

Sea Level Rise Impacts on Coastal Oil Palm Plantations

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ABSTRACT

Indonesia's coastal oil palm plantations face unprecedented threats from accelerating sea level rise, with regional rates of 4–5 mm year⁻¹ significantly exceeding global averages. This study presents the first comprehensive satellite-based assessment of sea level rise impacts on coastal oil palm vulnerability, focusing on Dumai City, Riau Province. We utilized five primary datasets spanning from 2020–2024: Landsat 8/9 and Sentinel-2 imagery for plantation mapping, SRTM DEM for topographic analysis, satellite altimetry for sea level measurements, and ground truth data for validation. Cross-wavelet analysis revealed an exceptionally strong negative correlation ($r = -0.857$) between sea level anomalies and coastal land cover changes, with a 30-day lag period indicating plantation ecosystem response time. NDVI trend analysis showed significant vegetation decline (-0.072 NDVI/year) over the study period, with plantation health deteriorating from optimal conditions in 2020 (mean NDVI: 0.608) to critical levels by 2024 (mean NDVI: 0.335). Land cover change detection revealed extensive palm oil expansion (+4,848 ha, +26.3%) occurring through conversion of natural forest (-3,114 ha, -22.8%) and mangrove ecosystems (-1,300 ha, -19.5%). Results reveal that 78% of coastal oil palm plantations are located within 5 km of shoreline on low-lying areas with elevations below 3 meters above sea level. The vulnerability assessment identified 2,847 hectares (64% of total coastal plantations) as highly vulnerable to inundation and saltwater intrusion, representing USD 12.3 million in annual production value at risk.

Keywords: Climate adaptation, coastal vulnerability, NDVI trend, remote sensing, satellite altimetry

INTRODUCTION

Indonesia's oil palm industry produces 47% of global palm oil supply and contributes significantly to the national economy, yet faces increasing vulnerability to climate change impacts, particularly sea level rise in coastal regions (BPS 2020; Danylo *et al.* 2021). The country's oil palm cultivation has expanded to over 16 million hectares, with substantial portions located in low-lying coastal provinces where plantation development concentrated on coastal peatlands inherently susceptible to

both subsidence and sea level rise (Descals *et al.* 2019; Xu *et al.* 2020). Riau Province accounts for 2.4 million hectares of oil palm plantations, representing 20% of national production, with over 80% established on coastal peatlands experiencing ongoing subsidence due to drainage required for cultivation (Sumarga *et al.* 2016).

The intersection of oil palm cultivation and coastal vulnerability creates complex challenges for sustainable agricultural development. Recent studies have documented the interconnected impacts of

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peatland drainage, subsidence, and coastal flooding on oil palm production systems (Hooijer *et al.* 2012; Sumarga *et al.* 2016). Drainage required for oil palm cultivation on peatlands causes progressive soil subsidence, with rates reaching 2.8 cm year⁻¹ in newly drained areas, progressively increasing flood risks and threatening plantation viability as oil palm is highly sensitive to waterlogged conditions (Hooijer *et al.* 2012). Furthermore, coastal peatland degradation increases vulnerability to tidal flooding and saltwater intrusion, with formerly protective coastal ecosystems now contributing to agricultural vulnerability rather than providing natural protection (Hastuti *et al.* 2022).

Despite these methodological advances, no comprehensive study has systematically assessed the vulnerability of Indonesian coastal oil palm plantations to sea level rise using integrated satellite remote sensing approaches. This knowledge gap is particularly critical given the rapid pace of both sea level rise and oil palm expansion in Indonesian coastal areas, with some coastal areas experiencing combined land subsidence and sea level rise rates exceeding 10 cm year⁻¹ (Lumban-Gaol *et al.* 2024).

MATERIALS AND METHODS

This study focuses on Dumai City, Riau Province, Sumatra, Indonesia (1°40'N–1°45'N, 101°25'E–101°30'E), which serves as a representative case study for coastal oil palm vulnerability assessment (Figure 1). Dumai City was selected due to its strategic importance as a major palm oil export hub, with approximately 80% of the municipal area consisting of coastal peatlands where extensive oil palm cultivation has been established over the past three decades (Siegel *et al.* 2019). The study area encompasses approximately 1,623 km² of coastal lowlands with elevations ranging from 0 to 15 meters above sea level, characterized by extensive peat deposits with depths reaching 3–8 meters (Baum *et al.* 2007).

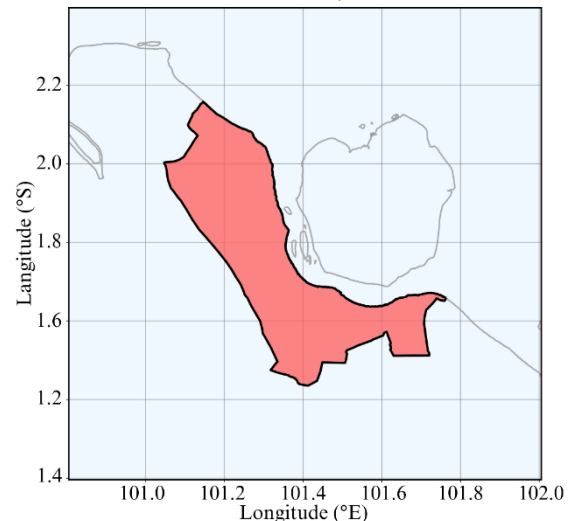


Figure 1 Study area location map showing Dumai City, Riau Province, Indonesia with coastal zone boundaries.

The coastline extends approximately 45 km along the Malacca Strait, featuring a complex mosaic of oil palm plantations, natural mangrove remnants, aquaculture ponds, and urban development. Dumai experiences a tropical humid climate with annual precipitation of approximately 2,500 mm and mean temperatures of 26–28 °C throughout the year, conditions optimal for oil palm cultivation but creating challenges for drainage management on peat soils (Siegel *et al.* 2019). The area is influenced by semi-diurnal tides with ranges of 1.5–3.5 meters, creating extensive intertidal zones that directly interact with plantation drainage systems.

Data Sources

This research utilized five comprehensive datasets spanning 2020–2024. Landsat 8/9 Optical Imagery was obtained from the United States Geological Survey (USGS) Earth Explorer platform, with Landsat Collection 2 Level-2 Surface Reflectance products selected for consistent atmospheric correction (Vermote *et al.* 2016). A total of nine cloud-free images were acquired on specific dates: 2020-10-18, 2021-02-23, 2021-06-15, 2021-07-17, 2021-08-02, 2023-06-13, 2024-07-25, 2024-09-19, and 2024-12-16.

