

SPATIOTEMPORAL VARIATION OF TERRESTRIAL CARBON SEQUESTRATION IN TROPICAL URBAN AREA (CASE STUDY IN SURAKARTA DISTRICT, INDONESIA)

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Manuscript received: April 15, 2021

Revised version: May 23, 2021

DANARDONO, SUNARIYA M.I.T., FIKRIYAH V.N., CHOLIL M., 2021. Spatiotemporal variation of terrestrial carbon sequestration in tropical urban area (case study in Surakarta District, Indonesia). *Quaestiones Geographicae* 40(3), Bogucki Wydawnictwo Naukowe, Poznań, pp. 5–20. 11 figs, 5 tables.

ABSTRACT: The value of terrestrial carbon sequestration in urban areas, due to lack of vegetation as a carbon sink, is rarely studied. In fact, urban areas have high carbon emission values, which must be minimised. On the other hand, the value of carbon sequestration in urban areas is very dynamic due to natural factors from the environment and non-natural factors from anthropogenic activities. The main objectives of this study are to identify the carbon dioxide sequestration in urban areas, especially in tropical climates, and to determine the dynamics of carbon sequestration in urban areas for a year. The results show that carbon sequestration in tropical urban areas has a significant value compared with urban areas in temperate climates. This condition happens because there are still green open spaces in gardens and agricultural lands. The value of carbon sequestration in this tropical urban area experiences monthly dynamics caused by rainfall variation and anthropogenic activities, such as land conversion and plant type conversion in agricultural lands.

KEYWORDS: carbon sequestration, net primary productivity, dynamic change, tropical urban climate

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Introduction

Reducing climate change risk is a main focus of discussion at the global and regional scales. One of the main agendas to reduce climate change risk through the Intergovernmental Panel on Climate Change (IPCC) Working Group 1 in 1990 and 2000 is by reducing the amount of carbon emissions in the atmosphere. Several strategic formulations have been initiated, such as the Reducing Emissions from Deforestation and Forest Degradation (REDD+) program, the carbon trade mechanism and the carbon fund (Guitart and

Rodriguez 2010, Torres et al. 2013). As a country participating in this conference panel, Indonesia also has a big commitment to reduce carbon emissions. This commitment is contained in a government regulation regarding the National Action Plan for Reducing Greenhouse Gas Emissions. This regulation contains the commitment of Indonesia to reduce carbon dioxide emissions by 26% independently and 41% with the help of other parties. The regulation also provides a direct mandate to the administrative areas under the Indonesian state to support the national emission reduction targets through regional action.

The existence of these regulations is binding on all Indonesian administrative areas, both urban and rural. This condition gives rise to a problem, especially in the urban areas. Human activities in urban areas related to increased built-up land areas cause a decrease in the green open space. Green open spaces, including forest areas, which play an important role in the efforts to reduce global carbon emissions, are actually decreasing as a result of being converted to built-up land areas. The reduced area of green open spaces in urban areas can reduce the potential of carbon dioxide sequestration and the target for

achieving a reduction in carbon dioxide emissions at the regional and global levels.

This condition occurs in Surakarta City, where the built-up land area has increased over the past 10 years (see Table 1). The development of built-up land areas in Surakarta City has reduced green open spaces, such as agricultural lands, private gardens and estates.

Several locations of green open land conversion in Surakarta City can be seen in Figure 1. Massive constructed built-up land has occurred in Surakarta City, which causes almost 80% of the city's area to be dominated by built-up land for industry and settlements. The actual condition of Surakarta City landuse can be seen in Figure 2.

This landuse conversion in Surakarta City is followed by an increasing trend of carbon dioxide emissions (Fig. 3). This increasing trend is triggered by the use of motorised vehicles and industrial activities that emit a large amount of carbon dioxide into the atmosphere. Therefore, it needs concrete efforts to reduce carbon emissions, one of which is by carrying out an inventory of potential carbon dioxide sequestration as a direction for land use change policies based on carbon sequestration in urban areas, especially in Surakarta City.

Table 1. Comparison of landuse area in Surakarta City in 2009 and 2019 (acc. to Statistical Bureau of Indonesia (Badan Pusat Statistik 2019).

Landuse	Year	
	2009 [ha]	2019 [ha]
Settlement	2809.64	2889.83
Industrial building	688.77	737.17
City/public garden	12.59	12.11
Agricultural land	136.56	86.63
Shrubs	257.74	237.14
Mixed garden	145.23	119.88
Riparian	46.62	46.62
Bare land	286.89	274.10
Total	4404.06	4404.06

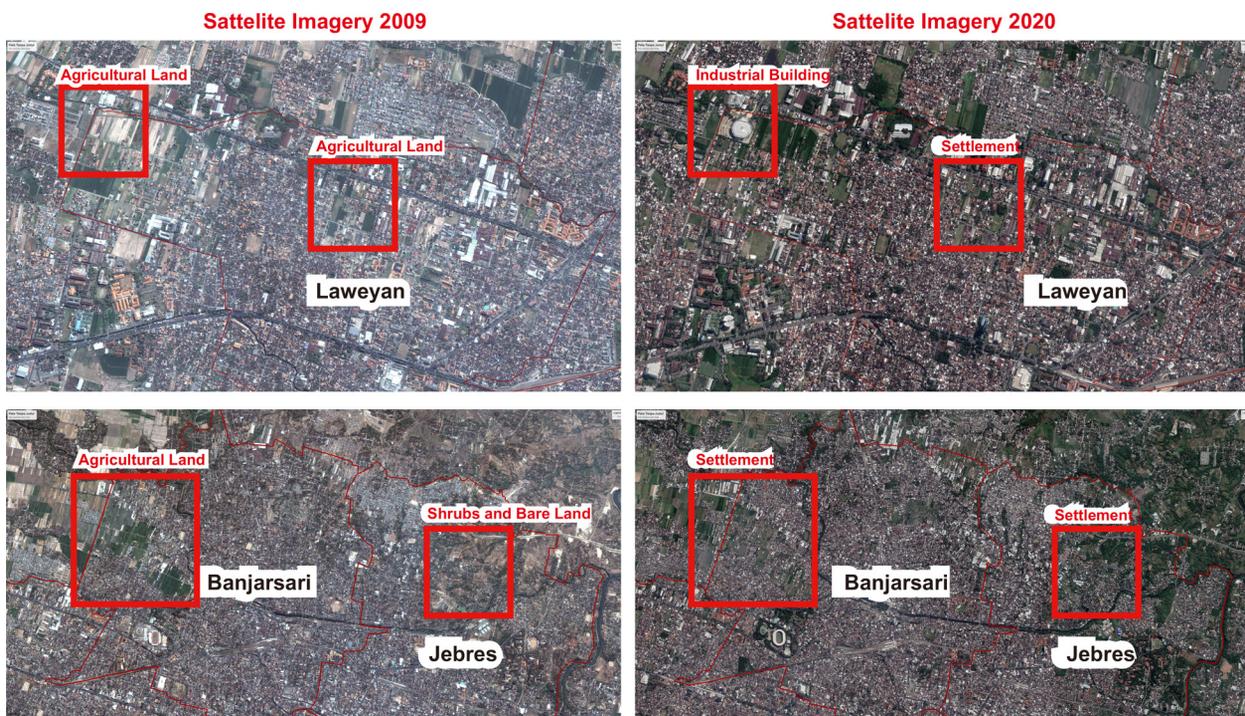


Fig. 1. Several locations of landuse change in Surakarta City during 2009–2019.

