Impact of Land Use Changes Due to Tourism on Ecosystem Services Using InVEST (Case Study: Badung Regency, Bali)

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Abstract. Ecosystem services play a vital role in supporting human life and environmental sustainability. However, tourism activities in Badung Regency, Bali, have led to significant changes in land cover and use, impacting the function of ecosystem services. This study integrates remote sensing, machine learning, and InVEST technology to understand the impact of Land Use/Land Cover (LULC) changes on ecosystem services in Badung Regency. The results show a decrease in non-agricultural vegetation area from 17659.65 hectares in 2014 to 11405.84 hectares in 2024. Meanwhile, built-up land experienced a drastic increase from 15074.47 hectares in 2014 to 22134.06 hectares in 2024. In addition, the InVEST model shows a decrease in carbon stock by 1379,841.68 tons in the period 2014 to 2024. Meanwhile, water yield, nitrogen export, and sediment export increased, reflecting a relationship between tourism development and the decline in ecosystem services. Correlation analysis shows a consistent negative correlation between water yield and carbon stock, as well as a positive correlation between nitrogen export and sediment export. The results of this study are expected to serve as a reference for further studies on the dynamics of ecosystem services and support sustainable environmental management efforts in areas with rapidly growing tourism activity.

Keyword: ecosystem services, InVEST, land use change, machine learning, remote sensing, tourism.

1. Introduction

Ecosystem services play a vital role in supporting human life and environmental sustainability. These services encompass four main categories: provisioning, regulating, supporting, and cultural services [1]. However, various studies indicate that ecosystem services are highly vulnerable to environmental change, particularly as a result of human activities. The IPBES (2019) report revealed that approximately 75% of global ecosystems have been degraded due to land-use change [2], confirming that landscape transformation poses a significant threat to the sustainability of ecosystem functions.

Land-use change has become a global environmental issue that directly impacts the ability of ecosystems to provide their services [3]. The conversion of vegetated land to built-up areas has the potential to reduce carbon sequestration capacity, reduce biodiversity, and disrupt the hydrological cycle [4]. The driving factors for these changes vary, ranging from urbanization, agricultural expansion, infrastructure development, and the rapid growth of the tourism sector in various regions of the world.

Tourism has been recognized as a sector with a significant contribution to the global economy, but it is also a major driver of land-use change. According to the World Tourism Cities Federation (2019), global tourism revenue reached US$5.34 trillion, or 6.1% of global GDP, in 2018. While providing economic benefits, poorly managed tourism can place significant pressure on ecosystems, as seen in Veracruz, Mexico, where the development of coastal tourism facilities triggered soil erosion and the loss of natural ecosystems [5]. Sustainable tourism development is a crucial strategy to minimize these negative impacts. This concept emphasizes efficient resource management, socio-economic balance, and the protection of biodiversity and local culture [6]. Its implementation requires integrated planning with policies, strategies, and plans that maximize economic benefits while minimizing environmental losses.

In Indonesia, Bali is a prime example of rapid tourism development. The island has been a prime destination since the 20th century [7] and has recorded a dominant contribution to the national tourism sector, with 75.86% of foreign tourists visiting Indonesia choosing Bali as their destination. In the second quarter of 2023, the accommodation and food and beverage sector contributed 19.54% of Bali Province's GRDP, making it the sector with the highest contribution. However, this rapid growth has also been accompanied by significant pressure on space and natural resources. The SARBAGITA region (Denpasar, Badung, Gianyar, Tabanan) is under the highest pressure, particularly Badung Regency, which contributes more than 60% of regional revenue from tourism [8]. According to Statistics Indonesia (BPS) data, from 2014–2024 the number of tourist lodges in Badung increased from around 1,000 to more than 2,500 units, while the number of star-rated hotels increased almost sevenfold. This surge is a strong indicator of the intensification of land requirements for tourism development.

Land-use changes due to tourism in Badung have created various ecological challenges. The Subak irrigation system, a world cultural heritage site, faces the threat of conversion from rice fields to agricultural land [9]. Previous research recorded a 52% increase in built-up area between 2000–2016, with the rapid conversion of agricultural land to tourism infrastructure [10]. This indicates that tourism is a dominant factor in land cover change, surpassing general urbanization or population growth.

The use of remote sensing technology and satellite imagery allows for accurate temporal and spatial monitoring of Land Use and Land Cover (LULC) changes [11]. This spatial analysis can be integrated with ecosystem models such as the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) to quantitatively assess the impact of land use change on ecosystem services [12]. InVEST not only assesses the value of natural capital but also maps trade-offs between ecosystem services [13].

Previous research has demonstrated the application of InVEST in various regions, for example, in the Erhai Lake Basin, China, where tourism expansion triggered a decrease in soil retention and increased nitrogen export [14], or in the Nansi Lake Basin, which demonstrated the effectiveness of an ecological conservation scenario in maintaining water yield [15]. In Heilongjiang Province, forest conversion to agricultural land and construction sites led to significant fluctuations in carbon storage [16]. However, the application of this model to the context of tourism in Indonesia, particularly in Bali, remains very limited.

In recent years, Badung Regency has experienced a noticeable shift in the dominant source of land conversion from non-agricultural vegetation to built-up areas driven by rapid tourism development. This pattern illustrates how the tourism sector has progressively expanded from coastal and rural areas. This transformation has not only altered land cover composition but also affected ecological balance and cultural identity. Ecologically, reduced vegetation cover increases surface runoff and carbon loss, while socio-culturally, it threatens the traditional Subak irrigation system and diminishes the integrity of Bali's cultural landscape. Therefore, understanding these multidimensional impacts is crucial for promoting sustainable spatial development and tourism. This study aims to fill this gap by evaluating the impact of tourism induced land use change on four key ecosystem services: carbon storage, water yield, sediment delivery ratio, and nutrient delivery ratio using the InVEST model based on multi-temporal satellite imagery data. The goal is to provide a scientific basis for formulating sustainable tourism policies that balance economic benefits and ecosystem sustainability.

The expected results will not only contribute to academic understanding of the relationship between tourism, changes in the LULC, and ecosystem services, but also support the achievement of sustainable development goals (SDGs) related to sustainable cities (SDG 11), climate change mitigation (SDG 13), and terrestrial ecosystem protection (SDG 15). Thus, the integrated approach used is expected to be able to produce relevant strategic recommendations for sustainable tourism management in vulnerable areas such as Badung Regency, Bali.

