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# Peatland Transformation: Land Cover Changes and Driving Factors in the Kampar Peninsula (1990–2020)

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**Abstract:** The Kampar Peninsula, spanning approximately 735,091 hectares, is critical for its carbon reserves and biodiversity, including the endangered Sumatran tiger. However, nearly half of the 4 million hectares of peat swamp in the region is deforested, drained, decomposing, or burning, largely due to settlements and development projects. This research employs a mixed-method approach, using quantitative spatial analysis of Landsat imagery from 1990 to 2020 based on the Spectral Mixture Analysis (SMA) model to detect forest disturbances and classify land cover changes, utilizing the Normalized Difference Fraction Index (NDFI). Ground truthing validates the image interpretation with field conditions. Additionally, qualitative analysis through interviews and regulatory review examines spatial change trends, context, and driving factors. The result showed, over 30 years, that natural forest in the Kampar Peninsula decreased significantly from 723,895.30 hectares in 1990 to 433,395.20 hectares in 2020. The primary factors driving land use changes include the construction of access roads by oil companies in 1975, leading to extensive deforestation, and government policies during the New Order period that issued forest exploitation concessions and promoted transmigration programs, resulting in widespread establishment of oil palm and acacia plantations.

**Keywords:** Kampar Peninsula; peatland; NDFI; spatial analysis; Riau Province



**Citation:** Novarina, D.; Supriatna, J.; Santoso, I.; Karuniasa, M. Peatland Transformation: Land Cover Changes and Driving Factors in the Kampar Peninsula (1990–2020). *Land* **2024**, *13*, 1699. https://doi.org/10.3390/land13101699

Academic Editor: Le Yu

Received: 26 July 2024
Revised: 30 September 2024
Accepted: 10 October 2024
Published: 17 October 2024



## 1. Introduction

Tropical forests and peatlands play a crucial role in providing ecosystem services to global, regional, and local communities, as well as to biodiversity [1]. Tropical peatland ecosystems offer various ecosystem services, such as carbon storage, water regulation, food production, and disaster mitigation [2–4]. The unique characteristics of natural peatland ecosystems, with their wet habitats that are difficult to access and nearly uninhabitable by humans, make them vital habitats for various endangered species.

Peatlands are spread across 175 countries, covering 3% of the earth's land area, or about 400 million hectares, with approximately 11% or 42 million hectares being tropical peatlands [5]. Southeast Asia has the largest expanse of tropical peatlands, particularly in Borneo, Sumatra, and Peninsular Malaysia, which has been known for over 300 years [6,7]. Southeast Asia's tropical peatlands cover 24.8 million hectares, representing about 56.6% of the global tropical peatland area (44.1 million hectares) and approximately 6% of the total global peatland area [7]. It was largely undeveloped until the 1980s due to challenging working conditions for heavy machinery, low agricultural potential, and sufficient availability of land on mineral soils. However, since the 1980s, the peatlands of insular Southeast Asia have been increasingly utilized, causing significant ecological, hydrological, and atmospheric effects [8].

Indonesia's peatlands span about 13.4 million hectares, accounting for 80% of Southeast Asia's and 50% of the world's tropical peatlands [9]. This makes Indonesia the largest owner of tropical peatlands globally and the fourth largest overall after Canada (170 million hectares), Russia (150 million hectares), and the United States (40 million hectares) [10]. Indonesia's peatlands have undergone significant changes due to various land use activities, often leading to ecosystem degradation. In the seven provinces under the Peatland and Mangrove Restoration Agency (BRGM) jurisdiction, there are 522 Peat Hydrological Units (KHGs) with a total area of 21,173,851 hectares. Peatlands cover 12,942,899 hectares, or approximately 61.13% of the total KHG area. The land cover of these peatlands includes 1.54 million hectares of open areas, 6.10 million hectares of cultivated areas, and 5.32 million hectares of forest cover. Based on Acacia Forest Product Utilization Permits (IUPHHK), land use in forest areas spans 3.26 million hectares across the seven BRGM provinces. This includes 575,951 hectares under Natural Forest Acacia Forest Product Utilization Permits (IUPHHK-HA or HPH) and 2,149,940 hectares under Industrial Plantation Acacia Forest Product Utilization Permits (IUPHHK-HT or HTI) [9].

Sumatra, with an area of approximately 470,000 km$^2$, is Indonesia's largest island and the world's sixth largest, supporting a population of 40 million people. The lowland forests cover around 118,300 km$^2$ of the eastern part of the island [9]. According to SPOT vegetation data from 2006, Sumatra's peat swamp forests cover approximately 33,600 km$^2$ [11]. Located on the island's eastern coast, these forests contain the deepest peat in Indonesia. Over 30 percent of Sumatra's peat exceeds 4 m in depth, with the majority found in the Sumatran province of Riau, where peatlands account for 56.1 percent of the total provincial area. Sumatra's lowland forests are home to a diverse range of species, including the Sumatran pine, *Rafflesia arnoldii* (the world's largest individual flower, measuring up to 1 m wide), and *Amorphophallus* species (featuring the world's tallest and largest inflorescence, reaching up to 2 m tall) [11]. The island is also home to the Sumatran tiger, orangutan, Sumatran rhinoceros, Sumatran elephant, Malayan tapir, Malayan sun bear, Bornean clouded leopard, and various birds and butterflies.

Between 2007 and 2015, the rate of peat forest loss was 2.6% per year in Sumatra and Kalimantan [12]. The growing demand for arable land, particularly for palm oil production, along with the suitability of peatlands' flat topography, has led to intense conversion and drainage. About half of the peatlands in Sumatra and Kalimantan are used for smallholder agriculture and industrial plantations, with oil palm accounting for 64% of industrial plantation areas and pulpwood (acacia) plantations primarily located in Sumatra making up the rest [13].

Pelalawan and Siak regencies are parts of the Kampar Peninsula, a significant peatland region in Riau. Tropenbos International Indonesia Programme [14] reported that this area covers about 735,091 hectares, about 18.16% of Riau Province's total area. The Kampar Peninsula features two central peat domes, with depths up to 16 m. These domes are crucial to the area's hydrological system, functioning as natural water reservoirs and regulators. This region is home to four protected areas, consisting of three wildlife reserves (Tasik Belat, Tasik Metas, and Tasik Serkap) covering 13,936 hectares and Zamrud National Park covering 31,643 hectares. Additionally, the region includes a peat ecosystem restoration concession of 130,095 hectares. The ratio of natural forest to non-forest area is approximately 1:2.5. This peat swamp forest is a crucial habitat for the Sumatran tiger, with female tigers' home ranges spanning 50–70 km$^2$ and males' 100 km$^2$, though, in low-density habitats, this can extend up to 289 km$^2$. It is estimated that about 13 Sumatran tigers inhabit the Kampar Peninsula.

In the Kampar Peninsula, nearly half of the 4 million hectares of peat swamp is already deforested, drained, decomposing, or burning, especially for settlements and large-scale development projects. Data from the National Disaster Management Agency in 2018 showed that Bengkalis and Pelalawan regencies have consistently experienced the highest number of hotspots, ranging from 400 to 900 annually. Specifically in 2011, Bengkalis recorded 854 hotspots, while Pelalawan had 460. This trend continued with high numbers in subsequent years, peaking in 2014 when Bengkalis recorded 825 hotspots and Pelalawan 617.