The first step that can be taken to reduce carbon emissions is by conducting an inventory of potential carbon storage areas. Until now, the carbon storage inventory used and calculated is the carbon storage of vegetation in forest areas (Schuur et al. 2001, Mukhortova et al. 2015). This is a problem for urban areas such as Surakarta City, which only has a narrow vegetated area. The narrow vegetated area will only result in a small potential carbon storage because the potential carbon storage is calculated based on the amount of vegetation type. In addition, the carbon storage estimation only illustrates the static potential that cannot change temporally due to environmental conditions change. Therefore, it needs more sensitive calculations to estimate carbon sequestration in narrow and dynamic vegetation areas according to environmental changes. Dynamic carbon sequestration calculation is expected to provide the potential for carbon sequestration in a given area per unit time.

Dynamic carbon sequestration can be modelled by estimating the value of ecosystem productivity.

Ecosystem productivity can describe the carbon flux between terrestrial and atmospheric ecosystems through photosynthesis and vegetation respiration. Photosynthesis can be used to determine the ability of a vegetated ecosystem to absorb carbon from the atmosphere (Wang et al. 2010, Gong et al. 2012, Bian et al. 2015). Meanwhile, respiration can be used to determine the carbon

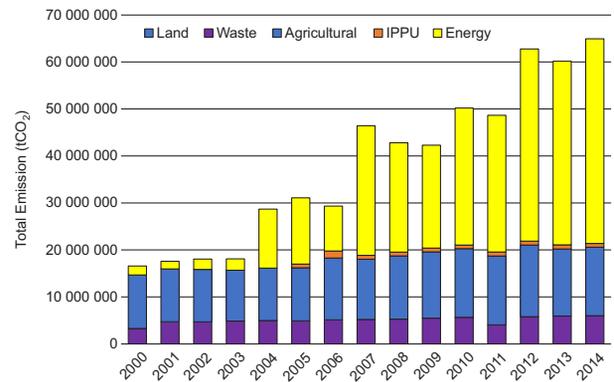


Fig. 3. Increasing trends of carbon dioxide emission form all sectors in Surakarta City (Kementerian Lingkungan Hidup dan Kehutanan Indonesia 2016).

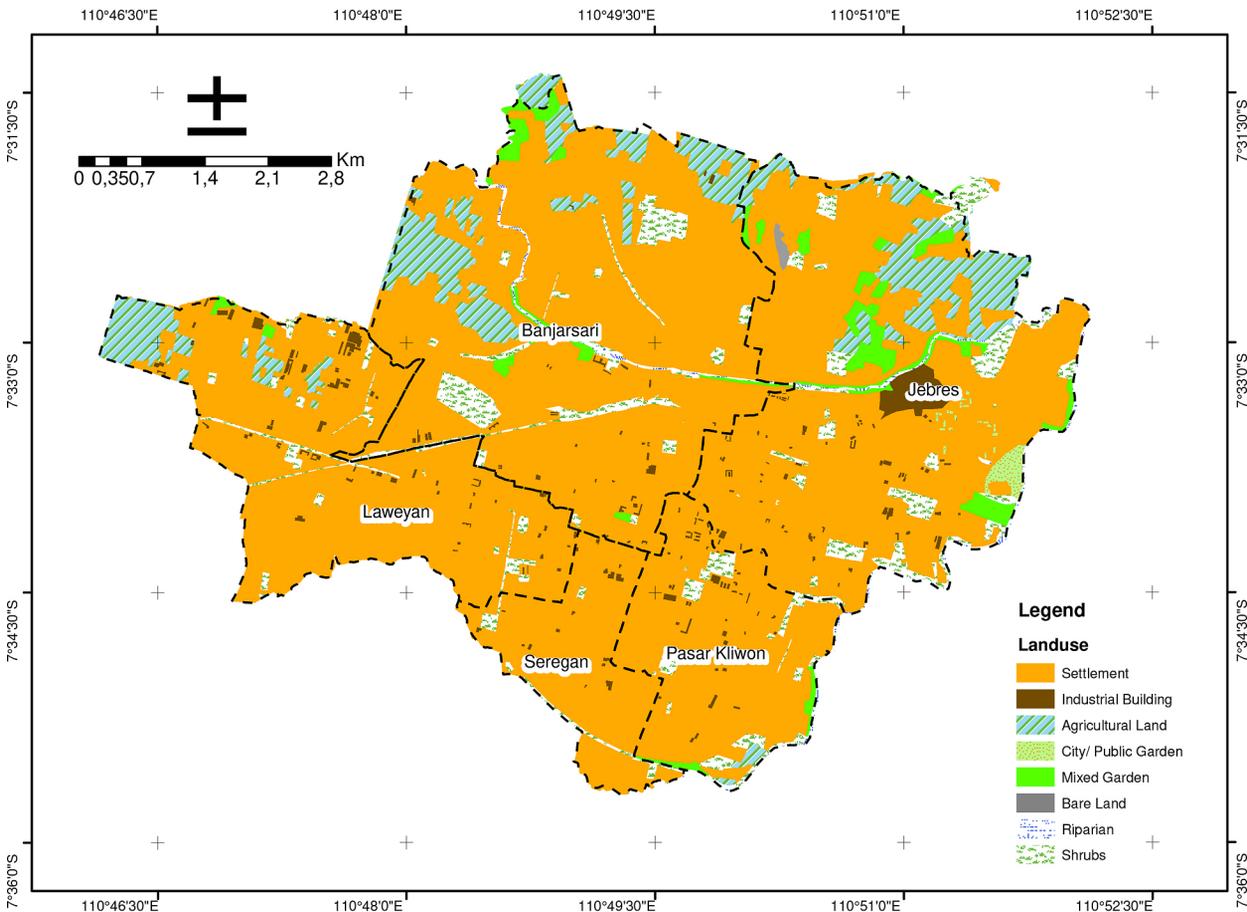


Fig. 2. Landuse map in Surakarta City.

flux from vegetated ecosystems to the atmosphere (Odum 1969, Prentice et al. 2000, Lovett et al. 2006). Ecosystem productivity modelling has been developed mainly by utilising remote sensing data. Several models have been developed such as the Carnegie–Ames–Stanford Approach (CASA) (Potter and Field 1993), the GLObal Production Efficiency Model or the GLO-PEM (Prince and Goward 1995), GLO-PEM 2 (Goetz et al. 2000) and the Vegetation Photosynthesis Model (VPM) (Xiao et al. 2005). The model is basically divided into three main theoretical frameworks, namely (1) Net Primary Productivity (NPP) value, which is related to the amount of solar energy absorbed by vegetation or called Absorbed Photosynthetically Active Radiation (APAR); (2) APAR and Fraction Absorbed Photosynthetically Active Radiation (FPAR), which can be estimated from remote sensing data with vegetation models such as spectral vegetation indices (SVI), normalised difference vegetation index (NDVI) and simple ratio (SR); and (3) the actual conversion from APAR to carbon, namely the maximum light use efficiency (LUE) caused by biophysical dynamics (Chen et al. 2004, Running et al. 2004).

All of these models are often applied to dense vegetated areas such as forest areas, either protected or production forests, to estimate the potential value of dynamic carbon sequestration from vegetation (Chen et al. 2017). Numerous studies in Indonesia have analyzed the response characteristics of terrestrial ecosystem NPP in tropical forest areas such as in Sumatra and Kalimantan (Potter et al. 2013, Basuki et al. 2019). However, it is still rare that research on estimating the carbon uptake using ecosystem productivity models carried out in sparsely vegetated areas, especially in urban areas covered by built-up areas (Chen et al. 2017, Wu et al. 2020). Research on the potential carbon sequestration in urban areas, especially using the ecosystem productivity model (NPP), has never been carried out in Indonesia. Several studies that have been carried out are limited to calculate the static carbon storage in green open spaces in urban areas (Oviantari et al. 2018, Yasin 2018).

