

Long-term urban expansion, land-cover transitions and estimated ecosystem service value in Kathmandu Valley, Nepal, 1988–2024

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Abstract

Rapid urban expansion can transform agricultural and ecological land and alter ecosystem-service provision. This study examines land-use and land-cover (LULC) change in Kathmandu Valley, Nepal, from 1988 to 2024 using a secondary reanalysis of a published six-date Landsat-derived LULC dataset. We quantify changes in major LULC classes, identify transition pathways associated with urban expansion, estimate ecosystem service value (ESV) using a consistent land-cover-based valuation framework, and assess dependence on alternative valuation coefficients. Built-up land increased from 37.98 km² in 1988 to 197.41 km² in 2024, whereas cropland declined from 418.32 to 245.08 km². Cropland-to-built-up conversion was the dominant observed transition in all five consecutive periods, totalling approximately 155.38 km². Estimated total annual ESV declined from USD 82.77 million in 1988 to USD 72.69 million in 2024, a reduction of 12.18%. Vegetation contributed the largest share of estimated ESV throughout the study period, and its coefficient-dependence ratio increased from 0.604 to 0.723. The findings indicate persistent agricultural-land conversion and a decline in coefficient-based estimated ESV, while showing that aggregate estimates are sensitive to valuation assumptions. The results support integrating agricultural-land conservation, vegetation and waterbody connectivity, and green and blue infrastructure into sustainable urban land-management strategies. Because the analysis uses a published LULC dataset and transferred valuation coefficients, the ESV estimates should be interpreted as comparative indicators of change rather than precise measures of monetary ecosystem-service loss.

Keywords: Land-use/land-cover change; Urban expansion; Ecosystem service valuation; Land-cover transitions; Sustainable land management; Kathmandu Valley

1. Introduction

Rapid urbanisation is a major driver of land-use and land-cover (LULC) transformation, particularly in rapidly growing metropolitan and peri-urban regions (Turner et al., 2007). Global land-change research further shows that urbanisation is embedded in broader processes of economic and demographic transformation (Lambin & Meyfroidt, 2011). The

projected expansion of urban land also has implications for biodiversity and carbon pools (Seto et al., 2012). Expansion of built-up surfaces commonly involves the conversion of agricultural land, vegetation, and other open spaces, altering landscape structure and ecological functions. Such changes can affect the capacity of landscapes to provide regulating, provisioning, habitat, and cultural ecosystem services (Millennium Ecosystem Assessment, 2005). Monetary assessments have likewise demonstrated the substantial societal value associated with ecosystem services (Costanza et al., 1997). Global synthesis further shows that ecosystem-service values vary across ecosystem types and service categories (de Groot et al., 2012). The consequences of urban expansion therefore depend not only on the amount of land converted but also on the type, spatial configuration, and ecological characteristics of the affected land cover (Grafius et al., 2016). Valuation and mapping studies similarly emphasise the importance of spatial representation when ecosystem services are linked to land-cover classes (Schägnier et al., 2013; Troy & Wilson, 2006). Understanding these transformations is therefore important for sustainable land management and urban planning, particularly where development pressure overlaps with productive agricultural land and ecologically important areas.

Kathmandu Valley provides an important case for examining long-term urban expansion and its implications for agricultural land, land-cover composition, and ecosystem-service provision in a rapidly urbanising Himalayan environment. Earlier Landsat-based research documented a 412% increase in built-up area between 1989 and 2016 and identified agricultural land as a major source of newly developed urban surfaces (Ishtiaque et al., 2017). Subsequent work also documented substantial urban growth and land-cover transformation in the valley (Rimal et al., 2017). Research using remote sensing and GIS has further examined the trajectory and prediction of land-use change in the Kathmandu region (Wang et al., 2020). More recent analysis indicates that agricultural land remains exposed to urban development pressure (Aryal et al., 2023). A multi-temporal assessment extending to 2024 has additionally documented continuing LULC transformation in Kathmandu and Pokhara (Rimal et al., 2025). Collectively, these studies provide evidence of sustained land-cover transformation while differing in observation periods, spatial extents, classification schemes, and analytical approaches. These differences highlight the value of a consistent long-term assessment that

examines not only changes in the amount of built-up land but also the land-cover pathways through which urban expansion occurs.

The relationship between LULC change and estimated ecosystem service value (ESV) has also been examined in Kathmandu Valley. Shrestha et al. (2022) assessed changes in estimated ESV between 1989 and 2019 and reported a decline in aggregate ESV alongside substantial changes in forest, cropland, shrubland, waterbody, and settlement classes. More broadly, ecosystem-service mapping frameworks emphasise the importance of linking spatial land-cover information with ecosystem-service assessment (Crossman et al., 2013). Economic valuation research also cautions that monetary estimates depend on the valuation framework and assumptions used to represent ecosystem services (Gómez-Baggethun & Ruiz-Pérez, 2011). Benefit-transfer applications may be sensitive to the transferability of valuation coefficients across ecological and socioeconomic contexts (Richardson et al., 2015). Recent work further shows that constant value coefficients can become problematic when land-cover changes are large because marginal values may vary with land-cover scarcity (Knoke et al., 2024). Studies of urban and peri-urban ecosystem services indicate that broad land-cover classes can also mask differences in ecological functions and service provision (Haase et al., 2014). Reviews of urban ecosystem services have similarly highlighted the need to account for heterogeneous urban ecological functions (Luederitz et al., 2015; Croci et al., 2021). Recent syntheses further emphasise the role of green infrastructure and nature-based solutions in urban sustainability (Fang et al., 2023; Herath & Bai, 2024). These methodological considerations are particularly relevant to Kathmandu Valley because the long-term LULC dataset used in this study represents a heterogeneous landscape using a relatively broad classification scheme.

Despite the availability of multi-temporal LULC and ESV studies in Kathmandu Valley, the relationships among the pathways of land-cover conversion, long-term changes in estimated ESV, and the sensitivity of those estimates to valuation assumptions remain insufficiently integrated. Endpoint comparisons of LULC areas indicate the magnitude of urban expansion but do not identify which land-cover classes supplied the newly developed area. Similarly, aggregate ESV estimates indicate changes in coefficient-based monetary values but do not, by themselves, reveal how strongly those estimates depend on the valuation coefficients assigned to individual land-cover classes. Examining transition pathways together with

coefficient-based ESV estimates and explicit sensitivity analysis can therefore provide a more transparent basis for interpreting long-term land-cover change and its implications for sustainable land management. Examining transition pathways together with coefficient-based ESV estimates and explicit coefficient-dependence analysis can therefore provide a more transparent basis for interpreting long-term land-cover change and the assumptions underlying its estimated ecosystem-service consequences. (Srivathsa et al., 2023; Cimatti et al., 2023).

Benefit-transfer approaches provide a practical basis for comparative ecosystem-service assessment where locally derived monetary estimates are unavailable (Richardson et al., 2015). Their results nevertheless depend on the classification of land cover and the valuation coefficients transferred to those classes (Schägnier et al., 2013). This dependence becomes particularly important when broad LULC classes represent ecologically heterogeneous landscapes. Sensitivity analysis can therefore help distinguish changes associated with land-cover composition from changes associated with assumptions embedded in the valuation framework (Knoke et al., 2024). In the Kathmandu Valley context, explicitly examining coefficient dependence provides a transparent way to evaluate how strongly the aggregate estimate responds to alternative valuation assumptions.

The present study undertakes a secondary-data reanalysis of the published six-date Kathmandu Valley LULC dataset for 1988, 1992, 2000, 2008, 2016, and 2024 (Rimal et al., 2025). Rather than producing a new satellite-image classification, the study uses the published LULC area statistics and transition matrices to examine long-term changes in land-cover composition and the pathways associated with urban expansion. These data are combined with a consistent land-cover-based ESV framework and coefficient-dependence analysis to examine how estimated ecosystem-service values vary over time and how strongly aggregate estimates depend on the valuation coefficients assigned to different land-cover classes. The analytical design therefore separates three levels of inference: observed LULC transitions, coefficient-based ESV estimates, and interpretation of those estimates under explicit valuation assumptions. This distinction is important because the study does not directly measure ecosystem-service flows, market values, or socioeconomic drivers. The resulting monetary estimates are consequently treated as comparative indicators of change under a consistent framework rather than as realised economic losses.

Accordingly, the study aims to:

1. quantify changes in the composition and extent of major LULC classes in Kathmandu Valley from 1988 to 2024;
2. identify the principal land-cover transition pathways associated with urban expansion, with particular attention to cropland-to-built-up conversion;
3. estimate changes in category-specific and total ESV associated with the observed LULC trajectories under the adopted valuation framework; and
4. evaluate the dependence of estimated ESV on alternative valuation coefficients and discuss the implications of the observed land-cover transitions for sustainable land management and urban planning.

2. Materials and Methods

2.1. Study Area

Kathmandu Valley is located in central Nepal and comprises the districts of Kathmandu, Lalitpur, and Bhaktapur. The valley is an important urban, economic, and administrative centre and has experienced substantial urban expansion over recent decades (Rimal et al., 2017). More recent assessments likewise document continuing urban growth and land-cover transformation (Aryal et al., 2023; Rimal et al., 2025). In the present study, Kathmandu Valley is analysed using the approximately 694.27 km² spatial extent adopted in the published multi-temporal LULC dataset used as the basis for this analysis (Rimal et al., 2025). The study area extends approximately from 27°31' to 27°50' N and 85°11' to 85°34' E.

