Widespread loss of important ecosystem services from rapidly urbanising Kathmandu Valley

Roshan Sharma[1,2*], Bhagawat Rimal[3], Bikash Ghimire[4]

[1] School of Life and Environmental Sciences, Deakin University, Burwood Campus, Deakin University, Melbourne

[2] School of Global, Urban, and Social Sciences, RMIT University, Melbourne

[3] College of Applied Sciences (CAS), Tribhuvan University, Nepal

[4] Forest Research Institute Deemed University Dehradun (FRI), India

* Corresponding author

email: roshan.sharma@deakin.edu.au

Abstract

Ecosystem services are crucial for human well-being as it offers benefits such as food production, water purification, and climate regulation. However, land use change caused by rapid urban expansion poses a significant threat to these services. We investigate the impact of urbanization on ecosystem services in the Kathmandu Valley, a region experiencing intense urban growth. We assessed changes in urban areas and their effects on four key ecosystem services: air quality regulation, carbon storage, food production, and habitat quality. We utilise historical and projected land use data from 2008 to 2032, and different socio-economic and geographical data. The future land use projection shows an increase in urban areas, from 97 km^2 in 2008 to 231 km^2 by 2032, a growth by 140% within a 24-year period. Majority of this conversion comes from cropland. This urban expansion results in a significant decline in ESs, particularly in food production and habitat quality. We project that by 2032, food production will decrease by 19%, habitat quality by 16%, air quality regulation by 5%, and carbon storage by 3%. Our analysis shows there is an urgent need for sustainable urban planning to balance development with the conservation of important ESs.

Keywords: urbanisation; land use change; ESs; agricultural loss; food security; carbon storage and sequestration

1. Introduction

Nature provides a wide range of valuable goods and services, commonly referred to as ecosystem services (ESs), that contribute to human well-being (MEA, 2005). Generally, these services are divided into four main types: provisioning services (e.g. food and timber), supporting services (e.g. nutrient cycling and soil formation), which help maintain the natural processes needed for life, regulating services (e.g. water purification, climate mitigation, and flood prevention), which keep the environment stable); and cultural services, which provide benefits like recreation and spiritual value (Kremen, 2005; Patterson 2011; Patterson & Coelho, 2009; Torres et al., 2021). These services are essential for humans, from the food we eat to the way our climate is regulated (Kremen, 2005). Despite the incredible contribution of ESs to support nature and survival and well-being of human being, ESs globally are experiencing continuous loss due to human activities resulting in conversion and clearing of ecosystems for different land use (MEA, 2005). The type of land use and land cover (LULC) in an area is directly linked to how much ESs it can provide. Changes in LULC, like turning forests into farms or cities, can change the kinds and amounts of services the ecosystem offers (Costanza et al., 1997; Kreuter et al., 2001; Polasky et al., 2010). For example, while expanding farmland over forests or grasslands might provide more food (a provisioning service), it can reduce other services, like water purification and carbon storage. Therefore, any change in land use can lead to trade-offs between different ESs, affecting both the environment and people’s well-being.

Land use and land cover (LULC) changes are recognised as major causes of ESs loss worldwide (Costanza et al., 2014; Kubiszewski et al., 2017; Chen et al., 2020; Sutton et al., 2016). One of the key processes driving this loss is urban expansion (Maimaiti et al., 2022). As cities expand, natural areas like forests and agricultural lands are often replaced with impervious surfaces such as roads and buildings. This change disrupts important ecosystem processes, including the movement of water and nutrients in the environment (Song et al., 2020, 2022; Tang et al., 2021). Consequently, many ESs are negatively affected. Urban expansion has been shown in many studies to cause the loss of multiple ESs at the same time (Delphin et al., 2016; Eigenbrod et al., 2011; Seto et al., 2012). For example, the conversion of natural land to urban areas can reduce carbon storage, decrease water regulation, and limit habitat for wildlife (Delphin et al., 2016; Eigenbrod et al., 2011; Nelson et al., 2010). These losses not only harm the environment but also impact human well-being by reducing the availability of clean water, food, and other essential resources (Fang et al., 2022; Yuan et al., 2019). As cities continue to grow, understanding how urbanization affects both land use and ESs becomes critical. Urbanisation doesn’t just reduce ESs; it also creates new demands for these services. Growing population needs more food, clean water, and air, as well as spaces for recreation. However, urban expansion often reduces the ecosystems that provide these services creating a challenge for city planners and policymakers, who must balance the need for development with the need to protect and maintain ESs. For sustainable urban development, it is essential to understand how urban growth impacts ESs. By doing so, cities can plan better, ensuring that development meets the needs of a growing population while also preserving the ESs that are vital to long-term well-being (Luederitz et al., 2015; Narducci et al., 2019; J. Wang et al., 2019).

Evaluating changes in ESs is crucial for land use planners, conservationists, and policymakers. These groups rely on understanding how land use changes affect ESs to make informed decisions. For land use planners, this knowledge helps in designing cities and infrastructure in ways that minimize environmental degradation while still meeting the needs of growing populations. Conservationists use this information to protect critical ecosystems and ensure that biodiversity is maintained. For policymakers, understanding the effects of land use change on ESs is essential for creating laws and policies that balance development with environmental protection. Thus, it is not enough to only look at how past land use changes have impacted ES (Narducci et al., 2019; Nelson et al., 2010; J. Wang et al., 2019). While examining past changes can provide valuable lessons about which services have been lost or gained, it is equally important to consider what might happen in the future. Planners and policymakers need to understand the possible outcomes if current trends continue. This means evaluating the synergies and trade-offs between different ESs—some services may improve with certain land use changes, while others may decline. For example, increasing agricultural land may boost food production (a provisioning service) but could lead to reduced carbon storage and water quality (regulating services). Looking to the future requires a scenario-based approach, a simple and straightforward scenario is where land use planners and policymakers assume that what has happened in the past will continue to occur. By doing so, they can predict potential losses and gains in ESs and plan accordingly (Gu et al., 2019; Liu et al., 2023). This forward-thinking approach is vital for sustainable development, allowing planners to take preventive measures and mitigate negative impacts on ESs before they occur. Understanding these future trade-offs and synergies ensures that land use policies are robust and capable of supporting both human needs and ecosystem health over time. This approach is especially relevant in regions experiencing rapid urban growth, where predicting land use changes and their effects on ESs can inform more sustainable planning decisions (Tao et al., 2022; Tian et al., 2022).