Vegetation trend analysis is a straightforward yet effective method for analyzing vegetation dynamics, including greenness trends and gradual changes. Zhu et al. [15]

examined vegetation greenness trends using all available Landsat 5, 7, and 8 images acquired between 1999 and 2014, employing a slope coefficient for analysis. Similarly, Morton et al. [16] used NDVI (MODIS) to identify gradual changes in forest cover by applying linear regression, identifying forest degradation through significant negative trends (*p*-value). The Normalized Difference Fraction Index (*NDFI*), calculated using the fractions of green vegetation (*GV*), non-photosynthetic vegetation (*NPV*), soil (*So*), and shade (*Sh*), is a fraction index derived from Spectral Mixture Analysis (*SMA*) [16,17]. The equation of *NDFI* analysis can be written as follows:

$$NDFI = \frac{GV_{Sh} - (NPV + So)}{GV_{Sh} + (NPV + So)}$$

$$GV_{Sh} = \frac{GV}{1 - Sh}$$

The study and monitoring of land use changes in the Kampar Peninsula and several surrounding regions have been intensifying over the years. Arjakusuma et al. [18] employed a combination of Global Forest Change (GFC) data and ClasLite software 3.2 with conventional supervised classification algorithms to analyze 30 m spatial resolution Landsat imagery in Riau, Indonesia. Adrianto et al. [19] utilized MODIS (Moderate Resolution Imaging Spectroradiometer) data from the Terra and Aqua satellites to study land use changes between 1990 and 2017. Suyanto et al. [20] conducted a landscape-level assessment using Landsat TM data to focus on general land cover types and changes over time. Meanwhile, IEEE [21] utilized SPOT 1, 2, and 4 satellite image data, which were received and preprocessed to level 2A by the Centre for Remote Imaging, Sensing, and Processing (CRISP) in Singapore. The high-resolution SPOT imagery offered a detailed view of land cover and facilitated the monitoring of land use changes with greater accuracy.

Despite these advancements in vegetation trend analysis, a significant research gap remains: current monitoring methods have not yet integrated the NDFI into their analyses. The NDFI is a new spectral index designed to enhance the ability to detect canopy damage caused by selective logging and forest fires. This index combines spectral and spatial information to map canopy damage more effectively. It is particularly useful for distinguishing between undisturbed forests, canopy gaps, open land, and dead vegetation, which can result from selective logging, forest fires, and forest fragmentation, where tree loss does not always completely alter the land cover type [22]. To enhance the understanding of land use changes, this study integrates NDFI with a qualitative analysis of historical regulations and policies that have influenced land use decisions during the study period (1990–2020). The novelty of this research lies in its innovative integration of NDFI with a qualitative analysis of historical regulations, offering a comprehensive and detailed approach to understanding land use changes in the Kampar Peninsula.

Building on this foundation, this research aims to detect forest cover changes using the NDFI and analyze the driving factors behind land use changes, focusing on converting natural forest cover to non-forest areas in the Kampar Peninsula over a 30-year period from 1990 to 2020. By understanding the extent and patterns of deforestation and land conversion, this study revealed the key influences behind these changes, providing valuable insights into the broader implications for environmental management and conservation strategies.

## 2. Materials and Methods

This research was carried out in the peat ecosystem of the Kampar Peninsula, which administratively belongs to Pelalawan Regency and Siak Regency in Riau Province (Figure 1). The Kampar Peninsula covers an area of approximately 735,091 hectares within the Siak River–Kampar River KHG. The climate in this region falls under category A (very wet) based on the Schmidt–Ferguson classification, with an average annual rainfall of 2100 mm [9,23]. Two significant peat domes are in the central part of the Kampar Peninsula, shown in the green circle area (Figure 1). These peat domes play a crucial role in the hydrological system of the region, with the deepest peat layers exceeding 16 m. The Kampar Peninsula is also home to several lakes, known locally as *tasik* [24]. These lakes give rise to various rivers, some of which flow northward into the Selat Panjang (such as the Rawa River, Belat River, and Metas River), while others flow southward into the Kampar River (such as the Kutup River, Turip River, Serkap River, and Sangar River). As of 2022, the population of the Kampar Peninsula landscape totals 40,554 people, with 10,766 residing in Siak Regency and 29,788 in Pelalawan Regency [25].

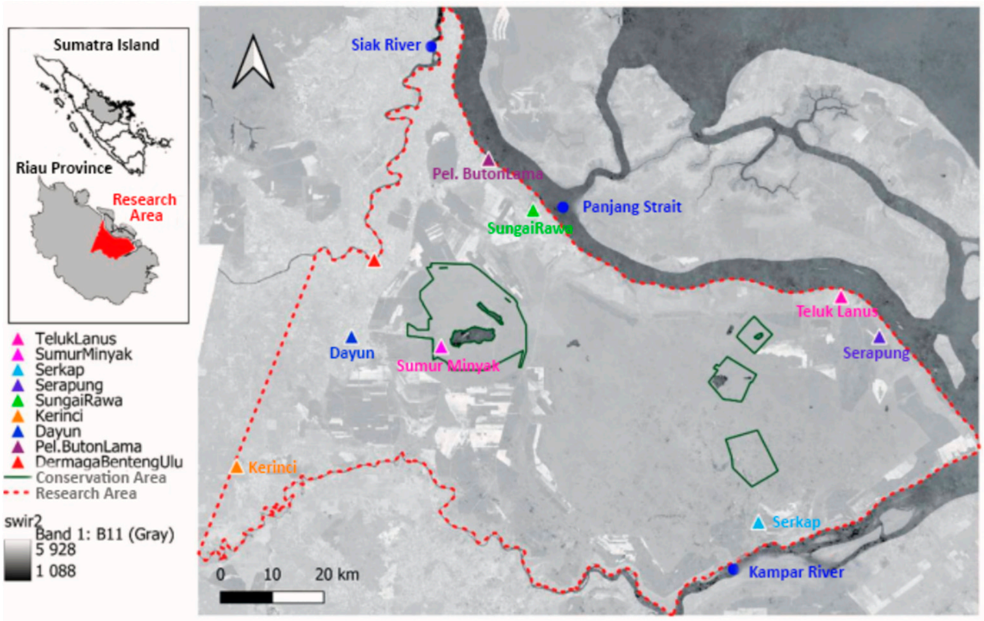


**Figure 1.** Map of the research area in the Kampar Peninsula, Riau Province.

## 2.1. Data Collection

The data collection for this research involved both quantitative and qualitative approach to ensure a comprehensive analysis. For quantitative analysis, the Landsat imagery data were collected over a 30-year period from 1990 to 2020, comprising a total of 2175 images. These images were meticulously selected for their spatial and temporal coverage to effectively capture land use changes over time. The data were processed at a high resolution of 30 m by 30 m, covering a total of approximately 735,091 hectares (equivalent to 8,167,678 cells). The Coordinate Reference System (CRS) used for this analysis was EPSG: 4326. Land and forest cover data were derived from the NDFI based on Landsat 4-5-7-8 images for the years 1995, 2000, 2010, 2015, and 2020.

In addition to quantitative data, qualitative data were gathered through in-depth interviews with various stakeholders involved in land use policy in the Kampar Peninsula. These interviews, conducted with community leaders, government officials, and NGO representatives, utilized structured interview guides and a comprehensive list of questions. The focus was on understanding government policies, which are defined as actions or decisions taken by the government to address societal issues. The qualitative analysis of these interviews provided valuable insights into the influence of government policies on land use decisions and changes in the Kampar Peninsula. These qualitative data are used to complement the understanding of the policy-related drivers contributing to land cover changes, which were quantitatively recorded through NDFI analysis.

## 2.2. Data Analysis

Quantitative data analysis involves a systematic process that includes selecting appropriate imagery, pre-processing the data, and selecting specific bands for analysis. This process is executed using a sequence of JavaScript functions within the Google Earth Engine platform. The main function, getLandsat(), is used to retrieve the necessary Landsat images.

This function works in conjunction with various other functions in the ccdcUtilities/api, which together handle a total of 19 bands [26,27].

For selecting and processing Landsat imagery from satellites 4, 5, 7, and 8, the workflow involves several steps that leverage cloud data and computing resources available through the open-source application Google Earth Engine using JavaScript. The data processing begins with the use of cloud data to access available Landsat images. These images are then organized into an image stack by the cloud engine. Specific years are selected for analysis, and the NDFI is calculated for these years to detect natural forest disturbances over time [28,29]. Prior to NDFI calculation, the spectral data from the different Landsat sensors were calibrated and harmonized. We employed standard radiometric correction techniques and cross-calibration methods to account for differences in spectral response between the sensors. Specifically, the Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS) and the Landsat Surface Reflectance Code (LaSRC) were utilized to derive consistent surface reflectance values across all datasets. Cross-calibration was crucial, particularly when harmonizing data between Landsat 5 and 7 (Thematic Mapper sensors) and Landsat 8 (Operational Land Imager, OLI). This process mitigated potential discrepancies in spectral response, as documented in previous studies [30,31]. These studies highlight the challenges posed by differences in spectral bandwidths between the Thematic Mapper and OLI sensors, which can affect the consistency of time-series analyses.

