

Green open space mapping and carbon stock estimation in Surakarta

*Sapta Suhardono*¹, *Titi Wahyuni*^{1*}, *Irfan Abu Nazar*¹, *Naila Maulida Ibriza*¹, and *Sovia Wijayanti*¹

¹Faculty of Mathematics and Science, Department of Environmental Science, Universitas Sebelas Maret, Surakarta 57126, Indonesia

Abstract. Development and urbanization have had a significant impact on the layout and land use in Surakarta. The research aims to map how far green open spaces have changed and estimate carbon reserves in Surakarta in 2019-2023. Green open space was mapped by accessing Sentinel 2A obtain by Google Earth Engine, whereas carbon stocks were assessed in each density class by the formula between carbon storage and NDVI values per pixel. The results, based on five years of annual data, indicate regions (GOS) with an extremely high concentration of vegetation decreased from 5,880 hectares in 2019 to 4,899.2 hectares in 2023. This trend reflects a loss in places with dense vegetation. Vegetation as the most substantial contributors to carbon stocks, based on data indicate the cumulative carbon storage decreased from 12,933,424.55 kg in 2019 to 12,518,281.65 kg in 2023, resulting in a loss of around 415,142.9 kg of carbon at the site during the past five years. These findings contribute to a greater understanding of plant dynamics and carbon storage capability in urban environments that giving useful insights for environmental planning and management in large cities.

1 Introduction

The development and the growth of a region usually always go hand in hand with an increase in population in an area, especially urban areas [1]. City development or urbanization often sacrifices the ecological value of land in exchange for more economical functions, in this case in the form of infrastructure development which generally takes the form of buildings and pavement which concretely support development. Cities have problems that continue to increase in spatial planning as time goes by. Not infrequently the problems that arise are caused by the development of the city itself. To be able to prevent this, city management is needed through a sustainable planning concept approach [1, 2]. Surakarta City, based on Law no. 26 of 2007 concerning Spatial Planning article 29 which states that the proportion of green open space (GOS) is at least 30% of the city area, consisting of 20% public green open space and 10% private green open space [1, 2, 3].

Open space is a space that is planned because of the demand for needs that can be done

* Corresponding author: titiwahyuni@staff.uns.ac.id

in open-air places. Theoretically, what is meant by open space is space that functions as a container for human life, both individually and in groups, as well as a container for other creatures to live and develop sustainably [4, 5]. Public Green Open Space is an important asset in cities that helps create a healthy, sustainable, and quality environment for the community. It is important for the government and local authorities to protect, maintain, and develop public green open spaces to provide benefits [6].

This is in line with the existence of green open spaces of important value in urban areas and must be taken into account in urban spatial planning both in terms of quality and quantity [7]. The functions of green open space include protecting the water system, reducing sound, fulfilling visual needs, preventing the development of built-up land or as a buffer, and protecting city residents from air pollution [6, 7]. Fulfillment of green open space is currently very much needed by a region, this can be done through planning and cooperation from various parties, namely collaboration between stakeholders, increasing community participation, and strengthening regulations which are carried out consistently and continuously. RTH as a public space is also a place for interaction that is able to increase social harmony so its existence is an absolute must in spatial planning [5, 6, 7].

High population growth in Surakarta results in high emissions [3]. Surakarta has very high potential and opportunities in terms of regional development and land conversion that will occur in the future. Surakarta has become a center of growth for the surrounding area which accommodates activities originating from Sukoharjo, Sragen, Karanganyar, Boyolali, Wonogiri, and Klaten [6, 7]. Meanwhile, carbon dioxide gas has a higher percentage in the time period 1750-2005 than other gases such as methane, nitrogen oxide, hydrocarbons, and other gases. The transportation sector is one of the largest sources of air pollution and greenhouse gases (GHG) in urban areas, followed by other sources of fine pollution emissions such as industry, households and commercial activities that produce CO₂, CH₄, and N₂O. According to Central Java Governor Regulation Number 43 of 2012, total emissions in 2010 reached 39,886,167 tons of CO₂(e) [6, 7].