Kathmandu Valley is one such region undergoing rapid land use change, primarily due to urban expansion (Rimal et al., 2018). The valley's growing population and land-based economic development are placing increasing pressure on natural ecosystems. However, there is still uncertainty about how future urban growth will unfold and how these changes will impact ESs. Understanding these dynamics is critical for informing both the public and policymakers about the potential gains or losses in ESs. Although previous studies have examined land use changes in the valley (Lamichhane & Shakya, 2019; S. Shrestha et al., 2022; S.W. Wang et al., 2020), none have specifically looked at how these changes affect ESs. In this study, we aim to assess both the historical and projected urban expansion in Kathmandu Valley, as well as the changes in ESs linked to this growth. Various methods have been used to project land use changes and estimate the corresponding impacts on ESs. Land use projections often rely on models such as cellular automata, agent-based models, and statistical approaches, which simulate future changes based on past trends and influencing factors. For this study, we utilize a LULC projection data from a previous study from Rimal et al., 2018. The authors used the TerrSet Land Use Change Modeller, which employs a Markov Chain model to predict future land use transitions based on observed changes over time (Al-Shaar et al., 2021; Hamad et al., 2018; Koko et al., 2020). This method allows us to capture the dynamic nature of urban expansion and its potential spread across the valley.

To estimate the changes in ESs, we apply the InVEST (Integrated Valuation of ESs and Tradeoffs) suite of models (Anjinho et al., 2022; Cong et al., 2020; Sánchez-Canales et al., 2012). This widely used tool enables us to quantify four key ESs: food production, sediment retention, habitat quality, and carbon storage. By combining land use projections with these ES models, we can gain insight into how urban expansion will affect not only the landscape but also the valuable services these ecosystems provide. Our objectives are to (i) analyze the urban expansion from 2008 to 2016, 2016 to 2024, and into 2032, and (ii) quantify the corresponding changes in ESs associated with this urban expansion.

2. Methods

2.1 Study Area

The study area is in the province number 3 of Nepal (Figure 1). The area incorporates 24 cities of Kathmandu valley (11 cities in Kathmandu district, 3 cities in Lalitpur district, and Bhaktapur: 4 cities) and Kabhrepalanchok district (6 cities), hereafter referred to as the CKVAKD complex, and covers a total of 1215.23 sq. Km. The geographic location is between northern latitudes of 27°31’40” and 27°49’10” and the eastern longitudes of 85°11′18″ and 85°43′44″ (Figure 1). The complex has experienced rapid urbanisation in the last decades, driven by rural-urban migration, economic activities, socio-political factors, and real estate boom. The total population of these four districts increased from 1,431,699 in 1991 to 2,032,764 in 2001 and to 2,900,971 to 2011 (Central Bureau of Statistics, 2014).

Figure 1. Map/location of Kathmandu valley, Nepal

2.2 Data

In this study, we used socio-economic, meteorological, geographic, and LULC data. LULC data for the year 2008 and 2016 were obtained from a previous study by Rimal et al., (Rimal et al., 2018). The study used Landsat images from the United State Geological Survey (USGS) website (https://earthexplorer.usgs.gov). The images were atmospherically and geometrically corrected and processed in ENVI environment. A supervised approach support vector machine (SVM) classifier, which is a supervised, non-linear, non-parametric classification technique widely used in remote sensing, was used for the classification of LULC (Mountrakis et al., 2011). The overall classification accuracy of 88.92% and 92.25% for the year 2008 and 2016 respectively were acquired. Similarly, the simulated LULC data for 2024 and 2032 using a CA Markov model was also acquired from the same study (Rimal et al., 2018). The method only considered simulation of urban areas and did not consider the conversion among other land use types. The Kno value, which is a measure of the accuracy of the model, was 0.91 indicated that the projection provided a reasonable estimate of the urban expansion (Pontius, 2000).

2.3 Methods – Mapping ESs (ESs)

2.3.1 Food Production

We calculated the quantity of food production in cultivated land use type by using a simple equation of yield multiplied by area. In the study region, there are three main crops paddy, wheat, and maize. We acquired the yield data per hectare and calculated the production in pixel (30m x 30 m or 90 sq. meters or 0.09 ha) in our LULC map. Equation 1 was used to calculate food production.

$$\mathrm{P}_{xy} = \sum_{\mathrm{g}=1}^{\mathrm{G}} \mathrm{A}_{xy} \times \mathrm{Y}_{gc} \qquad (1)$$

where, P_{xy} is the total food production of the cell (*x,y*) in cultivated land (C) in units of tons, A_{xy} is the area of the cell (*x,y*) which is equal to 0.09 ha or 900 sq. m and Y_{gc} is the yield per unit area for grains on LULC type cultivated land (ton/ha). The input parameters are provided in the supplementary information.