In addition, the ecosystem productivity model (NPP) can be used to determine the dynamic changes in carbon dioxide sequestration. Dynamic change in the NPP value is the result of multiple factors such as topographic,

soil characteristics, vegetation type and human activities (Wang et al. 2018, Chen et al. 2019). However, NPP is more sensitive to change in climate and anthropogenic activities, especially land use change and land manipulation (Jiao et al. 2018, Luo et al. 2018). Changes in seasonal vegetation types on agricultural lands or private gardens can affect changes in the NPP value in a short period (monthly).

This study attempts to estimate the ecosystem productivity using the CASA model in urban areas in Surakarta City. This research is done to determine the potential for carbon uptake in relatively narrow green open spaces in urban areas, so that the role and effectiveness of green open spaces can be identified in an effort to reduce carbon dioxide emissions.

Modelling of ecosystem productivity in urban areas in Surakarta City will be carried out on a monthly basis for a year. It is necessary to vary the temporal value of the monthly ecosystem productivity because some vegetated land in urban areas is very dynamic and volatile, such as agricultural land and mixed gardens. Changes in vegetation conditions in agricultural land and mixed gardens are possible because the age of the plants is classified as seasonal, only ranging from 3 months to 4 months. During rainy season, agricultural land and mixed gardens are planted with food crops such as paddy, vegetables, and/or fruits, while during dry season, these lands are planted with dry plants such as corn and cassava. In addition, the potential for conversion of vegetated land to built-up land in urban areas is enormous due to the relatively fast population growth in urban areas. Changes in vegetation conditions both vegetation phenology and as a result of human activities can affect the value of ecosystem productivity. Therefore, if temporal ecosystem productivity variation in urban areas is carried out, it will be possible to know the net carbon sequestration value produced by these areas for a year and the dynamic caused by climate condition and anthropogenic activity, especially vegetation types changing in crop lands. This can facilitate land use planning as an effort to reduce carbon emissions in urban areas. The purposes of this study are to determine the spatiotemporal variation of ecosystem productivity and carbon dioxide sequestration in urban areas in Surakarta, Central Java Province, Indonesia.

Methods

Study area

Surakarta City is part of the Central Java Province which is located at the coordinates of 7.521–7.597° south latitude and 110.766–110.871° east longitude. The city is located in the middle of Central Java Province along the Bengawan Solo River. The accurate location of Surakarta City can be seen in Figure 4. Surakarta City is administratively divided into five districts with a total area of 44.04 km².

The climate in Surakarta is tropical, according to the Schimdt–Fergusson climate classification. Based on the Bureau of Meteorology, Climatology, and Geophysics Indonesia or Badan Meteorologi, Klimatologi, dan Geofisika Indonesia (BMKG) data, rainfall conditions in the study area ranged from 2262 mm a⁻¹ with a wet month period of 8 months and a dry period of 4 months. The highest rainfall occurs from November to April. The temperature conditions

in Surakarta City during a year is in the warm category, ranging from 24.5°C to 26.5°C. Warm temperature in the study area during the year happens due to optimal solar radiation received in this city at a value range of 500 MJ m⁻² d⁻¹ every day.

The topography of Surakarta is dominated by lowland areas with slopes ranging from 0% to 3%. Almost all areas in Surakarta are located in plain areas with dominant geomorphological processes in the form of erosion and sedimentation resulting from the activity of the Bengawan Solo River. Therefore, the dominant landforms in Surakarta are alluvial plains and floodplains having typical soil called alluvial soil (Entisols) that originates from the process of river deposition. Alluvial soil dominates over Surakarta City because of the location of this city alongside the Bengawan Solo River (Rahayu 2017). The alluvial soil has a loamy texture with a balanced percentage of sand, dust and clay. The soil colour tends to be blackish-brown and contains high organic matter.

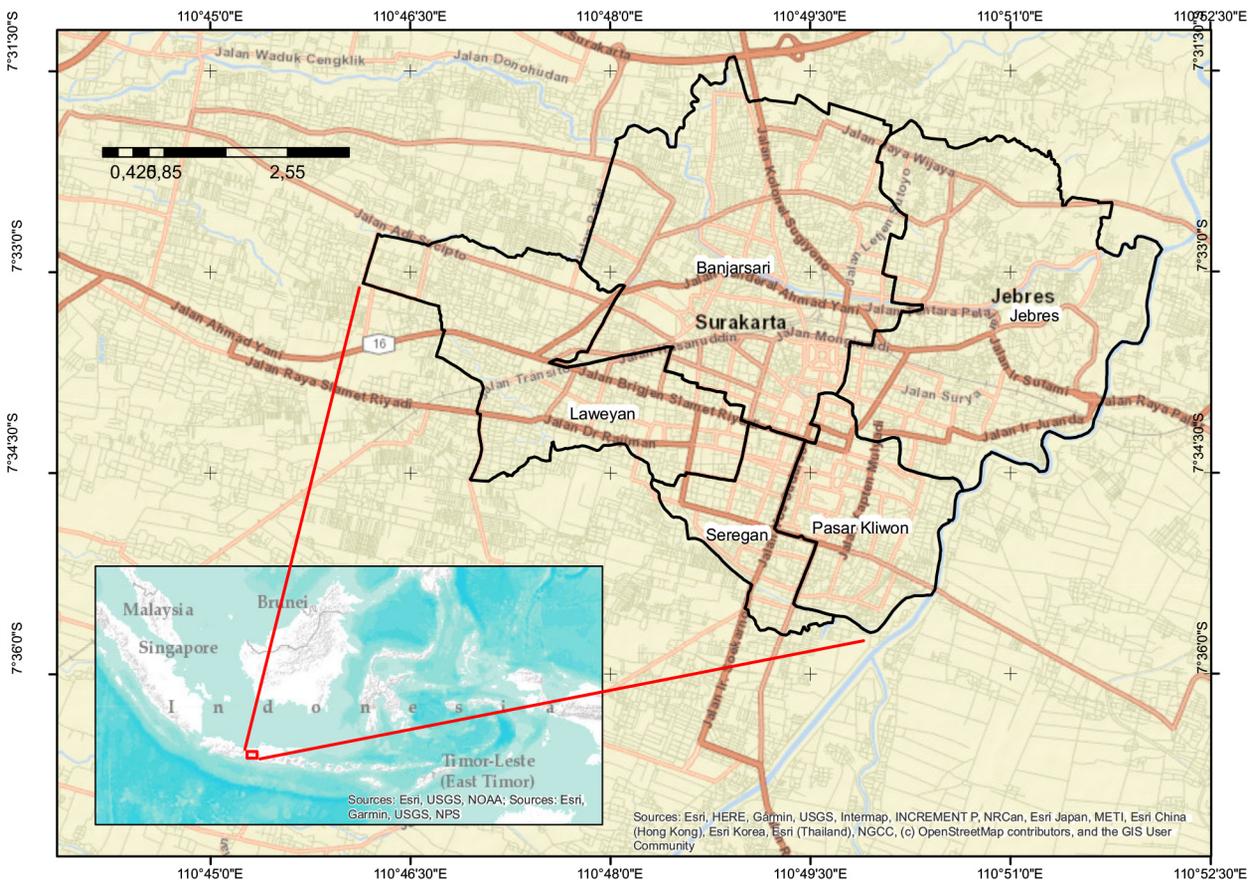


Fig. 4. Location of Surakarta City
Source: www.openstreetmap.org.

This topography and climate condition make the research area potential for abundant water and fertile land resources. It can be seen from the land use in Surakarta that it is dominated by agricultural land and built-up land. Agricultural land is scattered on the border of Surakarta City and extends to the surrounding districts, while the built-up land is scattered centrally and spread evenly throughout Surakarta City. Rapid

development of residential and industrial areas is the main reason for the large built-up land in Surakarta City.