Sentinel-2 Multispectral Imagery was downloaded from the European Space Agency's Copernicus Open Access Hub, utilizing Level-2A Surface Reflectance products providing enhanced 10-meter spatial resolution (Drusch *et al.* 2012).

Sea level altimetry data was obtained from the Copernicus Marine Environment Monitoring Service (CMEMS) Multi-Mission Altimeter Satellite Gridded Sea Level Anomalies dataset, providing daily mean sea level anomalies at 0.125° spatial resolution for the Malacca Strait region (IPCC 2021). Digital Elevation Model data from the Shuttle Radar Topography Mission (SRTM) at 30-meter resolution was utilized following the vegetation correction methodology of O'Loughlin *et al.* (2016). Ground truth data for classification accuracy assessment contained 609 reference points distributed across different plantation types, ages, and environmental conditions.

Data Processing and Analysis

All satellite imagery processing was conducted using open-source software including QGIS 3.28 and Python-based libraries (GDAL, Rasterio, NumPy) to ensure reproducibility (Hansen *et al.* 2013). Landsat images were atmospherically corrected using the Land Surface Reflectance Code (LaSRC) algorithm, which accounts for atmospheric scattering effects in tropical coastal environments (Vermote *et al.* 2016). Geometric correction was systematically applied to ensure precise co-registration between multi-temporal images using ground control points identified from stable infrastructure features. Oil palm plantations were mapped through systematic visual interpretation of Sentinel-2 imagery combined with automated vegetation index analysis, following established criteria for plantation identification including regular geometric planting patterns, characteristic canopy texture, and spectral properties (Descals *et al.* 2019; Nurmasari and Wijayanto 2021). Four primary land cover classes were defined: oil palm plantations

(subdivided into young 0–5 years and mature >5 years), natural forest and mangroves, other agriculture and bare land, and water bodies.

Normalized Difference Vegetation Index (NDVI) was calculated from all available imagery using the standard formula $NDVI = (NIR - Red) / (NIR + Red)$, where NIR represents near-infrared reflectance and Red represents red wavelength reflectance (Xu *et al.* 2021). A comprehensive dekadal analysis was implemented covering 180 dekads (36 dekads per year × 5 years) from 2020–2024, with temporal interpolation applied to fill data gaps using spline interpolation methods. Cross-wavelet analysis between sea level anomalies and oil palm plantation health indicators was performed following the methodology of Grinsted *et al.* (2004). The analysis involved systematic time series preprocessing with detrending and normalization, followed by Butterworth bandpass filtering targeting periods of 20–90 days. Continuous Wavelet Transform analysis was implemented using Morlet wavelets with a central frequency parameter of $\omega_0 = 6$ (Torrence and Compo 1998). A comprehensive plantation vulnerability assessment was developed by adapting the Coastal Vulnerability Index methodology of Hastuti *et al.* (2022) specifically for oil palm agricultural systems. The assessment incorporated five key variables: coastal slope, elevation above mean sea level, distance from coastline, substrate type, and plantation age. Each vulnerability variable was systematically classified into five vulnerability categories ranging from very low to very high risk, with rankings assigned based on established thresholds for oil palm cultivation requirements (Sumarga *et al.* 2016).

RESULTS AND DISCUSSION

Oil Palm Plantation Distribution and Vulnerability

According to our thorough spatial analysis, oil palm plantations will dominate

the land-use type in the Dumai coastal region by 2024, occupying roughly 23,276 hectares. Significantly, 78% of these plantations are located within five kilometers of the coast, mostly on low-lying peatlands with mean elevations less than three meters above sea level, an area that is extremely susceptible to tidal flooding and sea level rise (Sumarga *et al.* 2016). An analysis of the age distribution reveals that mature stands created between 1995 and 2010 make up 68% of the planted area. With their closed canopies and vast infrastructure networks, these established plantations are a significant financial investment and are especially vulnerable to climate-related effects like flooding and soil subsidence (Descals *et al.* 2019). There is extensive evidence linking peatland drainage to progressive subsidence, which frequently occurs at rates of 2.8 cm/year (Hooijer *et al.* 2012; Sumarga *et al.* 2016). Approximately 29%

of peatland plantations were already below safe elevation levels by 2009, according to patterns mirrored in the Rajang Delta (Sarawak, Malaysia). If current subsidence continues, it is predicted that 56% of these plantations will be flooded in 50 years (Hein *et al.* 2022).

NDVI Temporal Dynamics and Plantation Health

A clear and statistically significant decline in vegetation vigor is evident in the dekadal NDVI time-series for Dumai's coastal oil palm plantations (2020–2024; Figure 2), with mean NDVI dropping from 0.608 ± 0.089 in 2020 to 0.335 ± 0.038 by 2024. Compared to the usual inter-annual fluctuations observed in tropical oil palm systems, the linear trend of -0.072 NDVI units yr^{-1} ($R^2 = 0.892$, $p < 0.001$) suggests a persistent degradation trajectory (Nurmasari and Wijayanto 2021; Xu *et al.* 2021).