2.3.2 Habitat Quality

Habitat quality (HQ) is the ability of the ecosystem to provide conditions suitable for individual and population persistence. The HQ for the study area was measured using the InVEST Habitat Quality model. The model considers habitat quality as a function of habitat suitability and four threat parameters: the relative impact of each threat, relative sensitivity of each habitat type to threat, and the distance between the habitats and sources of threats. Also, it considers the degree to which the habitat type is legally protected. Eq (3) shows the calculation of habitat quality.

$$\mathrm{Q}_{xy} = \mathrm{H}_j \left(1 - \left(\frac{\mathrm{D}_{xj}^{z}}{\mathrm{D}_{xj}^{z} + \mathrm{k}^{z}} \right) \right) \qquad (3)$$

where, Q_{xy} is the habitat quality of cell (*x,y*). Hj is the habitat suitability of LULC type *j*, and $D_{xy}{}^{z}$ is the total threat level of the cell (*x,y*) in LULC type *j*. *k* is the halfsaturation value and z is a normalised constant. The value of Q_{xy} ranges between 0 and 1, with a higher value indicating higher habitat quality. Thus, when the value of Q_{xy} is 1, the cell's habitat quality it at it's maximum. The parameters for the model are provided in the supplementary information.

2.3.3 Carbon Storage

The InVEST carbon model uses a carbon cycle that quantifies the aggregate of static carbon storage and dynamic sequestration (or loss) based on four carbon pools: aboveground biomass, belowground biomass, soil organic matter, and dead organic matter (Sharp et al., 2016). The carbon on each of the four pools primarily depends upon the type of LULC (e.g., forests, agriculture, or shrublands), land management (e.g., forest rotation age, protected or managed for timber), and geographic and climatic factors (e.g., precipitation, slope). Due to the lack of data (e.g., age class of the different LULC), we assumed that the carbon storage in each LULC had reached an equilibrium state (Polasky et al., 2011). The total carbon in the landscape is thus estimated by using the relationship between the different LULC types in the landscape and the quantity of carbon in different carbon pools, which is one of the simplest methods for carbon estimations (Nelson et al., 2009). The total carbon stored CS_{jxy} for a given grid cell (*x,y*) with land use type *j* was calculated as (eq 4).

$$CS_{jxy} = A \; x \; (Ca_{jxy} + Cb_{jxy} + Cs_{jxy} + Cd_{jxy}) \qquad (4)$$

where, A is the actual area of each grid cell (ha), Ca_{jxy} is aboveground carbon density (ton ha^{-1}), Cb_{jxy}, is belowground carbon density (ton ha^{-1}), Cs_{jxy} is soil organic carbon density (ton ha^{-1}), and and Cd_{jxy} is the dead organic matter carbon density (ton ha^{-1}) for the grid cell (*x, y*) with land use type *j*.

2.3.4 Air Quality Regulation (AQR)

The concentration of particulate matter (PM) and more specifically PM10 to a large extent determine the quality of air. It is among an important environmental pollutant that impact human health. Thus, PM10 was used as an indicator of air quality regulation. Natural vegetation and forests capture large amounts of air pollutants such as PM10 by their large surface area to filter PM (Nowak & Walton, 2005). We used the methodology followed by Landuyt et al., (Landuyt et al., 2016) to estimate AQR service in our study area. Eq (5) shows the AQR estimation:

$$AQR_{jxy} = A_{xy} \text{ x } PM_{jxy} \qquad (5)$$

where AQR_{jxy} is the PM10 captured in the cell (x, y) of LULC type *j*, in kg, and A_{xy} is the cell size. The PM_{jxy} of vegetation and forests is provided in supplementary information.

3. Results

3.1 Analysis of urban expansion in CKVAKD

CKVAKD region experienced a remarkable increase in urban areas between 2008 and 2016 (Fig. 2). Urban area increased from 97 km^2 in 2008 to 139 km^2 in 2016, which is about an increase of 44 percent. Further, future prediction shows that the urban areas will continue to increase rapidly by 2032, and is projected to increase to 231 km^2, which is 140% increase compared to the extent of 2008. Further, transition analysis shows that the expansion of urban areas occurred at the expense of cultivated lands between 2008 and 2016 (42 km^2 of croplands converted to urban areas), and it is likely to continue with the same trend between 2024 and 2032 (38 km^2 of croplands converted to urban areas) (Fig. 3).