From the results of calculating CO₂ emissions in Surakarta in the transportation sector, it is known that emissions produced by motorized vehicles in Surakarta in 2017 were 343,195.63 tons/year [6, 7]. Total CO₂ emissions in Surakarta City in 2017 were 1,309,906.98 tons/year. The total emissions from all activity sectors will later be calculated to determine the capacity of green open space in the city of Surakarta [7]. This research aims to find out whether the area of green open space 2018-2023 has changed or not. Second, estimate carbon stocks from 2018-2023 in Surakarta City, whether there has been a change or not. Third, provide advice to related parties or the public based on research results and discussions.

2 Research Methods

2.1 Research Materials

The data for this research uses remote sensing to analyze carbon reserves in the Surakarta city region. The satellite imagery utilized in this study comes from high-resolution Sentinel 2A, obtained using Google Earth Engine. Accessing Sentinel 2A using Google Earth Engine has various advantages, such as allowing users to access photographs throughout a wide date range without to download the raw data first. This is appropriate for our research, which monitors NDVI over a 5-years period. The cloud-based platform known as Google Earth Engine (GEE) facilitates the effective processing and analysis of extensive satellite imagery for a range of Earth monitoring applications [8, 9]. The GEE platform offers users access to a wide range of satellite image collections and datasets, including spatial resolutions of up to

10 meters [9]. The software facilitates intricate automation processes for several activities including crop mapping, land use categorization, air quality monitoring, and cultural heritage monitoring [8, 10, 11]. The Sentinel imaging used in this research is level 2-A data, obtained between 2019 and 2023. Sentinel-2 is the first satellite launched under the Copernicus program, managed by the European Space Agency (ESA) [12]. A multitude of uses exist for Sentinel data in diverse domains such as environmental monitoring, spatial planning, water resources, forestry, vegetation, carbon assessment, natural resource management, and global agricultural assessment [13]. Sentinel-2 satellite imagery consists of 13 bands (Table 1).

Table 1. Sentinel-2 band information based on Sòria-Perpinyà et al. (2022)

Band Number	Spectral Region	Central Wavelength (nm)	Spatial Resolution (m)
1	Coastal aerosol	442.7	60
2	Blue	492.4	10
3	Green	559.8	10
4	Red	664.6	10
5	Red-edge 1	704.1	20
6	Red-edge 2	740.5	20
7	Red-edge 3	782.8	20
8	NIR	832.8	10
8a	NIR narrow	864.7	20
9	Water vapor	945.1	60
10	SWIR/Cirrus	1373.5	60
11	SWIR 1	1613.7	20
12	SWIR 2	2202.4	20

Regarding the assessment of carbon storage potential in each density class, this classification is based on earlier research conducted in Syracuse, NY, USA [14]. The results of the research conducted by Soojeong Myeong reveal that the relationship between carbon storage and NDVI values per pixel is as follows:

$$\text{Carbon} = 107.2 \cdot e^{(\text{NDVI} \cdot 0.0194)} \quad (1)$$

Where Carbon is carbon storage (kg C/pixel) and NDVI is the Landsat NDVI value. The R² for Eq. (1) is 0.67.

2.2 Image Processing Procedure

The Sentinel 2 imagery was processed using Google Earth Engine by translating spectral values into the Normalized Difference Vegetation Index (NDVI). According to Klompaker et al. (2018) [15], the NDVI is calculated as the ratio of observed

reflectance between the red band (R) and the near-infrared (NIR) band in the electromagnetic spectrum. These two bands are chosen as vegetation index measuring parameters because they are sensitive to chlorophyll absorption and/or green vegetation. The NDVI formula may be generally represented by the following equation:

$$NDVI = (NIR - R) / (NIR + R) \quad (2)$$

Where :

NDVI : Normalized Difference Vegetation Index

NIR : Near-Infrared Band

R : Red Band

In this investigation, band 8 from Sentinel 2-A was used as the near-infrared (NIR) band, and band 4 as the red band (R). Therefore, the formula utilized is "NDVI = (band 8 - band 4) / (band 8 + band 4)." This NDVI technique gives index values ranging from a minimum of -1 to a high of 1. Each index value reflects vegetation density in a pixel, from areas with no vegetation to areas with very dense plant cover [16].

2.3 Data Analysis

The NDVI is commonly used to quantify vegetation density and biophysical properties [17]. NDVI values scale from -1 to 1, with larger values correspond to more compact vegetation [18, 19]. However, NDVI tends to saturate at moderate-to-high biomass levels, limiting its usefulness under dense vegetation [17]. Research indicates a significant association between NDVI and vegetation density, with primary and secondary dry forests showing the greatest NDVI coefficients [19]. NDVI has been utilized to assess carbon stocks, where higher NDVI values indicate increased carbon storage [20].