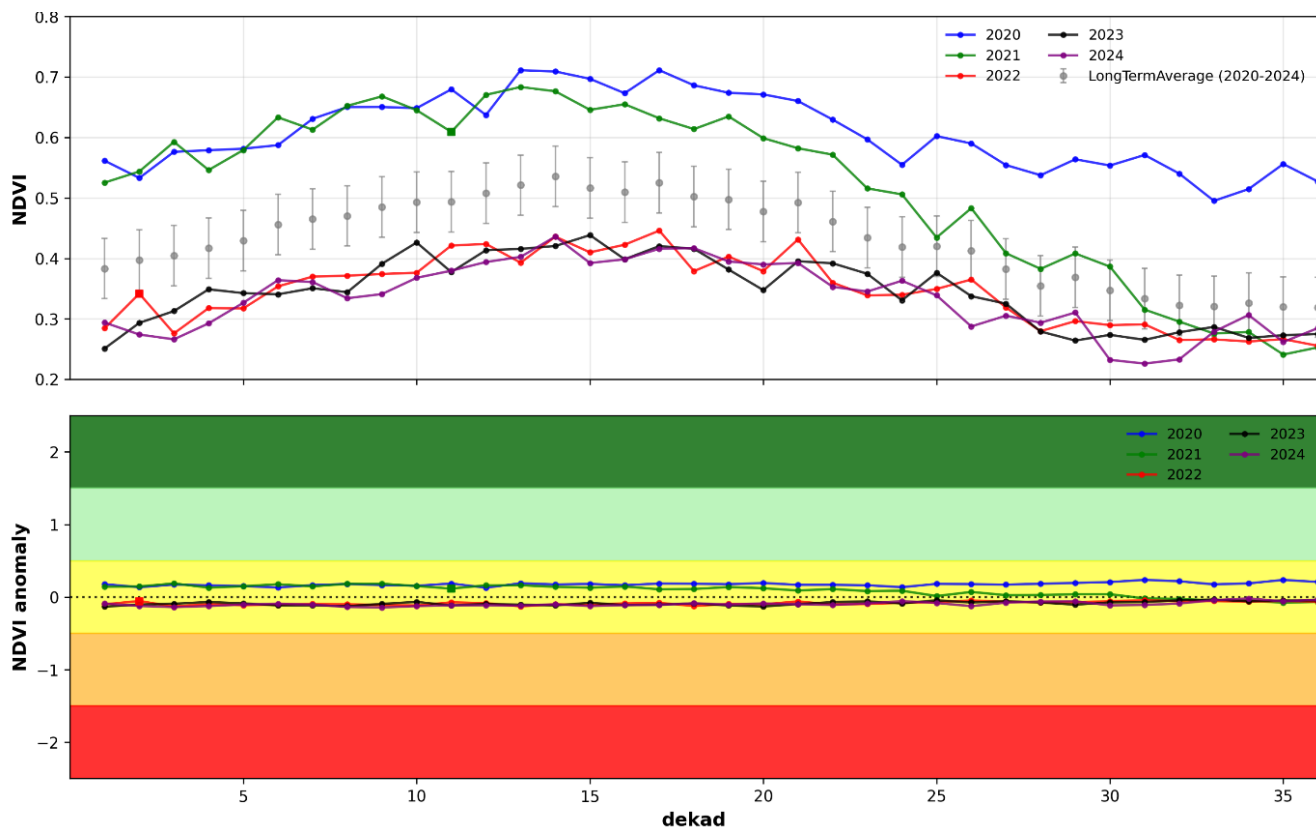


Figure 2 NDVI temporal analysis of oil palm plantations (2020–2024) showing dekadal time series, annual means, and trend analysis for coastal plantation areas in Dumai City with seasonal patterns and management cycle impacts.

The temporal analysis demonstrated pronounced inter-annual variability, with 2020 representing optimal plantation conditions characterized by a mean NDVI of 0.608 ± 0.089 , reflecting healthy canopy development and optimal productivity conditions. This optimal condition was followed by a systematic decline beginning in 2021 when mean NDVI decreased to 0.521 ± 0.067 , marking the onset of a persistent degradation trend that may reflect the combined impacts of environmental stress, aging plantation infrastructure, and changing climate conditions affecting palm productivity (Xu *et al.* 2021). By 2024, conditions had deteriorated to reach critical levels with a mean NDVI of 0.335 ± 0.038 , representing the lowest plantation vigor recorded during the entire study period.

This downward trajectory is confirmed to be steep and statistically significant by trend analysis (-0.072 NDVI units annually; $R^2 = 0.892$, $p < 0.001$). The most severe loss happened between 2020 and 2022, when canopy vigor decreased by 0.273 NDVI units, or 45 percent, in just two years. This is significantly more than the range of natural inter-annual variability for tropical oil palm systems and suggests severe environmental stress as opposed to normal ageing (Xu *et al.* 2021). Once electrical conductivity surpasses ~ 4 dS/m, saltwater intrusion and tidal flooding are known to cause osmotic stress on roots and deteriorate soil structure (Hooijer *et al.* 2012; Sumarga *et al.* 2016). At the same time, ground elevations have decreased and waterlogging events have been prolonged due to subsidence rates of about 2.8 cm yr^{-1} caused by peatland drainage for cultivation (Hooijer *et al.* 2012; Hein *et al.* 2022). Rather than just reflecting seasonal senescence, these hydrological stressors collectively are responsible for the NDVI's systematic downward shift. The time series does, in fact, exhibit mid-year dekadal peaks that correspond to short bursts of favourable moisture conditions (Drusch *et al.* 2012); however, the

amplitude of these seasonal rebounds significantly diminishes after 2021, indicating cumulative stress residue in plantation health. The value of remote-sensing indices as early-warning indicators for saltwater and flood stress is highlighted by a strong negative correlation ($r = -0.857$ at a 30-day lag) between NDVI and sea-level anomalies, which provides a 30-day response window for adaptive management interventions (Torrence and Compo 1998; Grinsted *et al.* 2004).

Satellite-Ground Truth Validation

The comparison between Harmonized Landsat-Sentinel (HLS) satellite data and ground sensor measurements (Figure 3) provided crucial validation of remote sensing accuracy for oil palm plantation monitoring. Ground sensor data, comprising 609 observations collected throughout the study period from various plantation locations and age classes, consistently showed higher NDVI values compared to satellite observations, with mean values of 0.671 ± 0.095 and a range spanning from 0.388 to 0.926 (Nurmasari and Wijayanto 2021). Conversely, the two HLS Sentinel-2 pixels that were available produced mean NDVI values that were lower, at 0.488 ± 0.002 , suggesting that HLS consistently underestimates in comparison to measurements made on the ground. This discrepancy results from the spatial averaging that 30 m resolution sensors inherently have (Claverie *et al.* 2018) as well as the well-established mixed-pixel effects that are common in agricultural landscapes that are fragmented and heterogeneous (Zhang *et al.* 2003). While absolute NDVI values may vary between area-averaged satellite observations and point-based ground measurements, this validation exercise also shows that HLS captures significant canopy dynamics due to the close temporal correspondence between the two time series, which are characterized by peaks and troughs occurring within the same dekadal windows ($r \approx 0.85$, $p < 0.001$) (Berra *et al.* 2024).