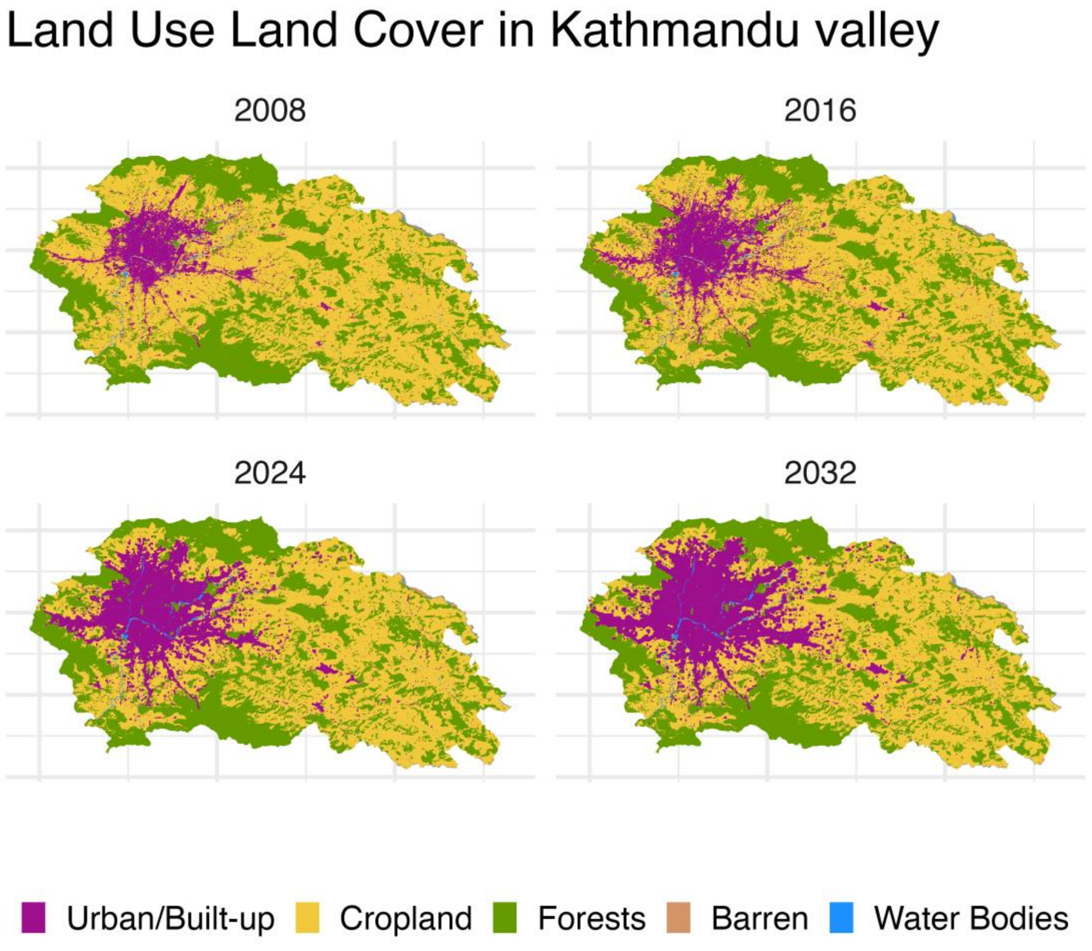


Figure 2: Land Use and Land Cover of Kathmandu Valley for 2008, 2016, 2024, and 2032

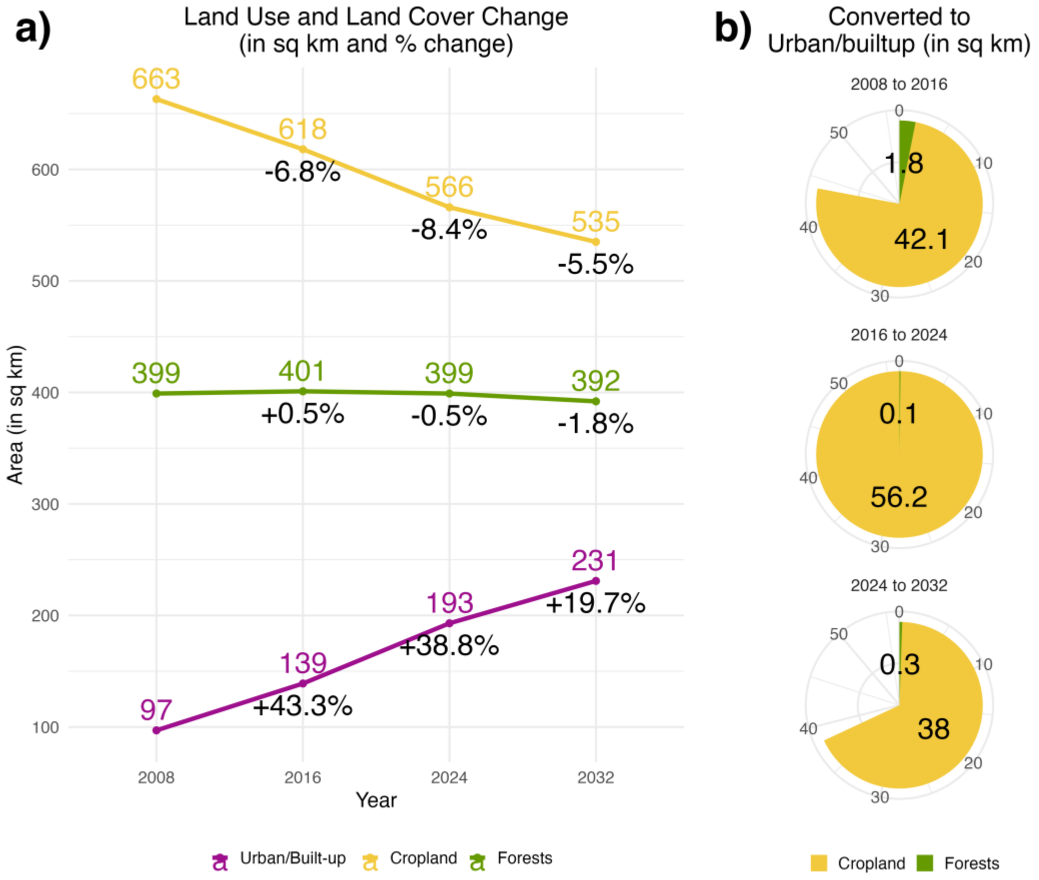
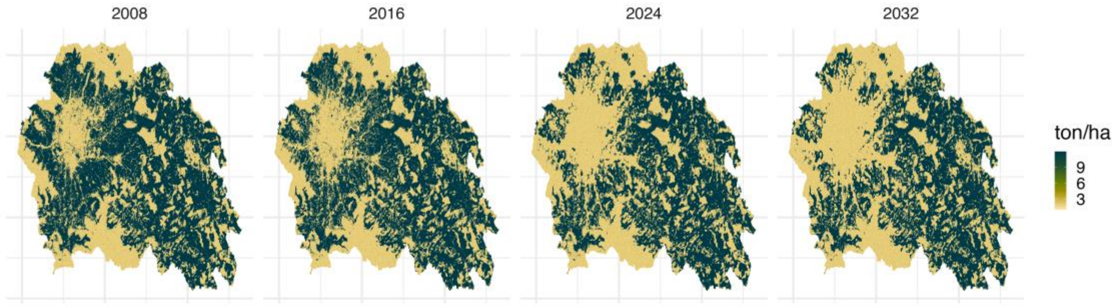


Figure 3. Trend of Land Use and Land Cover Change (panel a) and the land cover that has been converted to Urban/built up (panel b) between different time periods.