In cases where data from multiple Landsat sensors were combined, we minimized the temporal overlap between sensors to reduce potential impacts on the continuity of the time-series analysis. We prioritized the use of Landsat 8 data due to their superior radiometric resolution, supplementing them with Landsat 5 and 7 data only where Landsat 8 data were unavailable. While this approach mitigates significant discrepancies, it is acknowledged that the mixing of sensors can introduce minor variations in NDFI values due to differences in spectral resolution and sensitivity, particularly in the visible and near-infrared bands. Nonetheless, the applied cross-calibration methods effectively harmonized the datasets, ensuring that the impact on the analysis was minimized.

The cloud engine classifies areas into natural and non-natural forest categories and further classifies natural forest disturbances. The detection of these disturbances is performed by comparing NDFI values between different years. Subsequently, the cloud engine estimates land use changes over the selected years. Ground truth data are used to validate these changes and identify different land use types. Finally, the cloud engine classifies and estimates the land use types. This process is illustrated in Figure 2.

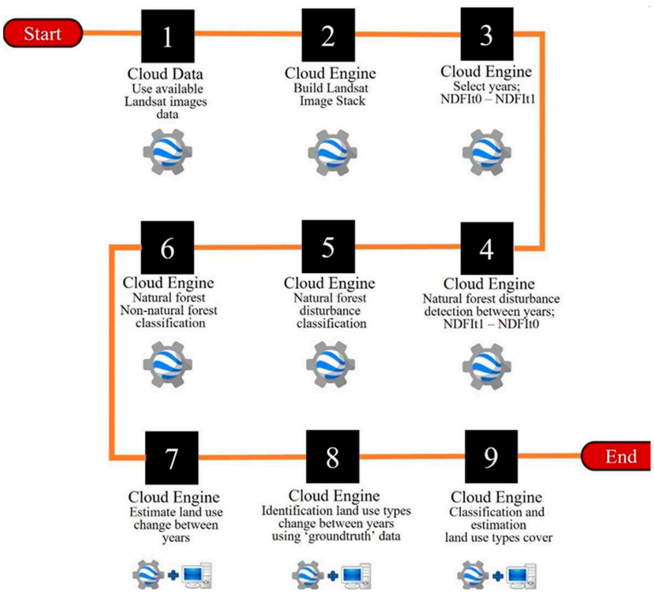


**Figure 2.** Flow chart of selecting and processing data from Landsat imagery.

Subsequently, land cover change maps were identified for specific periods, including 1990–1993, 1998–2000, 2000–2003, 2008–2010, 2010–2013, and 2018–2020. The identification process integrated NDFI detection change maps and ground check coordinate data. Visual inspection methods were applied to these maps, and the accuracy was validated through ground checks. Ground check data were obtained from two sources: the first source was a collection of field observation results gathered during surveys conducted from 2017 to 2021 with the field team, and the second source was visual observations based on GEE satellite imagery from 2021. Ground check data from field observations were collected using a Garmin 78S handheld device, recording points, track routes, and significant locations related to the historical dynamics of land use change in the Kampar Peninsula. The distribution of these observations is illustrated on the map in Figure 3. Key landmarks considered important by the author and still present today include oil wells that have been operational for five decades, an oil road constructed around 1982, the Benteng Ulu dock on the banks of the Siak River in the village of Mempura, where Sultan Siak II, who ruled from 1746 to 1765 AD, is buried, the Dutch fort built in 1827 AD, the Local Transmigration Village of Sawit initiated around 1985, Dayun Village, the old Buton Port, Pangkalan Kerinci City, Teluk Lanus Village, the Serkap River area, and Serapung Village.

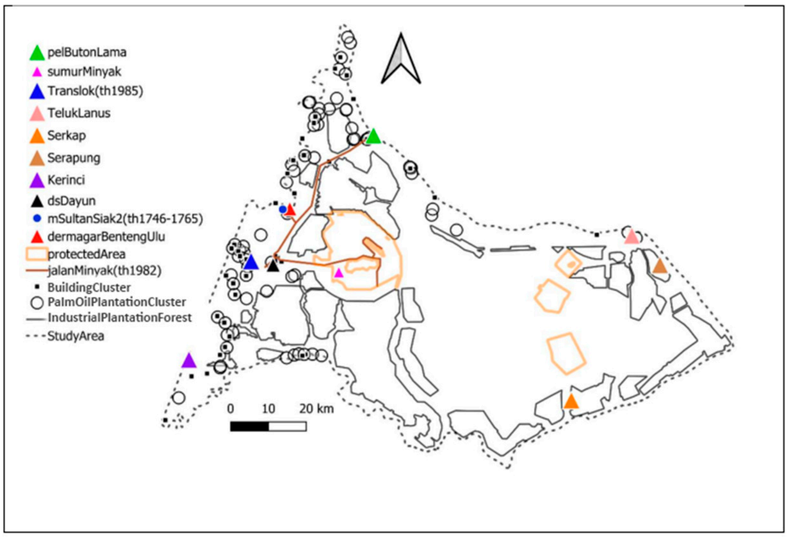


**Figure 3.** Distribution map of ground check data.

The identification process was divided into four clusters to differentiate the impacts of various land use types. Cluster A includes industrial infrastructure (e.g., oil and gas facilities, industrial forest plantations/HTI (*Hutan Tanaman Industri/Acacia* for pulp and paper)) to monitor significant industrial activities separately. Cluster B covers residential buildings to analyze urban expansion and settlement impacts distinctly. Cluster C focuses on oil palm plantations due to their rapid expansion and associated environmental concerns, while Cluster D encompasses acacia industrial forest plantations to understand the dynamics of industrial forestry practices. Visualizations for these four clusters are presented in Figure 4.

In conducting the qualitative analysis, the data processing involved examining interview results relating to the drivers of land use change, government policies, and sustainable peatland ecosystem management. The interview data processing began with transcription, creating comprehensive written descriptions of the interviews, including verbatim recording of any statements made in local languages.

Following transcription, a detailed coding analysis system was employed to systematically interpret the data. Initially, open coding was performed, where the transcriptions were reviewed line by line to identify key phrases and concepts. Each relevant segment of text was assigned a code representing a specific idea or theme.


**Figure 4.** Four classification clusters for identifying land use conditions: (**A**) Cluster A, consisting of oil and gas industry buildings, and industrial forest plantations—pulp and paper; (**B**) Cluster B, consisting of residential buildings; (**C**) oil palm plantation cluster; and (**D**) acacia industrial forest plantation cluster.

Next, axial coding was used to explore the relationships between these initial codes. This step involved grouping similar codes into categories and identifying connections between them to understand the broader themes emerging from the data. For instance, codes related to "deforestation drivers" might be grouped with those related to "infrastructure development" and "policy impacts".

These qualitative data provided valuable insights into the factors driving land use changes, complementing the quantitative findings.

### 2.2.1. Analysis of Forest Disturbance Detection and Classification

This analysis utilized a dataset comprising 2175 Landsat images, each with 19 bands, covering the period from 1990 to 2020, along with the application of Google Earth Engine (GEE) [26,32,33]. The data were analyzed using the Spectral Mixture Analysis (SMA) method. The SMA theory assumes each image pixel is a mix of various endmembers (spectral signatures) with pure spectral values. This method predicts the proportion of each pixel belonging to specific classes or features based on the spectral characteristics of its endmembers [34]. For example, the endmembers of Green Vegetation (GV) might have a spectral fraction composition of [0.0119, 0.0475, 0.0169, 0.625, 0.2399, 0.0675] across the blue, green, red, NIR, SWIR1, and SWIR2 bands, respectively [27]. Calculating each NDFI began by selecting six bands [BLUE, GREEN, RED, NIR, SWIR1, SWIR2] from the Landsat dataset (Table 1).

