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EXPLORING THE 21 YEARS TREND OF DEFORESTATION IN TERENGGANU STATE AND ITS IMPACT ON NATURAL HERITAGE

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ABSTRACT

Deforestation in Terengganu significantly threatens the local environment. This study uses Google Earth Engine (GEE), machine learning, and remote sensing data to identify changes in forest coverage over 20 years and their impacts on cultural heritage. Utilising Landsat 8, Sentinel-2, and the Hansen Global Forest Change dataset, the Normalised Difference Vegetation Index (NDVI) was calculated to quantify vegetation changes. The data show a decrease of 213,103 hectares in 2016 and 196,645 hectares in 2017, with a total loss of 287,328 hectares during the study period. The findings indicate substantial deforestation, particularly in metropolitan regions, with a strong negative correlation between forest cover and population, highlighting human activities' significant impact. The study also examines the relationship between deforestation and proximity to urban centres, noting higher forest loss around metropolitan areas between 2006 and 2011, mainly due to the East Coast Highway expansion. The study underscores the need for sustainable land use practices, conservation measures, and effective forest monitoring to combat deforestation in Terengganu.

Introduction

Deforestation is a major global problem that has serious effects on wildlife, the environment, and communities. Malaysia has experienced worrying decreases in its forest areas over the past 20 years or so. Studies have found that from 2000 to 2012, Malaysia lost approximately 14.4% of its woodland cover (Hansen *et al*., 2013). Clearing of land for food production and settlements expanded into forest regions. Trees have also been cut down extensively for commercial use and urban growth has consumed land that was previously forested. If deforestation continues at a high rate in Malaysia, it could seriously threaten plant and animal biodiversity. When forests disappear, the wildlife that calls those woods home loses places to live. The International Union for Conservation of Nature (IUCN) recognises the value of forests in supporting livelihoods, providing clean water, and maintaining ecological balance (IUCN, 2016).

According to Brinckerhoff *et al.* (2017), the conservation of forests is essential for maintaining ecosystem services and biodiversity. The United Nations Environment Programme (UNEP) report "Forest Resources Assessment 2020" also emphasises the global significance of deforestation as a threat to biodiversity, climate stability, and human livelihoods (Environment, 2020). It highlights the need for deeper investigations into localised deforestation impacts to inform context-specific solutions. Loss of tree cover also affects the weather since forests help regulate rain and temperatures (Kumar *et al*., 2022). Research has increasingly recognised the complex interlinkages between deforestation, climate change, and their combined impacts. Fan *et al.* (2019) determined that tropical forests are currently a net carbon source based on aboveground biomass measurements. Soil carbon released from erosion exacerbates climate change while forests play a vital role in sequestration (Li *et al*., 2020; Arakwiye *et al*., 2021).

Deforestation and climate feedback must be jointly addressed through mitigation and adaptation strategies (Mitchard, 2018). Fewer trees mean less carbon dioxide gets pulled from the air. On a local level, shrinking woodlands might cause problems for communities that have relied on forest resources for generations as a way of life (Maxwell *et al*., 2019). Things like gathering wood, finding medicinal plants, or practicing traditional farming may become harder. Hence, it is important to address deforestation both for protecting the environment and supporting rural people in Malaysia long into the future.

The United Nations Educational, Scientific and Cultural Organisation (UNESCO) emphasises the importance of protecting cultural assets to maintain cultural diversity and promote intercultural dialogue (Centre, 2019; UNESCO, 2021). Voigt *et al.* (2022) found deforestation in Malaysian Borneo significantly reduced orangutan populations. Similar impacts have been documented for other endangered species globally as forests disappear (Faison *et al*., 2023). Maintaining biodiversity is important for ecological resilience and sustainability.

Within Malaysia, the state of Terengganu stands out as a critical study site due to its extensive coastal forests, which support a high degree of biodiversity. Terengganu, a state situated on the east coast of Malaysia assumes significant importance as a study site within the given context. Terengganu encompasses an expansive area of approximately 4,600 squares kilometres, characterised by extensive coastal forests that exhibit a high degree of biodiversity. Terengganu also holds significant natural and cultural heritage values that are vulnerable to deforestation (Tan, 2012; Set *et al*., 2015). Archaeological sites offer insights into prehistoric human settlements that are at risk from habitat destruction (Wan Taib, 2017). Changes to forests also threaten indigenous communities' traditional livelihoods and cultural practices dependent on forest resources (Rudel, 2013; Ismail *et al.*, 2014). However, deforestation's socio-cultural impacts on Terengganu specifically remain underexplored (Dlamini, 2016).

The archaeological site presented by the findings of Set *et al.* (2015) provides additional support for the existence of the region's ancient past, which may be traced back several millennia. However, these forests are facing severe deforestation pressures. Changes to forests could disrupt indigenous groups' traditional ways of life too where forests play a crucial role in delivering important ecosystem services to the indigenous population (Toriman *et al*., 2018).

Advancing knowledge on localised deforestation impacts contributes insights for balancing environmental protection, development pressures, and cultural continuity (Wey *et al.*, 2022). However, prior studies have revealed that it has also been subjected to some of the most severe deforestation rates within the country throughout the past few decades (Hansen *et al*., 2013). This poses a significant threat to both the environmental and cultural heritage of the region.

The document from Global Forest Watch Open Data Portal (2023) reveals that Terengganu has experienced severe deforestation rates, making it essential to investigate the spatial and temporal patterns of deforestation in the region. Comprehensively understanding spatial and temporal deforestation dynamics is critical to balance development pressures with conservation needs (Arakwiye *et al*., 2021). While initiatives aim to reduce negative effects (Dlamini, 2016), integrated analyses of their effectiveness are still limited (Marzuki *et al*., 2023). Community-based and indigenous stewardship models show promise, but require further testing (Jones *et al.*, 2020).

According to the research by Talib (2015) in forestry sector in Malaysia, although more than 2,650 tree species have been found in Malaysian forests, additional research is required to comprehensively document the extensive biodiversity, as numerous plant and animal species are currently unrecorded. The inadequate documentation of species presents a difficulty in the efficient monitoring and preservation of forest resources in the long run.

Moreover, the existing information fails to provide sufficient specifics regarding the involvement with local people and the effects on indigenous groups. Enhancing the collection and reporting of data on species impacts, enforcement actions, social concerns, and adaptive responses to threats can bolster comprehensive forest management by addressing existing information deficiencies (Talib, 2015). Several studies have shown community-driven forest stewardship can achieve beneficial results in certain Southeast Asian regions (Levarto *et al.*, 2021).

However, more rigorous long-term analysis is still needed to fully assess impacts on deforestation rates (Smith *et al.*, 2018). Although Malaysia has made considerable advancements in certification and reviews, it is essential for the country to prioritise long-term monitoring, research, and knowledge-sharing in order to effectively and sustainably manage the intricate and rich forest ecosystems of Peninsular Malaysia.