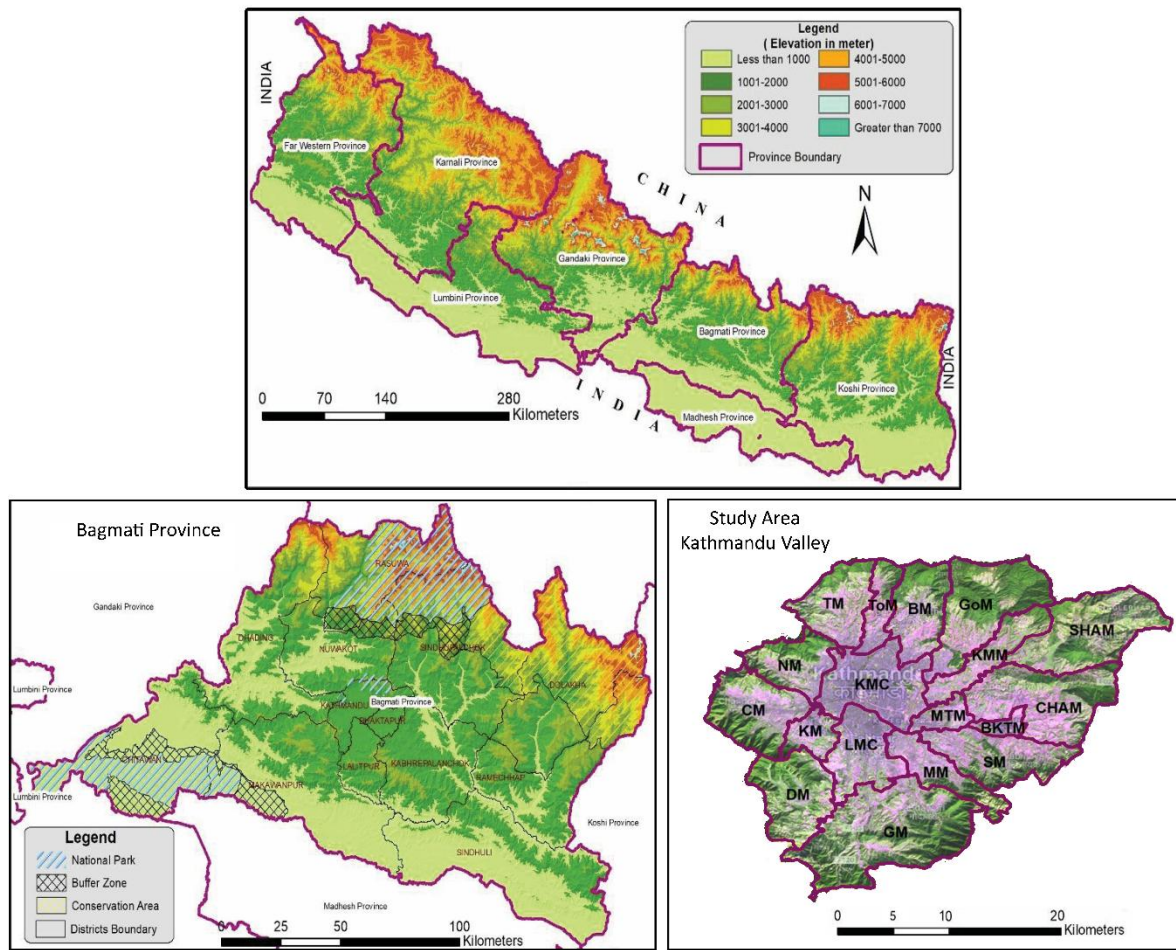


Figure 1. Location and spatial extent of Kathmandu Valley, Nepal, showing the study area used in the present analysis.

Source: Reconstructed by the authors based on Rimal et al. (2024, 2025).

The valley forms a relatively enclosed basin surrounded by the hills of the Himalayan middle mountains. Elevation ranges from approximately 837 to 2723 m above sea level, with much of the central valley floor occurring between approximately 1200 and 1500 m. The Bagmati River and its tributaries form the principal drainage network. The combination of enclosed topography, agricultural land, vegetated areas, water-related features, and expanding urban settlements produces a heterogeneous landscape relevant to land-cover transformation and land management (Rimal et al., 2017).

Kathmandu Valley has a dry-winter humid subtropical climate with strong seasonal variation associated with the South Asian monsoon. Previous studies report mean annual precipitation of approximately 1407 mm, with most precipitation occurring during the monsoon season

(Shrestha et al., 2022). These environmental characteristics provide contextual information for interpreting long-term land-cover transformation and estimated ecosystem-service patterns.

2.2. LULC Dataset and Data Sources

This study reanalyses a published six-date Landsat-derived LULC dataset for Kathmandu Valley covering six observation years: 1988, 1992, 2000, 2008, 2016, and 2024. The dataset was published by Rimal et al. (2025) and provides a common spatial extent and consistent five-class LULC framework for the selected observation years. The dataset was derived from Landsat satellite imagery and represents the principal data source for the present analysis.

The underlying Landsat observations include data from the Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM+), and Operational Land Imager (OLI) sensor generations. The original study conducted the satellite-image classification and reported the resulting LULC maps, area statistics, and transition information (Rimal et al., 2025). The present study does not repeat the original image classification, image preprocessing, training-data generation, or accuracy assessment. Instead, the published LULC dataset is treated as a secondary spatial dataset and reanalysed to quantify temporal LULC change, land-cover transitions, and associated changes in estimated ecosystem service value.

The published dataset uses a common spatial extent of approximately 694.27 km² across the six observation years. The five LULC categories are urban/built-up area, cropland, vegetation, other land, and waterbody (Rimal et al., 2025). Maintaining the original classification scheme allows the six observation years to be compared without introducing changes in class definitions.

The source study reported overall classification accuracies of 95%, 91%, 90%, 95%, 92%, and 92% for 1988, 1992, 2000, 2008, 2016, and 2024, respectively (Rimal et al., 2025). These accuracy values are characteristics of the published dataset and were not independently assessed in the present study. The corresponding Kappa statistics reported by the source study are provided in Supplementary Table S2.

The principal datasets and their applications are summarised in Table 1.

Table 1. Data sources and their applications in the present study.

Dataset/source	Years	Data type	Spatial extent	Application	Role in present study
(Rimal et al., 2025)	1988–2024	Published Landsat-derived LULC dataset and transition matrices	Kathmandu Valley	LULC area and transition analysis	Underlying secondary dataset
(Shrestha et al., 2022)	—	ESV valuation coefficients	Kathmandu Valley	Valuation coefficients	Main coefficient source
(Xie et al., 2015; Xie et al., 2017)	—	ESV valuation framework	—	Methodological basis	Supporting valuation framework

2.2.1 Secondary-Data Processing and Reproducibility

The present analysis was conducted as a secondary-data reanalysis. Published LULC area statistics and transition matrices were extracted for the six observation years and five consecutive transition periods. Area-change, percentage-share, ESV, category-contribution, and sensitivity calculations were independently recalculated from the published values using the equations described below. No reclassification of the original Landsat imagery, modification of the original class definitions, or independent accuracy assessment was undertaken. All derived quantities reported in this study therefore represent analytical results generated by the authors from the published LULC dataset and the adopted valuation framework.

AI-assisted tools were used during manuscript preparation and revision for language refinement, manuscript organization, equation checking, and preparation of a revised figure. The authors independently verified all calculations and reviewed the resulting interpretations and visual outputs. The authors take full responsibility for the accuracy, integrity, and final content of the manuscript.

2.3. LULC Classification Framework

The present study retains the five-class LULC classification used by Rimal et al. (2025) without modification. Retaining the published classification is necessary to preserve temporal consistency and avoid introducing a new classification scheme that could affect comparisons among observation years.

Urban/built-up area comprises developed surfaces associated with residential, commercial, institutional, industrial, transportation, and related urban uses. Cropland represents cultivated agricultural areas, including the agricultural classes identified in the source dataset. Vegetation represents the combined vegetated land classes included in the published classification, including forested and other vegetated surfaces. Other land comprises land that does not fall within the built-up, cropland, vegetation, or waterbody categories, including exposed or sparsely vegetated surfaces. Waterbody includes identifiable surface-water features such as rivers, lakes, ponds, canals, and reservoirs (Rimal et al., 2025).

The broad vegetation class requires particular consideration in the subsequent ESV analysis. Because the published LULC dataset combines different forms of vegetation rather than separately distinguishing forest, shrubland, and grassland, a single valuation coefficient must be assigned to the entire vegetation class. This introduces an important source of valuation uncertainty and is explicitly considered in the sensitivity and limitation analyses.

The original five-class scheme was retained without aggregation or reclassification to ensure comparability across all six observation years. Consequently, interpretation of changes in vegetation and other land remains subject to the level of thematic detail available in the source dataset (Grafius et al., 2016).

2.4. LULC Change Analysis

For each observation year, the area and proportional share of each LULC category were compiled from the published dataset (Rimal et al., 2025).

The proportional share of LULC category (i) in year (t) was calculated as:

$$P_{i,t} = \frac{A_{i,t}}{A_t} \times 100$$

where $P_{i,t}$ is the percentage share of LULC category (i) in year (t), $A_{i,t}$ is the area of category (i) in year (t) (km²), and A_t is the total study-area extent in year (t) (km²).

Absolute change in the area of each LULC category between two observation years was calculated as:

$$\Delta A_i = A_{i,t_2} - A_{i,t_1}$$

where A_{i,t_1} and A_{i,t_2} are the areas of LULC category (i) at the beginning and end of the selected period, respectively.

Relative percentage change was calculated as:

$$\Delta A_i(\%) = \frac{A_{i,t_2} - A_{i,t_1}}{A_{i,t_1}} \times 100$$

These measures were used to quantify the direction and magnitude of temporal changes in the five LULC categories over the full 1988–2024 period and between consecutive observation years. The calculations were performed using the published area statistics rather than by independently processing the original satellite imagery (Rimal et al., 2025). Therefore, all changes reported in the present study represent quantitative reanalysis of the published LULC dataset.

2.5. LULC Transition Analysis

To identify the principal pathways of land-cover transformation, the published cross-tabulated LULC transition matrices were analysed for the consecutive periods 1988–1992, 1992–2000, 2000–2008, 2008–2016, and 2016–2024 (Rimal et al., 2025).

For each transition period, the matrix element represents the area that changed from source LULC category (i) to destination category (j). Diagonal elements represent land that remained within the same LULC category, whereas off-diagonal elements represent land-cover conversions.