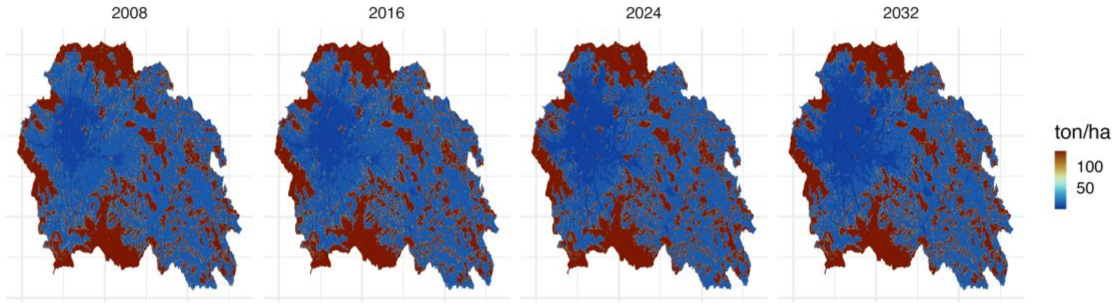
3.2 Impact of urban expansion on the ES from 2008 to 2032

By 2032, all ESs have experienced negative changes. The results show a steady decline in all four ES: Air Quality Regulation, Carbon Storage, Food Production, and Habitat Quality from 2008 to 2032 in the study area. Habitat Quality shows a sharp decrease, with a drop of 15.6% by 2032, while Food Production experiences the largest decline, falling by 19% over the same period. Air Quality Regulation and Carbon Storage also show negative trends, decreasing by 5.2% and 2.9% respectively.

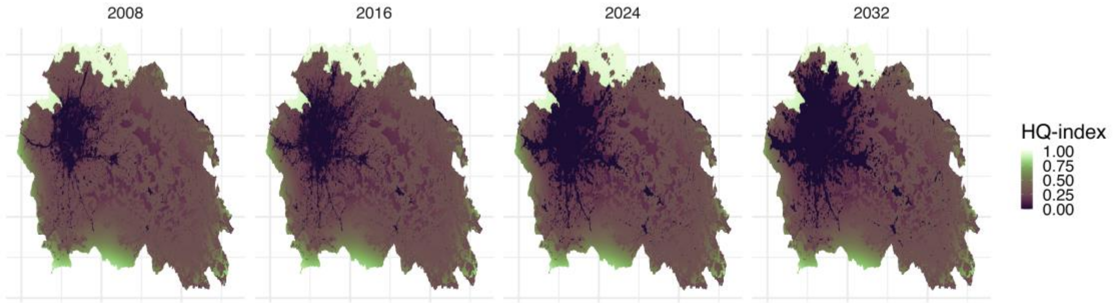
a) Food Production



b) Carbon Storage



c) Habitat Quality



d) Air Quality Regulation

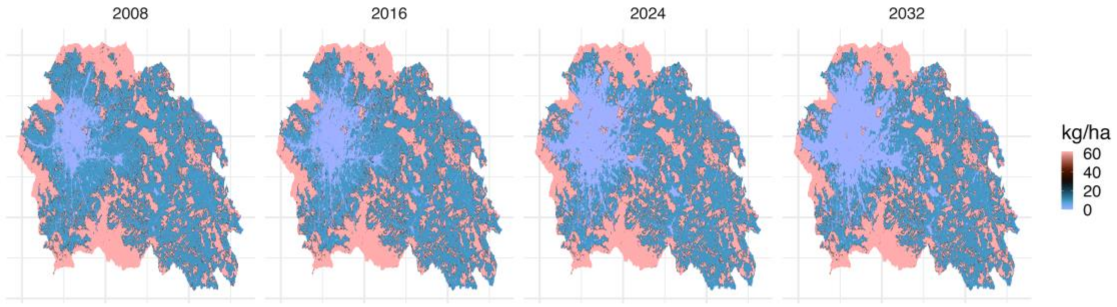


Figure 4. Spatial distribution of the quantified ESs and their changes across the different modelled years