Furthermore, as the United Nations Environment Programme pointed out in their 2020 forest assessment report, many nations have limited national-level information available on the underlying causes and patterns of shifts in woodland extent over time (Environment, 2020). Comprehensive data at this scale is important for accurately tracking progress and shaping relevant policies. Nevertheless, the state lacks comprehensive data regarding the spatial and temporal patterns of deforestation. Knowing exactly how much and where deforestation is happening over time is key to balancing development with protecting the environment.

To fill these gaps in existing research, this study employed a comprehensive approach by utilising a 21-year dataset of satellite images obtained through Google Earth Engine (GEE). Integrated Remote sensing, Geographic Information System (GIS) and Machine Learning (ML) approaches can better monitor deforestation (Wey *et al*., 2022). Remote sensing studies have mapped broad-scale deforestation trends (Hansen *et al*., 2013; Santika *et al*., 2019), yet localised patterns and impacts require deeper investigation to inform context-specific solutions (Mitchard, 2018).

The application of machine learning techniques facilitated the precise mapping of forest cover dynamics in Terengganu, Malaysia for the period spanning from 2001 to 2021. The research aims to identify the locations and timeframes of tree removal activities, analyse the geographical distribution of deforestation, and investigate the correlation between deforestation and its impact on significant cultural sites within Terengganu. By mapping deforestation at high spatio-temporal resolution, this research goes beyond broad-scale trend mapping to provide localised insights (Othman *et al*., 2019).

Investigating relationships between deforestation patterns (Al Faruq *et al*., 2016). Correlating forest loss with cultural sites represents an original approach to assess heritage impacts. Identifying historical trends and underlying socio-economic forces will advance knowledge of context-specific drivers. Informing sustainable management strategies tailored to Terengganu's natural and cultural values establishes the importance and distinctiveness of this research. This research sets to gain a deeper understanding of the phenomenon of deforestation in the region of Terengganu, Malaysia. The objectives are:

(1) Analyse temporal trends in deforestation patterns within forested regions. The utilisation of geospatial analysis methodologies, specifically employing the Google Earth Engine (GEE) platform, enables a precise assessment of deforestation patterns and rates between the years 2000 and 2021 through the analysis of satellite data. This cartographic representation offers significant insights into the extent and intensity of deforestation.

(2) Conduct an inquiry into the underlying factors contributing to deforestation. This study aims to analyse the primary factors contributing to forest loss in Terengganu, specifically focusing on agricultural development, logging, and urban growth. This research facilitates the formulation of initiatives aimed at mitigating deforestation.

(3) Analyse the effects on cultural heritage. This study aims to investigate the correlation between deforestation and the impact on culturally significant locations such as archaeological areas. This elucidates the impact of deforestation on local history and cultural practises.

(4) Facilitate the dissemination of sustainable management and preservation solutions. Based on the research findings, this study seeks to offer recommendations for safeguarding the forests and cultural assets in Terengganu's future. The integration of nature and cultural conservation is essential for achieving long-term sustainability.

By targeting these key objectives, this study aims to enhance strategic planning and decision-making for both forest and heritage conservation in Terengganu through a geospatial analysis of deforestation patterns, causes, and impacts over the past two decades. Effective forest management and historic preservation require a careful consideration of the various stakeholder interests and the potential trade-offs involved (Tóth, 2008). As noted by the United Nations Educational, Scientific and Cultural Organisation (UNESCO) in their 2001 report "Universal Value of Cultural Diversity", the preservation of forests and cultural resources is widely recognised as imperative for the long-term environmental and cultural viability of Terengganu and other countries.

Apart from that, this study aims to enhance the understanding of deforestation patterns in Terengganu by examining temporal and spatial trends. Additionally, it seeks to identify the underlying reasons that contribute to deforestation and assess its impacts on both the natural environment and cultural heritage. The findings of this study offer valuable insights for policymakers, conservation organisations, and local communities in devising effective strategies for the sustainable governance of forests and the safeguarding of cultural assets in Terengganu.

Literature Review

Ensuring accurate and thorough data is essential for monitoring and controlling the pace of global deforestation. Forestry companies and individuals typically depend on a combination of firsthand observations and data obtained through remote sensing to accomplish this significant undertaking (Hansen *et al.*, 2013; Achard *et al.*, 2014). Although direct observations may have limitations in terms of their spatial coverage and feasibility, remotely sensed observations have demonstrated their effectiveness in accurately measuring the extent of deforestation (Achard *et al.*, 2014).

The sources consist of reports from institutions, websites that present results from projects or research, published destructive events in the media, and photos obtained from Earth monitoring satellites (Hosonuma e*t al.*, 2012). The aforementioned sources provide an abundance of spatial datasets that are accessible to the public on a global and national scale (Hosonuma *et al.*, 2012). The compilation of these spatial datasets aims to offer dependable data on the geographical distribution, rates, and depletion of forests. They function as valuable assets for the formulation of policies, decision making, and assessment of the value of ecosystem services (Hosonuma *et al.*, 2012). The presence of these datasets enables the measurement and examination of deforestation, facilitating well-informed decision-making, and the adoption of efficient mitigation strategies (Hosonuma *et al.*, 2012).

Satellite sensors may have limitations in terms of their spatial and temporal resolution, their accuracy can vary depending on the specific sensor utilised (Hansen e*t al.*, 2013). The utilisation of Google Earth Engine (GEE) for deforestation monitoring offers numerous advantages over alternative solutions. GEE offers customers a significant benefit by granting them effortless access to a wide-ranging and varied collection of remote sensing data that covers the whole planet. GEE simplifies access to cutting-edge technologies by reducing the requirement for users to individually acquire and handle large datasets. This removes a limitation that typically confines the use of these methods to experts in remote sensing who have access to high-performance computing resources (Gorelick *et al.*, 2017; Amani *et al.*, 2020).

Machine learning techniques have proven to be effective in monitoring and predicting deforestation, offering valuable insights and opportunities for informed decision-making (de *et al.*, 2020). Machine learning is particularly advantageous in this case due to its ability to analyse and extract meaningful patterns from vast and complex data. Machine learning algorithms can be trained using satellite imagery and remote sensing data to automatically identify and map changes in forest cover over a period of time. This is a substantial enhancement compared to conventional manual mapping techniques, which require a lot of effort and are susceptible to mistakes made by humans (Jing *et al*., 2023).

According to Li *et al*. (2020), machine learning algorithms offer numerous benefits over traditional statistical methods for evaluating changes in land use. Machine learning algorithms have demonstrated their effectiveness in assessing changes in land use such as deforestation. These methodologies possess the capacity to accurately and efficiently assess intricate spatial and temporal patterns (Li *et al*., 2020). Machine learning algorithms demonstrate superior adaptability in comparison to other methods, since they contain the potential to capture non-linear correlations and intricate patterns in land use change data (Li *et al*., 2020). These algorithms have the ability to detect and analyse small changes in forest covering and uncover patterns in space and time that may not be noticed by conventional statistical methods. Machine learning has the ability to efficiently analyse large and diverse information, including remote sensing images, climate data, and socio-economic factors.