The magnitude of each specific transition was obtained directly from the corresponding transition-matrix element. Particular attention was given to conversions into urban/built-up land because these transitions identify the land-cover pathways contributing directly to the expansion of developed surfaces. Cropland-to-built-up and vegetation-to-built-up transitions were examined separately because both source categories have positive valuation coefficients under the adopted ESV framework.

For each transition period, the contributions of different source LULC categories to newly developed built-up land were also examined. This approach allows the dominant pathways of urban expansion to be identified rather than relying solely on comparisons of built-up area at the beginning and end of a period. Transition pathways were interpreted as observed changes

between the LULC categories represented in the source transition matrices and were not used to infer socioeconomic or institutional drivers of those changes.

Where transition areas are used to illustrate ESV implications, the calculation is treated as a coefficient-based accounting estimate rather than a measured monetary loss. For a transition from category (i) to category (j), the transition-associated difference in estimated ESV was calculated as:

$$\Delta ESV_{i \rightarrow j} = T_{ij} \times (VC_j - VC_i) \times 100$$

where A_{ij} is the transition area (km²), C_i and C_j are the valuation coefficients of the source and destination categories, respectively (USD ha⁻¹ yr⁻¹), and the factor 100 converts km² to hectares. This calculation represents the difference in estimated ESV implied by the adopted coefficients and is not interpreted as an observed or realised economic loss, avoided cost, or welfare change.

2.6. Ecosystem Service Valuation

2.6.1. Valuation framework

Estimated ecosystem service value was calculated using a benefit-transfer approach in which land-cover-specific monetary coefficients were applied to the corresponding LULC categories. The adopted coefficients were based primarily on the Kathmandu Valley assessment of Shrestha et al. (2022), while the equivalent-factor valuation framework provides the broader methodological basis (Xie et al., 2015). This approach permits temporal comparison using a common coefficient set, but it also makes the magnitude of the estimate conditional on the selected classification and transferred coefficients. The present study therefore treats coefficient dependence as an explicit analytical dimension rather than as a secondary caveat.

The valuation coefficients adopted in the present study are summarised in Table 2.

Table 2. Ecosystem-service valuation coefficients adopted for the five LULC categories.

LULC category	Corresponding valuation category	Coefficient (USD ha ⁻¹ yr ⁻¹)	Source
Built-up	Built-up	0	(Rimal et al., 2025; Shrestha et al., 2022)
Cropland	Cropland	699.37	(Shrestha et al., 2022)

Vegetation	Forest coefficient used as proxy for aggregated vegetation	2168.84	(Shrestha et al., 2022)
Other land	Other/barren	0	(Rimal et al., 2025; Shrestha et al., 2022)
Waterbody	Waterbody	6552.97	(Shrestha et al., 2022)

2.6.1.1. Mapping LULC Classes to Valuation Coefficients

The correspondence between the published LULC classes and valuation categories was established to preserve consistency with the source LULC framework while applying the available benefit-transfer coefficients. Cropland was mapped directly to the cropland valuation category, and waterbody was mapped to the corresponding waterbody category. The aggregated vegetation class was mapped to the forest coefficient because the source LULC dataset does not separately distinguish forest, shrubland, grassland, and other vegetated surfaces. Built-up and other land were assigned zero coefficients according to the adopted valuation framework. This mapping is an analytical approximation; it should not be interpreted as evidence that all land-cover types within a broad class provide identical ecosystem services.

Cropland is assigned a coefficient of USD 699.37 ha⁻¹ yr⁻¹, corresponding to the cropland coefficient used in the Kathmandu Valley assessment (Shrestha et al., 2022). The vegetation category is assigned the forest-cover coefficient of USD 2168.84 ha⁻¹ yr⁻¹ because the source LULC classification combines forest and other vegetated surfaces. This is a proxy assumption and may overestimate or underestimate the ESV of individual vegetation types within the aggregated class. The sensitivity analysis is intended to quantify the influence of this and the other adopted coefficients on the aggregate estimate. Waterbodies are assigned a coefficient of USD 6552.97 ha⁻¹ yr⁻¹, while built-up area and other land are assigned zero coefficients in accordance with the adopted valuation framework.

The zero-coefficient assigned to built-up land should not be interpreted as evidence that urban environments provide no ecosystem services. Urban trees, parks, gardens, wetlands, open spaces, and other green and blue infrastructure can provide ecological and social benefits. Rather, the zero coefficient represents the convention adopted for the broad built-up category within the selected benefit-transfer framework (Shrestha et al., 2022). Accordingly, the present ESV estimates should not be interpreted as a complete accounting of ecosystem services within urban areas (Haase et al., 2014).

Similarly, the vegetation coefficient is an approximation rather than a direct measurement of the value of all vegetation within the study area. The use of the forest coefficient for a combined vegetation class may overestimate or underestimate the value of portions of the class that are more appropriately represented by shrubland, grassland, or other vegetation categories. This limitation is important because the vegetation category contributes the largest share of estimated ESV and is also the most influential coefficient in the sensitivity analysis.

2.6.2. Calculation of ESV

The area of each LULC category was converted from km² to hectares using:

$$A_{i,t}^{ha} = 100A_{i,t}^{km^2}$$

where $A_{i,t}^{ha}$ is the area of LULC category i in hectares and $A_{i,t}^{km^2}$ is the corresponding area in km². The conversion uses $1 \text{ km}^2 = 100 \text{ ha}$.

The estimated annual ESV of each LULC category was calculated as the product of the category area in hectares and its corresponding valuation coefficient:

$$ESV_{i,t} = A_{i,t}^{ha} \times VC_i$$

where $ESV_{i,t}$ is the estimated annual ESV of LULC category (i) in year (t) (USD yr⁻¹), $A_{i,t}^{ha}$ is the area of category (i) in year (t) (ha), and VC_i is the corresponding valuation coefficient (USD ha⁻¹ yr⁻¹).

The total estimated annual ESV for each observation year was calculated as:

$$ESV_t = \sum_{i=1}^n ESV_{i,t}$$

Where (n) represents the five LULC categories.

The absolute change in estimated ESV between two observation years was calculated as:

$$\Delta ESV = ESV_{t_2} - ESV_{t_1}$$

and the relative change was calculated as:

$$\% \Delta ESV = \frac{ESV_{t_2} - ESV_{t_1}}{ESV_{t_1}} \times 100$$

The proportional contribution of each LULC category to total estimated ESV was calculated as a ratio:

$$C_{i,t} = \frac{ESV_{i,t}}{ESV_t}$$

where $C_{i,t}$ represents the proportional contribution of LULC category (i) to total estimated ESV in year (t). Values range from 0 to 1.

These calculations provide comparative estimates of temporal change in ESV under the adopted coefficient framework. They do not represent direct market prices, welfare estimates, or locally measured monetary values of ecosystem services.

2.7. Valuation-Coefficient Dependence and Scenario Analysis

Because benefit-transfer coefficients are subject to uncertainty, a coefficient sensitivity analysis was conducted to evaluate their influence on total estimated ESV. The analysis focused on the three non-zero coefficients: cropland, vegetation, and waterbody. Built-up and other land were excluded because their assigned coefficients are zero.

For each non-zero coefficient, sensitivity was assessed independently while holding LULC areas and all other valuation coefficients constant. The selected coefficient was varied relative to its baseline value to evaluate the response of total estimated ESV to alternative coefficient assumptions.

The coefficient-dependence ratio was calculated as:

$$S_{i,t} = \frac{(ESV_t^* - ESV_t)/ESV_t}{(VC_i^* - VC_i)/VC_i}$$

where $S_{i,t}$ is the coefficient-dependence ratio for valuation coefficient (i) in year (t); ESV_t is the baseline total estimated annual ESV; ESV_t^* is the total estimated annual ESV after modifying coefficient (i); VC_i is the baseline valuation coefficient; and VC_i^* is the modified valuation coefficient.

Under the linear ESV formulation used in this study, the coefficient-dependence ratio is equivalent to the proportional contribution of the affected LULC category to total estimated ESV.

To illustrate the dependence of aggregate ESV estimates on alternative coefficient assumptions, coefficient scenarios of -50%, -25%, +25%, and +50% relative to the baseline values were calculated independently for the three non-zero coefficients and are reported in Supplementary Table S5. These scenarios illustrate the dependence of aggregate ESV estimates on alternative coefficient assumptions and are not statistically derived confidence intervals.

2.8. Uncertainty and Methodological Limitations

Several sources of uncertainty are inherent in the analysis. First, the study uses a published LULC dataset rather than independently classifying the original satellite imagery. The results therefore depend on the classification methods, class definitions, spatial extent, and accuracy assessment reported by the source study (Rimal et al., 2025).

Second, the five-class LULC framework is relatively broad. In particular, the vegetation category combines land-cover types that may differ substantially in structure, ecological function, and ecosystem-service provision. Similarly, the other-land category is heterogeneous. Aggregation at this level may therefore obscure differences in ecosystem-service value (Grafius et al., 2016).

Third, the ESV coefficients are transferred from previously established valuation frameworks rather than derived from primary ecosystem-service valuation independently for each land-cover type in Kathmandu Valley. Benefit-transfer approaches provide a practical means of estimating ESV where locally specific valuation data are unavailable, but they introduce uncertainty when ecological and socioeconomic conditions differ between source and application contexts (Richardson et al., 2015).

Fourth, the use of a forest coefficient as a proxy for the combined vegetation class is a simplifying assumption and represents an important source of uncertainty in the present ESV estimates. The sensitivity analysis was therefore used to evaluate the influence of the adopted coefficients on aggregate ESV.

Fifth, built-up and other land are assigned zero coefficients under the selected framework. This convention does not imply that these land-cover categories provide no ecosystem services; rather, their contributions are not represented in the adopted coefficient system (Shrestha et al., 2022). The present ESV estimates should therefore not be interpreted as a complete accounting of ecosystem services within urban areas.

Finally, the analysis identifies temporal associations between LULC composition and estimated ESV rather than establishing causal relationships between urbanisation and ecosystem-service degradation. The results should therefore be interpreted as a comparative assessment of changes in land-cover composition and their implied ESV under the adopted valuation assumptions.