**Table 1.** Spectral endmembers (spectral signature) for analyzing spectral mixture endmembers used to estimate fractions of each pixel.

| Endmember | Blue | Green | Red | NIR | SWIR1 | SWIR2 |
|---|---|---|---|---|---|---|
| GV | 0.05 | 0.09 | 0.04 | 0.61 | 0.30 | 0.10 |
| NPV | 0.14 | 0.17 | 0.22 | 0.30 | 0.55 | 0.30 |
| Soil | 0.20 | 0.30 | 0.34 | 0.58 | 0.60 | 0.58 |
| Shade | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Cloud | 0.90 | 0.96 | 0.80 | 0.78 | 0.72 | 0.65 |

The data from these six bands at the initial time point (time0) were used to identify spectral signatures [GV (Green Vegetation), Soil, NPV (Non-Photosynthetic Vegetation), Shade, Cloud] (Table 1) for each cell of these bands through the process of spectral unmixing. This unmixing was performed using the unmix() function or the getSMAFractions() function. This process created five new bands representing the different spectral signatures, allowing for a detailed analysis of forest disturbances and land cover changes. The analysis was conducted using the identified spectral signatures over 12 observation periods from 1990 to 2020, as detailed in Table 2. This allowed us to track forest cover changes and disturbances over three decades. To minimize discrepancies due to sensor differences, we primarily used data from a single Landsat satellite, Landsat 8. For example, for a given time0 and time1, we preferred using images from Landsat 8 rather than mixing datasets from different satellites.

**Table 2.** Observation time groups for NDFI change detection.

| | NDFI0 | NDFI1 | NDF12 | NDF13 | NDF4 | NDF15 | NDF16 | NDF7 | NDF18 | NDF19 | NDF10 | NDF11 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| time0 | 1990 | 1993 | 1995 | 1998 | 2000 | 2003 | 2005 | 2008 | 2010 | 2013 | 2015 | 2018 |
| time1 | 1993 | 1995 | 1998 | 2000 | 2003 | 2005 | 2008 | 2010 | 2013 | 2015 | 2018 | 2020 |

2.2.2. Identification of Land Use Cover Change

Changes in land use area between natural forest and non-forest areas were calculated over the observation periods. The forest disturbance detection analysis data, which utilized the NDFI, served as a key variable in this process. At this stage, the initial 12 NDFI observation periods (as shown in Table 2) were consolidated into 6 observation periods for analyzing natural forest and non-forest areas (forest-non forest/FNF) as detailed in Table 3. This analysis employed the Random Forest (RF) algorithm, using a sample dataset of 500 randomly stratified points per classification category. For the training process, 80% of the samples were used for training, and the remaining 20% for validation. With 1000 trees in the trained classifier, an Overall Accuracy (OA) of 98.17% was achieved.

**Table 3.** Observation time groups for natural forest and non-forest (FNF).

| FNFtime | FNF1 | FNF2 | FNF3 | FNF4 | FNF5 | FNF6 |
|---|---|---|---|---|---|---|
| TimeObs | 1990–1995 | 1996–2000 | 2000–2005 | 2006–2010 | 2011–2015 | 2016–2020 |

This classification referenced the European Space Agency (ESA) WorldCover 10 m v.100, utilizing three category classes: tree cover (canopy cover), built-up (infrastructure such as buildings and roads), and open water (https://developers.google.com/earth-engine/datasets/catalog/ESA_WorldCover_v100 accessed on 23 May 2024). The analysis was conducted using cloud data and the Google Earth Engine (GEE) open-source application.

## 3. Results

Approximately five decades ago, before 1975, the peat ecosystem of the Kampar Peninsula was entirely natural forest. The wet habitat of the peat swamp forest was impenetrable and untouched by development activities. The first significant disturbance occurred in the protected area of the Danau Pulau Besar and Danau Bawah Wildlife Reserve, covering 28,000 hectares, where 3400 hectares were cleared for oil exploration and production at the Zamrud field [11]. The oil reserves at Zamrud field were discovered in 1975 beneath these two lakes at a depth of 3000 feet and began production in 1982 [20]. Between 1979 and 1982, the roads were built by the oil company, connecting Dayun Village, located near the Zamrud oil field, with surrounding villages such as Benteng Ulu Village on the banks of the Siak River (near the historical Dutch fort built in 1827), Teluk Mesjid Village, and the old Buton Port on the edge of Selat Panjang [14]. Since then, the process of land use change in the Kampar Peninsula peatlands has continued to the present day.

Currently, the peat forest cover of the Kampar Peninsula consists not only of natural forests but also industrial forest plantations (acacia), oil palm plantations, rubber plantations, residential areas, community agricultural lands, and areas developed for infrastructure. The ratio of natural forest to non-forest areas has reversed compared to several decades ago.

### 3.1. Detection of Forest Disturbances and Classification of Land Cover Using NDFI

The detection of forest disturbances using the NDFI is shown in Figure 5. It presents the result of detecting and classifying forest cover changes through continuous monitoring of forest disturbance events using a dataset of 2175 continuous Landsat images over the observation period from 1990 to 2020. Based on the calculation of NDFItime0–NDFItime1 for these observation periods, the monitored forest disturbance events were then classified into five classes, representing the chronology of forest disturbance events occurring during and before the monitoring period. The five classification classes are as follows:

- Class 1: Undisturbed old-growth forest or remnants of previous disturbances that have not undergone further disturbance or regrowth (no change between years, white);
- Class 2: Natural forest that has not experienced disturbance or has fully recovered (natural forest, green);
- Class 3: Forest disturbances due to fire and/or selective logging (forest disturbance, orange);
- Class 4: New forest disturbances or ongoing disturbances (new disturbance, light red);
- Class 5: Old forest disturbances or remnants of previous disturbances that have regrown (old disturbance, light blue).