Green open spaces, such as agricultural land, city/public garden, riparian, mixed garden, and shrubs, are still be found in Surakarta. Each type of green open space in Surakarta City has different types of vegetation. The types of vegetation found in the city/public gardens and riparian are dominated by woody plants with a wide canopy such as trembesi (*Samanea saman*), banyan (*Ficus benyamina*), mahogany (*Swettiana mahagoni*) and casia (*Cassia* sp.). The various types of vegetation found in these two landuses can be seen in Table 2. All vegetation that grows in city/public gardens and riparian has great potential in absorbing carbon dioxide, because it has a wide canopy. Vegetation types in these land uses tend to be constant and do not change seasonally. The vegetation conditions in city/public garden and riparian can be seen in Figure 5.

Meanwhile, the types of vegetation experience seasonal changes in agricultural land and mixed gardens. During the rainy season, the type of vegetation in agricultural land is paddy (*Oryza sativa*), while during the dry season, the agricultural land is planted with dry land crop plants such as corn (*Zea mays*) and cassava (*Manihot*

Table 2. Various types of vegetation in green open space in Surakarta City (acc. to Maridi et al. 2014).

Number	Name of species	
	Tree species	Lower crop species
1.	<i>Albizia falcata</i>	<i>Ageratum conyzoides</i>
2.	<i>Artocarpus altilis</i>	<i>Amaranthus spinosus</i>
3.	<i>Artocarpus integra</i>	<i>Amorphophallus titanum</i>
4.	<i>Cassia siamea</i>	<i>Canna edulis</i>
5.	<i>Ficus ampelas</i>	<i>Chloris barbata</i>
6.	<i>Hibiscus tiliaceus</i>	<i>Clitoria ternatea</i>
7.	<i>Leucaena glauca</i>	<i>Elephantopus scaber</i>
8.	<i>Morinda citrifolia</i>	<i>Eleusine indica</i>
9.	<i>Muntingia calabura</i>	<i>Galinsoga parviflora</i>
10.	<i>Samanea saman</i>	<i>Hyptis pectinata</i>
11.	<i>Swietenia mahagoni</i>	<i>Imperata cylindrica</i>
12.	<i>Tectona grandis</i>	<i>Kyllinga monocephala</i>
13.		<i>Lantana camara</i>
14.		<i>Mimosa invisa</i>
15.		<i>Mimosa pudica</i>



Fig. 5. Vegetation conditions in city/public garden and riparian.

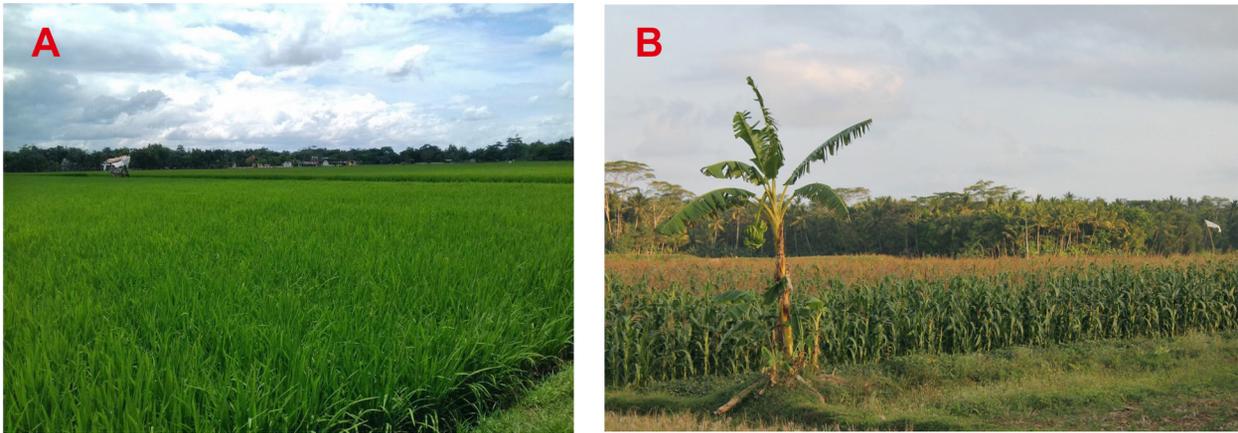


Fig. 6. Comparison of vegetation types in agricultural land during (A) wet season and (B) dry season.

esculenta). Agricultural land conditions during the rainy and dry seasons can be seen in Figure 6.

Furthermore, the mixed garden is dominated by annual cultivated plants that have high economic value, such as teak (*Tectona grandis*), mahogany (*Swettiana mahagoni*) and fruit plants such as banana, mango, sapodilla and guava. The types of vegetation in mixed gardens are also very dynamic, depending on human activities and desires. Most of the mixed gardens are privately owned by the community and are a part of house yards.

Data collecting

Data collected in this study were monthly NDVI (January–December) in 2019 - monthly climate data for the past 10 years (2008–2019) consisted of rainfall data, temperature, relative humidity and solar radiation - and land cover data of Surakarta City in 2019. Vegetation index data (NDVI) was obtained using Sentinel 2A imagery from January to December 2019, provided by ESA Copernicus through the website <https://scihub.copernicus.eu/>. Before being used for modelling, geometric and radiometric corrections were made on the Sentinel 2A images. The corrected images were used to calculate the normalized difference vegetation index (NDVI) using Formula 1.

$$\text{NDVI} = (\text{NIR} - \text{Red}) / (\text{NIR} + \text{Red}) \quad (1)$$

Furthermore, monthly climate data from 2008 to 2019 were obtained from the weather station of the Indonesian Climatology and

Geophysics Agency (BMKG) and data released by NASA through the website <https://power.larc.nasa.gov/data-access-viewer/>. Land cover data in 2019 were obtained from the Geospatial Information Agency through the Ina-geoportal website, which was detailed using satellite imagery released by Google Earth 2019. Land cover data updating was done using the interpretation technique and digitising directly on the satellite imagery. The land cover data used in this study were vegetation cover in Surakarta City to build the model of carbon sequestration from the photosynthesis process.

Data analysis

Carbon sequestration in the study area was modelled using NPP. NPP value was used to calculate the amount of carbon dioxide absorbed by vegetation during the photosynthesis process. NPP value was calculated using the method developed by CASA (Wang et al. 2010). NPP using CASA method was modelled using multispectral remote sensing images and climate parameter data (temperature, humidity, solar radiation, evaporation and rainfall) for at least 1 year. NPP was calculated with the following formula:

$$\text{NPP}_{(\text{month})}(x,t) = \text{GPP}(x,t) - \text{Rd}(x,t) \quad (2)$$

where:

- $\text{NPP}_{(\text{month})}$ is monthly net primary production ($\text{gC m}^{-2} \text{month}^{-1}$),
- GPP is monthly gross primary production ($\text{gC m}^{-2} \text{month}^{-1}$),
- Rd is autotrophic respiration consumption,

- (x,t) are spatial and time factors.

$$GPP(x,t) = \varepsilon \times SOL \times FPAR(x,t) \times 0.5 \quad (3)$$

where:

- ε is light energy utilisation,
- SOL is solar radiation ($MJ m^{-2}$),
- FPAR is fractional absorption of photosynthetically active radiation.