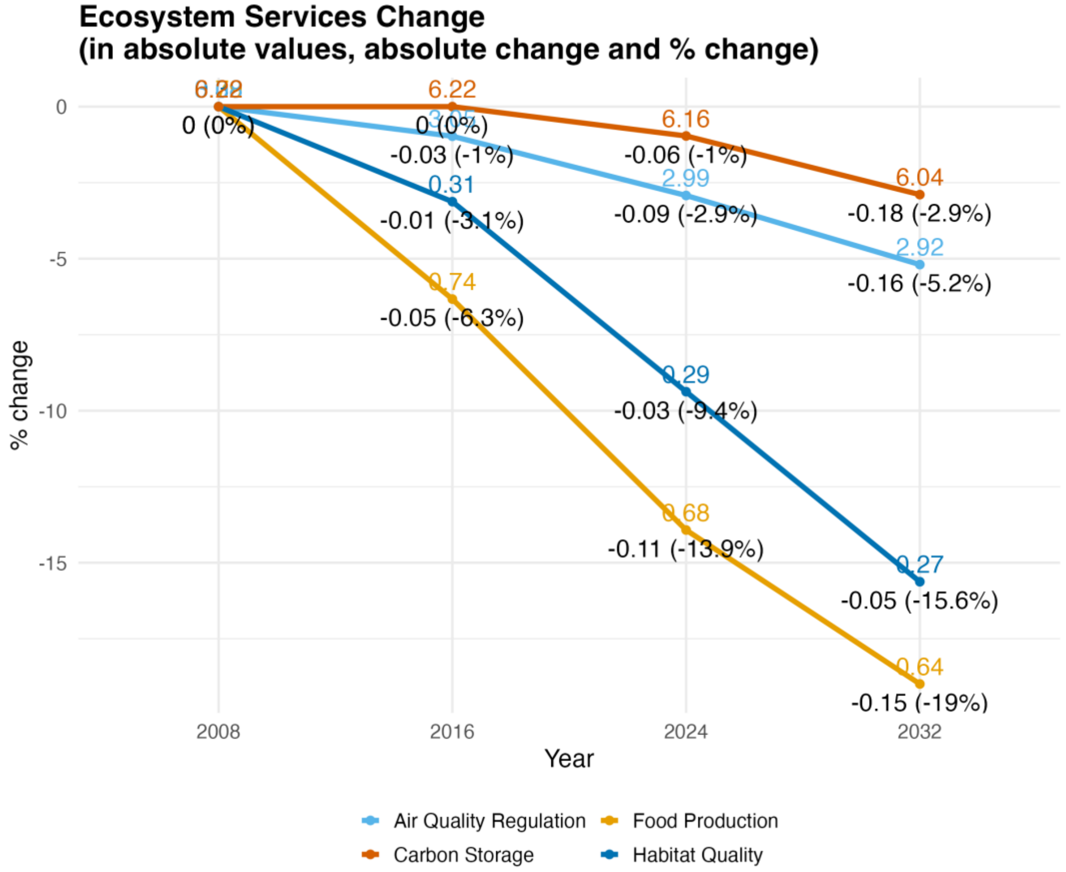


Figure 5. A line plot showing the estimates of different ESs and their changes (both in absolute and percentage terms with respect to the reference year 2008) in the study area. The values for Habitat Quality are mean index values, while for the other ESs, they are estimates in millions (x10⁶).

4. Discussion and Conclusion

Our study reveals that rapid urbanization in the Kathmandu Valley and surrounding areas has led to significant losses in important ecosystem services (ESs). Between 2008 and 2016, urban areas expanded considerably, replacing croplands and encroaching on forests. Projections indicate that this trend will continue, with urban areas expected to increase by 38% by 2024 and 20% by 2032. This growth pattern is troubling because urban expansion comes at the cost of biodiversity and environmental health (S.W. Wang et al., 2020). This concern is not unique to Kathmandu valley but reflects a broader, global trend where urban sprawl threatens essential ecological functions (Seto et al., 2012). As our model suggests that ESs losses could become even more severe in the coming years, it is essential to protect important ecological areas like forests and croplands to prevent large-scale loss of ESs in the region.

Our findings are consistent with global research linking urban expansion to the loss of various ESs. Several studies have documented reductions in provisioning, supporting, and regulating services due to urban sprawl. For example, Eigenbrod et al. (2011) and Seto et al., Seto et al. (2012) have shown that urban expansion leads to decreases in food production (FP), habitat quality (HQ), and carbon storage (CS). Xie et al. (2018) observed similar declines in Beijing, affecting not only FP, HQ, and CS but also air quality regulation (AQR) and water conservation. Other studies have reported reductions in additional ES, such as disease regulation, temperature regulation, and water quality (Foley et al., 2005) and in water supply and flood regulation (Blumstein & Thompson, 2015). Our study contributes to this body of knowledge by documenting the specific impacts of urbanization on multiple ES in the Kathmandu Valley, providing a localized perspective that complements global findings.

However, this study has several limitations. One limitation of our study is that it relies on projections, which might not reflect future changes in land use or policies. We also did not consider socio-economic factors that affect land use. Our analysis focused on only five land use classes, which may limit the comprehensiveness of our ES assessment. For instance, different types and conditions of forests offer varying levels of ES (Celentano et al., 2017), but our study did not differentiate among them. Additionally, the Landsat imagery used, with a resolution of 30 meters, may not capture finer details of urban landscapes such as green spaces and corridors, potentially leading to an underestimation of ES. Despite these limitations, our study offers detailed insights into how urban expansion affects ESs. It provides new information on how urban growth impacts both food production and habitat quality in Kathmandu valley. This information is useful for urban planners and policymakers in the region.

As urbanization continues worldwide, policymakers need to focus on protecting ecosystems that provide high levels of ES, such as croplands (Pan et al., 2021; Tao et al., 2022). Future projections suggest that urban land in developing countries will keep expanding over croplands. By 2050, urban areas are expected to increase fourfold, from 3.0 x 105 km^2 in 2000 to 1.2 x 106 km^2, with half of this new urban land coming from croplands (Angel et al., 2011). To ease the pressure on these ecosystems, land managers must identify areas vulnerable to urban expansion and protect them to maintain the supply of ESs. In Kathmandu and nearby regions, the growing population will demand more ESs, while expanding urban areas will reduce the supply of these services, putting additional strain on ecosystems and lowering the well-being of local communities. We recommend that policymakers and land managers in the region consider the impacts of ESs losses when making land use decisions. Additionally, we suggest that future studies focus on more detailed assessments with finer resolution data to better understand ESs in the region.

Author contributions

R.S conceptualised the idea of this manuscript. R.S and B.G wrote the first draft with input from B.R. R.S analysed and visualised the data. All authors commented on the manuscript and gave final approval for publication.

Data accessibility statement

All data and code supporting the results of the study will be made available upon request to the co-authors.

References

Al-Shaar, W., Nehme, N., & Adjizian Gérard, J. (2021). The Applicability of the Extended Markov Chain Model to the Land Use Dynamics in Lebanon. *Arabian Journal for Science and Engineering*, 46(1), 495–508.

Anjinho, P. da S., Barbosa, M. A. G. A., & Mauad, F. F. (2022). Evaluation of InVEST's Water ES Models in a Brazilian Subtropical Basin. *Water* (Switzerland), 14(10).

Angel, S., Parent, J., Civco, D. L., Blei, A., & Potere, D. (2011). The dimensions of global urban expansion: Estimates and projections for all countries, 2000–2050. *Progress in planning*, *75*(2), 53-107.

Blumstein, M., & Thompson, J. R. (2015). Land-use impacts on the quantity and configuration of ES provisioning in Massachusetts, USA. *Journal of Applied Ecology*, *52*(4), 1009-1019.

Celentano, D., Rousseau, G. X., Engel, V. L., Zelarayán, M., Oliveira, E. C., Araujo, A. C. M., & de Moura, E. G. (2017). Degradation of riparian forest affects soil properties and ESs provision in eastern amazon of brazil. *Land Degradation & Development*, *28*(2), 482-493.