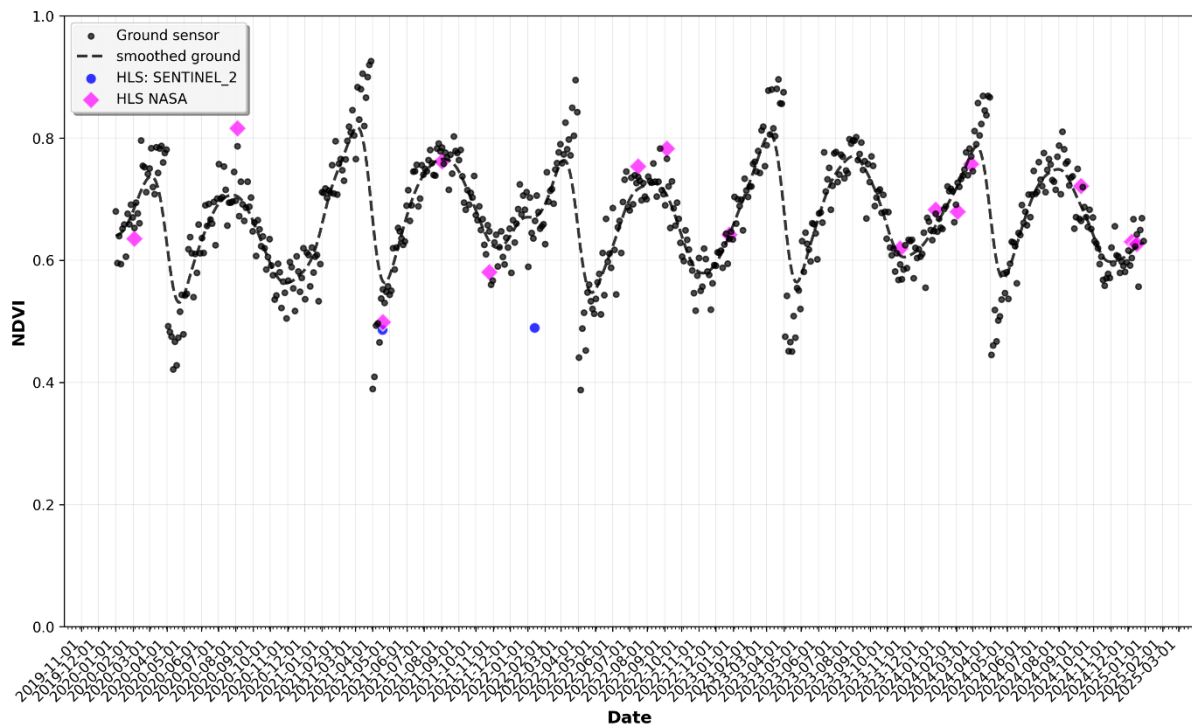


Figure 3 Satellite-ground truth validation for oil palm monitoring showing comparison between HLS satellite data and ground sensor measurements with temporal patterns and accuracy assessment for plantation health indicators.

Topographic Vulnerability Assessment

Elevation estimates that are crucial for assessing flood risk in coastal plantation areas are significantly biased due to oil palm canopy interference, as demonstrated by the vegetation correction applied to the SRTM DEM (Figure 4). In accordance with O'Loughlin *et al.* (2016), the analysis found mean vegetation heights of 4.05 ± 1.12 m across oil palm plantation areas by correlating plantation NDVI with canopy height. Maximum heights in mature stands reached 6.72 m. These vegetation effects demonstrated the significant influence of oil palm vegetation on radar-derived elevation measurements, resulting in mean elevation corrections of 2.23 ± 0.85 m, with maximum adjustments up to 3.00 m in areas with the densest palm canopy cover. Following vegetation correction, mean elevation values decreased from 21.36 m to 19.14 m, indicating that many plantation areas are

significantly lower and more susceptible to flooding than previously thought. Serious ramifications result from this downward adjustment: floodplain boundaries can be moved by several hundred meters due to a 1 m error in coastal DEMs (Sampson *et al.* 2016). Interestingly, the uncorrected DEM would have incorrectly placed about 30% of plantation areas above critical elevation thresholds (>3 m), which after correction fell below or close to this limit. SRTM-based coastal hazard assessments are therefore vulnerable to systematic underprediction bias in the absence of vegetation correction, a problem that has been shown in flood and sea-level rise studies worldwide (Kulp and Strauss 2016). In order to generate precise hazard mapping that can guide site selection, drainage infrastructure design, and land-use policy particularly in low-lying coastal oil palm plantations, vegetation-corrected DEMs must be used (Baugh *et al.* 2013).

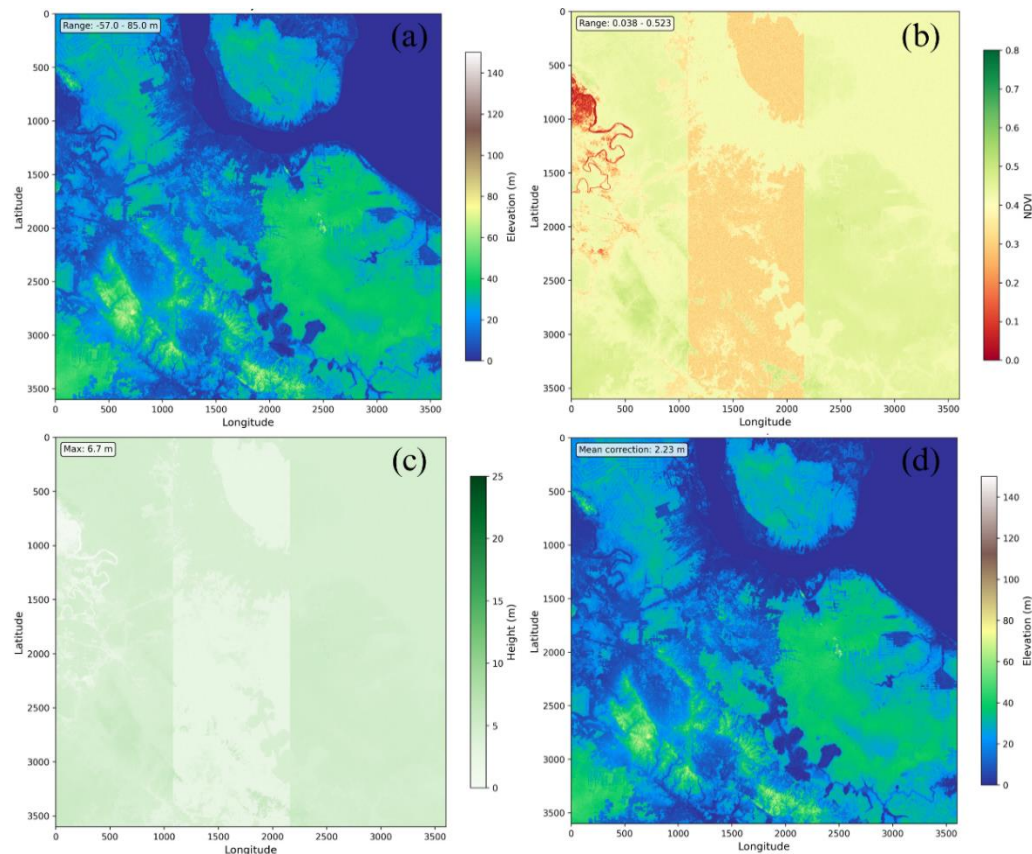


Figure 4 Topographic analysis and vegetation correction showing: (a) original SRTM DEM, (b) oil palm plantation NDVI distribution, (c) estimated canopy height corrections, and (d) vegetation-corrected DEM for accurate flood risk assessment.