Quantifying forest loss requires a thorough analysis of the factors driving land-use change and its subsequent consequences (Khatami *et al*., 2019). The integration of multiple data sources improves the precision of deforestation measurements. Machine learning has the ability to make predictions by analysing past deforestation trends and environmental conditions, allowing researchers to forecast future deforestation (Larrea-Gallegos & Vázquez-Rowe, 2021).

Forecasting future events is crucial for making informed judgements on land management and policy planning. This enables the implementation of proactive strategies to reduce deforestation and promote sustainable forest management. Machine learning algorithms offer a more efficient and automated alternative for estimating forest degradation, as opposed to human or rule-based approaches (Vapnik *et al*., 2017). Machine learning utilises computer capacity to efficiently examine large datasets, hence, decreasing the time and effort needed for analysis.

Research and Methodology

Study Area

Terengganu is in the East Coast region of peninsular Malaysia and is officially recognised as one of the 13 states in the country. The region has a land area of about 5,033 square miles and is located at 103.1° East longitude and 5.3° North latitude. Terengganu has a forest coverage of approximately 36% of its geographical area, which is equivalent to 4,632 square kilometres (Chee *et al*., 2008; Toriman *et al*., 2018). Previous research has indicated that deforestation in the Terengganu region between 2001 and 2016 resulted in a significant reduction in land area, equivalent to three times the size of Singapore (Social Forestry and Climate Change in the ASEAN Region, 2020).

The deforestation of Terengganu has had a significant impact on the region's cultural and recreational destinations. Sites such as Kuala Berang, Tasik Kenyir, and Bukit Besi, which hold cultural and historical significance have been affected by this environmental issue. Kuala Berang and Tasik Kenyir are known for their cultural and historical importance while the Terengganu Inscription Stone discovery area provides insights into the prehistoric customs and traditions of the region.

Tasik Kenyir, the largest artificial lake in Southeast Asia is a popular recreational destination, offering activities like fishing, boating, and eco-friendly sightseeing (Kamarudin *et al*., 2018). Bukit Besi, like other historically significant sites, served as a hub for iron ore extraction during British colonialism.

Nowadays, it attracts tourists who are interested in exploring the remnants of the mining operations and learning about the region's history. However, the deforestation practices in Bukit Besi not only harm the ecological system but also endanger the conservation and interpretation of this important historical site. Protecting these recreational areas and cultural landmarks requires the implementation of sustainable land-use practices, appropriate zoning regulations, and conservation initiatives (Zakaria *et al*., 2023).

It is crucial to raise awareness about the ecological, recreational, and cultural significance of these areas and to take measures to mitigate the negative effects of deforestation activities (Law *et al*., 2009). The forested regions of Terengganu not only provide habitat for diverse flora and fauna but also contribute to the visual appeal of the area (Azmir *et al*., 2022). To conduct the analysis of this research, the study area was mapped using ESRI's ArcGIS software (Jubit *et al*., 2023; 2024a; 2024b; Ahmad *et al*., 2024a; 2024b; 2024c; 2024d; 2024e; 2024f; Ariffin *et al*., 2024; Chabo *et al*., 2024).

Method

The overarching aim of this study focuses on analysing the trends of deforestation in Terengganu over a span of 20 years, from 2001 to 2021. To achieve this, the study employed various dataset and techniques, including Remote Sensing, Geographic Information System (GIS), and Machine Learning (ML) with Google Earth Engine (GEE).

Data collection played a crucial role in the study, with satellite imagery and datasets from multiple sources such as Malaysia shapefile; the United States Office of the Geographer provides the Large-Scale International Boundary (LSIB) dataset and Hansen Global Forest Change dataset, which is based on 650,000 images cameras at 30-metre resolution captured by Landsat 8 and Sentinel-2 satellites owned by National Aeronautics and Space Administration (NASA) and European Space Agency (ESA) as appropriate (Hansen *et al*., 2013), which provided consistent data sources for tracking forest cover change at a fine spatial temporal scale. Methodology of the study consisted of several steps that are shown in Figure 1. Firstly, the study area was delineated, with Terengganu, Malaysia selected as the specific region for analysis.

In order to further investigate the impact of deforestation on cultural heritage, the study utilised machine learning techniques to identify and quantify the extent of deforestation in metropolitan regions, providing valuable insights into the impact on cultural heritage. The JavaScript API within Google Earth Engine (GEE) was utilised to develop custom analysis workflows and process the imagery. JavaScript was chosen for its direct interface with the GEE catalogue and tools. Various methods were

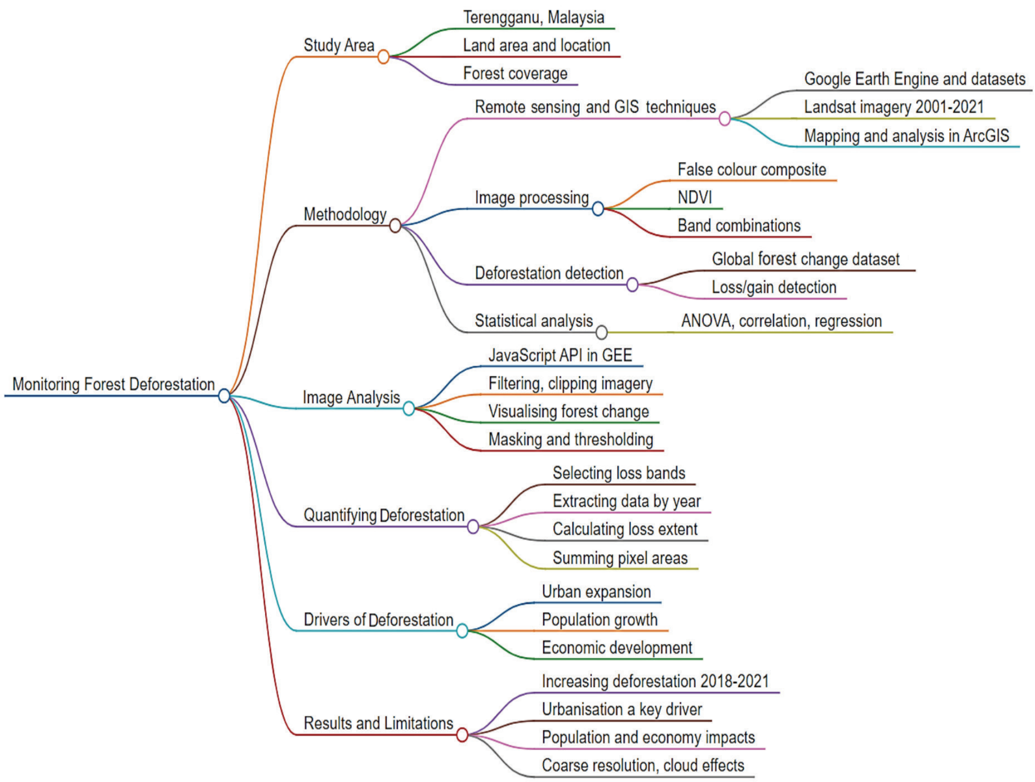

Figure 1: Research flow

employed such as filtering the ecoregions layer to Terengganu, clipping the global dataset, and generating false colour composites to effectively visualise forest change.