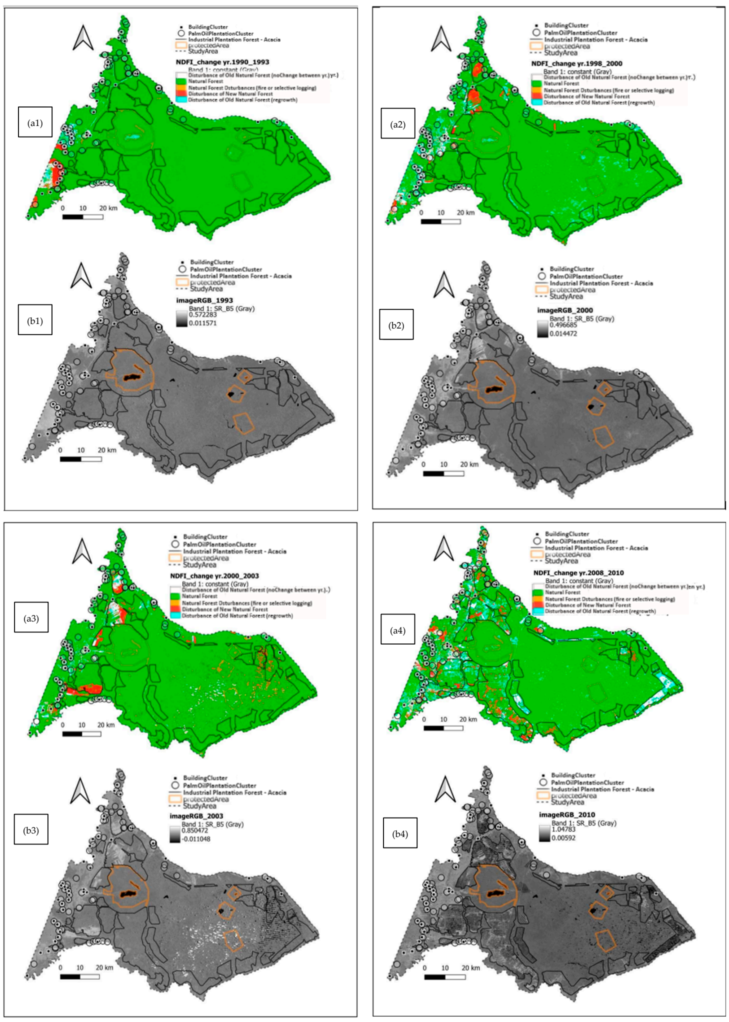


**Figure 5.** *Cont.*

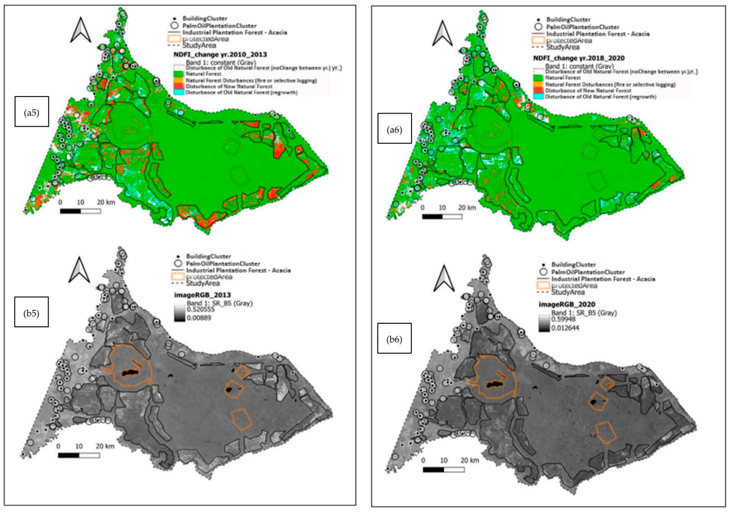


**Figure 5.** NDFI change overview (**a1**) NDFI change map between 1990 and 1993, (**a2**) NDFI change map between 1998 and 2000, (**a3**) NDFI change map between 2000 and 2003, (**a4**) NDFI change map between 2008 and 2010, (**a5**) NDFI change map between 2010 and 2013, (**a6**) NDFI change map between 2018 and 2020; (**b1**) Landsat image 1993, (**b2**) Landsat image 2000, (**b3**) Landsat image 2003, (**b4**) Landsat image 2010, (**b5**) Landsat image 2013, (**b6**) Landsat image 2020.

Figure 5 consists of two maps. Map (a) displays a classification of five classes resulting from the calculation of NDFItime0–NDFItime1 during the observation period. Map (b) is a true-color RGB map, covering the same observation period as map (a) and visually confirms the forest disturbance events classified in map (a), particularly showing events that occurred before the initial time0 observation period. The maps visually display the traces of forest disturbance events that occurred before the observation period of map (a), ranging from light gray to dark gray.

Based on Figure 5, the 2020 data were further developed into a map overlay to show the land use classification map of the Kampar Peninsula (Figure 6). This classification reveals the distribution and extent of various regional land cover types. The area and percentage of each land cover class are summarized in Table 4.

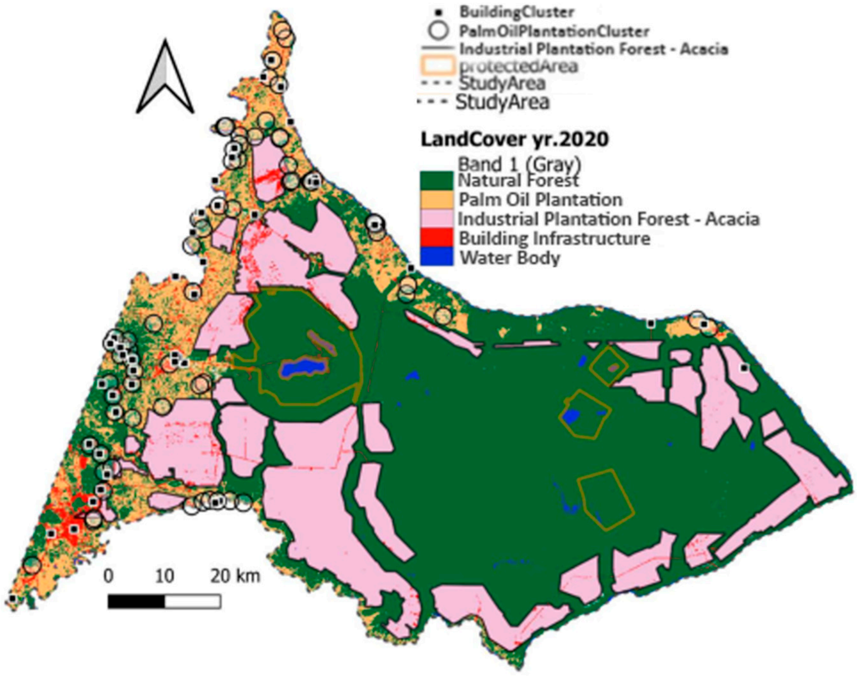


**Figure 6.** Land use classification map of 2020 with ground check data.

**Table 4.** Area of each land cover class in 2020.

| Category | Area (Ha) | Percentage (%) |
|---|---|---|
| Forest Area | 433,395.20 | 59.9 |
| Plantation | 76,602.24 | 10.4 |
| Industrial Pulpwood–Acacia | 200,510.10 | 27.3 |
| Infrastructure | 17,680.20 | 2.4 |
| Water Bodies | 6903.30 | 0.9 |

In 2020, natural forests occupied the largest portion of the Kampar Peninsula, covering 433,395.20 hectares, constituting 59.9% of the total land area, which had either not experienced disturbance or had fully recovered, depicted in green. Industrial pulpwood plantations, primarily consisting of acacia, covered 27.3% of the area, shown in purple. Plantations, mainly oil palm, accounted for 10.4% of the total and are marked in yellow. Infrastructure, including roads and buildings, made up 2.4% of the land area, indicated in grey. Water bodies, such as rivers and lakes, occupied 0.9% of the region, depicted in blue.

### *3.2. Land Use Change Analysis: Natural Forest and Non-Forest Areas*

The data from the forest disturbance detection analysis using NDFI were further grouped into six observation time groups, as presented in Table 5 and Figure 7. This analysis illustrates the change in land use from natural forest cover to non-forest cover (forest-non forest/FNF).

**Table 5.** Area of land use change based on forest cover change (natural forest and non-forest areas) from 1990 to 2020.

| Year | Natural Forest (ha) | Coverage (%) | Non-Natural Forest (ha) | Coverage (%) |
|---|---|---|---|---|
| 1990 | 723,895.30 | 99.41 | 4292.40 | 0.59 |
| 1995 | 646,695.18 | 88.8 | 81,492.50 | 11.2 |
| 2000 | 641,112.03 | 88.04 | 87,075.65 | 11.96 |
| 2005 | 441,519.66 | 60.63 | 286,668.02 | 39.37 |
| 2010 | 367,125.84 | 50.41 | 361,061.84 | 49.59 |
| 2015 | 437,866.23 | 60.13 | 290,321.45 | 39.87 |
| 2020 | 433,395.20 | 59.52 | 294,792.48 | 40.48 |


**Figure 7.** Natural forest cover change trend in Kampar Peninsula (1990–2020).

Table 5 and Figure 7 indicate that over 30 years, the natural forest area in the Kampar Peninsula decreased significantly from 723,895.30 hectares in 1990 to 433,395.20 hectares in 2020. In 1990, natural forests covered 723,895.30 hectares, representing 99.41% of the total area, with non-natural forests covering only 4292.40 hectares (0.59%). By 1995, natural forest areas decreased to 646,695.18 hectares (88.81%), while non-natural forest areas increased to 81,492.50 hectares (11.19%). This trend continued, with natural forest areas further declining to 641,112.03 hectares (88.04%) in 2000 and non-natural forest areas rising to 87,075.65 hectares (11.96%). The most dramatic changes occurred between 2000 and 2005, where natural forest areas dropped to 441,519.66 hectares (60.63%), and non-natural forest areas surged to 286,668.02 hectares (39.37%). By 2010, natural forest areas were reduced to 367,125.84 hectares (50.42%), almost equal to the non-natural forest areas at 361,061.84 hectares (49.58%). Although there was a slight recovery in natural forest areas to 437,866.23 hectares (60.13%) in 2015, the trend of reduction resumed, reaching 433,395.20 hectares (59.52%) in 2020, with non-natural forest areas standing at 294,792.48 hectares (40.48%).

The comparison of land use changes is illustrated in Figure 8, which juxtaposes imagery data from the periods 1990 to 1995 and 2016 to 2020. This comparison highlights the significant transformations in land cover over these decades.