2. Research Method

This study is based on the phenomenon that developed land in tourist areas is increasing along with the number of tourists. The increase in developed land will also indirectly impact ecosystem services due to changes in natural conditions. Therefore, it is necessary to identify the extent of change from vegetation land that supports ecosystems to developed land due to the growth of tourism. In addition, an evaluation of changes in ecosystem services is also carried out to anticipate severe ecosystem damage.

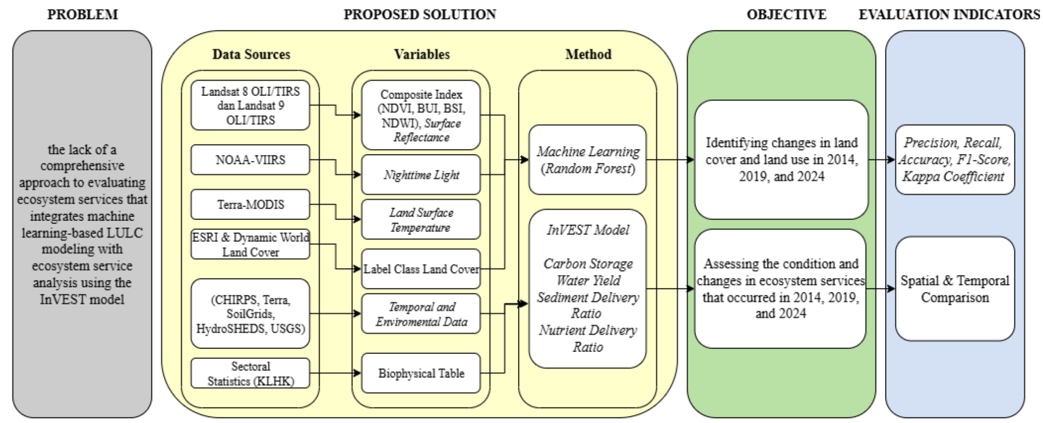

Figure 1. Research Framework.

2.1. Study Area

This study focuses on the area of Badung Regency, Bali Province, which covers an area of 398.75 km^2 and has six subdistricts, namely North Kuta, Kuta, South Kuta, Mengwi, Abiansemal, and Petang. Badung Regency was chosen because it is a major tourist destination in Bali, with rapid development in the tourism sector, especially in the construction of accommodation facilities to support tourism needs.

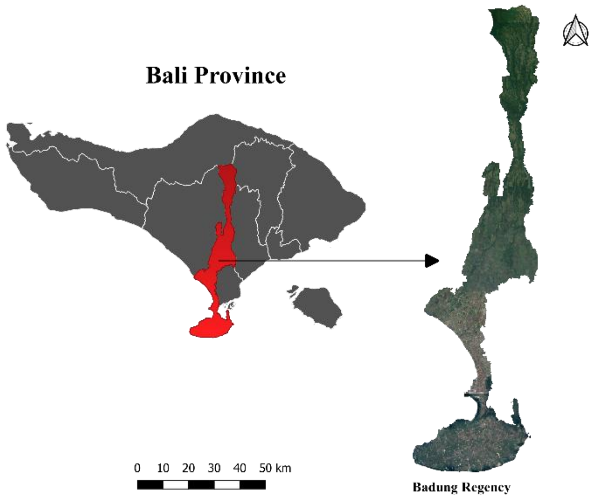

Figure 2. Research Study Area of Badung Regency.

2.2. Data and Data Sources

The data used in this study includes Landsat 8 and 9 imagery data, surface temperature data, nighttime light intensity data, land cover references, digital elevation models, rainfall, reference evapotranspiration, and soil characteristics such as available water capacity, root layer depth, rainfall erosivity index, and soil erodibility. Complete details regarding the data, its sources, and its relationship to the model used can be seen in Table 1.

Table 1. Data Summary and Data Sources.

Data	Source	Model
NDVI, BUI, BSI, NDWI, SR_B2, SR_B3, SR_B5, SR_B6	Landsat 8 OLI/TIRS dan Landsat 9 OLI/TIRS	LULC
Nighttime Light (NTL)	Suomi NPP-VIIRS	CSS, WY, SDR, NDR
Land Surface Temperature (LST)	Terra-MODIS	CSS, WY, SDR, NDR
Land Cover	ESRI Land Cover & Dynamic World	CSS, WY, SDR, NDR
Digital Elevation Model	https://www.usgs.gov/	NDR, SDR
Precipitation	CHIRPS	WY, NDR, SDR
Reference Evapotranspiration	https://modis-land.gsfc.nasa.gov/	WY
Plant available water content	ISRIC SoilGrids	WY
Depth to root restricting layer	ISRIC SoilGrids	WY

Rainfall Erosivity Index	CHIRPS	SDR
Soil Erodibility	ISRIC SoilGrids	SDR
Watersheds	https://hydrosheds.org/	WY, SDR, NDR
Biophysical Table	Sectoral Statistics (KLHK)	CSS, WY, SDR, NDR

2.3. *Identification of Land Use and Land Cover Changes*
Data for identifying LULC changes was obtained from Landsat satellite imagery covering two different periods, namely 2014 and 2019 (Landsat 8 OLI/TIRS) and 2024 (Landsat 9 OLI/TIRS) with a spatial resolution of 30m. Satellite image data collection was carried out using the Google Earth Engine API platform on Google Collaboratory with the Python programming language. Image preprocessing included pixel masking, band scaling, and median reduction. This study utilizes composite indices including NDVI (Normalized Difference Vegetation Index) to identify vegetation, BUI (Built Up Index) to detect built-up areas, BSI (Bare Soil Index) for vacant land, and NDWI (Normalized Difference Water Index) to detect water bodies. In addition, this study uses NTL (Nighttime Light) and LST (Land Surface Temperature) data. The integration of NTL and LST data with Landsat imagery provides additional information to identify built-up areas more accurately in land cover modeling. ESRI and Dynamic World reference maps are used for the land cover classification labels to be modeled.

