon. Carbon sequestration can even occur if there is a change in land cover with low to high carbon absorption, so a scenario is needed to maintain or increase carbon stocks to absorb CO₂. According to "(Murdiyarso et al., 2010; Sugiri & Buchori, 2016), reported that reduced forest and increased settlements have a significant impact on carbon emissions so that efforts to control land-use change are needed.

The scenario used is land cover, where 20% of the open land is mixed plantation land/vegetated land. The figure shows the results of the scenario applied to increase carbon stocks due to the increased area of vegetated land in 2024. The resulting carbon stock is 2,126.50 Gg, whereas the carbon stock before the scenario was 2,106.49 Gg.

Maintaining and adding vegetated land in Prabumulih City supports the government's commitment to handling climate change through Low Carbon Development Planning. President Joko Widodo's commitment at COP 21 in Paris, December 2015, is to reduce emissions by 29% (Fair scenario/using own capabilities) and 41% (ambitious scenario/ if international support). One of the efforts to realize this policy is to maintain and optimize green open space. According to Gómez-Baggethun et al. (2013) and Elmqvist et al. (2015), climate regulation is one of the primary regulatory services provided by urban green space.

The development of green open spaces requires efforts from various substances such as researchers, local governments, communities and other stakeholders because green open spaces are a form of climate change mitigation that supports CO₂ emission reduction. According to Helen et al. (2019), green infrastructure consisting of green open spaces has many benefits for urban residents. It contributes to current national policy goals related to urban sustainability and the transition to a green economy. Vegetation in urban green spaces absorbs and stores carbon by converting CO₂ into biomass both above-ground and below-ground, such as in stems, branches, leaves, and roots through photosynthesis (Nowak & Crane, 2002).

### Table 6 Carbon stock for each type of land cover

| Land cover          | Carbon stock (Gg ha⁻¹) |
|---------------------|------------------------|
|                     | 2008 | 2014 | 2020 | 2030 |
| Mixing plantation   | 2,288.76 | 2,012.09 | 2,061.13 | 1,872.74 |
| Oil palm            | 71.53   | 53.73  | 48.14  | 37.60  |
| Swamp shrub         | 60.25   | 61.88  | 52.38  | 52.89  |
| Built-up            | 7.42    | 19.87  | 21.59  | 31.9   |
| Open land           | 10.66   | 10.58  | 6.32   | 5.68   |
| Grassland           | 0.10    | 0.98   | 1.1    | 1.32   |
| Total               | 2,438.73 | 2,159.13 | 2,190.67 | 1,988.07 |

and grass (Table 6). Carbon stock in 2008 mixed plantations was 2,288.76 Gg and then decreased to 2012.09 Gg in 2014. In 2020 it increased slightly to 2,061.13 Gg, and it is predicted that in 2030 mixed plantations will experience a decrease in carbon stock to 1,872.74 Gg. The amount of carbon stock is influenced by the type of land cover where the area of mixed plantations in Prabumulih City reaches 70%.

When viewed from the type of land cover in Prabumulih City, this city only has vegetated land in the form of plantations. There are no more forests, both primary and secondary, which have the most significant carbon stock of 112,377 ton ha⁻¹, so the carbon stock in Prabumulih City, seen from the land cover classification, is classified as not diverse. According to Sukarna et al. (2021), low carbon stocks above the surface are related to ecosystem stability.

The figure illustrates that vegetated land in this area is decreasing in terms of the environment (Figure 9), so it is necessary to consider managing it as a potential carbon stock that helps absorb greenhouse gas emissions.

Biomass carbon concentration has been highly influenced by land use. The biomass carbon stock was, on average, five times higher in the dense forest than in open forest and twenty times higher than in grassland (Solomon et al., 2018). Carbon sequestration through planting fruit trees can be a cost-effective option to reduce global warming and, at the same time, increase farmers' incomes. However, the amount of wood biomass absorbed by C depends on plant age, stem density, site conditions, management practices, and climatic conditions (Fischer et al., 2013).

Vegetated land cover that continues to experience a reduction in the area will affect the stored carbon stock. According to Dewa & Sejati (2019), the reduction in carbon stock is caused by a decrease in canopied forests land cover,
In conclusion, the diversity of land cover types consisted of oil palm plantations, mixed plantations, grass, swamp shrubs, and rivers. In 2008, carbon stocks in this region reached 2,438.72 Gg, while in 2020, they amounted to 2,190.85 Gg. However, there are projections that by 2030, the carbon stock in land cover will be in excess of 1,988.07 Gg. Vegetated land cover that continues to experience a reduction in the area will affect the stored carbon stock. Adding vegetated land is carried out, whereas much as 20% of open land is used as vegetated land. There is an increase in carbon stock due to the vegetated land area, which was originally 2106.49 Gg to 2,126.50 Gg in 2024.

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