Moreover, to identify and quantify deforestation patterns in the study area, satellite imagery and datasets were processed and analysed using Google Earth Engine (GEE) and ArcGIS techniques. These techniques involved image processing and analysis procedures such as filtering, clipping, and masking to optimise the visualisation of forest change patterns and isolate deforested areas. In order to assess vegetation cover and density, calculations were performed on different spectral bands of satellite images (Table 1) while the Normalised Difference Vegetation Index (NDVI) is calculated using the Near-Infrared (NIR) and red bands.

Greenery absorbs visible blue and red rays, primarily due to pigments while reflecting green, which is why it appears green to our eyes (Al-Hamdan *et al*., 2017; Olpenda *et al*., 2018; Li *et al*., 2019). NDVI is computed by subtracting the reflectance values of the Near-Infrared (NIR) and red bands and then dividing the result by their sum. The formula is NDVI = (NIR - Red) / (NIR + Red) (Krakauer *et al*., 2017). This formula yields a numerical value that falls within the range of -1 to 1.

Areas with a high amount of vegetation typically have higher positive values of Normalised Difference Vegetation Index (NDVI), whereas non-vegetated areas like lakes or urban regions tend to have lower or negative NDVI values (Justice *et al*., 1985). How light reflects or scatters from plant surfaces depends on its wavelength (Hird *et al*., 2021). Calculations considering satellite colour readings also can emphasise different terrain types (Shi *et al*., 2022).

Table 1: Satellite image and band selected

No.	Date of Acquisition	Scene ID	Satellite	Bands
1	January 1, 2010 & December 31, 2018	LC08_L1TP_196030_20100101_20170602_01_T1	Landsat 8	B1-B9
2	October 5, 2015	S2A_MSIL1C_20151005T104515_N0207_R008_T30UWR_20151005T110515	Sentinel-2A	B1-B12
3	August 15, 2021	S2B_MSIL1C_20210815T104515_N0207_R008_T30UWR_20210815T110515	Sentinel-2B	B1-B12
4	January 1, 2000 - 1, 2016	UMD/hansen/global_forest_change_2015_v1_3	Landsat 7 thematic mapper plus (ETM+)	B 3, 4, 5, 7

Additional "false colour" images were created blending Short-wave Infrared, Near Infrared, and red bands to see patterns in forest cover over time (Yamada *et al*., 2020). This helped distinguish between vegetation and other ground types, offering insight into where deforestation was occurring spatially (Rissmann *et al*., 2019; Zhang, 2019; Shi *et al*., 2022). In this study, the combination of Bands 8, 4, and 3 created images maximising contrast at 100% brightness adjustment, highlighting plants and cleared areas specifically (Zhang, 2019). Remote sensing analysis characterised woodland more than 5 m tall within each 30 m pixel section (Rissmann *et al*., 2019). The update Mask function provides the capability to modify the transparency of individual pixels inside a mask image. To enhance the visibility of the loss area image, a palette and mask were implemented to facilitate the transition from a greyscale depiction to a green tint, as depicted in Figure 2. Notably, the loss area is represented by the yellow colour while the gain area is represented by the green colour.

Pixels that possess a non-zero value within the mask are utilised in computations, whereas pixels with a value of zero are disregarded. This phenomenon has an impact on the manner in which the visual representation is presented. This tools application is advantageous for the purpose of merging photographs, altering backdrops, eliminating or extracting items, and directing attention to specific regions rather than full layers. The technique maintains the integrity of the metadata and borders of the original image. This approach reduces the influence on the process of analysis. In order to discern specific pixels from a dataset, it is possible to aggregate correlated attributes into a construct known as a "Feature Collection". This enables the execution of various operations on the complete set such as region filtering, sorting, and generating estimations (Phan *et al*., 2020).

To identify forest loss, a mask was applied to isolate pixels representing loss areas. The "lossyear" band allowed for the extraction

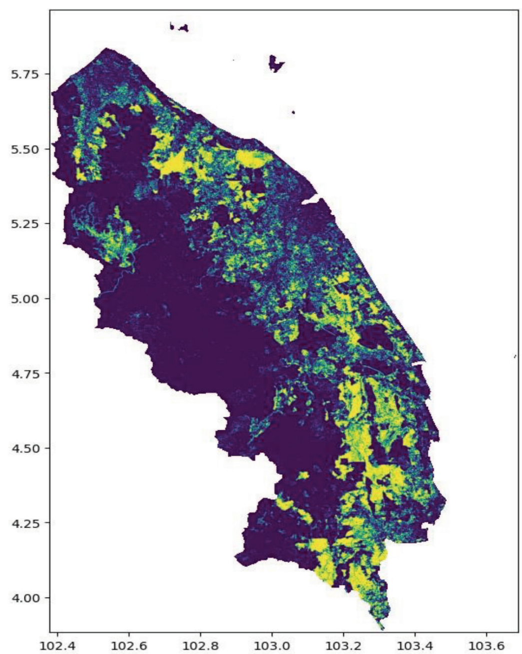

Figure 2: The loss and gain area of Terengganu State over a period of 20 years starting from year 2001 to 2021, by Hansen Global Data

of data for specific years such as 2004 in this study. By multiplying forest loss rasters by pixel area and summing within the region using the "Reduce Region" function, the extent of forest loss was calculated (Forest Cover and Loss Estimation | Google Earth Engine, 2022).

The "Reduce Region" function serves two main purposes in this analysis such as Calculating Forest Loss Extent, by multiplying forest loss raster data by pixel area and summing the results within the region of interest, "Reduce Region" enables the calculation of the total forest loss area (Forest Cover and Loss Estimation, Google Earth Engine, Google Developers, 2022). The purpose is Computing Statistical Measures and Consolidating Data, where the "Reduce Region" is also used to compute statistical measures from the image collection and consolidate the data. This suggests that the function might be used to derive metrics like the average forest loss per year or to aggregate data from multiple images into a single output. The analysis was performed at a 30-meter scale and the "maxPixels" parameter was set to 1e11, enabling the analysis of up to 100 billion pixels (Forest Cover and Loss Estimation | Google Earth Engine, 2021). The "Reducer" script generated an image where each pixel's value represented its area in square meters. This information, along with the "area" band produced by the "pixelArea" function was used to calculate yearly forest cover and loss area. To apply a reducer and calculate the mean pixel across an image, scripts (1) have been generated:

"imageCollectionMean = imageCollection.
reduce (ee. Reducer.mean)" (1)

The get () method in Google Earth Engine (GEE) is employed to obtain the outcome of the computation, specifically the summation of the forest loss area expressed in square metres. To analyse the extent of deforestation, the other techniques such as masking and thresholding were employed to identify and quantify deforested areas.