The sample data in this study was collected using stratified random sampling techniques by taking the sample size in each stratum/class. LULC classification was performed using a machine learning approach that allows for complex data analysis with more accurate and efficient results. In this study, the random forest algorithm was chosen because it is one of the most powerful classification methods and is known for its ability to provide good predictions even when there is missing data [17]. In addition, this method also reduces the problem of overfitting [18], producing more stable results and being more resistant to multicollinearity compared to other machine learning algorithms [19]. All training and test data were separated proportionally (80:20). In addition, class imbalance was also handled using the Synthetic Minority Over-sampling Technique (SMOTE) method. To produce the best model, this study used a combination of grid search and 5-fold cross validation methods for hyperparameter tuning. To evaluate the accuracy of LULC classification, precision, recall, F1-score, overall accuracy, and kappa coefficient were used. The formulas for the evaluation indicators used are as follows.

$$Precision = \frac{TP}{TP+FP} \times 100\% \quad (1)$$

$$Recall = \frac{TP}{TP+FN} \times 100\% \quad (2)$$

$$F1 - Score = \frac{2 \times Precision \times Recall}{Precision + Recall} \times 100\% \quad (3)$$

$$Overall\ Accuracy = \frac{TP+TN}{TP+TN+FP+FN} \times 100\% \quad (4)$$

$$Kappa\ Coefficient = \frac{\left(N \times \sum X_{ii}\right) - \sum (X_{i+} \times X_{+i})}{N^2 - \sum (X_{i+} \times X_{+i})} \quad (5)$$

2.4. *Assessment and Evaluation of Ecosystem Services*
This study uses the InVEST version 3.14.2 model to evaluate ecosystem services. InVEST is designed to spatially map the provision of ecosystem services and evaluate tradeoffs between different types of ecosystem services [14]. Although InVEST is standalone software, additional GIS applications are

required only for preprocessing data sets and visualizing results [13]. InVEST also enables spatial data-based analysis relevant to research on land use change and environmental management.

There are four main submodels used in this study, namely Carbon Storage and Sequestration, Water Yield, Sediment Delivery Ratio (SDR), and Nutrient Delivery Ratio (NDR). These four submodels were selected because of their relevance in measuring the impact of land use change due to tourism development on carbon storage, water availability, soil erosion, and nutrient pollution. The main input data came from LULC maps classified using Random Forest for 2014, 2019, and 2024. In addition, additional environmental data was used, including annual rainfall from CHIRPS, actual evapotranspiration (AET) from MODIS MOD16A2, USGS SRTM digital elevation model (DEM), and soil parameters from SoilGrids, which include plant available water content (PAWC), root depth, texture, and soil erodibility value (K-factor). The DEM was preprocessed through sink filling, slope and flow direction calculations, and sub-catchment delineation according to the downstream boundaries of the study area. All raster data were standardized at a spatial resolution of 30 m through resampling and reprojection processes.

Each InVEST model also requires a biophysical table in .csv format containing specific parameters for each LULC class, such as carbon stocks (aboveground, belowground, dead, soil), surface runoff coefficient (CN), erosion factor, nutrient load, Z value, and USLE parameters (R, K, C, and P). Carbon data is obtained from the Ministry of Environment and Forestry (KLHK) in accordance with national guidelines for carbon stock calculations, while other parameters are adapted from scientific literature on tropical ecosystems and adjusted to the biophysical conditions of the island of Bali.

The model results were evaluated through spatial-temporal analysis by comparing the spatial distribution and total value of each ecosystem service in 2014, 2019, and 2024. This analysis included identifying trends of change, such as a decline in carbon stocks in areas of vegetation conversion, an increase in water yield in built-up areas due to reduced infiltration, an increase in nitrogen export in intensive agricultural areas, and an increase in sediment export in areas with minimal cover. The results were visualized in maps for each year and graphs comparing total values to support the interpretation of changes.

As a follow-up analysis, a correlation test between ecosystem services was conducted for each year using Pearson's correlation. In addition to correlation analysis, further studies can use multivariate approaches such as principal component analysis (PCA), redundancy analysis (RDA), or spatial regression models to explore trade-offs and synergies between ecosystem services in greater depth. These methods can capture complex spatial interactions that are not fully explained by bivariate correlations alone. A total of 100 random sampling points were generated evenly across all subdistricts in Badung Regency to represent spatial diversity in the correlation analysis. This number was determined based on the minimum threshold that ensures computational efficiency and adequate coverage. To verify the representation, additional stratified random sampling was conducted based on LULC classes, and the resulting correlation coefficients differed by less than 0.05. This similarity indicates that the random sampling approach adequately represents the spatial heterogeneity of the study area.

3. Result and Discussion

3.1. Identification and Descriptive Analysis of Satellite Image Data

Before LULC modeling was carried out, identification and descriptive analysis were performed on the composite satellite image index data to be used. The results show that the distribution of NDVI values tends to cluster in the high range. Low NDVI values are seen in the southern region, which is a built-up area such as settlements and hotels. Meanwhile, the NDWI index successfully mapped water areas, which are marked by high NDWI values in areas that are water bodies. The mapping of these indices is presented in Figure 3 and Figure 5.

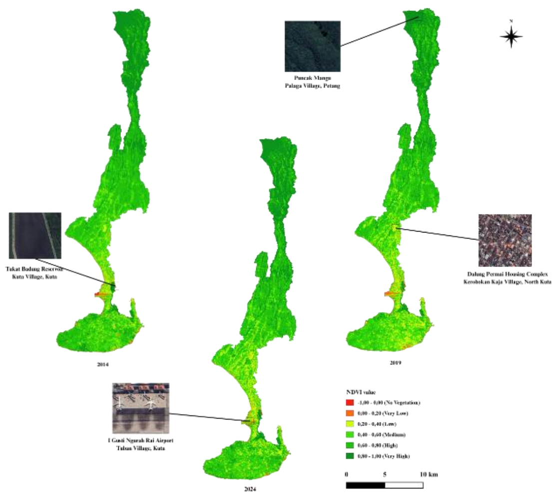

Figure 3. Identification of NDVI Value Distribution in Badung Regency.