Table 2. Classification of land cover density is based on the normalized vegetation difference index with the total potential carbon storage in each density class

Number	NDVI Scores	Vegetation Description
1	$n < 0.10$	Very low/almost no vegetation
2	$0.10 < n < 0.20$	Low
3	$0.21 < n < 0.31$	Middle
4	$0.32 < n < 0.70$	Dense
5	$n > 0.70$	Very dense

3 Result and Discussion

3.1 Assessment of NDVI trends in Surakarta City

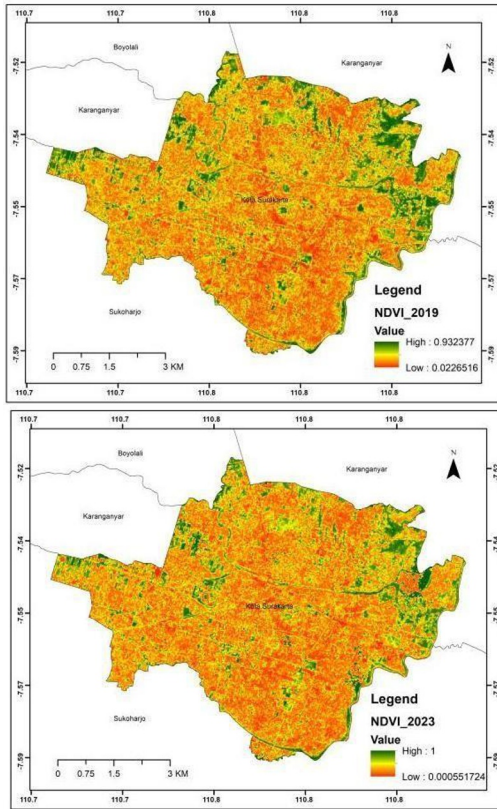


Fig. 1. Assessment of NDVI Trends in Surakarta City

An analysis of NDVI data for Surakarta City from 2019 to 2023 revealed numerous noteworthy patterns associated with vegetation changes in the area. The minimum Normalized Difference Vegetation Index (NDVI) values varied annually, starting at 0.02265 in 2019, decreasing to -0.00536 in 2021, and barely rising to 0.00055 in 2023. Negative values indicate places with no vegetation, such as water surfaces or open ground. Concurrently, the highest NDVI values consistently rose from 0.93237 in 2019 to 1 in both 2022 and 2023 indicating regions with highly well-maintained and densely packed vegetation.

Table 3. An analysis of NDVI data for Surakarta City

NDVI	2019	2020	2021	2022	2023
min	0.02265	-0.00323	-0.00536	-0.00295	0.00055
max	0.93237	0.98295	0.99288	1	1
mean	0.39447	0.37599	0.37387	0.36805	0.35908
Std dev	0.20726	0.21072	0.20626	0.22366	0.21171

Notwithstanding the rise in highest values, the mean NDVI declined from 0.39447 in 2019 to 0.35908 in 2023. This reduction suggests that, overall, vegetation in Surakarta City has seen deterioration or a decline in quality. This deterioration in vegetation health may have been influenced by factors such as heightened urbanization, land conversion, or other human activities. The NDVI variable's standard deviation rose from 0.20726 in 2019 to 0.21171 in 2023, reaching its highest point in 2022. This implies a rising variety in NDVI values, indicating significant variations between places with dense vegetation and those with more open or less vegetated zones.

Recent research has demonstrated that both climatic variables and human activities exert a substantial impact on the dynamics of NDVI. While precipitation is often the dominant climatic driver of vegetation changes [21, 22], the impact of temperature has lessened over time [23]. Analysis [21] has shown that human activities, particularly changes in land use, account for more than 70% of the variations in NDVI in certain areas. Factors such as agricultural growth, changes in fallow times, and adjustments in pastoral activities might affect NDVI trends [24]. Meng et al. (2023) [21] have demonstrated that the execution of ecological engineering projects plays a crucial role in promoting higher levels of vegetation in specific regions. However, the relationship between anthropogenic causes and NDVI is complex and often non-linear [22]. Understanding these dynamics is critical for effective vegetation management and restoration, particularly in arid and semi-arid settings [22, 21].