Additionally, statistical analysis techniques, including a one-way Analysis of Variance (ANOVA), correlation, and regression were utilised to investigate relationships and trends between deforestation and various factors such as population and proximity to urban areas. To further analyse the data, GEE images were analysed in a Jupyter notebook and converted to Tagged Image File Format using an Operating System module. This allowed for inter-annual trend comparisons by calculating loss pixel counts. Finally, the results were exported to Google Drive in GeoTIFF format for analysis in other GIS software to represent the final map and also involved training the ML algorithm on the dataset and then using it to generate the time lapse map. By integrating Remote Sensing, Geographic Information System (GIS), and statistics, insights emerged on the factors propelling deforestation and their implications.

Result and Data Interpretation

Machine Learning (ML) and statistical techniques applied such as correlation analysis and Analysis of Variance (ANOVA) testing, provided robust evidence for interpreting the influences of socioeconomic factors and variability between years on deforestation levels. Directly tying the key findings to the analytical methods used strengthens the validity and significance of the results. The result of data trend forest change over 20 years starting from year 2001 to 2021 clearly showed the annual deforestation figures over the study period.

The totals pixels representing loss forest in Terengganu is about 287,328.1231 hectare. This deforestation activity probability caused the change of land cover from vegetation to build up i.e., the city. During 20 years between year 2001 and 2021, Terengganu underwent a significant rate of deforestation during the year 2016 and 2017, with a total of 213,103 hectares being deforested in 2016 and 196,645 hectares in 2017 (Figure 3).

Both maps in Figure 4 illustrate the changes in the amount of deforestation between 2016 and 2018. The map on the left corresponds to the year 2016, whereas the one on the right shows the year 2018. These maps were generated utilising diverse approaches to

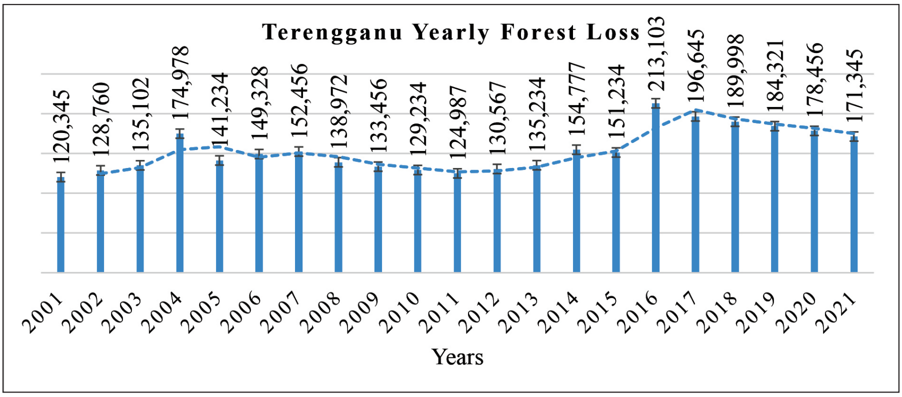

Figure 3: Deforestation activity from 2001 until 2021

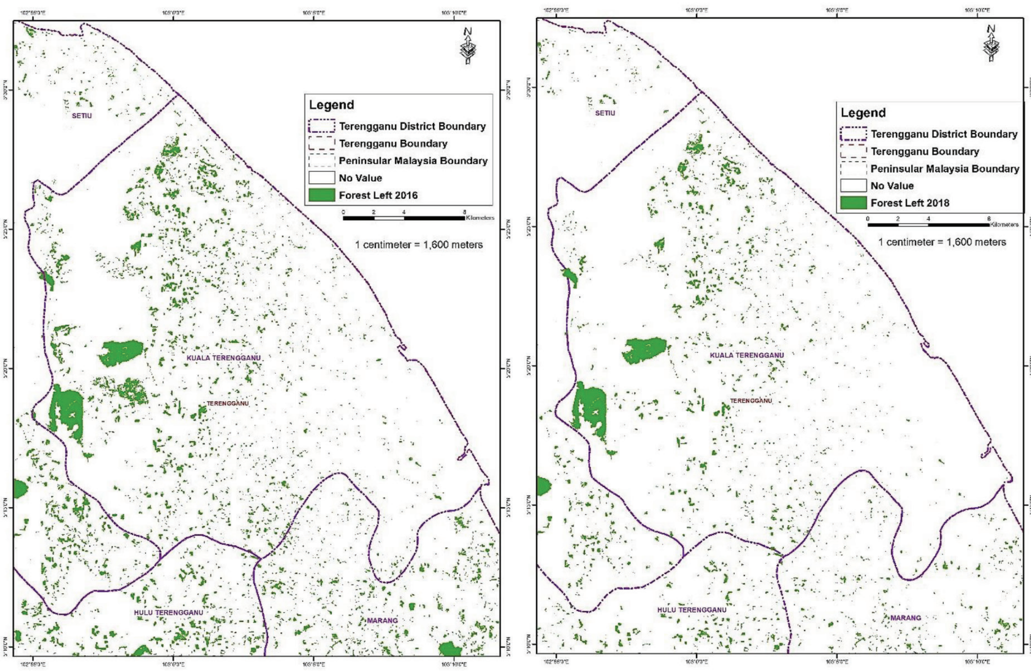

Figure 4: Forest loss area in year 2016 and 2018

enhance comprehension of the alterations in forest area. The green areas on the map depict forested zones, which experienced a decrease in prominence in 2018. This phenomenon is more prominently observable in the map generated by Jupyter Notebook Figure 5. The maps also offer a detailed perspective on forest logging activity and alterations in land use.