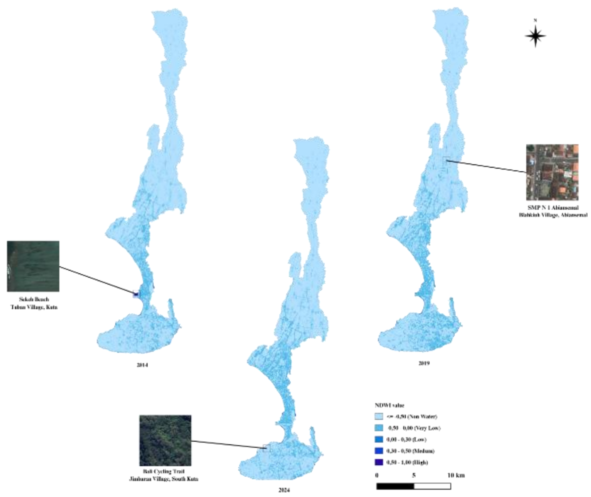

Figure 4. Identification of NDWI Value Distribution in Badung Regency.

Judging from the BUI value, it can be seen that the BUI value tends to increase significantly in the southern region and around economic growth centers. The increase in BUI value from 2014 to 2024 indicates the expansion of infrastructure, commercial areas, and settlements, especially in tourist zones. Meanwhile, the distribution of BSI values in Badung Regency is in the lower-middle range with a negative average. This shows that there is not much open land in Badung Regency. The distribution of conditions in the BUI and BSI index values is presented in Figures 5 and 6 below.

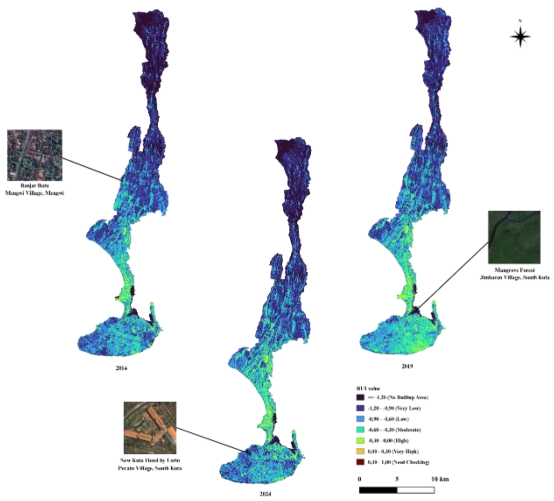

Figure 5. Identification of BUI Value Distribution in Badung Regency.

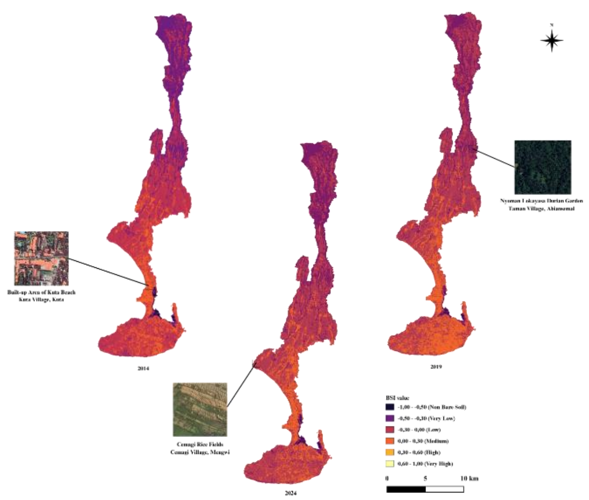

Figure 6. Identification of BSI Value Distribution in Badung Regency.

In addition to composite indices from Landsat satellite imagery, other data such as LST and NTL were also identified. Figure 7 shows the distribution of NTL values in the Badung Regency area. High NTL values are seen in urban and tourist areas such as Kuta, Jimbaran, and Nusa Dua. The increase in NTL values from 2014 to 2024 indicates significant economic growth and development expansion in these areas. Meanwhile, Figure 8 shows that high LST values are mostly found in areas with high BUI values, especially in densely built-up areas such as Kuta and its surroundings. This pattern shows the link between urbanization and the urban heat island effect, with a consistent trend of increasing temperatures over the last decade.

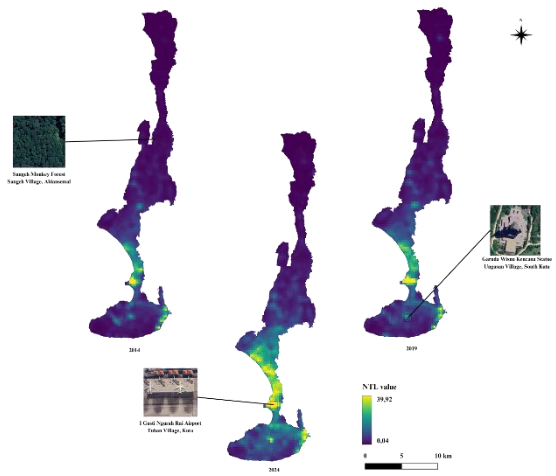

Figure 7. Identification of NTL Value Distribution in Badung Regency.

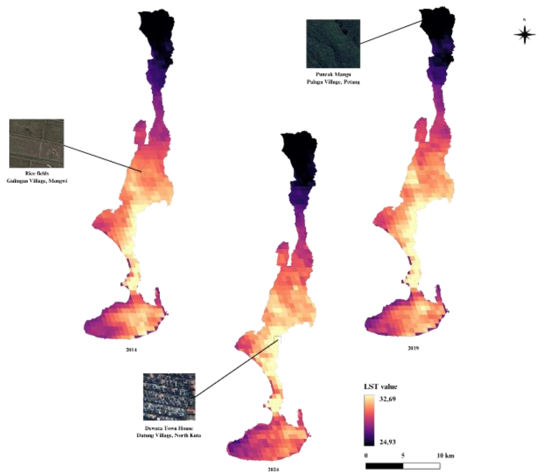

Figure 8. Identification of LST Value Distribution in Badung Regency.

3.2. Modeling Land Use and Land Cover

Land cover modeling was performed by conducting hyperparameter tuning grid search on the model. The samples used in this study were proportional to each class. After modeling, model performance was evaluated using Overall Accuracy (OA), Kappa Coefficient, as well as Precision, Recall, and F1-Score for each class. The evaluation results show that the model accuracy is relatively high, with an Overall Accuracy of 0.89 in all years of the study, as presented in Table 2. The Kappa Coefficient value of 0.85 indicates that the model has a high classification agreement with the actual reference, and there are no random predictions.