3. Results

3.1. Temporal LULC Dynamics

The published LULC dataset indicates substantial changes in the composition of Kathmandu Valley between 1988 and 2024, particularly an increase in urban/built-up land and a decrease in cropland (Rimal et al., 2025). Figure 2 shows the temporal trajectories of the five LULC classes, and Table 3 presents their areas and changes over the study period.

Urban/built-up land increased from 37.98 km² in 1988 to 197.41 km² in 2024, representing an absolute increase of 159.43 km² and a relative increase of 419.77%. Its share of the study area increased from 5.47% to 28.43%. Built-up area increased from 37.98 km² in 1988 to 40.70 km² in 1992, 73.90 km² in 2000, 95.45 km² in 2008, 138.37 km² in 2016, and 197.41 km² in 2024. The largest increase between consecutive observation years occurred during 2016–2024, when built-up area increased by 59.04 km².

Cropland showed the opposite temporal pattern. Its area decreased from 418.32 km² in 1988 to 245.08 km² in 2024, corresponding to a reduction of 173.24 km² or 41.41% relative to its 1988 extent. Its share of the study area declined from 60.25% to 35.30%. The decline was larger during the later observation intervals, particularly after 2000.

Vegetation occupied 230.69 km² in 1988 and 242.17 km² in 2024, representing a net increase of 11.48 km² or 4.98%. Its share of the study area increased from approximately 33.23% to

34.88%. The trajectory was not monotonic, with a decrease between 1988 and 1992 followed by increases during the subsequent observation periods.

Other land increased from 1.97 km² in 1988 to 5.00 km² in 2024, corresponding to an increase of 3.03 km² or 153.81%. Waterbody area decreased from 5.31 km² to 4.62 km², corresponding to a net reduction of 0.69 km² or 12.99%. Waterbody remained below 1% of the total study area throughout the observation period.

Overall, the largest absolute changes were the increase in built-up land and the decrease in cropland. The complete LULC composition and percentage changes are presented in Table 3.

Table 3. LULC composition and temporal change in Kathmandu Valley, 1988–2024.

LULC	1988 (km ²)	1992 (km ²)	2000 (km ²)	2008 (km ²)	2016 (km ²)	2024 (km ²)	Change 1988–2024 (km ²)	Change 1988– 2024 (%)
Built-up	37.98	40.70	73.90	95.45	138.37	197.41	+159.43	+419.77%
Cropland	418.32	417.70	380.91	356.63	313.78	245.08	-173.24	-41.41%
Vegetation	230.69	227.67	232.13	235.40	236.27	242.17	+11.48	+4.98%
Other land	1.97	2.67	2.02	3.34	1.86	5.00	+3.03	+153.81%
Waterbody	5.31	5.52	5.30	3.45	3.98	4.62	-0.69	-12.99%

Percent change is calculated relative to the 1988 area of each LULC category. Minor differences in percentages may occur because of rounding.

Source: Recalculated from Rimal et al. (2025).

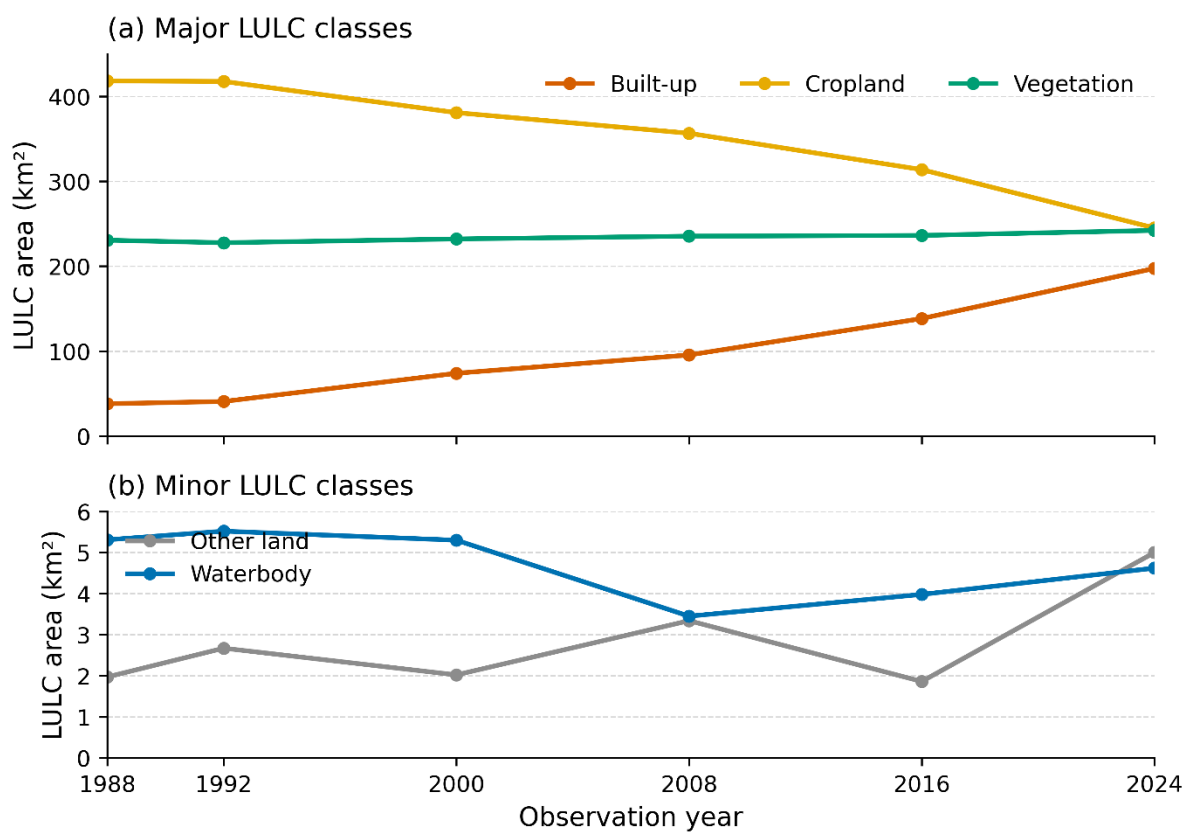


Figure 2. Temporal changes in LULC area in Kathmandu Valley, 1988–2024. (a) Changes in built-up, cropland, and vegetation areas; (b) changes in other land and waterbody areas.

Values are based on the published LULC dataset of Rimal et al. (2025).

Source: Authors' calculations based on Rimal et al. (2025).

The spatial distribution of the five LULC classes across the six observation years is shown in Figure 3.

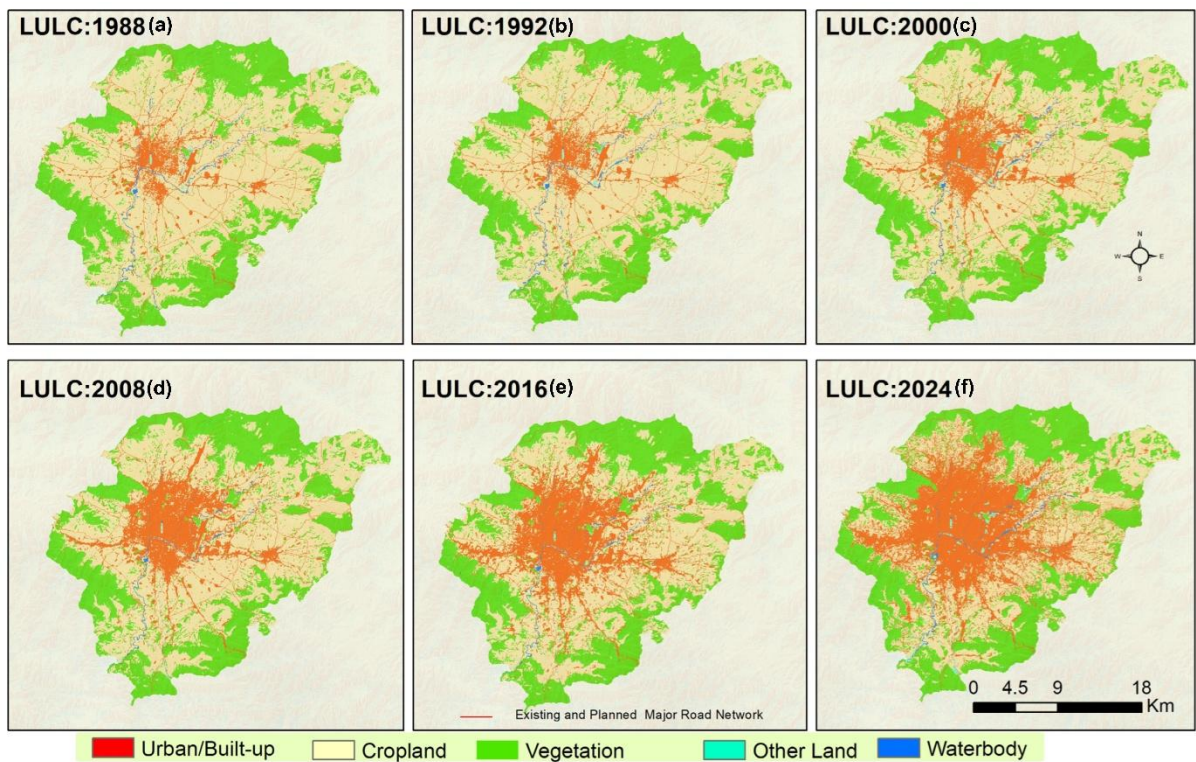


Figure 3. Spatial distribution of the five LULC classes in Kathmandu Valley for (a) 1988, (b) 1992, (c) 2000, (d) 2008, (e) 2016, and (f) 2024.

Source: reconstructed by the authors based on Rimal et al. (2025).

The contrasting trajectories of built-up and cropland area are further illustrated in Figure 4.