FPAR value was approximated by the transformation value of the NDVI. Initially, NDVI was developed to perform the spectral enhancement of vegetation and to reduce the effects of atmospheric transmittance, topography and solar elevation-azimuth (Danoedoro 2012). Myneni and Williams (1994) then created a formula using the NDVI linear model to find the FPAR.

$$FPAR = 0 \quad NDVI < 0.123$$

$$FPAR = \{1.164 \times NDVI - 0.04393\} \quad NDVI > 0.123 \quad (4)$$

$$NDVI = (NIR - Red) / (NIR + Red) \quad (5)$$

where:

- NIR is reflectance value of near-infrared band,
- Red is reflectance value of red band.

$$\varepsilon_{(x,t)} = T_{\varepsilon}(x,t) \times W_{\varepsilon}(x,t) \times \varepsilon_{\max} \quad (6)$$

where:

- T_{ε} is temperature effect on light energy consumption,
- W_{ε} is temperature effect on light energy consumption,
- ε_{\max} is maximum value of light energy utilisation in each ecosystem.

This value is taken from the BIOMECC-BGC classification (Running et al. 2000). The value of ε_{\max} based on BIOMECC-BGC classification can be seen in Table 3.

$$T_{\varepsilon}(x,t) = \frac{1}{(1 + e^{4.5 - T}) - (1 + e^T - 37.5)} \quad (7)$$

where:

- T is monthly temperature ($^{\circ}C$).

$$W_{\varepsilon}(x,t) = 0.5 + 0.5 \times \frac{E(x,t)}{Ep(x,t)} \quad (8)$$

where:

- E is actual evapotranspiration (mm),
- Ep is potential evapotranspiration (mm).

$$E(x,t) = \frac{P(x,t) \times Rn(x,t) \times [(P(x,t))^2 + (Rn(x,t))^2 + P(x,t) \times Rn(x,t)]}{[P(x,t) + Rn(x,t)] \times \{(P(x,t))^2 + (Rn(x,t))^2\}} \quad (9)$$

where:

- Rn is monthly clear solar radiation ($MJ m^{-2}$),
- P(x,t) is monthly precipitation (mm).

$$Rn = SOL \times (1 - r) - I \quad (10)$$

where:

$$r = 0.54r_1 + 0.32r_2 + 0.035,$$

- r_1 is reflectance value of red band,
- r_2 is reflectance value of near-infrared band.

$$I = 4.903 \times 10^{-9} \times (273 + T)^4 \times 0.48 \times (0.10 + 0.90) \left(\frac{n}{N}\right) \quad (11)$$

$$\left(\frac{n}{N}\right) = \text{solar radiation duration:}$$

$$\frac{\text{Total day in 1 month} \times \text{Solar radiation duration (h)}}{360}$$

$$Ep(x,t) = (E(x,t) + E_{po}(x,t)) / 2 \quad (12)$$

where:

- $E_{po}(x,t)$ is evapotranspiration potential local. This value can be calculated using the Thornthwaite-Matter Model (Thornthwaite 1948) (mm)

Table 3. Value of ε_{\max} based on Biomec-GCC classification (acc. to Running et al. (2000)).

Biomec-GCC classification	ε_{\max} value ($gC^{-1} Mj^{-1}$)
EBF	1.259
ENF	1.008
DBF	1.004
DNF	1.103
Mixed forest	1.116
Woodland	0.864
Closed shrubland	0.888
Closed shrubland	0.774
Cropland	0.604
Wooded grassland	0.768
Grass	0.604

DBF - deciduous broadleaf forest; DNF - deciduous needleleaf forest; EBF - evergreen broadleaf forest; ENF - evergreen needleleaf forest.

$$Epo(x,t) = 1.62 [10 \cdot T_n / I] a \times \left(\frac{n}{N} \right) \quad (13)$$

where:

- T_n is monthly temperature ($^{\circ}\text{C}$),
- I is annual heat index (S_i),
- i is monthly heat index $(T_n/5)^{1.514}$,
- a is coefficient $a = 675.10^{-9} \times I^3 - 771.10^{-7} \times I^2 + 179.10^{-4} \times I + 0.4923$.

$$Rd = \frac{7.825 + 1.145T}{100} \times GPP \quad (14)$$

Furthermore, the value from the NPP model resulted in single carbon (C) sequestration, which was converted into carbon dioxide (CO_2) sequestration with Eq. (15) (Archer 2010).

$$\text{Total value of } \text{CO}_2 \text{ sequestration} = \text{NPP values} \times (44 \text{ gCO}_2 / 12 \text{ gC}) \quad (15)$$

Results

Annual net carbon sequestration value

Carbon sequestration in the study area was modelled using net productivity value through a photosynthesis process known as NPP. NPP describes the amount of solar radiation energy that is converted by vegetation into chemical energy to produce food. This process requires an amount of carbon to be absorbed from the atmosphere around vegetation. The modelling results show that the annual average NPP in Surakarta City is $4.79 \text{ tC ha}^{-1} \text{ a}^{-1}$. The highest average annual NPP value is in Jebres District at $5.82 \text{ tC ha}^{-1} \text{ a}^{-1}$, whereas the lowest value is in Seregan District at $3.82 \text{ tC ha}^{-1} \text{ a}^{-1}$. The annual average NPP value district-wise in Surakarta City can be seen in Figure 7.

Based on the NPP value, the carbon dioxide sequestration in the study area can be calculated. The calculation results show that the average carbon dioxide sequestration in Surakarta is $14.38 \text{ tC ha}^{-1} \text{ a}^{-1}$. Similar to the NPP value, the largest average value of carbon dioxide sequestration was found in the Jebres District area at $17.47 \text{ tC ha}^{-1} \text{ a}^{-1}$, while the lowest value was in Seregan District area at $11.52 \text{ tC ha}^{-1} \text{ a}^{-1}$. The average annual value of carbon dioxide sequestration district-wise in Surakarta City is presented in Figure 7.

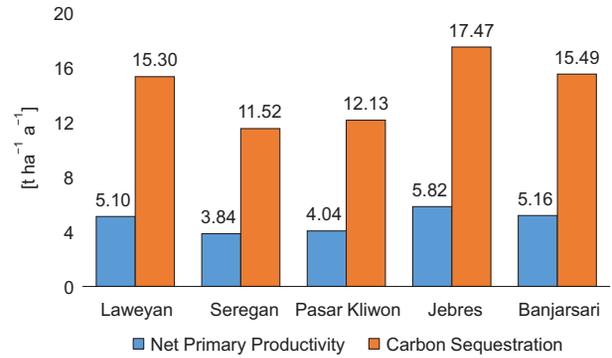


Fig. 7. Annual value of net primary productivity (NPP) and carbon dioxide sequestration in Surakarta City.

The NPP and carbon dioxide sequestration in Surakarta City form a unique spatial pattern. The NPP and carbon dioxide sequestration values in the middle of the study area have a very low value, even close to zero. Meanwhile, the highest NPP and carbon dioxide sequestration values spread in the suburbs of Surakarta City bordering other regencies or cities. These values are scattered in the northern part and extend westward along the Jebres, Banjarsari and Laweyan Districts. These areas form the border between Surakarta City and Boyolali and Karanganyar Regencies. The spatial pattern of the NPP and carbon dioxide sequestration follows the land cover pattern. In the western and northern parts of Surakarta, the NPP and carbon dioxide sequestration values are very high due to the existence of irrigated agricultural land. High carbon sequestration in irrigated agricultural land is caused by the existence of crop vegetation such as paddy, corn and cassava, which have the potential to absorb some carbon dioxide from the atmosphere. While, on the eastern side, which extends from north to south (the areas of Pasar Kliwon and Banjarsari sub-districts), the NPP and carbon sequestration also have a high value. These areas are the riparian zone of the Bengawan Solo River, which on the right and left are still overgrown with vegetation. The vegetation types in this area are dominated by woody plants that have a wide canopy such as trembesi, mahogany and banyan. In the middle of the study area, the NPP and carbon dioxide values also have a high value, especially in the city park area/public garden that is deliberately intended for public green open spaces. Vegetation types in public gardens are similar with riparian vegetation such as trembesi,