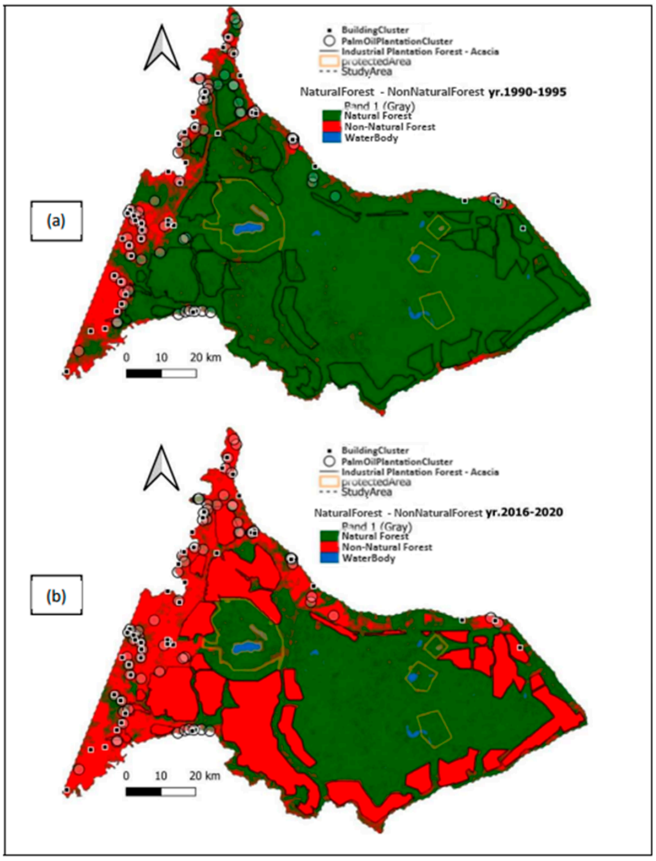


**Figure 8.** Land use change map indicating the transition from natural forest to non-forest areas from 1990 to 2020. (**a**) Changes occurred between 1990 and 1995, and (**b**) between 2016 and 2020.

As shown in Figure 8, the remaining natural forest areas are located in the central part of the Kampar Peninsula, where the peat dome is situated. Naturally, this area is difficult to access, which is beneficial since the peat dome is crucial for the integrity of the peatland ecosystem. Industrial forest plantations on the outskirts of the natural forest area also help restrict access to the central part of the Kampar Peninsula.

### *3.3. Qualitative Overview of Historical Events Related to the Land Cover Change*

This section provides a qualitative overview of the historical events and policy developments that have significantly influenced land cover changes in the Kampar Peninsula. The qualitative data presented here are intended to support the results of the quantitative analysis conducted using the NDFI. Table 6 summarizes key historical events and policy implementations, categorized into "Infrastructure Development" and "Policy Impacts."

**Table 6.** Historical events and policy impacts on land cover change in Kampar Peninsula.

| Time Period | Description of Historical Events | Classification |
|---|---|---|
| 1973 | Caltex recorded a peak production of 1 million barrels per day. The oil fields managed by PT CPI contributed over 12 billion barrels to national production, largely from the Minas oil field. | Infrastructure Development |
| Early 1950s–1998 | Resource extraction activities during the New Order era impacted land cover. | Policy Impacts |

**Table 6.** *Cont.*

| Time Period | Description of Historical Events | Classification |
|---|---|---|
| Early 1990s | Establishment of acacia industrial plantations, factory construction, employee housing, and supporting facilities. | Infrastructure Development |
| 1993 | PT Riau Andalan Pulp and Paper (RAPP) began operations, initially processing natural forest wood and later using acacia wood from industrial plantations. | Infrastructure Development |
| 1980s–1998 | Issuance of forest exploitation (HPH) permits, transmigration programs, and development of oil palm plantations. | Policy Impacts |
| 1990s | Issuance of permits for industrial forest plantations to supply raw materials for the pulp and paper industry. | Policy Impacts |
| 2009 | Indonesia committed to reducing greenhouse gas emissions through its Nationally Determined Contribution (NDC). | Policy Impacts |
| 2011 | Issuance of a Presidential Regulation on a moratorium, halting new concession permits in primary natural forests or peatlands. | Policy Impacts |
| 2012–2015 | Decrease in the rate of natural forest conversion to non-forest areas, likely related to the moratorium on new concession permits. | Policy Impacts |

As stated in Table 6, a multitude of historical events occurred during the period from 1990 to 2020. Among these events, three were classified as infrastructure development, while the remaining were related to policy impacts. This underscores the significant influence of policy, in addition to development efforts, as regulatory measures play a crucial role in shaping land use changes. Consequently, the involvement of the government is of paramount importance in this context. The results of this qualitative analysis are utilized to enhance the discussions by not only incorporating relevant studies but also providing a deeper context to the quantitative findings from the NDFI analysis.

## 4. Discussion

Our quantitative approach using NDFI analysis reveals significant shifts in land cover driven by various socio-economic and environmental factors. The changes in forest cover in the Kampar Peninsula have been ongoing since the region was still an intact tropical peat swamp forest. These land cover changes have been occurring since the era of the Sultanate of Siak, along the banks of the Siak River, and continue to the present day. The identified driving factors behind these land cover and land use changes in the Kampar Peninsula are detailed in the following discussion.

### *4.1. Historical Land Use Changes in Kampar Peninsula*

#### 4.1.1. Pre-1990 Period

Prior to 1990, land cover changes in the Kampar Peninsula were influenced by two main periods: the era of the Siak Sultanate and the New Order government. In Figure 8a, representing the period from 1990 to 1995, the Kampar Peninsula was predominantly covered by natural forest, especially in the central and eastern regions. The western side, however, shows the early stages of deforestation and land conversion activities. This area is primarily near old settlements, connected by river access and subsequently built roads, such as between Dayun Village near the Zamrud area and Buton Port, as well as the historical settlements of the Siak Sultanate along the Siak River and Pangkalan Kerinci Village, which later became the capital of the regency with Pekanbaru City.

During the Siak Sultanate era, land cover changes occurred primarily along the Siak River, near the Sultanate's capital, Siak Sri Indrapura. NDFI detection from 1990 to 1993 shows historical land cover changes around Mempura Village, near the mouth of the Mempura River (Figure 9). Key landmarks from this era include the tomb of the second Sultan of Siak (1746–1765) and a Dutch fort built in 1827. The Mempura River was a vital access route to the interior via the Dayun River, leading to the Tasik Zamrud forest. Locals used the Benteng Ulu ferry dock in Mempura to cross the Siak River before the Siak bridge was built [35]. From 1990 to 1995, the early stages of deforestation and land conversion in the western side of the Kampar Peninsula are evident [14]. This early deforestation is linked to historic settlements and the development of infrastructure connecting these areas.

For instance, roads were built to connect settlements like Dayun Village and Buton Port, facilitating access and further land conversion. The influence of the Siak Sultanate is also visible, with land cover changes occurring along significant historical routes, such as the Siak River and the Mempura River [36].

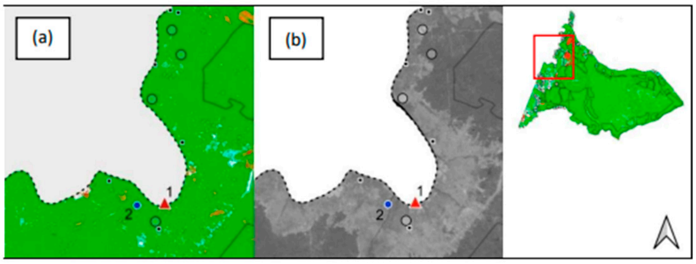

**Figure 9.** NDFI change detection (1990–1993) in the Mempura Village area on the banks of the Siak River: 1. Benteng Ulu Dock, 2. Tomb of the 2nd Sultan of Siak (**a**) NDFI change map (1990–1993); (**b**) Landsat image (1993).

During the New Order government (1965–1998), significant land cover changes began in the Kampar Peninsula, particularly in the Danau Besar and Danau Bawah Wildlife Reserve (now Zamrud National Park since 2016), driven by oil exploration and production activities starting in the early 1970s. The establishment of the Zamrud oil field, notably the Idris Oil Well, marked the beginning of these changes. The construction of roads between 1975 and 1982, which connected Dayun Village to the Benteng Ulu dock in Mempura, played a crucial role in facilitating access and stimulating economic activities in Dayun and its surrounding areas (Figure 10).