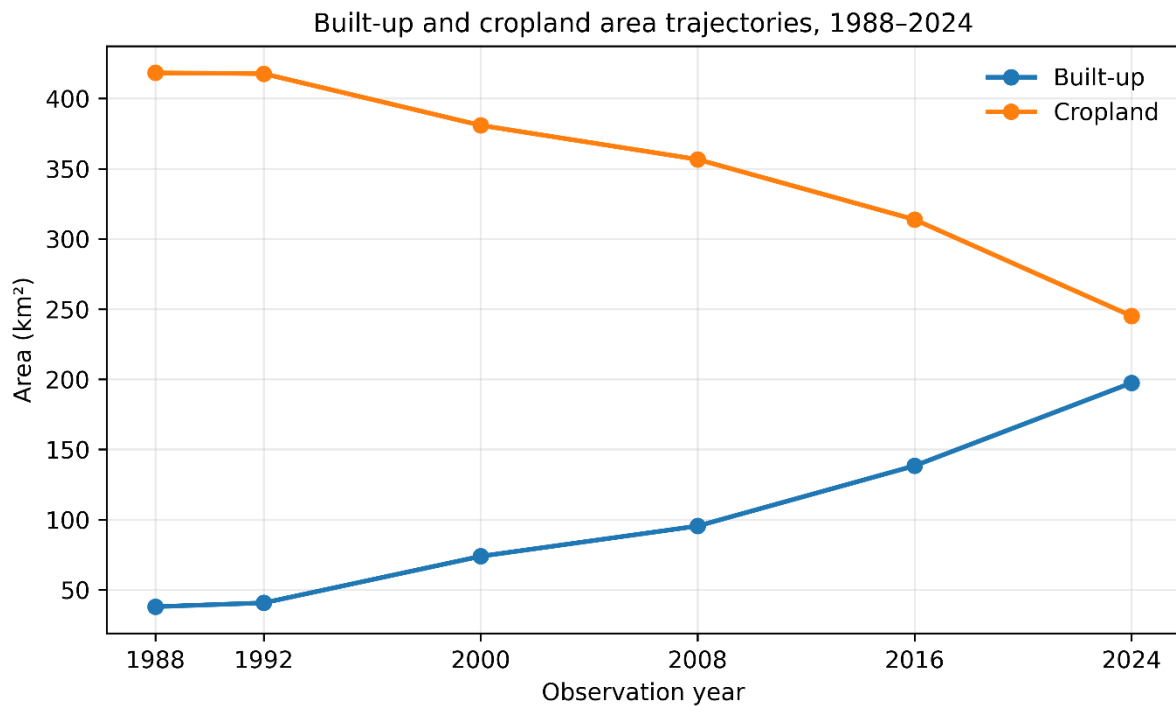


Figure 4. Built-up and cropland area trajectories in Kathmandu Valley, 1988–2024.

Source: Authors' calculations based on Rimal et al. (2025).

3.2. LULC Transition Pathways Associated with Urban Expansion

The transition matrices showed that cropland-to-built-up conversion was the dominant observed transition into urban/built-up land during each of the five consecutive observation periods (Rimal et al., 2025). The converted area increased from 2.58 km² during 1988–1992 to 31.90 km² during 1992–2000, 20.48 km² during 2000–2008, 40.97 km² during 2008–2016, and 59.45 km² during 2016–2024. The cumulative cropland-to-built-up transition across the five periods was approximately 155.38 km². The magnitude of this cumulative pathway should not be interpreted as an independent measure of net urban growth because transition totals and endpoint differences represent different accounting quantities.

The 2016–2024 interval recorded the largest single-period cropland-to-built-up conversion, with 59.45 km² of cropland converted to urban/built-up land. During the same interval, net built-up area increased by 59.04 km². These quantities represent different measures: the former is a specific transition pathway from cropland to built-up land, whereas the latter is the net balance of all transitions into and out of the built-up category.

Vegetation-to-built-up conversion occurred during all five transition periods, with a cumulative transition of approximately 6.81 km². Other source categories contributed smaller areas to built-up expansion. Across the observed transition pathways, cropland represented the largest source category for newly developed built-up land.

Table 4 summarises the major transition pathways into built-up land, while Figure 5 presents their temporal variation. The complete transition matrices, including persistence and all off-diagonal transitions, are provided in Supplementary Table S3.

Table 4. Major LULC transitions associated with urban expansion (km²).

Period	Cropland → Built-up	Vegetation → Built-up	Other land → Built-up	Waterbody → Built-up	Net built-up increase
1988–1992	2.58	0.09	0.10	0.17	2.72
1992–2000	31.90	0.14	0.94	0.50	33.20
2000–2008	20.48	0.51	0.37	0.48	21.55

Period	Cropland → Built-up	Vegetation → Built-up	Other land → Built-up	Waterbody → Built-up	Net built-up increase
2008–2016	40.97	1.67	0.50	0.10	42.92
2016–2024	59.45	4.40	0.09	0.10	59.04

Source: Recalculated from the published transition matrices of Rimal et al. (2025).

Note: Net built-up increase represents the balance of all transitions into and out of the built-up category and therefore does not equal the magnitude of any individual transition pathway.

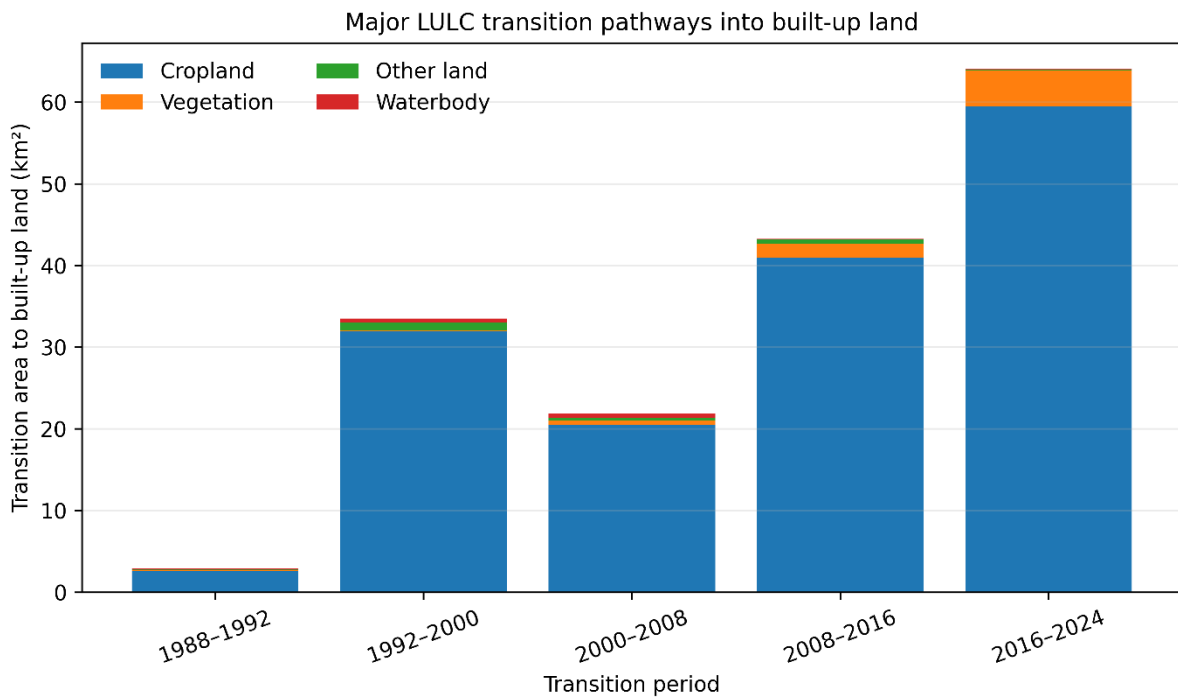


Figure 5. Major LULC transition pathways into built-up land across consecutive observation periods. Values represent transition areas (km²).

Source: Recalculated from the published LULC transition matrices of Rimal et al. (2025).

3.3. Temporal Variation in Estimated Ecosystem Service Value

Estimated annual ESV varied across the six observation years according to changes in the areas of LULC categories assigned non-zero valuation coefficients. Under the adopted valuation framework, cropland, vegetation, and waterbody contributed to total estimated ESV, whereas built-up and other land were assigned zero coefficients (Shrestha et al., 2022). The resulting values therefore represent coefficient-based estimates conditional on the adopted land-cover classification and valuation assumptions.

Total estimated annual ESV decreased from USD 82.77 million yr⁻¹ in 1988 to USD 72.69 million yr⁻¹ in 2024, representing an absolute reduction of approximately USD 10.08 million yr⁻¹ or 12.18%. Estimated total ESV was USD 82.77 million yr⁻¹ in 1988, USD 82.21 million yr⁻¹ in 1992, USD 80.46 million yr⁻¹ in 2000, USD 78.26 million yr⁻¹ in 2008, USD 75.80 million yr⁻¹ in 2016, and USD 72.69 million yr⁻¹ in 2024.

As shown in Table 5, cropland-associated ESV decreased from USD 29.26 million yr⁻¹ in 1988 to USD 17.14 million yr⁻¹ in 2024. Vegetation-associated ESV increased from USD 50.03 million yr⁻¹ to USD 52.52 million yr⁻¹ over the same period, while waterbody-associated ESV changed from USD 3.48 million yr⁻¹ to USD 3.03 million yr⁻¹.

The temporal changes in category-specific and total estimated ESV are presented in Table 5 and Figure 6.

Table 5. Estimated annual ecosystem service value by LULC category and observation year (USD million yr⁻¹).

LULC	1988	1992	2000	2008	2016	2024
Cropland	29.26	29.21	26.64	24.94	21.94	17.14
Vegetation	50.03	49.38	50.35	51.05	51.24	52.52
Waterbody	3.48	3.62	3.47	2.26	2.61	3.03
Total	82.77	82.21	80.46	78.26	75.80	72.69

Source: Authors' calculations based on LULC areas from Rimal et al. (2025) and valuation coefficients from Shrestha et al. (2022).

The temporal trajectory of total estimated ESV is shown in Figure 6.