In addition, the maps indicate the locations where deforestation is taking place, particularly in the beach region near the city of Kuala Terengganu. Activities have extended outside the city centre to include the suburbs and countryside, particularly those around the city of Terengganu. The primary cause of forest loss in remote areas is clandestine deforestation carried out by certain organisations for profit. This map provides a succinct representation of the actions that resulted in the deforestation during that particular period. It is beneficial for monitoring

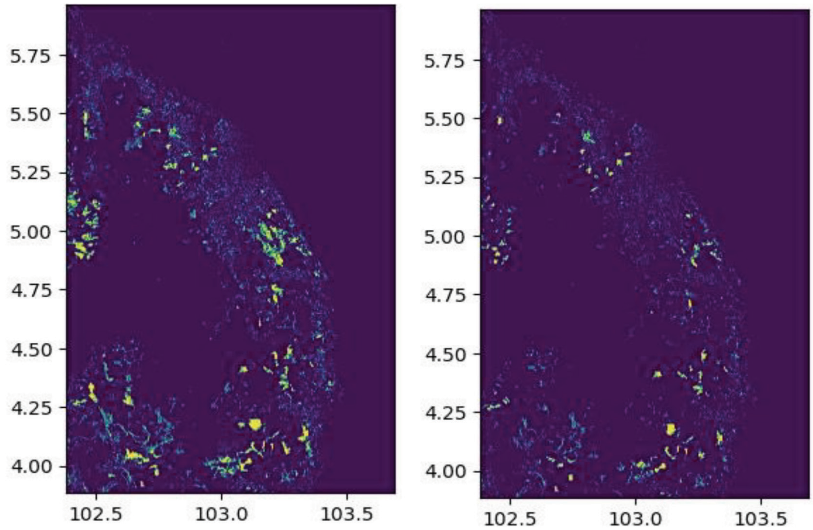

Figure 5: Terengganu forest loss occurs in years 2016 (left) and 2018 (right) seen using machine learning algorithm

and analysing changes in the environment and how land is being used. In year 2004, there was a sharp increase in deforestation after a political shift in power, with forests losing 174,9780 hectares compared to the previous year. The analysis also highlighted an elevated rate of deforestation in the immediate vicinity of urban regions, particularly due to the expansion of the East Coast Highway. The construction of the East Coast Expressway or *Lebuhraya Pantai Timur* 2 (LPT2) linked to the loss of forest areas near suburban areas in year 2006 to 2011. However, between 2014 and 2019, deforestation continued at a large scale, exceeding 154,7771 hectare per year and the average annual forest loss in Terengganu is approximately 135,74. Tree loss annually can harm the natural system and forest-dependent communities.

The archaeological sites found in Terengganu offer significant perspectives on the historical civilisations and early settlement practices of the region. The discovery of the Terengganu Inscription Stone in Kuala Berang has yielded valuable insights into the customs and societies of prehistoric times. As noted by Set *et al*. (2015), the Kampung Buluh archaeological site in Hulu Terengganu has provided evidence of prehistoric human settlement. The presence of prehistoric and early historical settlements in Tasik Kenyir is also supported by the rock shelters at Gua Bewah (Tan, 2012). During excavations conducted by experts from the National Museum, various archaeological artifacts, including the remains of a Neolithic man's skeleton were unearthed in the cave (Wan Taib, 2017).

However, the deliberate process of deforestation poses a significant threat to the archaeological heritage of Kampung Buluh in Hulu Terengganu. This phenomenon not only results in the loss of valuable artifacts but also undermines our understanding of prehistoric human habitation in the area (Pounsin *et al*., 2018).

Additionally, the continuous depletion of forest cover hampers the ecological framework necessary for comprehending early human settlements. Notably, in 2007, visible instances of deforestation and land use changes were observed near the Bukit Besi area (Figure 6). The Bukit Besi Mine site still retains various pieces of mining equipment used during its operational period. These remaining artifacts provide valuable insights into technological advancements and methods employed in earlier times.

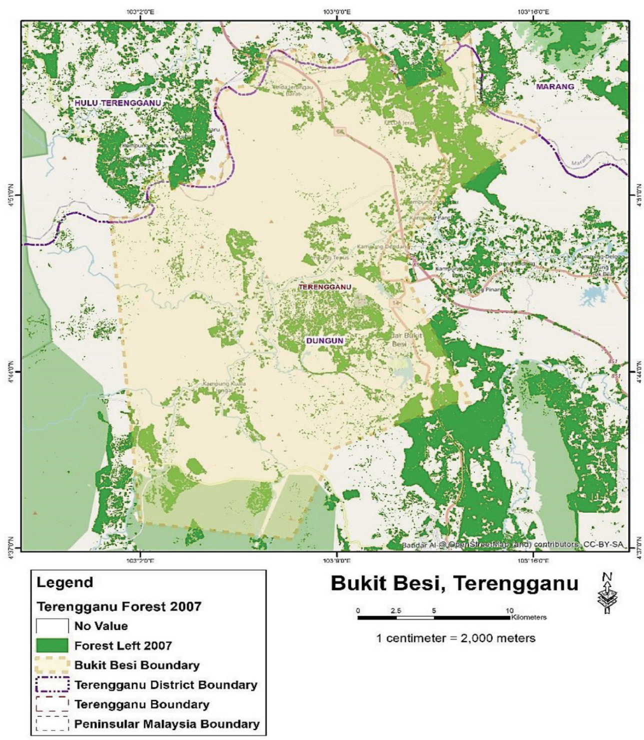

Figure 6: Bukit Besi deforestation area in 2007

Moreover, the presence of the Bukit Besi War Memorial in the area serves as a tribute to the bravery and sacrifice of local individuals during World War II. Bukit Besi also serves as a space for preserving numerous cultural artifacts associated with indigenous communities, including traditional crafts, tools, and remnants from the mining industry. The artifacts found at Bukit Besi contribute significantly to our understanding of the cultural heritage and capabilities of past societies, shedding light on the ways in which indigenous groups lived and worked in the region throughout history. It is crucial to preserve these remnants for educational purposes, allowing people to gain a deeper appreciation of Terengganu's rich human history.

While the result analysis from the dataset Figure 6 and Figure 7 shows the correlation coefficient and Analysis of Variance (ANOVA) between population and Gross Domestic Product (GDP) by sector yield a correlation value of 0.9047, a value that is close to 1 indicates a strong positive linear association between population and GDP. The purpose of a one-way ANOVA model is to examine the correlation between GDP (the response variable) and population (the factor variable). The summary function returns the F-value (31.627) and p-value (0.002477). Since the p-value is less than 0.05, there is enough evidence to reject the null hypothesis. Furthermore, by refuting the null hypothesis, this study can affirm the alternative hypothesis where that population means impact GDP levels. A correlation study utilising Pearson's coefficient indicated highly robust positive connections between population and GDP ($r = 0.9047$), as well as moderate to strong negative correlations between GDP and forest loss ($r = -0.8576$), and population and forest loss ($r = 0.7931$). The results of a one-way ANOVA examining the impact of population (independent variable) on GDP (dependent variable) showed a very significant F-ratio of 31.627 and an effect size of $\eta 2=0.327$. This indicates that the population

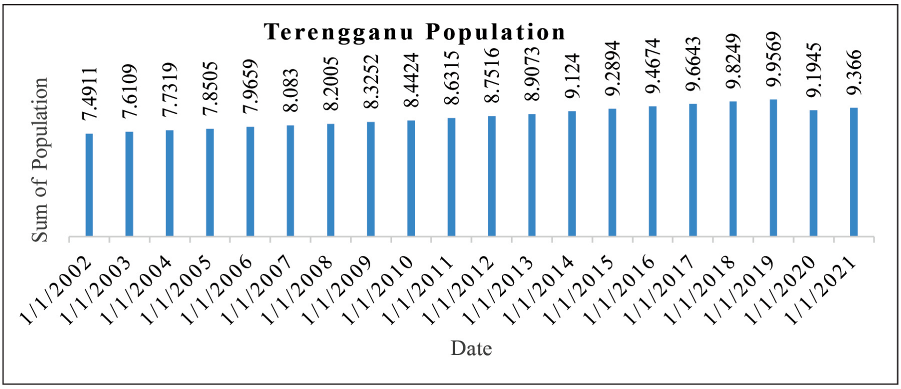

Figure 7: Graph shows the total of population in Terengganu state start from year 2002 untill 2021

accounts for 32.7% of the variation in GDP. Controlling for population influence, the partial correlation revealed a decreased coefficient of -0.6035 between GDP and forest loss. This indicates that the population mediates the effect of GDP.