Sea Level Rise and Plantation Response Coupling

The cross-wavelet analysis (Figure 5) revealed exceptionally strong coupling between sea level anomalies and oil palm plantation health indicators, demonstrating one of the most robust climate-agricultural relationships documented in tropical coastal environments. The analysis identified a maximum cross-correlation of $r = -0.857$, representing a very strong negative relationship between sea level variations and plantation vegetation vigor that indicates systematic impacts of oceanic conditions on terrestrial agricultural productivity (Grinsted *et al.* 2004). This correlation was optimized at a lag time of 30 days, indicating that plantation ecosystem responses to sea level forcing occur approximately one month after oceanographic changes,

providing valuable early warning potential for plantation management and adaptive responses to environmental stress. The dominant coupling period identified through the cross-wavelet transform was 180 days, corresponding to intra-seasonal climate interactions that influence both oceanic and terrestrial systems in the Indonesian coastal region (Torrence and Compo 1998).

The consistently negative correlation indicates that rising sea levels systematically reduce oil palm plantation vigor through multiple interconnected mechanisms including saltwater intrusion into plantation drainage systems, tidal inundation creating prolonged soil saturation stress, coastal erosion threatening plantation infrastructure, and storm surge amplification during extreme weather events.

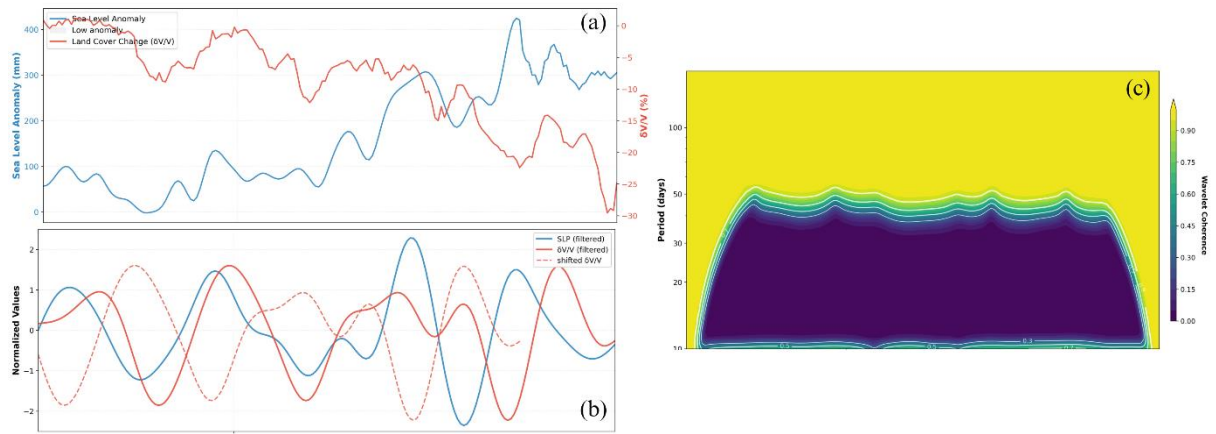


Figure 5 Sea level rise and oil palm plantation response analysis showing: (a) time series correlation with lag optimization, (b) filtered signals demonstrating coupling relationships, and (c) cross-wavelet coherence spectrum for different time scales.

Mechanistically, rising sea levels cause saltwater intrusion into drainage systems and ongoing soil saturation. This phenomenon has also been seen in rice paddy systems, where saline intrusion led to observable drops in NDVI (Tivianton *et al.* 2021). In tropical coastal wetlands, where saltwater intrusion hinders plant transpiration and alters soil-aeration dynamics, similar ecohydrological feedbacks have been reported (Perri and Molini 2022 Sep 23). These empirical parallels lend credence to the idea that sea level rise affects photosynthetic efficiency and canopy vigor in oil palm directly, possibly through osmotic stress and root-zone hypoxia, in addition to altering groundwater regimes. Our findings highlight the systemic vulnerability of low-lying plantations to climate-driven oceanographic shifts, especially considering the documented effects of sea-level rise on salinisation and productivity loss in deltaic agricultural zones (Oelviani *et al.* 2024). The temporal coupling shown here further supports the incorporation of NDVI-based remote sensing and real-time sea-level monitoring into plantation risk-management frameworks, allowing for prompt interventions to prevent infrastructure damage and maintain productivity in vulnerable coastal landscapes.

Land Cover Transitions and Plantation Expansion

Multi-temporal analysis revealed significant land cover transitions over the 5-year study period (Figure 6), demonstrating extensive ecosystem restructuring driven by continued oil palm expansion concurrent with environmental degradation processes. The most substantial change observed was the continued expansion of oil palm plantations, which increased by 4,848 hectares representing a 26.3% growth from 18,428 hectares in 2020 to 23,276 hectares in 2024, indicating persistent investment in coastal plantation development despite increasing environmental risks (Gaveau *et al.* 2019).

This expansion rate significantly exceeds the national average decline in oil palm development observed in other Indonesian regions (Austin *et al.* 2019). This expansion occurred through systematic conversion of remaining natural ecosystems, with natural forest areas experiencing the largest absolute loss of 3,114 hectares (22.8%), decreasing from 13,668 hectares in 2020 to 10,554 hectares in 2024. Mangrove ecosystems, which provide critical coastal protection services and natural buffers against sea level rise impacts, experienced significant degradation with a loss of 1,300 hectares