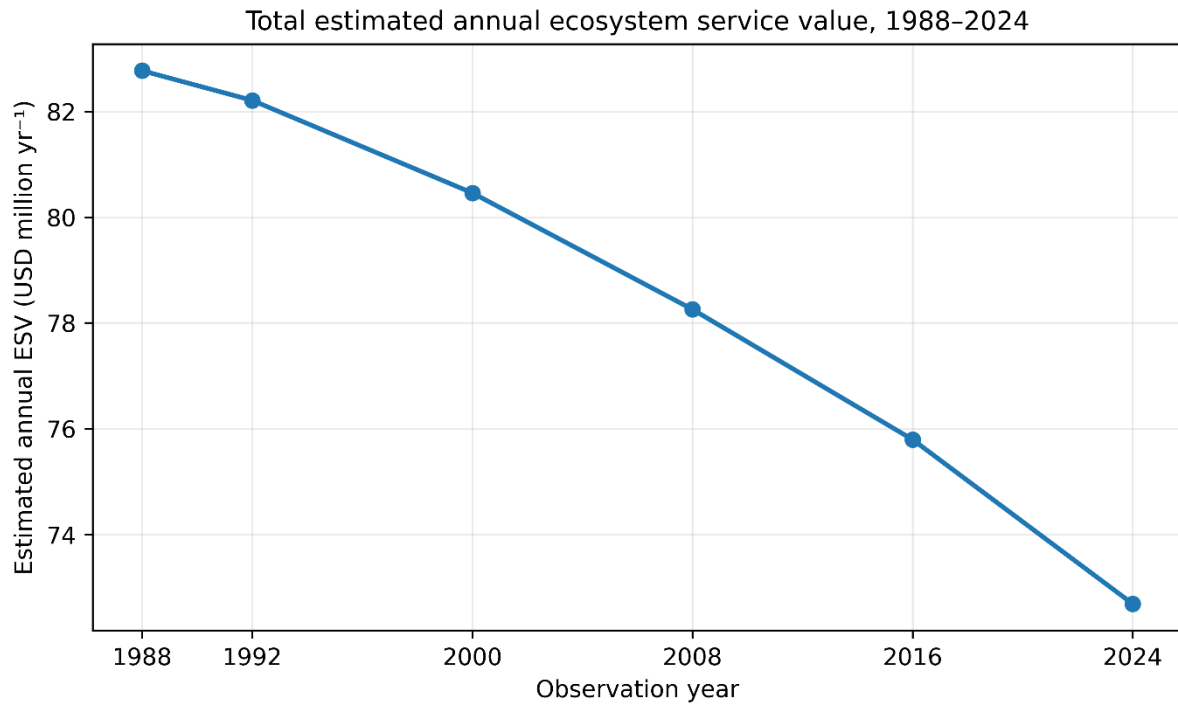


Figure 6. Total estimated annual ecosystem service value in Kathmandu Valley for the six observation years, 1988–2024, under the adopted valuation-coefficient framework.

Source: Authors' calculations based on Rimal et al. (2025) and valuation coefficients from Shrestha et al. (2022).

3.4. Contribution of LULC Categories to Estimated ESV

The proportional contribution of the valued LULC categories to total estimated ESV changed between 1988 and 2024. Vegetation accounted for approximately 60.45% of total estimated ESV in 1988 and 72.26% in 2024. The contribution of cropland decreased from approximately 35.35% to 23.58%, while the contribution of waterbody remained comparatively small, ranging from approximately 2.9% to 4.4%.

The increase in the proportional contribution of vegetation occurred alongside a relatively small net increase in its mapped area. Because the vegetation category had a higher valuation coefficient than cropland, changes in the relative contributions of these categories affected the composition of total estimated ESV. This is a compositional effect within the valuation model rather than evidence that vegetation became more valuable in ecological terms. Built-up and other land did not contribute directly to the estimated total under the adopted framework because both were assigned zero valuation coefficients.

The category-specific contributions and their temporal changes are summarised in Figure 6 and Table 5.

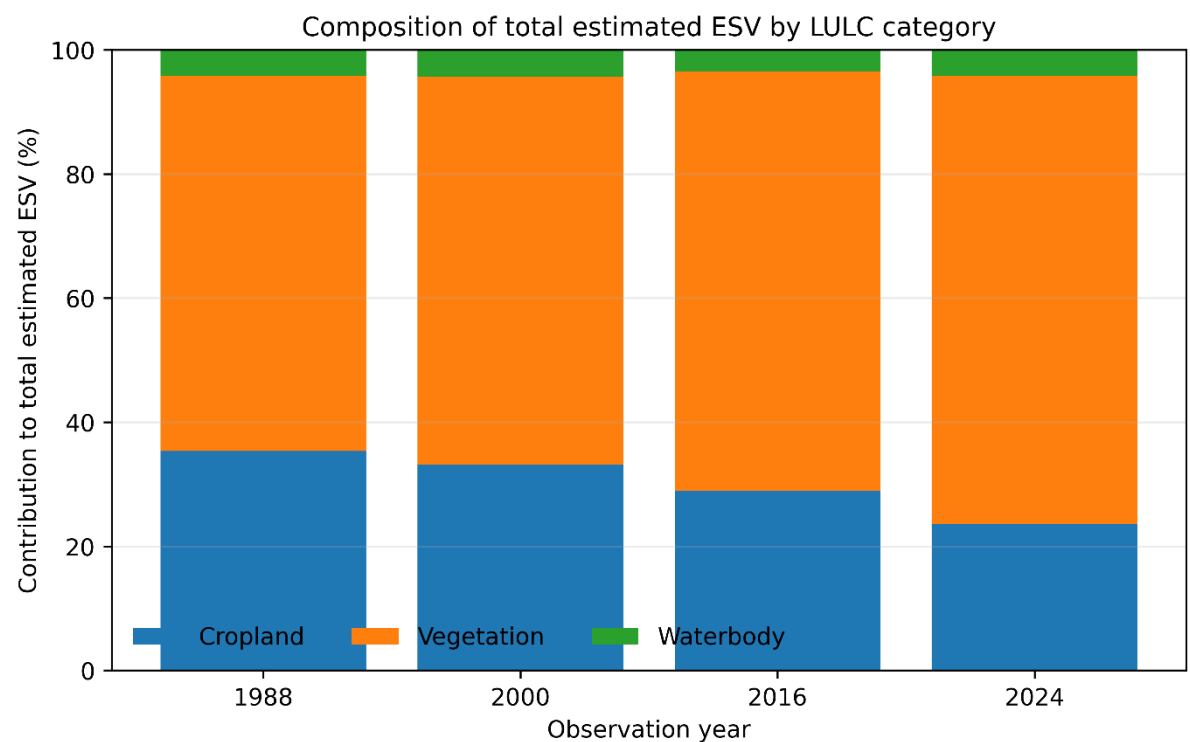


Figure 7. Composition of total estimated ecosystem service value by LULC category for selected observation years under the adopted valuation-coefficient framework. Only LULC categories with non-zero valuation coefficients are shown.

Source: Authors' calculations based on Rimal et al. (2025) and Shrestha et al. (2022).

3.5. Sensitivity of Estimated ESV to Valuation Coefficient Assumptions

The coefficient-dependence analysis examined the relative influence of the three non-zero valuation coefficients—cropland, vegetation, and waterbody—on total estimated ESV while holding LULC areas and all other coefficients constant. The resulting coefficient-dependence ratios are presented in Table 6.

Vegetation had the largest coefficient-dependence ratio in all six observation years. Its ratio increased from 0.604 in 1988 to 0.723 in 2024. The cropland ratio decreased from 0.353 to 0.236, whereas the waterbody ratio remained comparatively low, ranging from 0.029 to 0.044.

Because the ESV formulation is linear, the coefficient-dependence ratio corresponds to the proportional contribution of the affected LULC category to total estimated ESV under the

baseline coefficient set. The temporal changes in these ratios therefore reflect changes in the relative contributions of the corresponding LULC categories to the aggregate estimate.

The coefficient-perturbation scenarios further showed that independently varying the three non-zero coefficients by -50% , -25% , $+25\%$, and $+50\%$ changed the corresponding total estimated ESV. The magnitude of the resulting change depended on the baseline contribution of the affected LULC category. Detailed scenario calculations are provided in Supplementary Table S5.

The results of the coefficient-dependence analysis are summarised in Table 6.

Table 6. Dependence of total estimated ecosystem service value on valuation coefficients by LULC category and observation year, 1988–2024.

Year	Cropland coefficient-dependence ratio	Vegetation coefficient-dependence ratio	Waterbody coefficient-dependence ratio	Most influential coefficient
1988	0.353	0.604	0.042	Vegetation
1992	0.355	0.601	0.044	Vegetation
2000	0.331	0.626	0.043	Vegetation
2008	0.319	0.652	0.029	Vegetation
2016	0.290	0.676	0.034	Vegetation
2024	0.236	0.723	0.042	Vegetation

Source: Authors' calculations.

Note: The coefficient-dependence ratio represents the proportional contribution of the affected LULC category to total estimated ESV under the linear valuation model. It should not be interpreted as an independent measure of ecological sensitivity, statistical uncertainty, or a confidence interval.

4. Discussion

4.1. Urban Expansion and Agricultural-Land Conversion

The results demonstrate a substantial restructuring of Kathmandu Valley's land-cover composition between 1988 and 2024, characterised by a marked expansion of built-up land

alongside a pronounced contraction of cropland. More importantly, the transition analysis shows that this restructuring was not simply a difference between two endpoint maps: cropland-to-built-up conversion was the dominant observed pathway in every transition period, with a cumulative transition of approximately 155.38 km². The particularly large transition during 2016–2024 indicates that agricultural land remained an important source of newly developed urban surfaces during the most recent observation interval. At broader scales, recent evidence likewise shows that urban expansion can restructure agricultural and natural land systems through direct land conversion and displacement effects (De Vos et al., 2024).