The linear regression analysis revealed that both GDP and population (as factors) had positive and statistically significant coefficients in predicting forest loss. The correlation, ANOVA, partial correlation, and regression analyses collectively offer strong quantitative evidence from various statistical viewpoints that within this dataset, there is a significant and positive relationship between increasing population and GDP levels, and higher deforestation rates over the observed period. In a study conducted by Santika *et al.* (2019) in Java, it was discovered that deforestation increased at a faster rate in areas surrounding cities, although to a lesser extent than the highest levels reported in Terengganu. This indicates that the growing anthropogenic elements such as human settlements and economic activities have a role in the process of deforestation.

A one-way ANOVA test was conducted to further examine the influence of time on forest loss. The analysis revealed a substantial impact of the year on deforestation, as indicated by an F-value of 43.21 and a p-value of less than 0.001. A higher F-value signifies a larger amount of variation between the means of different groups compared to the variation within each group. The F-value of 43.21 indicates a significant disparity between the average values on an annual basis. The p-value suggests a very small likelihood (<0.1%) that these changes were due to random chance alone, offering robust statistical proof that the year had a substantial and quantifiable influence on the extent of forest loss in Terengganu throughout the examined timeframe. Figure 8 shows the annual nominal GDP for multiple sectors from 2016 until 2021.

Discussion

This research makes a significant contribution to the existing body of knowledge on deforestation in Terengganu state, Malaysia and its impact on natural heritage. Deforestation in these regions can lead to the degradation of the ecological landscape, loss of biodiversity, and erosion of cultural and historical heritage (Kujawa *et al*., 2016). This research provides a substantial addition to the current information on deforestation in Terengganu state, Malaysia and its effects on the region's natural heritage. Deforestation in these places can result in the deterioration of the natural environment, depletion of biodiversity, and erosion of cultural and historical legacy (Kujawa *et al*., 2016).

An analysis of 20 years of forest loss data from 2001 to 2021 in Terengganu, Malaysia has uncovered a noteworthy finding. The research

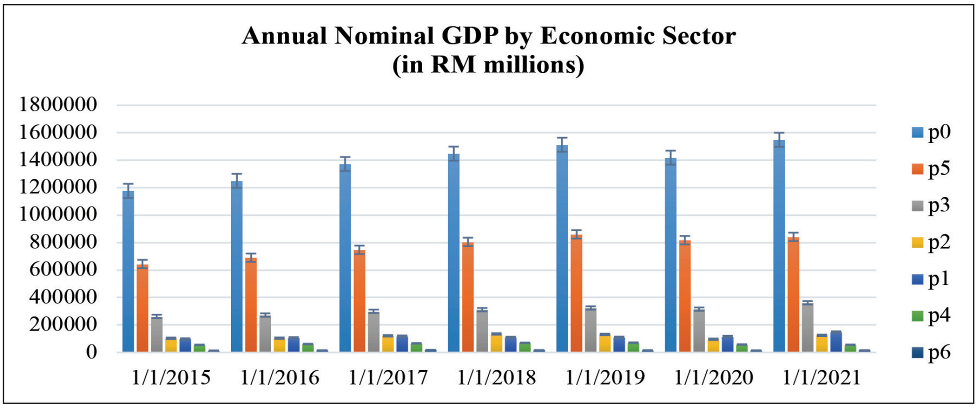

Figure 8: Annual nominal GDP for multiple sectors from year 2016 untill 2021, where p1 (Agriculture), p2 (Mining & Quarrying), p3 (Manufacturing), p4 (Construction), p5 (Service), and p6 (Import Duties)
Source: data.gov.my

reveals that a total of 2,806,865 hectares of forest land was lost during this period, along with the specific places where the loss occurred. The annual deforestation varied, reaching a low of 120,345 hectares in 2001 and a high of 213,103 hectares in 2016. In general, the rate of deforestation experienced an upward trend in early years before stabilising at a consistent level in recent times. Terengganu suffered substantial losses of over 200,000 hectares in both 2016 and 2017.

This finding is consistent with prior research that has identified Terengganu as the Malaysian region with the highest increase in deforestation in 2016. The continuous destruction of about 170,000 hectares annually poses substantial threats to both biodiversity and cultural heritage. The alarming rate at which forest coverage has decreased, dropping from 86% to 30% within a span of 20 years is a matter of grave worry (Global Forest Watch, 2023).

Spatial hotspots of forest loss were consistently identified in districts such as Kuala Terengganu and Hulu Terengganu while districts like Dungun and Setiu experienced lower rates of deforestation. This research contributes original geospatial and statistical analyses of deforestation dynamics in Terengganu at both the state-wide and sub-district levels over a period of two decades. The validated remote sensing methods used in this study also enhanced comparability to similar studies conducted internationally. Quantifying spatial and temporal change patterns can provide valuable information about risk factors, which can be used to update conservation policies and initiatives.

By utilising satellite imagery, Google Earth Engine (GEE), and Machine Learning (ML) techniques, this approach enabled the identification of spatial hotspots as well as temporal and annual trends that may have otherwise gone undetected at coarser scales. Consequently, decision-makers can prioritise areas requiring the most urgent conservation actions.

This study provides valuable insights into the spatial and temporal patterns of deforestation over a span of 20 years (2001-2021). The Machine Learning (ML) and statistical techniques applied such as correlation analysis and Analysis of Variance (ANOVA) testing provided robust evidence for interpreting the influences of socioeconomic factors and variability between years on deforestation levels. Directly tying the key findings to the analytical methods used strengthens the validity and significance of the results. This information is crucial for understanding the extent and intensity of deforestation in the state.

Additionally, the study goes beyond the environmental aspect and sheds light on the impact of deforestation on cultural heritage sites, wetlands, and the renowned Tasik Kenyir region. One of community-based forest management helping conservation efforts in Terengganu is the Kuala Berang Community Forest. Local villagers were engaged in reforestation activities and ecotourism ventures like guided hikes and homestays in the 700-hectare forest (Shahimi *et al*., 2019).