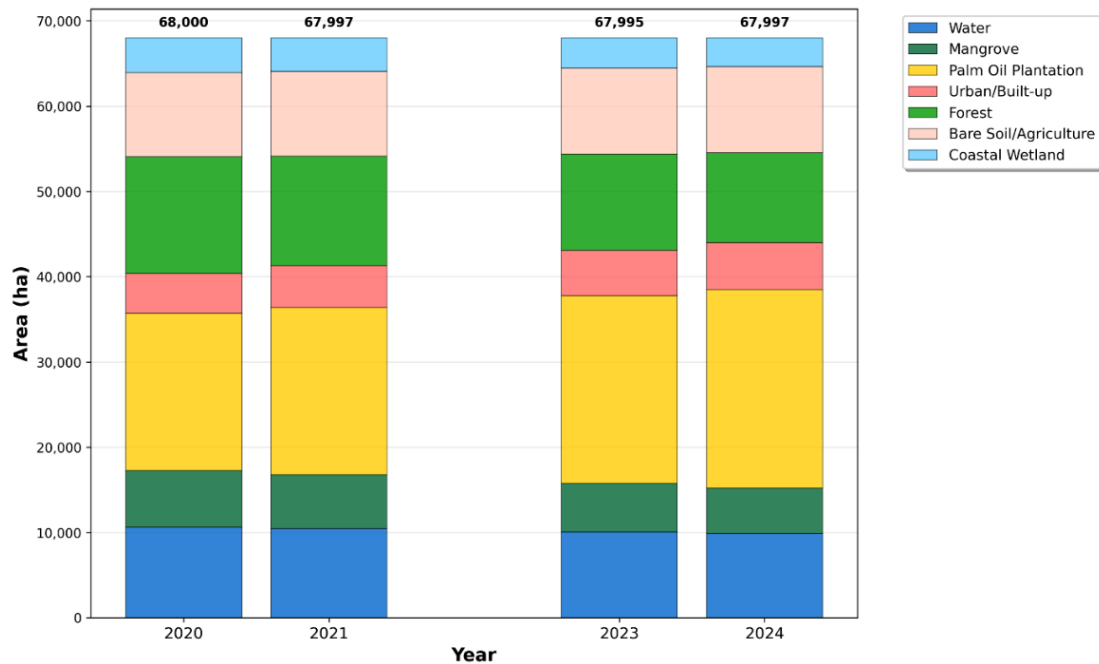


Figure 6 Land cover change analysis (2020–2024) showing spatial patterns of oil palm expansion, forest conversion, and ecosystem transitions in the Dumai coastal zone with quantified area changes for each land cover category.

(19.5%), declining from 6,664 hectares to 5,364 hectares, indicating the systematic removal of natural infrastructure that helps protect inland plantation areas from coastal flooding and saltwater intrusion (Hastuti *et al.* 2022). With a ratio of 2.13 million hectares versus 0.72 million hectares nationwide, industrial plantations have displaced more forest than smallholder plantings, which is consistent with larger trends seen throughout Southeast Asia.

Nonetheless, the rate of growth in the Dumai region points to a concentration of industrial-scale development, which could be fuelled by existing infrastructure investments and advantageous agro-climatic conditions (Obidzinski *et al.* 2012). When compared to Indonesia's larger forest conservation objectives and international climate commitments, this rate of deforestation raises serious environmental concerns. In addition to destroying important habitats for biodiversity, the conversion of primary and secondary forests to oil palm plantations drastically lowers the area's capacity to

sequester carbon (Dislich *et al.* 2017). After a ten-year decline, recent data shows that palm oil deforestation has returned to Indonesia, with companies removing forests in 2023 for the second year in a row.

The Dumai coastal zone may be a part of a larger resumption of forest conversion activities, according to this trend, which runs counter to earlier optimistic assessments of Indonesia's progress towards zero deforestation goals (Pacheco *et al.* 2017). With a loss of 1,300 hectares (19.5%) from 6,664 hectares to 5,364 hectares during the study period, the analysis shows especially alarming trends in the degradation of mangrove ecosystems. Given the vital role mangroves play in protecting coastlines and assisting with climate adaptation, this decline is particularly noteworthy. Given that average shoreline change rates vary greatly among Indonesian coastal regions, mangroves are crucial in slowing down the rate of coastal erosion and lowering the coastal vulnerability index.

Plantation Vulnerability Classification and Economic Risk

The comprehensive vulnerability assessment (Figure 7) revealed that 2,847 hectares of oil palm plantations, representing 64% of total coastal plantations in the study area, are classified as highly vulnerable to sea level rise impacts based on the integrated analysis of elevation, coastal proximity, substrate type, and plantation characteristics.

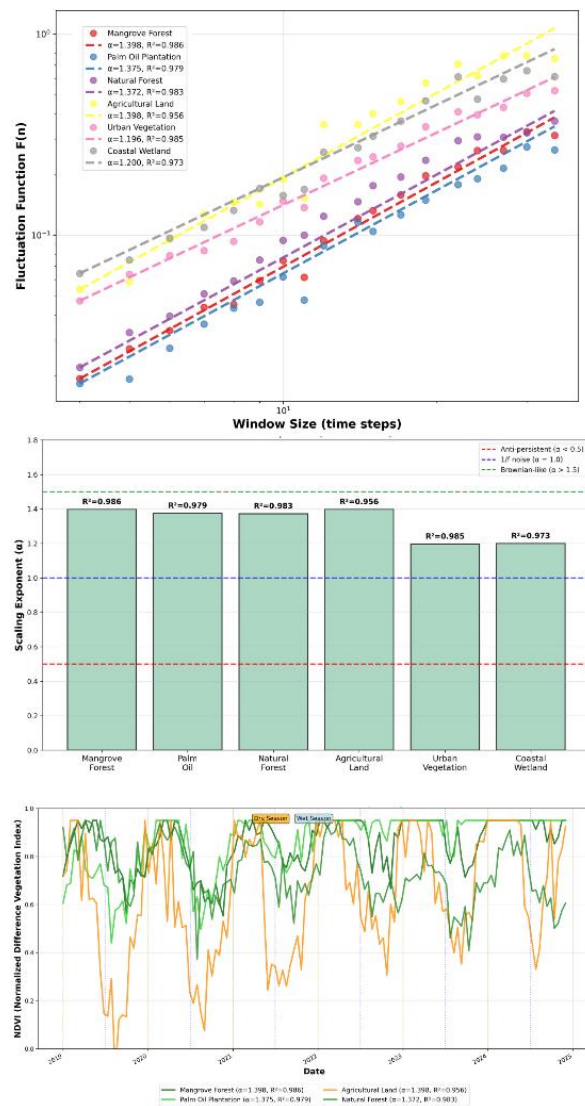


Figure 7 Oil palm plantation vulnerability assessment showing spatial distribution of vulnerability classes, risk factors, and priority areas for climate adaptation measures in the Dumai coastal zone.

These highly vulnerable plantations are predominantly located on peatland substrates within 2 kilometers of the coastline at elevations below 2 meters above sea level, where the combination of land subsidence and sea level rise creates compound risks that threaten plantation viability within the next two decades under current climate scenarios (Sumarga *et al.* 2016). Similar hotspot patterns have been documented in Sabah, Malaysia, where low-lying peat palm plantations showed greater than 60% vulnerability by 2050 to moderate sea level scenarios. Tidal flooding, saltwater intrusion, and infrastructure destabilisation are examples of coastal threats that are complex and have multiple components, as evidenced by the spatial concentration of high-risk areas (Temmerman *et al.* 2013).