This pattern is consistent with the longer-term urbanisation trajectory documented in Kathmandu Valley. Ishtiaque et al. (2017) identified agricultural land as an important source of newly developed urban surfaces between 1989 and 2016. Rimal et al. (2017) likewise documented substantial urban growth and land-cover transformation in the valley. Wang et al. (2020) reported continuing land-use change and urban expansion in the Kathmandu region. More recent analysis indicates continued development pressure on agricultural land (Aryal et al., 2023). Evidence from other rapidly urbanising Nepalese cities also shows that increases in built-up land commonly occur at the expense of agricultural land and, in some locations, vegetation (Devkota et al., 2023). The present analysis therefore provides further evidence of a persistent land-cover transformation rather than identifying a fundamentally new direction of change. Its additional contribution is to extend the temporal assessment to 2024 and explicitly identify the transition pathways underlying the change in endpoint LULC composition. Comparable evidence from global assessments shows that urban expansion can exert pressure on cropland and other productive land, while the resulting effects depend on the wider land-use system rather than on urban area growth alone (Ren et al., 2022).

The distinction between net change and transition magnitude is important for interpreting the results. Built-up land increased by 159.43 km² between 1988 and 2024, whereas the cumulative cropland-to-built-up transition across consecutive observation periods was approximately 155.38 km². These quantities are not equivalent because net built-up change represents the balance of all transitions into and out of the built-up category, whereas the cumulative transition represents one specific pathway across successive observation intervals.

Nevertheless, the close magnitude of the two measures indicates that agricultural-land conversion was a major observed component of the long-term increase in developed land.

The concentration of cropland-to-built-up conversion during the later observation periods is also noteworthy. The 2016–2024 interval recorded the largest single-period cropland-to-built-up transition, at 59.45 km². Similar studies of Kathmandu Valley have shown that urban growth has progressively extended into peri-urban and agricultural areas (Thapa & Murayama, 2012). Scenario-based work has also identified agricultural land and environmentally sensitive areas as important considerations in managing future urban growth (Lamichhane & Shakya, 2019). These studies provide context for the observed spatial trajectory but do not establish the mechanisms responsible for the transitions quantified here. The present study does not identify the socioeconomic, institutional, infrastructural, demographic, or land-market mechanisms responsible for the observed changes; those mechanisms should therefore not be inferred from the transition matrices alone. The importance of retaining agricultural land within land-system planning is also consistent with recent work showing that land-use transitions can redistribute environmental pressures across space and sectors (Lobell & Villoria, 2023).

The results nevertheless have implications for how urban expansion is monitored. Endpoint measures of built-up area capture the magnitude of urban growth but do not indicate which land-cover types are being displaced. Transition-specific analysis provides this additional information and can distinguish forms of urban expansion with potentially different implications for agricultural production, ecological connectivity, and ecosystem-service provision. In Kathmandu Valley, the persistent dominance of cropland-to-built-up conversion indicates that agricultural-land monitoring should be considered an integral component of urban land-change assessment rather than treated separately from urban-growth monitoring. This transition-based perspective is also consistent with global biodiversity assessments showing that land-use priorities can overlap with areas under pressure from urban expansion and other development demands (Cabernard et al., 2024). Land-use change can also create biodiversity impacts beyond the immediate converted footprint, particularly where habitat-rich areas are affected or pressures are displaced through broader land systems (Pang et al., 2024).

4.2. Implications for Ecosystem Service Value

The estimated total annual ESV declined from approximately USD 82.77 million yr⁻¹ in 1988 to USD 72.69 million yr⁻¹ in 2024, representing a reduction of 12.18% under the adopted valuation framework. This decline occurred alongside substantial contraction of cropland and expansion of built-up land. The association should, however, be interpreted as a correspondence between land-cover composition and coefficient-based estimated value rather than as evidence that urbanisation alone caused a quantified monetary loss of ecosystem services. This distinction is consistent with broader cautions about interpreting benefit-transfer estimates as direct measures of welfare or realised economic value (Richardson et al., 2015). Similar long-term assessments elsewhere have found declining ecosystem-service potential following LULC alteration, while also showing that the magnitude of change depends on the assessment framework and spatial context (Gupta et al., 2024).

The direction of change is broadly consistent with the earlier Kathmandu Valley assessment by Shrestha et al. (2022), which reported a decline in aggregate estimated ESV over an earlier observation period. The present results extend the temporal assessment to 2024 and provide a transition-based interpretation of the land-cover changes underlying the valuation estimates. The absolute monetary estimates from the two studies should not, however, be treated as directly comparable measures of economic value because the studies differ in observation periods, spatial and thematic classification, treatment of vegetation, valuation categories, and valuation coefficients.

The category-specific results provide a clearer explanation of the aggregate decline. Cropland-associated ESV decreased substantially as cropland area contracted, whereas vegetation-associated ESV remained comparatively stable and became a larger proportion of total estimated ESV. This shift does not indicate that vegetation became more valuable in ecological terms. Rather, it reflects the interaction between mapped area and the coefficient assigned to each land-cover category, a characteristic feature of coefficient-based valuation frameworks (Xie et al., 2015). At broader scales, assessments of nature's contributions to people likewise show that the ecological importance of land is not captured by a single monetary measure and that multiple contributions can overlap spatially (Cimatti et al., 2023).

This result illustrates an important characteristic of land-cover-based ESV accounting: changes in aggregate estimated value depend jointly on land-cover area and the coefficients assigned to those classes. A land-cover category can therefore represent an increasing proportion of

aggregate estimated ESV without experiencing an equivalent improvement in ecological condition. The increase in the vegetation contribution in the present study should consequently be interpreted as a compositional effect within the valuation model rather than as evidence of ecological restoration or improved ecosystem functioning (Gómez-Baggethun & Ruiz-Pérez, 2011).

The zero-coefficient assigned to built-up land requires similar caution. The increase in built-up area does not directly appear as an increase in estimated ESV because the adopted framework assigns no monetary coefficient to the broad built-up category. Urban landscapes nevertheless contain parks, street trees, gardens, wetlands, riparian spaces, and other green and blue infrastructure that can provide ecosystem services (Haase et al., 2014). Recent reviews further emphasise the contribution of green infrastructure and nature-based solutions to urban sustainability (Fang et al., 2023). The present five-class framework does not resolve these features separately and should therefore not be interpreted as a complete accounting of ecosystem-service provision within the urban landscape. Recent global evidence further demonstrates that urban vegetation can provide substantial cooling benefits, while the quantity and quality of green space differ strongly among cities and regions (Chen et al., 2025).

The estimated monetary decline should therefore be understood primarily as a reduction in the area of LULC categories assigned positive valuation coefficients under the adopted framework, particularly cropland. It should not be interpreted as a complete measure of ecosystem-service loss associated with urbanisation. The estimates are most useful for identifying the direction and relative magnitude of change under a consistent valuation framework, whereas their absolute monetary magnitude remains sensitive to classification and coefficient assumptions (Schägnier et al., 2013; Knoke et al., 2024). The broader ecosystem-service literature similarly stresses that monetary estimates should be interpreted alongside ecological and spatial information rather than as complete representations of nature's contributions to people (Srivathsa et al., 2023).

4.3. Vegetation and Waterbody Dynamics

The relatively small net increase in mapped vegetation area between 1988 and 2024 requires careful interpretation. Vegetation increased from 230.69 km² to 242.17 km², but the underlying LULC category combines multiple vegetated land-cover types rather than

distinguishing forest, shrubland, grassland, and other vegetation separately. An increase in mapped area within such an aggregated class does not necessarily indicate improvement in forest condition, habitat quality, biodiversity, carbon storage, or other ecosystem functions. The observed change should instead be interpreted as a change in mapped land-cover extent within the classification used by the source dataset. Recent global evidence is particularly relevant to this interpretation because urbanisation can simultaneously reduce vegetation directly while stimulating vegetation gains indirectly, with markedly different patterns between Global South and Global North cities (Chen et al., 2025). The ecological interpretation of land-cover trajectories also depends on the fate of agricultural land and the subsequent pathways of land-use change; recent biodiversity research shows that cropland transitions can have heterogeneous ecological consequences across landscapes (Crawford et al., 2024).

This issue is important because the spatial and thematic resolution of LULC data can influence ecosystem-service assessment. Grafius et al. (2016) demonstrated that ecosystem-service modelling outputs may vary with the spatial resolution and aggregation of input land-cover data. Similarly, the use of broad land-cover classes in ecosystem-service valuation can obscure differences among ecosystems with different ecological functions and service profiles. In the present study, the aggregation of several vegetation types into a single class is therefore both a source of temporal consistency and a limitation on ecological specificity.

The classification issue has direct implications for the ESV results because the vegetation category was assigned the forest valuation coefficient and consequently contributed the largest share of estimated ESV. The sensitivity analysis further showed that the vegetation coefficient had the largest coefficient-dependence ratio in every observation year, increasing from 0.604 in 1988 to 0.723 in 2024. The aggregate ESV estimate is therefore particularly dependent on how the broad vegetation class is defined and valued, illustrating the importance of classification detail in ecosystem-service modelling (Grafius et al., 2016). This interpretation is also consistent with evidence that land-use and land-management changes can affect ecological multifunctionality in ways that are not reducible to a single land-cover-area metric (Xu et al., 2024).

Waterbody dynamics present a complementary case. Waterbody area declined from 5.31 km² in 1988 to 4.62 km² in 2024. Although this represents a relatively small absolute change,

waterbody had the highest valuation coefficient among the non-zero LULC categories. Consequently, changes in mapped waterbody area can affect aggregate estimated ESV disproportionately relative to their spatial extent. At the same time, the broad waterbody category does not distinguish among rivers, lakes, ponds, canals, reservoirs, or other water features and does not provide information about ecological condition or water quality. The estimated waterbody ESV should therefore be interpreted as an area-and-coefficient effect rather than a direct measure of hydrological or ecological change.

Taken together, the vegetation and waterbody results demonstrate that the land-cover significance within the adopted classification of LULC change cannot be inferred from area change alone. Spatial extent, thematic classification, ecological condition, valuation coefficient, and spatial configuration all influence interpretation of ecosystem-service outcomes (Crossman et al., 2013). More spatially and ecologically resolved assessments would therefore be useful for distinguishing major vegetation types and individual waterbody systems in future studies. Recent global mapping work similarly highlights the need to consider multiple nature contributions and biodiversity objectives together when identifying land-management priorities (Dawkins et al., 2024).