Table 2. Overall Accuracy and Kappa Coefficient Evaluation Values.

Data	2014	2019	2024
Overall Accuracy	0.89	0.89	0.89
Kappa Coefficient	0.85	0.85	0.85

After that, a more detailed evaluation is described in Tables 3, 4, and 5, showing that the best classification performance was obtained in the water and open land classes, with high precision and recall values ranging from 0.89 to 0.98. The agricultural and non-agricultural vegetation classes also showed good performance, although the f1-score values were slightly lower. The model's performance in the built-up land class tended to be stable, with f1-scores ranging from 0.90 to 0.91.

Table 3. Model 2014 Evaluation Score.

LULC Class	Precision	Recall	F1-Score
Water bodies	0.98	0.99	0.98
Non-agricultural vegetation	0.93	0.89	0.91
Agricultural vegetation	0.79	0.82	0.80
Built-up land	0.89	0.91	0.90
Open land	0.97	0.97	0.97

Table 4. Model 2019 Evaluation Score.

LULC Class	Precision	Recall	F1-Score
Water bodies	0.93	0.97	0.95
Non-agricultural vegetation	0.92	0.86	0.89
Agricultural vegetation	0.87	0.85	0.86
Built-up land	0.89	0.92	0.90
Open land	0.83	0.88	0.86

Table 5. Model 2024 Evaluation Score.

LULC Class	Precision	Recall	F1-Score
Water bodies	0.97	0.97	0.97
Non-agricultural vegetation	0.91	0.87	0.89
Agricultural vegetation	0.81	0.80	0.81
Built-up land	0.90	0.92	0.91
Open land	0.90	0.95	0.92

The map results in Figure 9 show a clear spatial distribution of LULC, with built-up land dominating the southern part of Badung Regency (Kuta, Jimbaran, Nusa Dua) since 2014 and continuing to expand until 2024, while the central and northern areas are dominated by non-agricultural and agricultural vegetation. Validation was carried out through ground truth checking using sample points and Google Earth imagery.

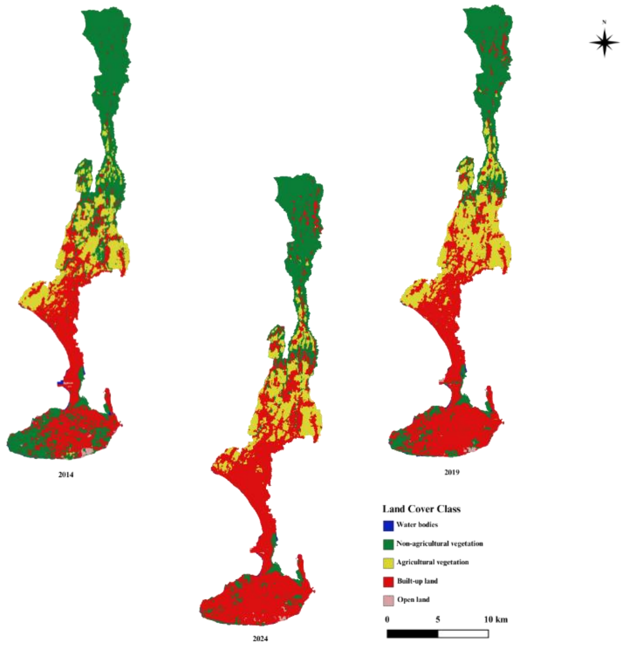

Figure 9. LULC Classification Results in Badung Regency.

Agricultural vegetation increased from 7427.36 ha to 9425.52 ha in 2019 before declining to 6828.18 ha in 2024. This change indicates a shift from agricultural land to development. Open land decreased from 260.51 ha to 134.61 ha, while water bodies decreased from 163.49 ha to 82.79 ha, partly influenced by changes in image resolution and the classification of small areas such as estuaries and beaches. Overall, these changes confirm the dominance of mass tourism as the main driver of landscape transformation in Badung. The complete changes in each class are presented in Table 6.

Table 6. Land Cover Area as Classified (Hectares).

LULC Class	2014	2019	2024
Water bodies	163.49	107.23	82.79
Non-agricultural vegetation	17659.65	12145.15	11405.84
Agricultural vegetation	7427.36	9425.52	6828.18
Built-up land	15074.47	18737.17	22134.06
Open land	260.51	170.42	134.61
Total	40585.48	40585.48	40585.48

3.3. Analysis of Land Use and Land Cover Change

More detailed changes are visualized in Figure 10, which shows the transition of land cover from 2014 to 2019 and from 2019 to 2024. The colors on the change map indicate the type of transition, for example, from vegetation to built-up land, or from agriculture to open land. This map provides a deeper understanding of the dynamics of land use change, especially in areas with high development pressure.

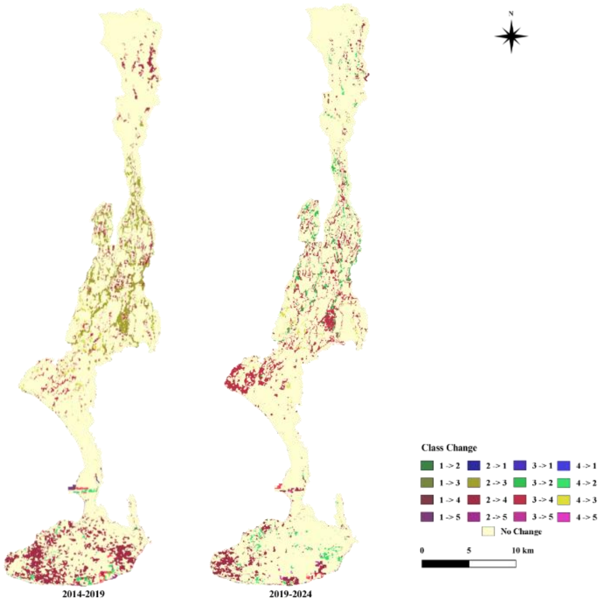

Figure 10. Identification of LULC Changes from 2014 to 2019 and 2019 to 2024.