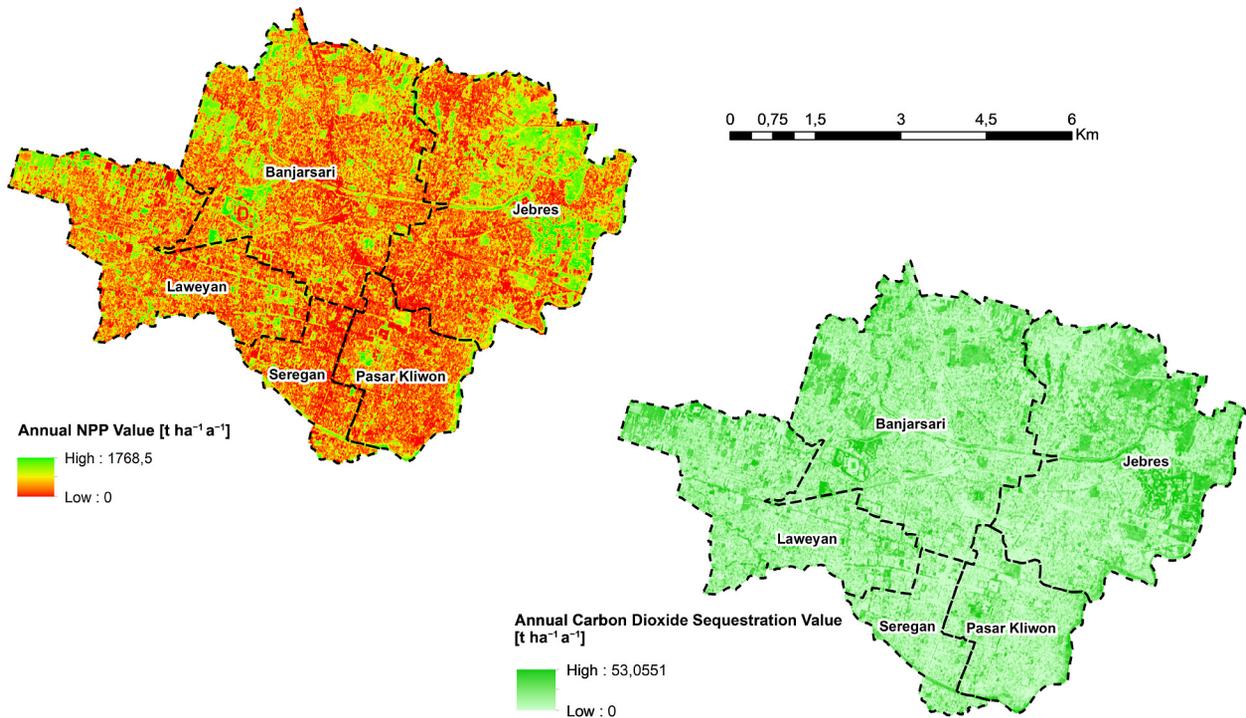


Fig. 8. Distribution of annual net primary productivity (NPP) and carbon dioxide sequestration in Surakarta City.

banyan and cassia, which have a high potential to absorb carbon. The spatial pattern of NPP and carbon dioxide sequestration values in Surakarta City can be seen in Figure 8.

The average value of carbon dioxide sequestration can be used to determine the potential of the ecosystem in Surakarta City to absorb carbon dioxide from the atmosphere during a year. The total value of carbon dioxide sequestration potential in Surakarta City for a year is $7.12 \text{ GtCO}_2 \text{ a}^{-1}$. This value is mostly contributed by the vegetation in the green open space area. The forms of green open space in the study area are mixed gardens, yards, city parks and agricultural land.

Spatiotemporal variation of carbon sequestration

The NPP and carbon dioxide sequestration values in Surakarta City not only have spatial variations but also unique temporal variations during a year. The NPP and carbon dioxide sequestration values in Surakarta have increased and decreased trends during 1 year. The annual dynamics of these values are divided into three periods. The first period occurs from January

to March, where the NPP and carbon dioxide sequestration values increase until reaching the peak in March. This condition occurs during the rainy season and the transition between the rainy and dry seasons. It is marked by high rainfall values from January to February and decreases towards March. The second period occurs from April to August, where the NPP and carbon dioxide sequestration decrease along with the decreasing value of rainfall or nearing the peak of dry season. The third period occurs from September to December, where the NPP value and carbon dioxide sequestration values increase. This condition occurs in the transition between the dry and rainy seasons, which is marked by increasing rainfall from September to December. The annual temporal variation of the NPP value and climate factors in Surakarta can be seen in Figure 9.

Based on Figure 9, it can be seen that the peak of NPP value occurs during the transition from the rainy season to dry season, while the lowest NPP value occurs at the peak of the dry season (rainfall value is low). The highest value of NPP in Surakarta was in March at $529.10 \text{ gC m}^{-2} \text{ month}^{-1}$, while the lowest value occurred in

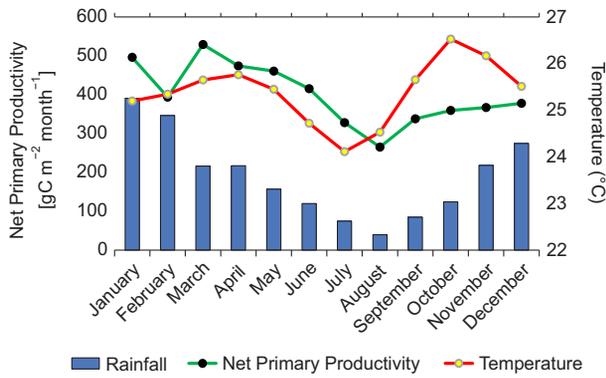


Fig. 9. Temporal variation of net primary productivity (NPP) and climate condition in Surakarta City.

August at $265.05 \text{ gC m}^{-2} \text{ month}^{-1}$. Furthermore, based on Figure 9 it was known that the dynamic change in carbon dioxide sequestration value is similar to the dynamics change in NPP value during a year.

The annual temporal variation in carbon dioxide sequestration in the sub-districts of Surakarta has the exact same pattern as the annual variation of the carbon dioxide sequestration throughout Surakarta. The variation values of NPP and carbon dioxide sequestration during the year in five sub-districts in Surakarta are presented in Figure 10.

Based on Figure 10, it can be seen that the highest monthly NPP and carbon dioxide sequestration values are found in Laweyan District. This condition happens in every month during the year, except in February and October. In February, the highest monthly NPP and carbon dioxide sequestration values are found in Jebres District area, while in October it is in Banjarsari District. Seregan District is the region with the lowest NPP and carbon dioxide sequestration value in every month. Figure 10 shows that a significant change in the monthly NPP and carbon dioxide sequestration during the year occurs in Jebres District. This is indicated by the highest value of carbon dioxide sequestration at $1.46 \text{ t ha}^{-1} \text{ a}^{-1}$, while the lowest value of carbon dioxide sequestration is $0.70 \text{ t ha}^{-1} \text{ a}^{-1}$. This condition can be seen in the spatiotemporal pattern of the NPP and carbon dioxide sequestration values for a year throughout the Surakarta City area in Figure 11.