4.4. Sustainable Land Management and Urban Planning

The results have several implications for sustainable land management in Kathmandu Valley. The strongest land-change signal is the persistent dominance of cropland-to-built-up conversion, indicating that agricultural land remains closely connected to the spatial expansion of developed surfaces. This finding suggests that assessment of urban growth should incorporate agricultural-land conversion as an explicit land-management indicator rather than focusing only on the total amount of built-up expansion. Previous Kathmandu Valley studies similarly identify agricultural land as an important component of the valley's urban transformation (Ishtiaque et al., 2017). Related evidence from subsequent urban-growth assessments supports the continuing relevance of agricultural-land conversion (Rimal et al., 2017; Wang et al., 2020). More recent work further documents agricultural-land pressure in the valley (Aryal et al., 2023).

The findings also indicate the value of integrating green and blue infrastructure considerations into urban land-change monitoring. Although the adopted valuation framework assigns a zero

coefficient to built-up land, urban areas contain heterogeneous green and blue elements that can provide regulating, cultural, habitat, and other ecosystem services (Haase et al., 2014). Reviews of urban ecosystem services likewise emphasise the importance of recognising multiple functions within heterogeneous urban landscapes (Luederitz et al., 2015). Recent literature on green infrastructure and nature-based solutions further supports their relevance to urban sustainability (Fang et al., 2023; Herath & Bai, 2024). Consequently, broad built-up classes may conceal environmentally important features that are not represented in the present ESV accounting framework. Global evidence also indicates that nature-based solutions are increasingly being used to address interconnected climate, biodiversity, and societal challenges in cities (Goodwin et al., 2023).

A transition-specific monitoring approach can provide additional information for sustainable land management. Monitoring aggregate built-up growth identifies the magnitude of urbanisation, but transition matrices additionally identify which land-cover categories are being replaced. In the Kathmandu Valley context, simultaneous monitoring of agricultural areas exposed to conversion, ecologically connected vegetation, and waterbody networks could provide a more spatially informative basis for assessing land-cover change and its potential implications for food production, ecological connectivity, and ecosystem-service provision (Haase et al., 2014).

The temporal pattern also suggests that monitoring frequency matters. The 2016–2024 interval recorded the largest increase in built-up area and the largest cropland-to-built-up transition among the observed periods. Although the present study does not establish the mechanisms responsible for this temporal concentration, it demonstrates that assessments based only on widely separated endpoints may obscure changes in the intensity of particular transition pathways. Scenario-based urban-growth research in Kathmandu Valley likewise shows the value of examining temporal and spatial pathways rather than relying only on endpoint conditions (Thapa & Murayama, 2012). This reinforces the value of pathway-sensitive monitoring because different land-use transitions can have different environmental consequences even when their net area changes appear similar (Pratzer et al., 2023).

These findings support a land-management perspective in which urban-growth monitoring, agricultural-land conservation, and ecosystem-service considerations are examined together. The present analysis does not evaluate the effectiveness of specific zoning regulations, land-

market interventions, infrastructure policies, or development controls, and therefore does not provide evidence for selecting one particular policy instrument over another. Instead, it identifies the land-cover transitions and valuation assumptions that may warrant greater attention in future spatial planning and monitoring, consistent with the broader emphasis on integrated ecosystem-service information for planning and decision support (Maes et al., 2012). Recent urban sustainability scholarship further emphasises that urban planning needs to connect environmental outcomes with broader social, institutional, and governance contexts rather than treating land-cover change as an isolated spatial process (Keith et al., 2023).

4.5. Research limitations and future research

Several limitations affect the interpretation and transferability of the findings. First, the analysis is based on a previously published multi-temporal LULC dataset rather than an independent classification of the original Landsat imagery. The present study therefore inherits the source study's classification decisions, class definitions, spatial processing, and reported uncertainty. The classification accuracies and period-specific Kappa statistics reported by the source study describe the published dataset and should not be interpreted as independent validation undertaken in the present analysis.

Second, the five-class LULC framework simplifies a heterogeneous landscape. The vegetation category combines land-cover types that may differ substantially in ecological structure and ecosystem-service functions, while the other-land category is similarly heterogeneous. Such aggregation improves temporal comparability but limits the ecological specificity of the transition and ESV analyses. Research on urban ecosystem-service modelling has shown that modelling outputs can vary with the spatial scale and aggregation of land-cover inputs (Grafius et al., 2016).

Third, the ESV analysis relies on transferred valuation coefficients rather than locally derived monetary estimates for individual ecosystem services. Benefit transfer provides a practical basis for comparative assessment when locally specific valuation data are unavailable (Richardson et al., 2015). However, transferred coefficients can introduce uncertainty when ecological and socioeconomic conditions differ between source and application contexts (Schägner et al., 2013). Recent work further indicates that constant value coefficients may

become problematic when land-cover changes are large because marginal values can vary with land-cover scarcity (Knoke et al., 2024). Recent global valuation and land-use research likewise show that the environmental consequences of land-use change can be displaced across regions and supply chains, underscoring the importance of clearly defining the valuation boundary and interpretation of transferred estimates (Cabernard et al., 2024). In addition, scenario studies show that land-use pressures can involve trade-offs among production, biodiversity and emissions, which reinforces the need to avoid interpreting a single transferred coefficient as a comprehensive environmental outcome (Schneider et al., 2024).

Fourth, the use of the forest coefficient as a proxy for the aggregated vegetation class is a particularly important assumption. Because the vegetation category combines multiple vegetation types, the resulting ESV estimate may not accurately represent the value of each component. The sensitivity analysis partially addresses this issue by demonstrating how strongly the aggregate estimate depends on the vegetation coefficient, but it cannot resolve the underlying classification uncertainty. Research on the social value of land-related environmental change likewise illustrates that the valuation consequences of land-cover change depend on the ecological and socioeconomic context in which changes occur (Knoke et al., 2023).

Fifth, built-up and other land are assigned zero coefficients under the selected valuation framework. This convention does not imply that urban or other land-cover categories provide no ecosystem services. Urban green and blue infrastructure can provide multiple services that are not represented by the broad built-up category (Luederitz et al., 2015). Recent reviews similarly emphasise the importance of accounting for these features in urban sustainability assessments (Fang et al., 2023; Herath & Bai, 2024).

Finally, the analysis identifies temporal associations between LULC composition and coefficient-based estimated ESV rather than establishing causal relationships between urbanisation and ecosystem-service degradation. The study does not include socioeconomic, demographic, infrastructure, land-market, governance, or household-level variables capable of explaining why particular transitions occurred. The observed decline in estimated ESV should therefore not be attributed to urbanisation alone.

Future research could address these limitations through higher-resolution LULC classification, field-based ecosystem-condition indicators, spatially explicit ecosystem-service modelling, and integration of LULC data with demographic, infrastructure, land-market, and planning information. More detailed classification of forest, shrubland, grassland, agricultural, wetland, river, pond, and built-up subtypes would also permit more differentiated valuation and transition analysis. In addition, locally derived or empirically calibrated ecosystem-service indicators could complement transferred monetary coefficients and provide a stronger basis for assessing ecological condition and management outcomes. Future work should also examine how land-use decisions are shaped by institutional and cultural contexts, because land-use pathways reflect more than biophysical suitability alone (Hodel et al., 2024).

5. Conclusions

This study examined long-term land-use and land-cover (LULC) dynamics and their implications for estimated ecosystem service value (ESV) in Kathmandu Valley, Nepal, from 1988 to 2024 using a secondary reanalysis of a published six-date Landsat-derived LULC dataset. Built-up land increased from 37.98 km² in 1988 to 197.41 km² in 2024, whereas cropland declined from 418.32 km² to 245.08 km². Transition analysis showed that cropland-to-built-up conversion was the dominant observed pathway across all five consecutive periods, with a cumulative transition of approximately 155.38 km².

Under the adopted land-cover-based valuation framework, total estimated annual ESV declined from approximately USD 82.77 million yr⁻¹ in 1988 to USD 72.69 million yr⁻¹ in 2024, representing a reduction of 12.18%. Cropland-associated ESV decreased substantially, whereas vegetation remained the largest contributor to aggregate estimated ESV. The coefficient-dependence analysis showed that vegetation had the largest proportional influence on the aggregate estimate in every observation year, increasing from 0.604 in 1988 to 0.723 in 2024. This result demonstrates that changes in aggregate estimated ESV reflect both land-cover composition and the valuation coefficients assigned to individual LULC categories.

The findings highlight the importance of monitoring agricultural-land conversion alongside built-up expansion and considering vegetation and waterbody connectivity and green and blue infrastructure within urban-growth assessment. However, the estimated ESV values

remain conditional on the published LULC classification and transferred valuation coefficients and should therefore be interpreted as comparative indicators of change rather than precise measures of monetary ecosystem-service loss. Future research should combine more detailed LULC classification, field-based ecosystem-condition indicators, spatially explicit ecosystem-service modelling, and socioeconomic and planning data to better distinguish changes in land-cover extent from changes in ecological condition and to examine the processes underlying future urban expansion.

Supplementary Materials

Supplementary Tables S1–S5 are provided as a separate Supplementary Materials file and contain source-dataset accuracy statistics, full transition matrices, detailed ESV calculations, and sensitivity scenarios.

Data Availability Statement

The LULC area statistics and transition information analysed in this study were obtained from the published Kathmandu Valley LULC dataset reported by Rimal et al. (2025). Derived LULC-change calculations, estimated ecosystem service value calculations, and valuation-coefficient sensitivity results generated in this study are provided in Supplementary Tables S4 and S5. The underlying published dataset is available from Rimal et al. (2025).

(<https://doi.org/10.3390/land14081675>).

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The authors acknowledge the researchers who generated and published the underlying Kathmandu Valley LULC dataset used in this study.

Conflicts of Interest

The authors declare no conflict of interest.

AI/AI-Assisted Technologies Disclosure

During the preparation and revision of this manuscript, the authors used ChatGPT (OpenAI) and Grammarly to assist with language refinement, manuscript organization, equation checking, and preparation of a revised figure. The authors independently verified all

calculations and reviewed the generated text and visual outputs. The authors take full responsibility for the accuracy, integrity, and final content of the manuscript.

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