Based on Table 7, during the 2014–2019 period, the largest conversion occurred from non-agricultural vegetation to developed land covering an area of 3,563.88 ha or 50.15% of the total change, followed by a conversion from agricultural vegetation covering an area of 503.20 ha. This reflects the intensification of development in vegetative areas and productive land. In the 2019–2024 period, agricultural land became the main source of conversion to built-up land covering an area of 2,107.08 ha (38.95%), followed by non-agricultural vegetation covering an area of 1,786.14 ha (33.02%). This change indicates increased development pressure on productive and natural land, especially in the southern part of Badung Regency (Kuta, South Kuta, and North Kuta), which is the center of tourism growth and its supporting infrastructure.

Table 7. Change Of Class to Built-Up Land.

Class Origin	Period	Area (ha)	Percentage
Non-agricultural vegetation	2014 - 2019	3563.88	50.15
Agricultural vegetation	2014 - 2019	503.2	7.08
Open land	2014 - 2019	142.57	2.01
Water bodies	2014 - 2019	20.31	0.29
Non-agricultural vegetation	2019 - 2024	1786.08	33.02
Agricultural vegetation	2019 - 2024	2107.08	38.95
Open land	2019 - 2024	90.41	1.67
Water bodies	2019 - 2024	24.71	0.46

Spatial analysis indicates that the main source of land conversion in Badung Regency has shifted from non-agricultural vegetation to built-up areas between 2014 and 2024. This transition reflects intensified tourism and residential development, especially in the southern and central subdistricts. Ecologically, it has reduced vegetation cover and carbon storage while increasing surface runoff and nutrient loading. Socio-culturally, it has disrupted traditional irrigation networks and weakened the sustainability of cultural landscapes that support community-based tourism. These findings demonstrate that tourism driven land expansion directly affects both ecological functions and local heritage systems.

3.4. Ecosystem Service Assessment and Evaluation Results

In this study, the evaluation of ecosystem service changes was conducted using the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model. Four main InVEST models were used, including Water Yield, Carbon Storage and Sequestration, Nutrient Delivery Ratio, and Sediment Delivery Ratio. These models simulate how changes in land use from 2014, 2019, to 2024 affect the region's capacity to provide ecosystem services. The results of the temporal comparison evaluation of the four models are presented in Table 8 below.

Table 8. Temporal Comparison of Ecosystem Service Outcomes.

Model	2014	2019	2024
Water Yield (m^3)	397846323.08	354878455.67	608595181.26
Carbon Stock (ton)	5150416.55	4084009.04	3770574.87
Nitrogen Export (kg)	38196.4411	51201.05091	43164.69724
Sedimen Export (ton)	55789.62781	54641.34429	58830.41894

The results of the temporal comparison of the InVEST model show significant dynamics in ecosystem services in Badung Regency during the 2014–2024 period. Water yield increased from 39.78 million m^3 in 2014 to 60.89 million m^3 in 2024, indicating an increase in runoff due to urbanization. Carbon stocks declined sharply by about 26.8%, reflecting the loss of natural vegetation. Nitrogen export rose from 38.20 tons (2014) to 51.20 tons (2019), then decreased to 43.16 tons (2024), indicating nutrient pressure from human activities despite signs of improvement. Sediment export showed a fluctuating pattern, decreasing from 55.79 thousand tons (2014) to 54.64 thousand tons (2019), then increasing again to 58.83 thousand tons (2024), indicating a persistently high risk of erosion. These findings underscore the impact of land conversion on ecosystem function changes and the need for mitigation strategies based on sustainable land management.

Spatially, the highest water yield values in 2024 are concentrated in the south of Badung Regency, particularly in Kuta, Jimbaran, and Nusa Dua, which are centers of tourism development. The conversion of non-agricultural vegetation to impervious surfaces in these areas inhibits infiltration and accelerates rainfall runoff, thereby increasing water yield. These findings are consistent with research [20] which states that urbanization increases water yield due to the reduced ability of the soil to absorb water.

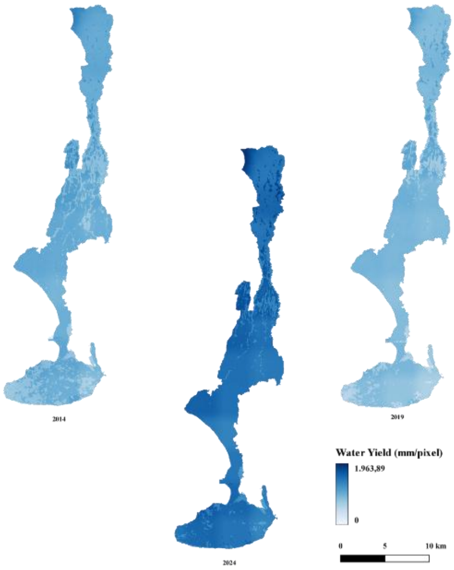

Figure 11. Water Yield Results in Badung Regency.

Meanwhile, the spatial map presented in Figure 12 shows that the southern region of Badung Regency, including Kuta, Jimbaran, Benoa, and Nusa Dua, experienced the most significant carbon storage degradation during the period from 2014 to 2024. These areas were originally dominated by secondary vegetation, mixed gardens, or shrubs, which were then converted into built-up land for the construction of tourism facilities and supporting settlements.

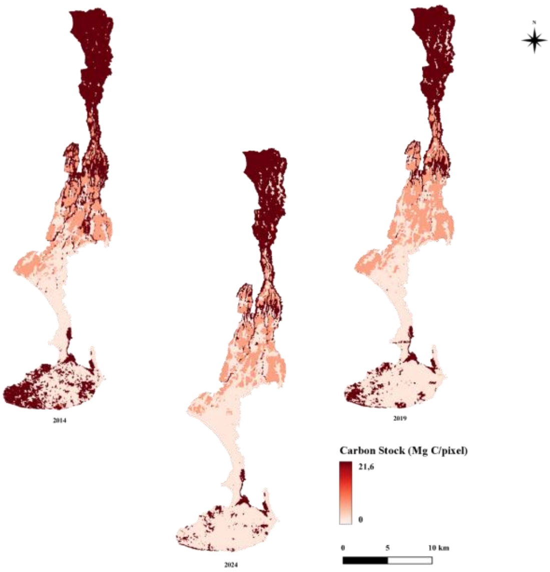

Figure 12. Results of Carbon Storage and Sequestration in Badung Regency.