Based on Figure 11, it can be seen that the NPP and carbon dioxide sequestration values are

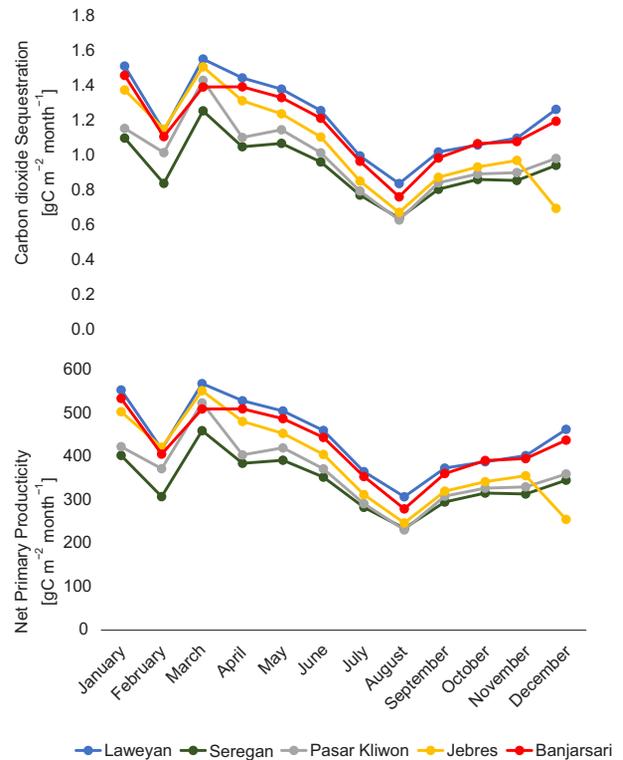


Fig. 10. (A) Temporal variation of carbon dioxide sequestration and (B) net primary productivity (NPP) in each district of Surakarta City.

very dynamic in the border areas of Surakarta, especially in the northern, western and eastern parts. From January to April, the northern area extending from west to east of Surakarta has a thick colour with NPP value range from 1.6 to $1.8 \text{ t ha}^{-1} \text{ month}^{-1}$ and carbon sequestration value range from 5 to $6 \text{ t ha}^{-1} \text{ month}^{-1}$, which indicate the high value of NPP and carbon dioxide sequestration. Meanwhile, from July to November the dark colour fades, which indicates that the NPP and carbon dioxide sequestration have reduced. The NPP value during this period ranges from 0.9 to $1.2 \text{ t ha}^{-1} \text{ month}^{-1}$, while the carbon sequestration value ranges from 2.4 to $3.6 \text{ t ha}^{-1} \text{ month}^{-1}$. Areas with highly dynamic NPP and carbon dioxide sequestration are vegetated areas, either in mixed gardens or agricultural land. Areas in the middle of the study area do not show any significant changes during the year. The NPP and carbon dioxide sequestration values in the middle of the study area tend to be small. When it is related to land cover, this area is mostly covered by built-up land area such as residential or office areas.

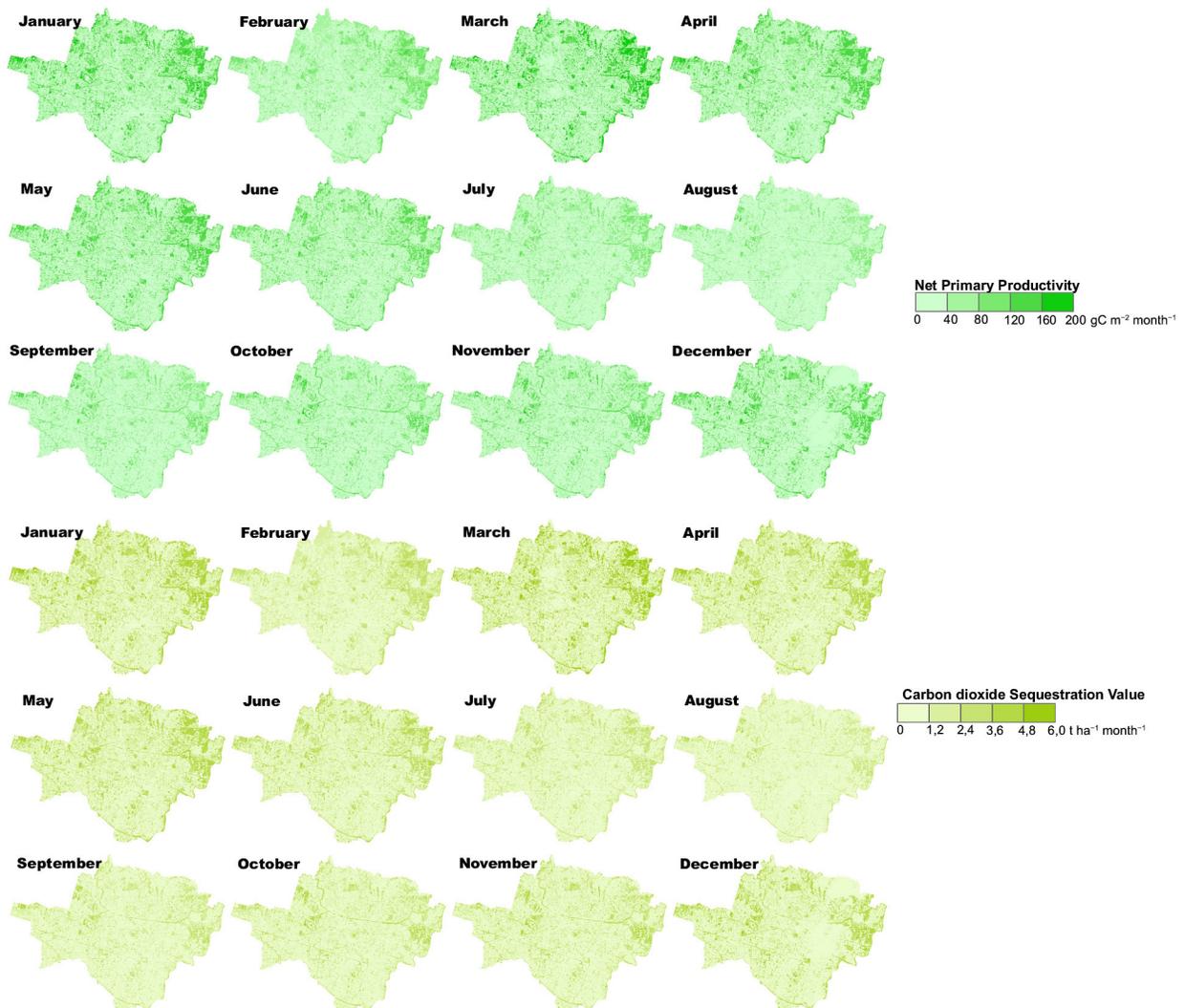


Fig. 11. Spatiotemporal maps of net primary productivity (NPP) and carbon dioxide sequestration in Surakarta City.

Discussion

The modelling results in the study area show that the carbon sequestration value follows the trend of the NPP value. Spatiotemporal patterns of carbon sequestration values are similar to those formed by the NPP values. The NPP in urban areas mainly in Surakarta City shows a value of 383–582 $\text{gC m}^{-2} \text{a}^{-1}$. This value is very small when compared with the value of NPP in the tropical forest areas. Several previous studies show that NPP in forest areas such as West Kalimantan (Basuki et al. 2019); Leuser forest area; Berau forest area in East Kalimantan; Papua forest area (Potter et al. 2013); and Sulawesi forest areas (Hertel et al. 2009) had much greater values. A comparison of the NPP value in various

tropical forest areas and study areas is presented in Table 4.

Based on Table 4, it can be seen that the NPP values between the urban and forest areas show very high disparity, even though they are both located in tropical areas. The difference in NPP values between these two areas is due to the vegetation density and variation type (Malhi et al. 2011, Basuki et al. 2019, Ji et al. 2020, Yang et al. 2020). Vegetation in forest areas has a high-density value compared to the vegetation in urban areas. Vegetation in urban areas that only grows on home yards or city parks is not as dense as in forest areas, due to human cutting and maintenance activities to make it look neat. In addition, vegetation in urban areas, which tends to be homogeneous, makes the NPP value relatively small. The

NPP value on land with low vegetation diversity (homogeneous) will be much smaller compared to that on land with high vegetation diversity (heterogeneous), such as in tropical forest areas (Malhi et al. 2011, Ji et al. 2020).