Central Bureau of Statistics. (2014). *Population Monograph of Nepal*.

Chen, J., Yu, L., Yan, F., & Zhang, S. (2020). ES loss in response to agricultural expansion in the Small Sanjiang Plain, Northeast China: Process, driver and management. *Sustainability* (Switzerland), 12(6).

Cong, W., Sun, X., Guo, H., & Shan, R. (2020). Comparison of the SWAT and InVEST models to determine hydrological ES spatial patterns, priorities and trade-offs in a complex basin. *Ecological Indicators,* 112.

Costanza, R., d'Arge, R., De Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'neill, R. V., & Paruelo, J. (1997). The value of the world's ESs and natural capital. *Nature*, *387*(6630), 253.

Costanza, R., de Groot, R., Sutton, P., Van der Ploeg, S., Anderson, S. J., Kubiszewski, I., Farber, S., & Turner, R. K. (2014). Changes in the global value of ESs. *Global Environmental Change*, *26*, 152-158.

Delphin, S., Escobedo, F., Abd-Elrahman, A., & Cropper, W. (2016). Urbanization as a land use change driver of forest ESs. *Land Use Policy*, *54*, 188-199.

Eigenbrod, F., Bell, V., Davies, H., Heinemeyer, A., Armsworth, P., & Gaston, K. (2011). The impact of projected increases in urbanization on ESs. *Proceedings of the Royal Society of London B: Biological Sciences*, rspb20102754.

Fang, Z., Ding, T., Chen, J., Xue, S., Zhou, Q., Wang, Y., Wang, Y., Huang, Z., & Yang, S. (2022). Impacts of land use/land cover changes on ESs in ecologically fragile regions. *Science of the Total Environment,* 831.

Foley, J. A., DeFries, R., Asner, G. P., Barford, C., Bonan, G., Carpenter, S. R., Chapin, F. S., Coe, M. T., Daily, G. C., & Gibbs, H. K. (2005). Global consequences of land use. *Science*, *309*(5734), 570-574.

Grunewald, K., & Bastian, O. (2015). XII, 312 p. 67 illus., 14 illus.

Gu, Y., Qiao, X., Xu, M., Zou, C., Liu, D., Wu, D., & Wang, Y. (2019). Assessing the impacts of urban expansion on bundles of ESs by DMSP-OLS nighttime light data. *Sustainability*, 11(21).

Hamad, R., Balzter, H., & Kolo, K. (2018). Predicting land use/land cover changes using a CA-Markov model under two different scenarios. *Sustainability,* 10(10).

Koko, A. F., Yue, W., Abubakar, G. A., Hamed, R., & Alabsi, A. A. N. (2020). Monitoring and predicting spatio-temporal land use/land cover changes in Zaria City, Nigeria, through an integrated cellular automata and markov chain model (CA-Markov). *Sustainability,* 12(24), 1-21.

Kremen, C. (2005). Managing ESs: What do we need to know about their ecology? In *Ecology Letters* (Vol. 8, Issue 5, pp. 468–479).

Kreuter, U. P., Harris, H. G., Matlock, M. D., & Lacey, R. E. (2001). Change in ES values in the San Antonio area, Texas. *Ecological economics*, *39*(3), 333-346.

Kubiszewski, I., Costanza, R., Anderson, S., & Sutton, P. (2017). The future value of ESs: global scenarios and national implications. *ESs*, *26*, 289-301.

Lamichhane, S., & Shakya, N. M. (2019). Alteration of groundwater recharge areas due to land use/cover change in Kathmandu Valley, Nepal. *Journal of Hydrology: Regional Studies*, 26.

Landuyt, D., Broekx, S., Engelen, G., Uljee, I., Van der Meulen, M., & Goethals, P. L. (2016). The importance of uncertainties in scenario analyses–A study on future ES delivery in Flanders. *Science of the total environment*, *553*, 504-518.

Li, X., Chen, G., Zhang, Y., Yu, L., Du, Z., Hu, G., & Liu, X. (2022). The impacts of spatial resolutions on global urban-related change analyses and modeling. *IScience*, 25(12).

Luederitz, C., Brink, E., Gralla, F., Hermelingmeier, V., Meyer, M., Niven, L., Panzer, L., Partelow, S., Rau, A. L., Sasaki, R., Abson, D. J., Lang, D. J., Wamsler, C., & von Wehrden, H. (2015). A review of urban ESs: Six key challenges for future research. *ESs* (Vol. 14, pp. 98–112). Elsevier.

Maimaiti, B., Chen, S., Kasimu, A., Mamat, A., Aierken, N., & Chen, Q. (2022). Coupling and Coordination Relationships between Urban Expansion and ES Value in Kashgar City. *Remote Sensing*, 14(11).

MEA. (2005). *Ecosystems and Human Well-being: A Framework for Assessment* (I. Press, Ed. Vol. 1). Island Press.

Mountrakis, G., Im, J., & Ogole, C. (2011). Support vector machines in remote sensing: A review. *ISPRS Journal of Photogrammetry and Remote Sensing*, *66*(3), 247-259.

Msofe, N. K., Sheng, L., Li, Z., & Lyimo, J. (2020). Impact of land use/cover change on ES values in the Kilombero valley floodplain, southeastern Tanzania. *Forests,* 11(1).

Narducci, J., Quintas-Soriano, C., Castro, A., Som-Castellano, R., & Brandt, J. S. (2019). Implications of urban growth and farmland loss for ESs in the western United States. *Land Use Policy*, 86, 1–11.

Nelson, E., Mendoza, G., Regetz, J., Polasky, S., Tallis, H., Cameron, D., Chan, K., Daily, G. C., Goldstein, J., & Kareiva, P. M. (2009). Modeling multiple ESs, biodiversity conservation, commodity production, and tradeoffs at landscape scales. *Frontiers in Ecology and the Environment*, *7*(1), 4-11.