The conversion of natural vegetation into buildings releases stored carbon into the atmosphere, increasing CO_2 emissions and exacerbating climate change. These findings are consistent with study [21], which cites tourism expansion as a major contributor to carbon emissions in tropical regions.

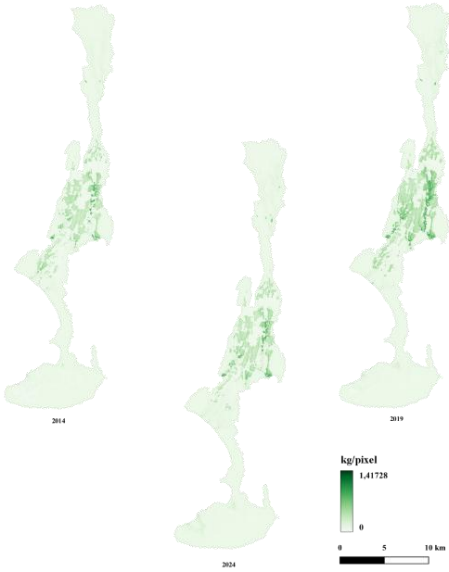

Figure 13. Nutrient Delivery Ratio Results in Badung Regency.

In 2014, nitrogen export values were relatively low, with limited intensity distribution mainly in the southern and central regions. However, in 2019 there was a significant increase in nitrogen export values, with high concentrations appearing in densely populated residential areas and intensive agricultural land. The areas with the highest nitrogen export values were consistently found in the southern and central parts of Badung Regency, which is an area with high anthropogenic pressure, such as residential and tourism activities, as well as intensive fertilizer use on agricultural land. The maximum nitrogen export value reached more than 1.41 kg/pixel in this area.

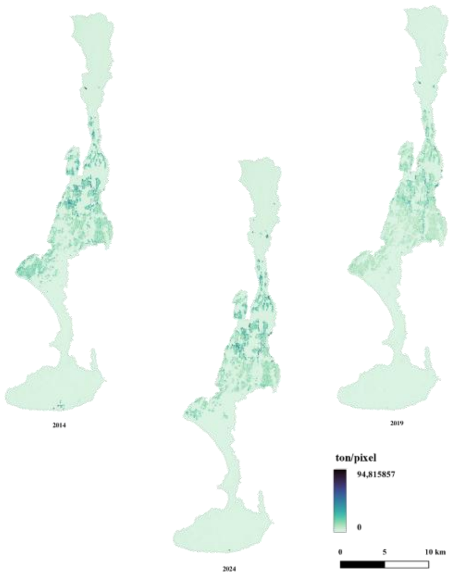

Figure 14. Sediment Delivery Ratio Results in Badung Regency.

Meanwhile, Figure 14 shows a map of SDR values for 2014, 2019, and 2024 in Badung Regency. It can be seen that areas with high SDR values are scattered in the central and northern parts of Badung Regency, which are generally areas with steep slopes and are beginning to experience land cover change. These areas tend to have a higher potential for erosion, especially if their vegetation cover declines. This condition shows that land conversion from natural vegetation to built-up or agricultural land without proper soil conservation causes an increase in the rate of sediment transport. Impermeable surfaces such as concrete or asphalt increase surface runoff and reduce the ability of the soil to retain sediment.

To assess the robustness of the InVEST model results, a sensitivity analysis was conducted by varying key parameters in the biophysical table by ±10%. The resulting variation in total carbon stock and water output was within the range of ±4%, indicating the stability and reliability of the model under conditions of parameter uncertainty. This confirms that InVEST outputs are not overly sensitive to small parameter deviations, thereby supporting the validity of the findings.

Further analysis, namely correlation analysis between the four main ecosystem services of water yield, carbon stock, nitrogen export, and sediment export in each year. The results show the complex dynamics of the relationship between 2014, 2019, and 2024. These changes reflect the significant impact of anthropogenic activities, particularly land cover changes due to development and expansion of built-up areas in Badung Regency. Correlation analysis shows a strong negative relationship between water yield and carbon storage, which has increased from -0.73 in 2014 to -0.77 in 2024. This indicates that built-up land expansion reduces carbon storage capacity. The high positive correlation between nitrogen export and sediment export (0.66–0.68) indicates that erosion carries nitrogen loads into water bodies. The relationship between water yield and nitrogen export tends to be positive but weakening, while carbon storage and sediment export show no significant correlation. This pattern confirms the trade-off between ecosystem services due to LULC changes, making sustainable spatial management important for maintaining ecological balance amid tourism growth.

4. Conclusion

Based on the results of the study, there were significant changes in land use in Badung Regency in 2014, 2019, and 2024, where the area of non-agricultural vegetation decreased from 17659.65 hectares in 2014 to 11405.84 hectares in 2024, while built-up land increased from 15074.47 hectares to 22134.06 hectares during the same period. These changes were driven by the rapid development of tourism infrastructure, especially in coastal areas and their surroundings. The impact of these changes can be seen in the decline in ecosystem service capacity, particularly carbon storage due to the reduction of vegetation as the main carbon sink, as well as increased surface water runoff and dissolved nitrogen content, which has the potential to reduce water quality and trigger eutrophication.

In response to these findings, several policy recommendations are proposed to mitigate ecosystem degradation amid tourism growth in Badung Regency. First, integrate routine land use/land cover (LULC) monitoring using remote sensing into spatial planning and zoning regulations. Second, encourage the implementation of green infrastructure and low impact development (LID) approaches in tourist areas to minimize surface runoff and urban heat accumulation. Third, strengthen conservation incentives to preserve vegetation areas as ecological buffers. These strategies are in line with the principles of sustainable tourism development and support the achievement of Sustainable Development Goals (SDGs) 11, 13, and 15.

References

[1] K. Luo *et al.*, "Study on trade-offs and synergies of rural ecosystem services in the Tacheng-Emin Basin, Xinjiang, China: Implications for zoning management of rural ecological functions," *J Environ Manage*, vol. 363, Jul. 2024, doi: 10.1016/j.jenvman.2024.121411.