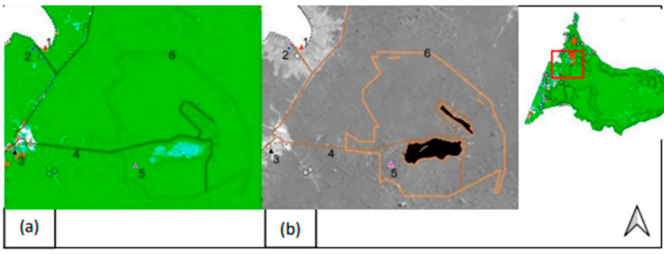

**Figure 10.** NDFI change detection (1990–1993) in the Mempura Village area on the banks of the Siak River: (1) Benteng Ulu Dock, (2) Tomb of the 2nd Sultan of Siak, (3) Dayun Village, (4) oil road built 1975–1982, (5) Idris Oil Well, and (6) boundaries of Zamrud National Park (**a**) NDFI change map (1990–1993); (**b**) Landsat image (1993).

Richard H. Hopper, in his book, notes that in May 1973, Caltex recorded a peak production of 1 million barrels per day. Since production began in the early 1950s, the oil fields in Kampar Peninsula, managed by PT CALTEX PACIFIC INDONESIA (PT CPI), had contributed over 12 billion barrels to national production cumulatively, with a significant portion coming from the giant Minas oil field. This massive production output underscores the scale of resource extraction activities during the New Order era and their impact on the region's land cover.

The development of roads to accommodate oil exploration significantly influenced land use changes during this period. The newly constructed infrastructure facilitated the transportation of resources and personnel, thus accelerating deforestation and the conversion of natural forests into non-forest land uses. These roads provided vital access routes, enabling the expansion of agricultural and industrial activities, further driving land cover changes. The roads built to support oil exploration not only provided access to previously inaccessible areas but also encouraged further development and exploitation of natural resources. This infrastructure development was a critical factor in transforming the landscape of the Kampar Peninsula. The improved connectivity allowed for the more efficient extraction of oil, which in turn boosted economic activities and job opportunities in the region. However, this also resulted in significant environmental impacts, including extensive deforestation and habitat fragmentation.

#### 4.1.2. Period of 1990–2000

Following the initial developments in the Danau Besar and Danau Bawah Wildlife Reserve, the subsequent phase of land cover changes was observed in the Local Transmigration (Translok) areas, where oil palm plantations were established around 1985 near Dayun Village and Pangkalan Kerinci.

One notable area, Kampung Sawit Permai, was formed in 1991 as a result of administrative decisions. This settlement emerged from the provincial and national policies aimed at developing transmigration units. According to the Bengkalis Regency Head's letter dated 12 December 1990, and the Riau Governor's Decree No. KPTS: 305/VI/1991, these areas were officially recognized. The Ministry of Home Affairs facilitated the handover of transmigration settlement units to the Riau governor as per document No. 475.1/669/SJ.

Figure 11 illustrates these changes, with locations a1 and a2 indicating the expansion of transmigrant settlements. Residents in these areas primarily planted oil palm as their livelihood, marking a significant shift from natural forest cover to agricultural land use. The establishment of these settlements and plantations facilitated economic activities and provided job opportunities, further driving land cover changes.

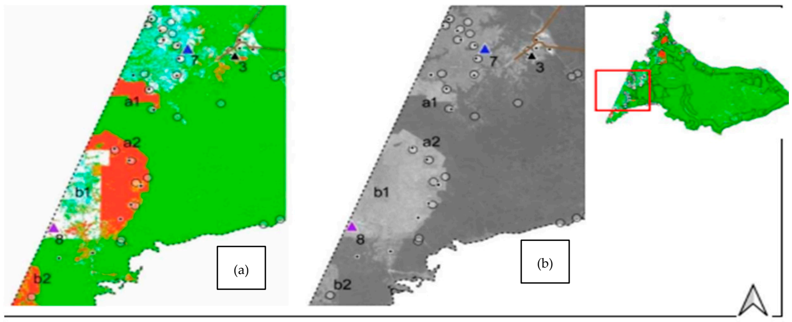


**Figure 11.** NDFI change detection results (1990–1993): Land cover changes occurred at locations a1, a2, and b2 in 1993 (red). Locations b1, Kerinci (8), and Translok (7) experienced previous land cover changes, showing no visual changes (white) and regrowth (light blue). (**a**) NDFI change map (1990–1993); (**b**) Landsat image (1993).

In locations b1 and b2 in Pangkalan Kerinci, land cover changes are associated with the pulp and paper industry. The early 1990s saw the establishment of acacia industrial plantations, factory construction, employee housing, and supporting facilities. PT Riau Andalan Pulp and Paper (RAPP) began operations in 1993, initially processing natural forest wood and later using acacia wood from industrial plantations in the Kampar Peninsula and other areas as raw materials [14]. The strategic location of Pangkalan Kerinci, with road access connecting it to Pekanbaru, the capital of Riau Province, further facilitated these industrial activities.

#### 4.1.3. Period of 2001–2020

The NDFI change detection from 2000 to 2003 reveals further land cover changes in Pelalawan Regency, which separated from Kampar Regency based on Indonesian Law No. 53 of 1999. Initially comprising the districts of Langgam, Pangkalan Kuras, Bunut, and Kuala Kampar, Pelalawan Regency was officially inaugurated on 12 October 1999, by the Minister of Home Affairs. Covering 13,924.94 km$^2$ of mostly mainland with some islands, its capital is Pangkalan Kerinci (Figure 12).

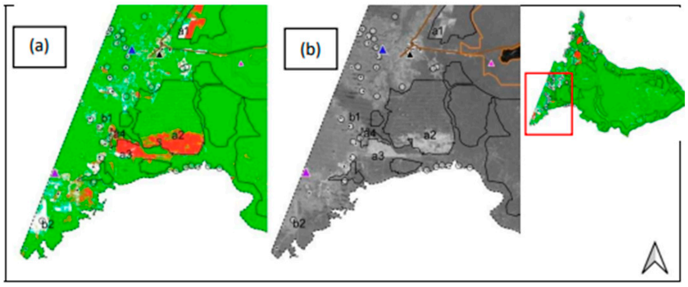


**Figure 12.** NDFI change detection results (2000–2003): Continued land cover changes and acacia expansion at locations a1 and a2. Location a3 shows land cover changes related to the acacia HTI industry, including a jet runway at location a4. Locations b1 and b2 indicate oil palm plantation expansion. (**a**) NDFI change map (2000–2003); (**b**) Landsat image (2003).

From 2008 to 2017, the total area of oil palm plantations in Pelalawan Regency steadily increased, alongside the expansion of acacia HTI. This expansion peaked around 2010 when the Indonesian government implemented a two-year moratorium, which started in 2011, on converting natural forests and peatlands. Announced under a USD 1 billion partnership with Norway to reduce emissions from deforestation and forest degradation (REDD+), this moratorium prohibited new conversion permits but did not affect permits issued before 2011 [37].

The findings of Rustiadi et al. [38] indicate that the expansion of oil palm plantations in peatland can positively improve the community's economic conditions and accelerate regional development. However, uncontrolled expansion of oil palm plantations can also have negative consequences, including the potential for conflicts that may lead to violent disputes between oil palm plantation companies and local communities, as well as among the communities themselves. One such conflict occurred on 19 June 2024, when 15 security personnel forcibly detained four plantation workers in Desa Segati. According to circulating reports, the workers were stopped while their truck was transporting oil palm and subsequently taken to the Pelalawan Police Station. This case involved PT Nusantara Sentosa Raya (NSR) and the farmers in Segati Village, Langgam District, Pelalawan, concerning allegations that the farmers had entered PT NSR's concession area.

### *4.2. Analysis of Key Drivers of Land Cover Change in the Kampar Peninsula*

The overall analysis of natural forest disturbance traces or changes recorded in each continuous Landsat image cell indicates that land cover changes in the Kampar Peninsula initially began on the western side of the Kampar Peninsula landscape. These changes were particularly prominent in areas close to old settlement centers, connected by river access and subsequently constructed roads. Notable examples include the area between Dayun Village near the Zamrud region and Buton Port, along with historical settlements from the era of the Siak Sultanate along the banks of the Siak River, and Pangkalan Kerinci Village, which later became the capital of the regency with Pekanbaru City.