Nelson, E., Sander, H., Hawthorne, P., Conte, M., Ennaanay, D., Wolny, S., Manson, S., & Polasky, S. (2010). Projecting global land-use change and its effect on ES provision and biodiversity with simple models. *PloS one*, *5*(12), e14327.

Nowak, D. J., & Walton, J. T. (2005). Projected urban growth (2000–2050) and its estimated impact on the US forest resource. *Journal of Forestry*, *103*(8), 383-389.

Pan, H., Page, J., Cong, C., Barthel, S., & Kalantari, Z. (2021). How ecosystems services drive urban growth: Integrating nature-based solutions. *Anthropocene*, 35.

Patterson, T. M. (2011). ESs. In Encyclopedia of Life Sciences. Wiley.

Patterson, T. M., & Coelho, D. L. (2009). ESs: Foundations, opportunities, and challenges for the forest products sector. *Forest Ecology and Management*, 257(8), 1637–1646.

Polasky, S., Nelson, E., Pennington, D., & Johnson, K. A. (2011). The Impact of Land-Use Change on ESs, Biodiversity and Returns to Landowners: A Case Study in the State of Minnesota [journal article]. *Environmental and Resource Economics*, *48*(2), 219-242.

Pontius, R. G. (2000). Quantification error versus location error in comparison of categorical maps. *Photogrammetric engineering and remote sensing*, *66*(8), 1011-1016.

Rimal, B., Zhang, L., Keshtkar, H., Haack, B. N., Rijal, S., & Zhang, P. (2018). Land use/Land cover dynamics and modeling of urban land expansion by the integration of cellular automata and markov chain. *ISPRS International Journal of Geo-Information*, *7*(4), 154.

Sánchez-Canales, M., López Benito, A., Passuello, A., Terrado, M., Ziv, G., Acuña, V., Schuhmacher, M., & Elorza, F. J. (2012). Sensitivity analysis of ES valuation in a Mediterranean watershed. *Science of the Total Environment*, 440, 140–153.

Seto, K. C., Güneralp, B., & Hutyra, L. R. (2012). Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. *Proceedings of the National Academy of Sciences*, *109*(40), 16083-16088.

Shrestha, M., & Acharya, S. C. (2021). Assessment of historical and future land-use–land-cover changes and their impact on valuation of ESs in Kathmandu Valley, Nepal. *Land Degradation and Development,* 32(13), 3731–3742.

Shrestha, S., Poudyal, K. N., Bhattarai, N., Dangi, M. B., & Boland, J. J. (2022). An Assessment of the Impact of Land Use and Land Cover Change on the Degradation of ES Values in Kathmandu Valley Using Remote Sensing and GIS. *Sustainability,* 14(23).

Sharp, R., Tallis, H., Ricketts, T., Guerry, A., Wood, S., Chaplin-Kramer, R., Nelson, E., Ennaanay, D., Wolny, S., Olwero, N., Vigerstol, K., Pennington, D., Mendoza, G., Aukema, J., Foster, J., Forrest, J., Cameron, D., Arkema, K., Lonsdorf, E.,…Douglass, J. (2016). *InVEST +VERSION+ User’s Guide* (The Natural Capital Project, Issue.

Song, S., He, C., Liu, Z., & Qi, T. (2022). Evaluating the influences of urban expansion on multiple ESs in drylands. Landscape Ecology, 37(11), 2783–2802. https://doi.org/10.1007/s10980-022-01500-1

Song, S., Liu, Z., He, C., & Lu, W. (2020). Evaluating the effects of urban expansion on natural habitat quality by coupling localized shared socioeconomic pathways and the land use scenario dynamics-urban model. *Ecological Indicators*, 112.

Sutton, P. C., Anderson, S. J., Costanza, R., & Kubiszewski, I. (2016). The ecological economics of land degradation: Impacts on ES values. *Ecological Economics*, 129, 182–192.

Tang, L., Ke, X., Chen, Y., Wang, L., Zhou, Q., Zheng, W., & Xiao, B. (2021). Which impacts more seriously on natural habitat loss and degradation? Cropland expansion or urban expansion? *Land Degradation and Development,* 32(2),

Tao, Y., Tao, Q., Sun, X., Qiu, J., Pueppke, S. G., Ou, W., Guo, J., & Qi, J. (2022). Mapping ES supply and demand dynamics under rapid urban expansion: A case study in the Yangtze River Delta of China. *ESs*, 56.

Tian, S., Wu, W., Shen, Z., Wang, J., Liu, X., Li, L., Li, X., Liu, X., & Chen, H. (2022). A cross-scale study on the relationship between urban expansion and ESs in China. *Journal of Environmental Management*, 319.

Torres, A. V., Tiwari, C., & Atkinson, S. F. (2021). Progress in ESs research: A guide for scholars and practitioners. *ESs* (Vol. 49).

Wang, J., Zhou, W., Pickett, S. T. A., Yu, W., & Li, W. (2019). A multiscale analysis of urbanization effects on ESs supply in an urban megaregion. *Science of the Total Environment*, 662, 824–833.

Wang, S. W., Gebru, B. M., Lamchin, M., Kayastha, R. B., & Lee, W. K. (2020). Land use and land cover change detection and prediction in the kathmandu district of nepal using remote sensing and GIS. *Sustainability,* 12(9).

Yuan, Y., Chen, D., Wu, S., Mo, L., Tong, G., & Yan, D. (2019). Urban sprawl decreases the value of ESs and intensifies the supply scarcity of ESs in China. *Science of the Total Environment*, 697.

Xie, W., Huang, Q., He, C., & Zhao, X. (2018). Projecting the impacts of urban expansion on simultaneous losses of ESs: A case study in Beijing, China. *Ecological Indicators*, *84*, 183-193.