[2] Y. Li *et al.*, "The role of land use change in affecting ecosystem services and the ecological security pattern of the Hexi Regions, Northwest China," *Science of the Total Environment*, vol. 855, Jan. 2023, doi: 10.1016/j.scitotenv.2022.158940.

[3] M. Jabbar, M. Nasar-U-minallah, and M. M. Yusoff, "Predicting The Impact of Land Use Changes on Thermal Environment in Lahore, Pakistan: Implications for Urban Planning," *Geography, Environment, Sustainability*, vol. 17, no. 1, pp. 95–109, 2024, doi: 10.24057/2071-9388-2023-2862.

[4] M. Waleed, M. Sajjad, and M. S. Shazil, "Urbanization-led land cover change impacts terrestrial carbon storage capacity: A high-resolution remote sensing-based nation-wide assessment in Pakistan (1990–2020)," *Environ Impact Assess Rev*, vol. 105, Mar. 2024, doi: 10.1016/j.eiar.2023.107396.

[5] G. Mendoza-González, M. L. Martínez, D. Lithgow, O. Pérez-Maqueo, and P. Simonin, "Land use change and its effects on the value of ecosystem services along the coast of the Gulf of Mexico," *Ecological Economics*, vol. 82, pp. 23–32, Oct. 2012, doi: 10.1016/j.ecolecon.2012.07.018.

[6] W. An and S. Alarcón, "How can rural tourism be sustainable? A systematic review," Sep. 01, 2020, *MDPI*. doi: 10.3390/SU12187758.

[7] A. B. Rimba *et al.*, "Identifying land use and land cover (LULC) change from 2000 to 2025 driven by tourism growth: A study case in Bali," in *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives*, International Society for Photogrammetry and Remote Sensing, Aug. 2020, pp. 1621–1627. doi: 10.5194/isprs-archives-XLIII-B3-2020-1621-2020.

[8] K. L. Chong, "The side effects of mass tourism: the voices of Bali islanders," *Asia Pacific Journal of Tourism Research*, vol. 25, no. 2, pp. 157–169, Feb. 2020, doi: 10.1080/10941665.2019.1683591.

[9] I. N. Norken, "Efforts to preserve the sustainability of subak irrigation system in Denpasar city, Bali Province, Indonesia," *MATEC Web of Conferences*, vol. 276, p. 04002, 2019, doi: 10.1051/matecconf/201927604002.

[10] A. B. Rimba, S. K. Chapagain, Y. Masago, K. Fukushi, and G. Mohan, "2019 IEEE International Geoscience & Remote Sensing Symposium: proceedings : July 28-August 2, 2019, Yokohama, Japan," in *2019 IEEE International Geoscience and Remote Sensing Symposium*, IEEE, 2019, pp. 1621–27.

[11] A. Valero-Jorge, R. González-De Zayas, F. Matos-Pupo, A. L. Becerra-González, and F. Álvarez-Taboada, "Mapping and Monitoring of the Invasive Species Dichrostachys cinerea (Marabú) in Central Cuba Using Landsat Imagery and Machine Learning (1994–2022)," *Remote Sens (Basel)*, vol. 16, no. 5, Mar. 2024, doi: 10.3390/rs16050798.

[12] Y. Zhang, X. Liao, and D. Sun, "A Coupled InVEST-PLUS Model for the Spatiotemporal Evolution of Ecosystem Carbon Storage and Multi-Scenario Prediction Analysis," *Land (Basel)*, vol. 13, no. 4, Apr. 2024, doi: 10.3390/land13040509.

[13] A. Mukhopadhyay, J. P. Hati, R. Acharyya, I. Pal, N. Tuladhar, and M. Habel, "Global trends in using the InVEST model suite and related research: A systematic review," 2024, *Elsevier B.V.* doi: 10.1016/j.ecohyd.2024.06.002.

[14] J. Li, Y. Bai, and J. M. Alatalo, "Impacts of rural tourism-driven land use change on ecosystems services provision in Erhai Lake Basin, China," *Ecosyst Serv*, vol. 42, Apr. 2020, doi: 10.1016/j.ecoser.2020.101081.

[15] Y. Liu, Y. Jing, and S. Han, "Multi-scenario simulation of land use/land cover change and water yield evaluation coupled with the GMOP-PLUS-InVEST model: A case study of the Nansi Lake Basin in China," *Ecol Indic*, vol. 155, Nov. 2023, doi: 10.1016/j.ecolind.2023.110926.

[16] X. Li *et al.*, "Spatio-Temporal Patterns of Carbon Storage Derived Using the InVEST Model in Heilongjiang Province, Northeast China," *Front Earth Sci (Lausanne)*, vol. 10, Mar. 2022, doi: 10.3389/feart.2022.846456.

[17] H. Ebrahimy, B. Mirbagheri, A. A. Matkan, and M. Azadbakht, "Per-pixel land cover accuracy prediction: A random forest-based method with limited reference sample data," *ISPRS Journal of Photogrammetry and Remote Sensing*, vol. 172, pp. 17–27, Feb. 2021, doi: 10.1016/j.isprsjprs.2020.11.024.

[18] S. Amini, M. Saber, H. Rabiei-Dastjerdi, and S. Homayouni, "Urban Land Use and Land Cover Change Analysis Using Random Forest Classification of Landsat Time Series," *Remote Sens (Basel)*, vol. 14, no. 11, Jun. 2022, doi: 10.3390/rs14112654.

[19] S. Amare *et al.*, "Susceptibility to gully erosion: Applying random forest (RF) and frequency ratio (FR) approaches to a small catchment in Ethiopia," *Water (Switzerland)*, vol. 13, no. 2, Jan. 2021, doi: 10.3390/w13020216.

[20] E. Alshammari, A. A. Rahman, R. Rainis, N. A. Seri, and N. F. A. Fuzi, "The Impacts of Land Use Changes in Urban Hydrology, Runoff and Flooding: A Review," *Current Urban Studies*, vol. 11, no. 01, pp. 120–141, 2023, doi: 10.4236/cus.2023.111007.

[21] M. Kabir *et al.*, "Climate change due to increasing concentration of carbon dioxide and its impacts on environment in 21st century; a mini review," Jul. 01, 2023, *Elsevier B.V.* doi: 10.1016/j.jksus.2023.102693.