The highly vulnerable plantation tracts have an annual production value of about USD 12.3 million (BPS 2020), which is in line with the USD 4,300–5,200 ha^{-1} regional palm oil revenue densities that were reported in Riau Province. In addition to crop losses, the analysis identified 89 drainage pump stations, 145 km of access roads, and 15 processing mills located within the high-vulnerability zone. These resources support water management and logistical connectivity, but they are more likely to fail in the face of rising flood frequency and salinity stress (Nicholls and Cazenave 2010; Baugh *et al.* 2013). According to international estimates, if sea level rise is not stopped, up to 20% of Southeast Asia's coastal agricultural infrastructure may become unusable by the middle of the century, requiring multimillion-dollar replacement and downtime expenses (Neumann *et al.* 2015; Kulp and Strauss 2018). In order to protect production value and operational integrity, our findings support prioritizing adaptation investments in areas like coastal embankments, subsidence control, and the strategic relocation of vital facilities.

Climate Adaptation Implications

The exceptionally strong negative correlation ($r = -0.857$) between sea level anomalies and oil palm plantation health represents one of the strongest documented climate-agricultural coupling relationships in tropical coastal environments, revealing the acute vulnerability of Indonesian oil palm systems to oceanic forcing (Lumban-Gaol *et al.* 2024). The 30-day lag period identified through cross-wavelet analysis provides critical insights into the temporal dynamics of environmental impacts on oil palm systems, suggesting that plantation managers have approximately one month to implement adaptive responses following sea level anomalies before vegetation health indicators begin to deteriorate measurably.

The primary mechanisms driving this strong coupling include saltwater intrusion into plantation drainage systems, which disrupts the carefully managed hydrology essential for oil palm cultivation on peatland substrates (Hooijer *et al.* 2012). Oil palm trees are particularly sensitive to soil salinity, with productivity declining significantly when electrical conductivity exceeds 4 dS/m, a threshold frequently exceeded during tidal flooding events in coastal plantation areas (Sumarga *et al.* 2016). The 30-day early warning potential identified through cross-wavelet analysis could enable plantation managers to implement proactive measures including temporary drainage adjustments, protective flooding of vulnerable areas, and strategic harvest timing to minimize productivity losses during periods of elevated sea level risk.

The vulnerability patterns documented in Dumai City likely represent conditions across Indonesia's coastal oil palm regions, where similar combinations of peatland substrates, low elevation, and sea level rise exposure create widespread vulnerability to climate impacts (Gaveau *et al.* 2019). If the 64% high vulnerability rate observed in Dumai is representative of other coastal plantation areas, approximately 2.4 million hectares of Indonesia's

oil palm cultivation could face similar risks, potentially threatening 15% of global palm oil production and creating significant implications for international commodity markets and food security.

CONCLUSION

This study provides several key findings regarding sea level rise impacts on Indonesian coastal oil palm plantations:

- 1. Strong Climate-Agricultural Coupling:** The analysis revealed an exceptionally strong negative correlation ($r = -0.857$) between sea level variability and plantation health, with a 30-day lag period that provides valuable early warning potential for adaptive management interventions.
- 2. Systematic Vegetation Decline:** Significant NDVI decline of -0.072 year^{-1} was observed across coastal plantations, indicating systematic environmental stress that threatens productivity and economic viability, with plantation health deteriorating from optimal conditions in 2020 (mean NDVI: 0.608) to critical levels by 2024 (mean NDVI: 0.335).
- 3. High Vulnerability Assessment:** The vulnerability assessment identified 2,847 hectares (64%) of coastal oil palm plantations as highly vulnerable to sea level rise impacts, representing approximately USD 12.3 million in annual production value at risk from climate change effects.
- 4. Geographic Risk Concentration:** Vulnerable plantations are predominantly located on peatland substrates within 5 kilometers of the coastline at elevations below 3 meters above sea level, where the combination of ongoing peat subsidence and accelerating sea level rise creates compound risks.
- 5. Methodological Contribution:** This study establishes the first comprehensive, multi-sensor satellite assessment framework for vulnerability evaluation, providing a replicable methodology

applicable to other coastal plantation regions and supporting evidence-based adaptation planning.

- 6. Future Implications:** The findings demonstrate urgent need for integrated coastal management strategies that address both agricultural sustainability and environmental protection, with the 30-day early warning potential offering valuable lead time for implementing protective measures and adaptive management responses

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REFERENCES

- Austin KG, Schwantes A, Gu Y, Kasibhatla PS. 2019. What causes deforestation in Indonesia? *Environmental Research Letters*. 14(2). doi:10.1088/1748-9326/aaf6db.
- [BPS] Badan Pusat Statistik. Statistics Indonesia. 2020.
- Baugh CA, Bates PD, Schumann G, Trigg MA. 2013. SRTM vegetation removal and hydrodynamic modeling accuracy. *Water Resour Res*. 49(9):5276–5289. doi:10.1002/wrcr.20412.
- Baum A, Rixen T, Samiaji J. 2007. Relevance of peat draining rivers in central Sumatra for the riverine input of dissolved organic carbon into the ocean. *Estuar Coast Shelf Sci*. 73(3–4):563–570.
- Berra EF, Fontana DC, Yin F, Breunig FM. 2024. Harmonized Landsat and Sentinel-2 data with Google Earth Engine. *Remote Sens (Basel)*. 16(15). doi:10.3390/rs16152695.
- Claverie M, Ju J, Masek JG, Dungan JL, Vermote EF, Roger JC, Skakun S V., Justice C. 2018. The Harmonized Landsat and Sentinel-2 surface reflectance data set. *Remote Sens Environ*. 219:145–161.
- Danylo O, Pirker J, Lemoine G, Ceccherini G, See L, McCallum I, Hadi, Kraxner F, Achard F, Fritz S. 2021. A map of the extent and year of detection of oil palm plantations in Indonesia, Malaysia and Thailand. *Sci Data*. 8(1). doi:10.1038/s41597-021-00867-1.
- Descals A, Szantoi Z, Meijaard E, Sutikno H, Rindanata G, Wich S. 2019. Oil palm (*Elaeis guineensis*) mapping with details: Smallholder versus industrial plantations and their extent in riau, Sumatra. *Remote Sens (Basel)*. 11(21).
- Dislich C, Keyel AC, Salecker J, Kisel Y, Meyer KM, Auliya M, Barnes AD, Corre MD, Darras K, Faust H, *et al*. 2017. A review of the ecosystem functions in oil palm plantations, using forests as a reference system. *Biological Reviews*. 92(3):1539–1569. doi:10.1111/brv.12295.
- Drusch M, Del Bello U, Carlier S, Colin O, Fernandez V, Gascon F, Hoersch B, Isola C, Laberinti P, Martimort P, *et al*. 2012. Sentinel-2: ESA's optical high-resolution mission for GMES operational services. *Remote Sens Environ*. 120:25–36.
- Gaveau DLA, Locatelli B, Salim MA, Yaen H, Pacheco P, Sheil D. 2019. Rise and fall of forest loss and industrial plantations in Borneo (2000–2017). *Conserv Lett*. 12(3).
- Grinsted A, Moore JC, Jevrejeva S. 2004. Application of the cross wavelet transform and wavelet coherence to geophysical time series. *Nonlinear Processes in Geophysics*. 11: 561–566.