3.2 Vegetation Density Dynamics in Surakarta City

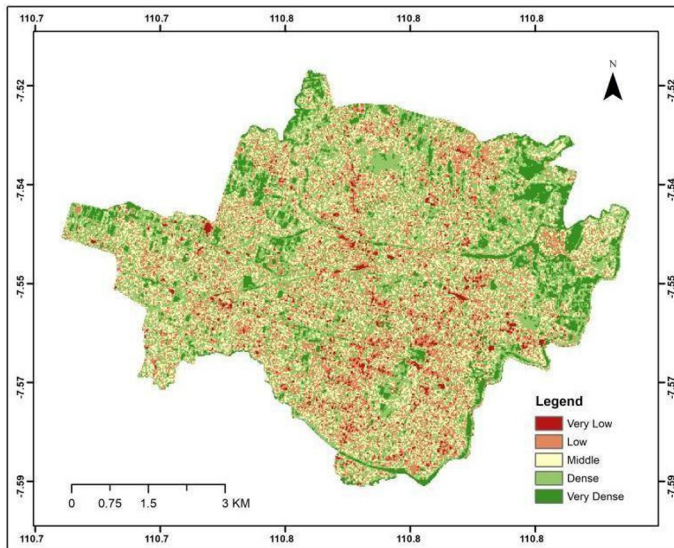


Fig. 1. Vegetation density dynamics in Surakarta City

Analysis of vegetation density data for Surakarta City between 2019 and 2023 reveals a notable rise in regions characterized by extremely low and low vegetation density. In 2019, regions with very low vegetation covered only 408 hectares, but by 2023, this had expanded to 1,513.6 hectares. Similarly, areas with limited vegetation rose from 8,167.6 hectares in 2019 to 11,001.2 hectares in 2023. This trend implies a growth in vegetation degradation, perhaps due to urbanization, development, or land conversion for other uses.

Table 4. An analysis of vegetation density data for Surakarta City

Vegetation description	2019	2020	2021	2022	2023
Very low	408	1261.2	1032.8	1858.8	1513.6
Low	8167.6	9882.8	9129.6	11096.4	11001.2
Middle	12615.2	11910.8	13474.4	11705.2	12656
Dense	20818.8	19331.6	19010.4	17397.2	17819.6
Very dense	5880	5503.2	5242.4	5832	4899.2

On the other hand, areas with medium vegetation density remained largely consistent, changing slightly but overall steady from 12,615.2 hectares in 2019 to 12,656 hectares in 2023. Although there was an uptick in 2021, the area declined again in 2022. However, the most apparent tendency is the drop in places with high and extremely high vegetation density. regions characterized by a high concentration of vegetation declined from 20,818.8 hectares in 2019 to 17,819.6 hectares in 2023. Similarly, regions with an extremely high concentration of vegetation decreased from 5,880 hectares in 2019 to 4,899.2 hectares in 2023. This trend reflects a loss in places with dense vegetation, presumably induced by human activities or alterations in land use.

Surakarta City has experienced a severe reduction in vegetation quality and coverage during the previous five years. Zones characterized by abundant vegetation have experienced a reduction in size, whilst those with limited or deteriorated vegetation have seen an increase. The aforementioned phenomenon can be understood as an outcome of the influence of development pressure and urbanization within the area, thereby presenting a potential risk to the long-term environmental sustainability and the preservation of natural vegetation. These changes underscore the need for more sustainable urban planning to conserve the vegetative environment.

The impact of urbanization on vegetation deterioration is complex and varies across different places and time periods. While fast urbanization can contribute to vegetation loss, especially in urban fringe zones [25, 26], many urban areas have experienced vegetation improvements due to restoration efforts and increased demand for higher environmental quality [23, 27]. Climate change and urbanization are primary drivers of urban vegetation dynamics, with climate frequently having a more significant impact than urbanization itself [26]. The effects of urbanization on vegetation vary on characteristics such as urban development intensity, population density, and background climate, with more positive affects seen in cities with cold and arid settings [27]. To prevent vegetation degradation, it is necessary to adopt good urban landscape design, focus on vegetation protection and restoration, and carefully manage urban fringe development [23, 25, 26].