However, a challenge is balancing commercial interests with conservation, which can be addressed through certification programs with stringent environmental and social standards. Sustainable forest management practices have been implemented at the Tasik Kenyir Forest Reserve with techniques like reduced-impact logging and planting of native tree species.

However, enforcement of regulations within the reserve faces challenges like lack of resources and patrol coverage. This could be remedied through public-private partnerships that provide additional funding and technology for monitoring. Cultural mapping of heritage sites in Terengganu like the Terengganu Inscription Stone archaeological park has helped raise awareness of their importance. But integrating cultural considerations into development often meets resistance among local communities without clear economic incentives. Offering training and markets for traditional crafts can help communities directly benefit from cultural preservation. This interdisciplinary approach bridges the gap between environmental conservation and cultural preservation, providing a comprehensive understanding of the implications of deforestation.

From a conceptual framework perspective, this study aligns with the broader understanding of the importance of sustainable forest management and the preservation of natural and cultural heritage. By highlighting the negative consequences of deforestation such as biodiversity loss, soil erosion, and the disruption of traditional livelihoods, this research reinforces the need for policy-oriented approaches to mitigate these impacts. The findings of this study have implications for future research in the field of deforestation and natural heritage conservation. Firstly, the study establishes a baseline dataset and methodology that can be used for monitoring and assessing deforestation trends in Terengganu in subsequent years. This allows for the identification of emerging patterns and the evaluation of the effectiveness of conservation efforts.

Furthermore, this research opens avenues for exploring the socio-economic aspects of deforestation in Terengganu. Future studies can investigate the economic drivers behind deforestation, the socio-cultural impacts on local communities, and the potential for sustainable alternative livelihoods in forested areas. Moreover, the study highlights the need for collaborative efforts between environmental and cultural heritage sectors. This calls for further research on integrated approaches to conservation that consider both natural and cultural values, ensuring the preservation of Terengganu's unique heritage for future generations.

The findings from this research have important implications for developing targeted policy interventions and land management strategies in Terengganu. The analysis indicates the need for strengthened urban planning regulations and afforestation initiatives in the suburban buffer zones to curb future expansion into forested areas.

Understanding causal factors can help craft policies that either restrict similar activities or mandate stronger safeguards. By assessing changes in forest cover over two decades, this research provides a valuable baseline for ongoing monitoring efforts. Periodic re-analysis using the methodology established here can evaluate the effectiveness of policies enacted since 2021. This allows adaptive improvements to conservation strategies.

Conclusions

This study has provided valuable insights into deforestation trends in Terengganu over the past two decades. However, more work remains to be done to effectively implement conservation strategies on the ground. Drawing from examples in Terengganu can help strengthen the recommendations. In contrast to recovery trends observed in other regions, this highlights the urgent need for coordinated monitoring and alternative policy solutions to achieve a balance between biodiversity conservation and development priorities for the long-term sustainability of this region (Murtazashvili *et al*., 2019).

At the Tasik Kenyir Forest Reserve, reduced-impact logging and native tree planting have helped restore forests and wildlife habitats. But enforcement of no-hunting zones within the reserve is difficult due to the large patrol area. Drones and satellite monitoring, as demonstrated in this study could help monitor remote locations more effectively with minimal resources.

Cultural mapping of heritage sites like the Terengganu Inscription Stone Park helped increase awareness but more can be done to involve communities. Training local youth in traditional crafts and providing markets for their products may help strengthen cultural transmission while supporting livelihoods. However, gaining buy-in from multiple stakeholders requires clear coordination between agencies. While this study provides a strong foundation, ongoing monitoring is needed to evaluate policy impacts over time.

Expanding the analysis to higher resolution data and socioeconomic modelling could offer deeper insights but requires further resources and capacity building. Long-term research partnerships between academia and local communities may help address this. By drawing from on-the-ground examples and thoughtfully considering challenges, more targeted recommendations can be made to strengthen natural and cultural heritage conservation in Terengganu into the future.

Continued research and collaborative action are needed to achieve the sustainable balance outlined in this study. In order to safeguard these leisure spaces and cultural landmarks, it is imperative to implement sustainable land-use strategies, appropriate zoning regulations, and conservation initiatives (Dlamini, 2016). Raising awareness about the ecological, recreational, and cultural importance of these areas and implementing measures to mitigate the negative impacts of deforestation activities are essential (Nasser, 2003; Hasbollah, 2015).

Furthermore, this study emphasises the importance of integrating cultural heritage into national policies and development plans (Murtazashvili *et al*., 2019). Incorporating cultural heritage considerations into regulatory frameworks, sustainable tourism initiatives, economic progress strategies, global partnerships, and knowledge-sharing networks is essential for promoting a holistic approach to heritage preservation and utilisation (Harfst *et al*., 2021).

Certified forestry, which encompasses sustainable management practices that are ecologically sound, socially accountable, and financially feasible plays a vital role in forest preservation (Arakwiye *et al*., 2021). Active participation of local communities in the management of forest resources through community-based forest management and the inclusion of indigenous people in sustainable ecotourism activities can contribute to the preservation of forests in Terengganu (Wahab *et al*., 2023).

Landscape planning that considers environmental sustainability, visual appeal, and practical needs should be integrated into forest management strategies to ensure ecological sustainability, aesthetic value, and functional requirements are met (Wahob & Samad, 2020). Biodiversity preservation, carbon dioxide sequestration, climate regulation, watershed management, forest fire management, and the incorporation of indigenous knowledge and practices should be prioritised in forest management efforts (Smith & Johnson, 2019; Wey *et al.*, 2022).

Evidence-based research and monitoring are essential for effective forest management based on empirical evidence. The achievement of Sustainable Development Goals (SDGs) related to heritage can be facilitated through the implementation of various conservation strategies, with the involvement of government bodies, local communities, non-governmental organisations, academic institutions, and international organisations (Katila *et al.*, 2019).

Collaboration and multi-stakeholder partnerships are crucial in forest management, requiring the participation of government, non-governmental, and private sector entities in policymaking and implementation. Dedicated funds and financing mechanisms can be utilised by landowners, communities, and businesses to support sustainable forest management, reforestation, and the development of value-added forest-based industries (Hsieh, 2022). Further research is needed to analyse the relationships and trade-offs between the conservation of cultural heritage and other Sustainable Development Goals (SDG) objectives (Katila *et al*., 2019).

The participation of local communities and their indigenous knowledge in heritage conservation within the context of the SDGs requires more scholarly attention (Asbeck & Frey, 2022). Understanding the vulnerability of cultural heritage to climate change, developing adaptation approaches, and integrating climate resilience into heritage preservation efforts aligned with the SDGs are critical areas for further investigation (Kujawa *et al.*, 2016; Frame *et al*., 2022). Empirical studies on the impacts of deforestation on both cultural and natural heritage sites are needed to comprehend the long-term effects and develop effective conservation strategies.

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Conflict of Interest Statement

The authors declare that they have no conflict of interest.

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