On the other hand, NPP in the study area has a relatively high value compared with that of the NPP value in urban areas located in temperate climates. Several studies in urban areas, especially temperate climate areas such as Anhui, China (Yang et al. 2020); Nanjing, China (Zhou et al. 2015); Southeastern, United States (Milesi et al. 2003); Liaoning, China (Chen et al. 2017); and Guangzhou City, China (Wu et al. 2020) showed relatively small NPP values compared with the NPP values in the study area. A comparison of the NPP value in the study area with other urban areas can be seen in Table 5. The NPP value in Surakarta is still high due to the presence of open spaces overgrown by vegetation, such as in public gardens, house yards (private garden), mixed garden and riparian zones. In addition, the existence of agricultural land in the border of Surakarta City also plays an important role in contributing to the NPP value in the study area. This condition is very different from China and the United States, where the urban areas in the two countries are dominated by built-up area in the form of residential and industrial areas which have an NPP value close to zero (Milesi et al. 2003, Zhou et al. 2015, Wu et al. 2020).

Another factor that affects the difference between the NPP value in urban areas with the

tropical and moderate climates is the annual dynamics of the NPP value. The NPP value in the study area shows the monthly dynamics during the year. The NPP value increases at the end of the dry season leading to the rainy season (growing season) and declines again towards the dry season. This dynamic trend occurs due to variation in the environmental factors, especially climate and anthropogenic activity.

Anthropogenic activities that can lead to NPP variation value are human intervention in land such as land conversion and changes in vegetation types (Milesi et al. 2003, Chen et al. 2017, Yang et al. 2020). Land conversion from vegetated land to built-up land is a dominant factor that declines the NPP value (Yang et al. 2020). Losing vegetation as an actor producing NPP value is the main cause for this condition. However, this condition cannot be proven in this research because there are no indications of any land conversion activity during the year of observation in the study area. Meanwhile, changing the type of vegetation, especially on agricultural land located on the border of Surakarta City, causes NPP value in this land to fluctuate. When agricultural land is planted with rice or 'palawija' such as corn, cassava and nuts, the NPP value tends to be higher than when the agricultural land is harvested and left as bare land. It can be seen from the NPP value in agricultural land, which has a high value during the planting season, and will decline drastically close to zero during the dry season. Whereas, in the other green open spaces

Table 4. Comparison of net primary productivity (NPP) in several tropical climate areas.

	Area	NPP value ($\text{gC m}^{-2} \text{a}^{-1}$)	Source
1.	Ketapang, Kalimantan Barat	13.200	Basuki et al. 2019
2.	Leuser, Aceh	8.950.000	Potter et al. 2013
3.	Berau, Kalimantan Timur	10.300.000	
4.	Kamulo Doso, Papua New Guinea	10.120.000	
5.	Merang, Sumatera Selatan	10.790.000	
6.	Sulawesi	8.400	Hertel et al. 2009

Table 5. Comparison of net primary productivity (NPP) in several urban areas.

	Area	NPP value ($\text{gC m}^{-2} \text{a}^{-1}$)	Source
1.	Anhui, China	200	Yang et al. 2020
2.	Nanjing, China	250-300	Zhou et al. 2015
3.	Laoning, China	227-252	Chen et al. 2017
4.	Guangzhou, China	183	Wu et al. 2020
5.	Guangdong, China	384	Jiang and Wu 2015
6.	Southern, United States	231-269	Milesi et al. 2003

areas such as public garden, mixed garden and riparian, the vegetation types are similar both in the dry and wet seasons. Woody plants such as trembesi, banyan, mahogany and teak do not change during a year. Therefore, the NPP value in these green open spaces has a relatively similar value during a year.

The climatic factors that cause differences in the NPP value are rainfall, temperature and solar radiation intensity (Wang et al. 2017, Ji et al. 2020). When rainfall is high, plants get a lot of water to grow, so the photosynthesis process takes place intensively, which is indicated by the high value of NPP (Lin et al. 2017, Yangyang et al. 2019). This happens in the study area from November to April, where there is a high rainfall value followed by an increase in the NPP value. The NPP value is dependent on the air temperature conditions. When air temperature is warm due to optimal solar radiation, the photosynthetic process is more intensive (Mao et al. 2014, Wang et al. 2017, Yangyang et al. 2019). This condition cannot be proven in the study area, because air temperature and solar radiation intensity have the same relative value every month during a year; however, the NPP value fluctuates every month. Therefore, the dynamics of NPP value in urban areas, especially in the tropical climate region are more likely to be controlled by human activities on land and rainfall conditions.

NPP in the study area shows dynamic trends annually with insignificant differences between the highest and lowest values ranging at $20 \text{ gC m}^{-2} \text{ month}^{-1}$. On the other hand, the NPP value in temperate urban areas actually in China has a significant difference between the highest and lowest value ranging at $80 \text{ gC m}^{-2} \text{ month}^{-1}$ (Wang et al. 2017). This condition makes the NPP value in the study area have a still higher value than the NPP value in the temperate urban areas. The difference in the dynamics of the NPP value during a year in the tropical and temperate urban areas is due to the length of the growing season. The longer the growing season the higher the NPP values (DeLucia et al. 2007, Yangyang et al. 2019). This condition is very suitable in the study area where the growing season occurs for 6 months from November to April, while in China the growing season occurs only for 3 months from March to May (Wang et al. 2017). The growing season is marked by high rainfall

accompanied by optimal solar radiation intensity. Optimal solar radiation in the study area for a year makes the possibility of an intensive photosynthetic process, so that the NPP value can remain high. This can have an impact on the ability of the ecosystem to absorb carbon dioxide from the atmosphere intensively during a year.

Conclusions

Carbon dioxide sequestration in urban areas shows a relatively small value compared with forest areas. The low carbon dioxide sequestration value in urban areas is due to the low vegetation density and homogeneous vegetation types. However, this value is relatively large compared to the other urban areas located in a temperate climate with four seasons. This condition happens because the urban areas in the study area still have some land that is devoted to overgrown vegetation in the green open spaces, either owned by the government or privately. In addition, the existence of large agricultural land in the border of study area also contributes to the carbon dioxide sequestration. Therefore, it is very important to quantify the carbon dioxide sequestration owned by urban areas in tropical climates, because it can be used as an effort to achieve targets for reducing carbon dioxide emissions.

The value of carbon dioxide sequestration in urban areas, especially in tropical climates, experiences monthly dynamics during a year. Increasing carbon dioxide sequestration occurs during 6 months during the transition from the rainy to the end of the rainy season. On the other hand, the carbon dioxide sequestration decreases during the dry season to the end of the dry season. These dynamic trends are influenced by two main factors, namely climate and anthropogenic activity. The climatic factor that causes the dynamics of carbon dioxide sequestration is rainfall. Temperature did not really matter because the study area had insignificant variations of temperature values during a year. The optimal reception of solar radiation is the cause of the temperature to be relatively warm during the year. Anthropogenic activity that affects the dynamics of carbon dioxide sequestration is the human activity of changing vegetation types. Apart from these two factors, there are other

factors that cause the dynamics of carbon dioxide sequestration. Therefore, further studies are needed by considering the dynamics of urban development such as conversion of built-in land as an antropogenic activities in urban areas and other environmental factors that affect vegetation growth such as the availability of groundwater, nutrients and organic matter. Production of carbon dioxide from antropogenic activities also needs to be done to assess the effectivity of the terrestrial ecosystem in urban areas, especially the green open space, to reduce carbon dioxide from the atmosphere.

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