3.3 Carbon Stock Estimation for Surakarta City

Based on the carbon stock data analysis in Surakarta from 2019 to 2023, recorded by Sentinel-2 satellite photography, there is a definite decrease trend in the amount of stored carbon. The mean carbon content per pixel experienced a modest decline, dropping from 119,724 pixels in 2019 to 115,939 pixels in 2023. This loss is most

likely attributed to alterations in land use, urbanization, or impairment of vegetation.

This fall in pixel count contributes to a decrease in the total carbon stored in the Surakarta area. The cumulative carbon storage decreased from 12,933,424.55 kg in 2019 to 12,518,281.65 kg in 2023, resulting in a loss of around 415,142.9 kg of carbon at the site during the past five years. While this loss is not significant, it nonetheless shows changes harming the region's ability to retain carbon.

Table 5. An analysis of carbon stock estimation data for Surakarta City

Year	Average carbon / kg	Number of pixel	Total carbon (kg)	Total carbon (tons)
2019	108.027	119724	12933424.5	12933.42
2020	108.005	116570	12590142.9	12590.14
2021	107.997	117141	12650876.6	12650.88
2022	107.996	115076	12427747.7	12427.75
2023	107.973	115939	12518281.6	12518.28

Overall, the drop in carbon stocks suggests environmental degradation, probably by land-use changes and urbanization. This could significantly damage the ecosystem's function in carbon storage in Surakarta. Land rehabilitation and conservation initiatives are needed to prevent further reductions and maintain the area's carbon storing potential in the future.

Urbanization greatly effects carbon storage in terrestrial ecosystems. Studies from China's Yangtze River Delta and Su-Xi-Chang regions demonstrate that fast urbanization leads to large carbon losses, particularly in urban-rural edges and growing urban districts [26, 28]. Land conversion, especially farmed land, is a key source to carbon stock depletion [28]. However, urban green spaces can somewhat counterbalance these losses, with one study finding a 49.70% compensation [29]. The impacts of urbanization on carbon storage vary across time, with the highest losses happening during periods of fast urbanization [28]. Interestingly, urban ecosystems can gradually absorb carbon following conversion, perhaps compensating for initial losses within 70-100 years, although sequestration rates fall with time [30]. The results underscore the requirement of including the impacts of urbanization in evaluations of regional carbon balance and demonstrate the significance of sustainable urban planning in reducing carbon losses.

4 Conclusions

This study highlights the effectiveness of using remote sensing data into mapping green open spaces and calculating carbon stocks in Surakarta City using NDVI data and Sentinel- 2 satellite imagery. Analyzing time-series data from 2019 to 2023 provided significant insights into thick vegetation areas and carbon storage. The findings revealed regions (GOS) with an extremely high concentration of vegetation decreased from 5,880 hectares in 2019 to 4,899.2 hectares in 2023. This trend reflects a loss in places with dense vegetation. Vegetation as the most substantial contributors to carbon stocks, based on data indicate the cumulative carbon storage decreased from 12,933,424.55 kg in 2019 to 12,518,281.65 kg in 2023, resulting in a loss of around 415,142.9 kg of carbon at the site during the past five years. This research is contributed to a greater understanding of plant dynamics and carbon storage capability in urban environments, giving useful insights for environmental planning and management in large cities. Despite these promising results, the study acknowledged limitations. Data resolution restrictions that could impact the accuracy of estimations and a dearth of data on

certain variables contributing to vegetation reduction. For future research, it is proposed to employ higher-resolution data and perform field studies to identify the primary drivers of vegetation changes. The environmental ramifications encompass a possible decrease in the capacity of urban ecosystems to capture carbon, therefore intensifying atmospheric warming. For policymakers, these findings underline the need of efforts to safeguard and repair green open spaces, as well as the necessity for regulations supporting vegetation management to maintain environmental quality and reduce climate change.