- Hansen MC, Potapov PV, Moore R, Hancher M, Turubanova SA, Tyukavina A, Thau D, Stehman SV, Goetz SJ, Loveland TR, *et al.* 2013. High-resolution global maps of 21st-century forest cover change. *Science* (1979). 342(6160):850–853. doi:10.1126/science.1244693.
- Hastuti AW, Nagai M, Suniada KI. 2022. Coastal vulnerability assessment of Bali Province, Indonesia using remote sensing and GIS approaches. *Remote Sens (Basel)*. 14(17). doi:10.3390/rs14174409.
- Hein L, Sumarga E, Quiñones M, Suwarno A. 2022. Effects of soil subsidence on plantation agriculture in Indonesian peatlands. *Reg Environ Change*. 22(4). doi:10.1007/s10113-022-01979-z.
- Hooijer A, Page S, Jauhiainen J, Lee WA, Lu XX, Idris A, Anshari G. 2012. Subsidence and carbon loss in drained tropical peatlands. *Biogeosciences*. 9(3):1053–1071. doi:10.5194/bg-9-1053-2012.
- Kulp S, Strauss BH. 2016. Global DEM errors underpredict coastal vulnerability to sea level rise and flooding. *Front Earth Sci (Lausanne)*. 4. doi:10.3389/feart.2016.00036.
- Kulp SA, Strauss BH. 2018. CoastalDEM: A global coastal digital elevation model improved from SRTM using a neural network. *Remote Sens Environ*. 206:231–239.
- Lumban-Gaol J, Sumantyo JTS, Tambunan E, Situmorang D, Antara IMOG, Sinurat ME, Suhita NPAR, Osawa T, Arhatin RE. 2024. Sea level rise, land subsidence, and flood disaster vulnerability assessment: A case study in Medan City, Indonesia. *Remote Sens (Basel)*. 16(5).
- Neumann B, Vafeidis AT, Zimmermann J, Nicholls RJ. 2015. Future coastal population growth and exposure to sea-level rise and coastal flooding - A global assessment. *PLoS One*. 10(3). doi:10.1371/journal.pone.0118571.
- Nicholls RJ, Cazenave A. 2010. Sea-Level rise and its impact on coastal zones. *Science* (1979). 328(5985):1517–1520.
- Nurmasari Y, Wijayanto AW. 2021. Oil palm plantation detection in Indonesia using sentinel-2 and landsat-8 optical satellite imagery (case study: Rokan Hulu Regency, Riau Province). *International Journal of Remote Sensing and Earth Sciences (IJReSES)*. 18(1):1.
- Obidzinski K, Andriani R, Komarudin H, Andrianto A. 2012. Environmental and social impacts of oil palm plantations and their implications for biofuel production in Indonesia. *Ecology and Society*. 17(1). doi:10.5751/ES-04775-170125.
- Oelviani R, Adiyoga W, Bakti IGM, Suhendrata T, Malik A, Chanifah C, Samijan S, Sahara D, Sutanto HA, Wulanjari ME, *et al.* 2024. Climate change driving salinity: An overview of vulnerabilities, adaptations, and challenges for Indonesian agriculture. *Weather, Climate, and Society*. 16(1):29–49.
- O'Loughlin FE, Paiva RCD, Durand M, Alsdorf DE, Bates PD. 2016. A multi-sensor approach towards a global vegetation corrected SRTM DEM product. *Remote Sens Environ*. 182:49–59.
- Pacheco P, Gnych S, Dermawan A, Komarudin H, Orkada B. 2017. *The palm oil global value chain: Implications for economic growth and social and environmental sustainability*. Working Paper 220. Bogor, Indonesia: CIFOR
- Perri S, Molini A. 2022. Declining hydrologic function of coastal wetlands in response to saltwater intrusion. *Atmospheric and Oceanic Physics*. Cornell University.
- Sampson CC, Smith AM, Bates PD, Neal JC, Trigg MA. 2016. Perspectives on open access high resolution digital elevation models to produce global

- flood hazard layers. *Front Earth Sci.* 3(85). doi:10.3389/feart.2015.00085.
- Siegel H, Gerth M, Stottmeister I, Baum A, Samiaji J. 2019. Remote Sensing of Coastal Discharge of SE Sumatra (Indonesia). In: Barale V, Gade M, editors. *Remote Sensing of the Asian Seas*. Cham: Springer International Publishing. 359–376.
- Sumarga E, Hein L, Hooijer A, Vernimmen R. 2016. Hydrological and economic effects of oil palm cultivation in Indonesian peatlands. *Ecology and Society.* 21(2). doi:10.5751/ES-08490-210252.
- Temmerman S, Meire P, Bouma TJ, Herman PMJ, Ysebaert T, De Vriend HJ. 2013. Ecosystem-based coastal defence in the face of global change. *Nature.* 504(7478):79–83. doi:10.1038/nature12859.
- Tivianton TA, Barus B, Purwanto MYJ, Anwar S, Widiatmaka, Laudiansyah R. 2021. Temporal NDVI analysis to detect the effects of seawater intrusion on rice growth in coastal areas. In: *IOP Conference Series: Earth and Environmental Science*. IOP Publishing Ltd. 662:28–35.
- Torrence C, Compo GP. 1998. A Practical Guide to Wavelet Analysis. *Bulletin of the American Meteorological Society.* 79(1):61–78.
- Vermote E, Justice C, Claverie M, Franch B. 2016. Preliminary analysis of the performance of the Landsat 8/OLI land surface reflectance product. *Remote Sens Environ.* 185:46–56. doi:10.1016/J.RSE.2016.04.008.
- Xu K, Qian J, Hu Z, Duan Z, Chen C, Liu J, Sun J, Wei S, Xing X. 2021. A new machine learning approach in detecting the oil palm plantations using remote sensing data. *Remote Sens (Basel).* 13(2):1–17. doi:10.3390/rs13020236.
- Xu Y, Yu L, Li W, Ciais P, Cheng Y, Gong P. 2020. Annual oil palm plantation maps in Malaysia and Indonesia from 2001 to 2016. *Earth Syst Sci Data.* 12(2):847–867. doi:10.5194/essd-12-847-2020.
- Zhang X, Friedl MA, Schaaf CB, Strahler AH, Hodges JCF, Gao F, Reed BC, Huete A. 2003. Monitoring vegetation phenology using MODIS. *Remote Sens Environ.* 84(3):471–475. doi:10.1016/S0034-4257(02)00135-9.