The research findings indicate two primary factors driving land use change in the Kampar Peninsula peat swamp forests. The first factor is the introduction of vehicular access roads into previously inaccessible wetland habitats. The intensity of forest disturbances varied significantly between areas with road access and those without. For example, regions such as Teluk Lanus Village in the northeastern Kampar Peninsula and the Serkap area in the southeastern Kampar Peninsula, which lack road connectivity, experienced less intense forest disturbances. In contrast, disturbances were more pronounced along the edges of water bodies like the coast of Selat Panjang and the Kampar River towards the east, especially around the central peat dome of the Kampar Peninsula.

Allan et al. [39] highlighted that urban growth contributes to changing urban areas' spatial structure and land use/land cover (LULC), driven by transportation infrastructure, accessibility, and industrial development. This is particularly relevant as the industrial sector, unlike agriculture, has a higher potential for inducing environmental, regional, and national changes. The introduction of roads not only facilitates transportation but also acts as a catalyst for industrial and agricultural expansion, leading to significant land cover changes. Furthermore, research by Dohong et al. [40] identified logging roads as a major factor in deforestation and peatland forest degradation, subsequently driving land use change. The results are also compared with findings from the study by Song et al. [38], which assessed land cover changes in peatlands from 1992 to 2020 in Jambi, Indonesia. The result showed decreased forests and wetlands alongside increased agriculture, grassland, and built-up areas. This trend highlights the widespread nature of land cover changes across different peatland regions in Sumatra, driven by similar factors such as agricultural expansion and infrastructural development. However, in the Kampar Peninsula, it was oil companies, rather than logging companies, that initially constructed access roads around 1975. These roads broke the region's isolation and connected various locations, starting with Buton Lama Port, enabling human movement into the western interior of the Kampar Peninsula and fostering social and economic growth.

Government policy is the second driving factor behind natural forest cover changes and land use transformation in the Kampar Peninsula. During the New Order era, from the 1980s to 1998, the Indonesian government issued regulations for the management of production forests. During this period, concession permits for forest exploitation (HPH) were granted in the Kampar Peninsula, alongside transmigration programs that were coupled with the development of oil palm plantations. Permits for oil palm plantations were also issued independently of the transmigration programs. In the 1990s, the government issued permits for industrial forest plantations to supply raw materials for the pulp and paper industry.

A significant reduction in natural forest area occurred from the early 2000s to the 2010s. Investigations into permit issuance, government regulations, and interviews with representatives from the Ministry of Environment and Forestry (KLHK) suggest that during this period, there was likely a substantial issuance of industrial forest plantation (HTI) permits and oil palm plantation permits. The trend shows a decrease in the rate of natural forest conversion to non-forest areas around 2012–2015. This decrease is believed to be related to the issuance of a Presidential Regulation (Perpres) of the Republic of Indonesia on a moratorium, which halted new concession permits in primary natural forests or peatlands in May 2011. Additionally, in 2012, the government began issuing ecosystem restoration permits, which were exempt from the moratorium, in the Kampar Peninsula. The peatland natural forest's conservation and restoration efforts have had positive results.

Extending the plantation moratorium to include secondary and primary forests would also help reduce the conversion of natural forests and the frequency of fires. Reducing the susceptibility of the landscape to fire through restoring, rewetting, and revegetating degraded shrublands, particularly peatlands, is a priority. Since 2016, the Indonesian government has enacted a policy to restore degraded peatland in seven priority provinces, including West Kalimantan, with a total protected area of 28,136 ha, a permitted cultivation area of 64,078 ha, and a non-permitted area of 27,239 ha. In Kampar Peninsula, the total targeted area for restoration is 815,180 ha, with a protected area of 43,810 ha, a permitted cultivation area of 707,836 ha, and a non-permitted cultivated area of 43,810 ha [9,23,37].

As a result, development centers have become industry-based, particularly in regions with limited agricultural development potential. Government policies and regulations have significantly influenced the growth of residential areas and industrial activities. In developing countries, government-led initiatives often dominate urbanization and land use changes. Consequently, how the government acts can be regarded as one of the significant stimuli for the formation and change of spatial structure and land use/land cover changes.

In 2009, Indonesia committed to reducing greenhouse gas emissions through its Nationally Determined Contribution (NDC) submitted to the UNFCCC. These commitments led to a policy shift from promoting forest exploitation to curbing deforestation. In May 2011, Indonesia implemented a moratorium on new concessions in primary natural forests and peatlands. This policy, which has been extended to the present, aims not only to halt deforestation but also to restore ecosystem functions and promote sustainable forest management. The research indicates that this policy has affected the rate of land use change in the Kampar Peninsula, showing a stabilization in non-forest land cover between 2010 and 2020, with non-forest area remaining between 361,061.8 ha and 294,792.5 ha. Additionally, the government's issuance of ecosystem restoration concessions in the Kampar Peninsula, exempt from the moratorium, supports the preservation of natural forests, connecting several protected areas within the landscape.

## 5. Conclusions

Over the 30-year period from 1990 to 2020, the Kampar Peninsula has undergone substantial land use changes. The natural forest area decreased dramatically from 723,895.30 hectares in 1990 to 433,395.20 hectares in 2020. This study identifies two primary drivers behind these changes.

The first major driver was the construction of access roads, initially by oil companies in 1975. These roads opened previously inaccessible areas, facilitating extensive deforestation and land conversion. This infrastructure development enabled the expansion of human activities into interior regions, significantly altering natural forest cover and land use patterns. The second key driver was government policy. During the New Order period, forest exploitation concessions and transmigration programs were promoted, leading to widespread establishment of oil palm and acacia plantations. These policies transformed large areas of natural forest into industrial and agricultural lands, resulting in significant environmental impacts such as habitat loss, biodiversity decline, and increased greenhouse gas emissions. Recent policy shifts, such as the 2011 moratorium on new concessions in primary forests and peatlands, have aimed to curb deforestation and promote sustainable land management. These measures have contributed to the stabilization of non-forest land cover between 2010 and 2020. There was a slight recovery in natural forest areas, increasing to 437,866.23 hectares (60.13%) in 2015. However, the trend of reduction resumed, and by 2020, natural forest areas had decreased to 433,395.20 hectares (59.52%), with non-natural forest areas standing at 294,792.48 hectares (40.48%).

To address the complex challenges identified in this study, it is essential for related stakeholders to adopt a collaborative and multi-faceted approach. Government agencies should strengthen implementing and enforcing environmental regulations, such as the moratorium on new concessions in primary forests and peatlands, to curb deforestation effectively. Policymakers must consider revising and updating land use policies to promote sustainable practices, ensuring that economic development does not come at the expense of environmental degradation. Private sector stakeholders, including companies involved in oil palm and acacia plantations, should adopt sustainable land management practices and invest in restoration projects to mitigate their environmental impact. Furthermore, these companies should engage in transparent and inclusive dialogues with local communities to address conflicts and foster cooperative land use planning. Non-governmental organizations (NGOs) and academic institutions can play a crucial role by conducting ongoing research and monitoring to provide data-driven insights and advocating for policies that balance ecological conservation with economic growth. Finally, local communities should be actively involved in the decision-making processes, ensuring that their livelihoods and traditional knowledge are respected and integrated into sustainable land use strategies.

Future research should focus on a more detailed analysis of the socio-economic impacts of land use changes in the Kampar Peninsula, examining how local communities are affected by and respond to these changes. Additionally, longitudinal studies tracking the long-term ecological consequences of different land management practices will provide valuable insights into the effectiveness of current policies and practices.

**Author Contributions:** Conceptualization, D.N. and J.S.; methodology, D.N.; software, D.N.; validation, J.S., I.S. and M.K.; formal analysis, D.N.; investigation, D.N.; resources, I.S.; data curation, D.N.; writing—original draft preparation, D.N.; writing—review and editing, J.S., I.S. and M.K.; visualization, D.N.; supervision, J.S.; project administration, J.S.; funding acquisition, M.K. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Data Availability Statement:** The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

**Acknowledgments:** The author expresses sincere appreciation to the management teams of PT Riau Andalan Pulp and Paper and APRIL Group for their generous support and the provision of crucial data and information. Heartfelt thanks are also extended to the Wildlife Management Laboratory at the Faculty of Forestry, Universitas Gadjah Mada, for their unwavering support. Gratitude is due to the Government of Riau Province and all associated stakeholders, including local communities and NGOs, for their pivotal contributions to this research.

**Conflicts of Interest:** The authors declare no conflicts of interest.

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