References

1. S. S. Lebang, H. Siswanto, Ariyanto, Y. Ruslim, *Jurnal AGRIFOR*, **22**, 2 (2023)
2. N. H. Prabowoningsih, R. A. Putri, E. F. Rini, *Jurnal Pembangunan Wilayah dan Perencanaan Partisipatif*, **13**, 2 (2018).
3. A. A. Azra, *Elipsoida: Jurnal Geodesi dan Geomatika*, **7**, 1 (2024)
4. R. Dwihatmojo, *Pemanfaatan Citra Quickbird untuk Identifikasi ruang terbuka hijau Kawasan perkotaan (studi kasus Kecamatan Serpong, kota Tangerang Selatan)*, In Seminar Nasional Pendayagunaan Informasi Geospasial Untuk Optimalisasi Otonomi Daerah (2013)
5. D. R. Zulkia, L. Hartati, H. Fitriansyah, M. A. Aldouri, *Zoning: Journal of Urban and Regional Planning*, **1**, 1 (2023)
6. D. S. Nugraheni, R. A. Putri, E. F. Rini, *Jurnal Pembangunan wilayah dan perencanaan partisipatif*, **13**, 2 (2018)
7. D. Irundu, A. I. Idris, P. Sudiarmiko, Irlan, *Jurnal Hutan dan Masyarakat* **15**, 1 (2023)
8. A. Shelestov, M. Lavreniuk, N. Kussul, A. Novikov, S. Skakun, *Frontiers in Earth Science*, **5** (2017)
9. A. V. Uzhinskiy, *The 6th International Workshop on Deep Learning in Computational Physics (DLCP2022)*, **429** (2022)
10. A. Agapiou, *International Journal of Digital Earth*, **10**, 1 (2017)
11. S. Suhardono, I. Y. Septiariva, S. Rachmawati, H. H. A. Matin, N. Qona'ah, B. Nirwana, I. W. K. Suryawan, M. M. Sari, W. Prayogo, *Journal of Ecological Engineering*, **24**, 4 (2023)
12. Z. Szantoi, P. Strobl, *European Journal of Remote Sensing*, **52**, 1 (2019)
13. T. Gunawansa, K. Perera, A. Apan, A. N. Hettiarachchi, *Journal of Advances in Engineering and Technology*, **1**, 1 (2022)
14. S. Myeong, D. J. Nowak, M. J. Duggin, *Remote Sensing of Environment*, **101**, 2 (2006)
15. J. O. Klompaker, G. Hoek, L. D. Bloemsma, U. Gehring, M. Strak, A. H. Wijga, C. V. D. Brink, B. Brunekreef, E. Lebret, N. A. H. Janssen, *Environmental Research*, **160** (2018)
16. A. Ashok, H. P. Rani, K. V. Jayakumar, *Remote Sensing Applications: Society and Environment*, **23** (2020)
17. A. A. Gitelson, *Journal of Plant Physiology*, **161**, 2 (2004)
18. K. H. Pangestu, A. Jauhari, Udiansyah, *Jurnal Sylva Scientiae*, **6**, 3 (2023)
19. A. Zaitunah, Samsuri, G. A. Ahmad, R. A. Safitri, *IOP Conference Series: Earth and Environmental Science* **126** (2018)
20. D. Karmila, A. Jauhari, R. Kanti, *Jurnal Sylva Scientiae*, **3**, 3 (2020)
21. N. Meng, N. Wang, H. Cheng, X. Liu, Z. Niu, *Journal of Geographical Sciences*, **33**, 3

(2023)

22. L. Zhu, J. Meng, L. Zhu, *Ecological Indicators*, **117** (2020)
23. Y. Liu, Y. Wang, J. Peng, Y. Du, X. Liu, S. Li, D. Zhang, *Remote Sensing*, **7**, 2 (2015)
24. A. Carlsson, Antropogen påverkan i Sahel – påverkar människans aktivitet NDVI uppmätt med satellite, **142** (2008)
25. K. Yang, W. Sun, Y. Luo, L. Zhao, *Journal of Environmental Management*, **291** (2021)
26. H. Li, Y. Hu, H. Li, J. Ren, R. Shao, Z. Liu, *Sustainability (Switzerland)*, **15**, 19 (2023)
27. L. Zhang, L. Yang, C. M. Zohner, T. W. Crowther, M. Li, F. Shen, M. Guo, J. Qin, L. Yao, C. Zhou, *C. Science Advances*, **8**, 27 (2022)
28. Q. Fu, L. Xu, H. Zheng, J. Chen, *Processes*, **7**, 11 (2019)
29. B. Wu, Y. Zhang, Y. Wang, X. Lin, Y. Wu, J. Wang, S. Wu, Y. He, *Journal of Environmental Management*, **359** (2024)
30. C. Zhang, H. Tian, G. Chen, A. Chappelka, X. Xu, W. Ren, D. Hui, M. Liu, C. Lu, S. Pan, G. Lockaby, *Environmental Pollution*, **164** (2012)