OPEN ACCESS Plant Protection, 09 (04) 2025. 943-953 DOI:10.33804/pp.009.04.5935

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Available Online at EScience Press

Plant Protection

ISSN: 2617-1287 (Online), 2617-1279 (Print)

http://esciencepress.net/journals/PP

Research Article

Ecological Niche Modeling of the Distribution and Spread of Paper Mulberry (Broussonetia papyrifera) in Haripur, Hazara, Pakistan

[a]Muhammad Naveed, [a]Manzoor Hussain, [b]Zafeer Saqib, [c]Saleha Ashfaq, [a]Nazia Shaheen, [a]Muhammad Azhar Khan, [d]Gulzaman William, [a]Abdul Majid, [e]Fawaz Manzoor

[a] *Department of Botany, Hazara University Mansehra, Pakistan.*
[b] *GIS and Eco-Informatics Laboratory, Department of Environmental Science, International Islamic University, Islamabad, Pakistan.*
[c] *Department of Biology, The University of Haripur, Pakistan.*
[d] *Department of Environmental Science, University of Gujrat, Gujrat, Pakistan.*
[e] *Department of Earth and Environmental Sciences Hazara University Mansehra, Pakistan.*

ARTICLE INFO

Article history
Received: 29th September, 2025
Revised: 11th December, 2025
Accepted: 13th December, 2025

Keywords
Invasive alien species
Ecological niche modeling
Broussonetia papyrifera
Habitat suitability mapping
Species distribution modeling (MaxEnt)

ABSTRACT

The rapid expansion of paper mulberry (*Broussonetia papyrifera*) in Haripur, Hazara division, Khyber Pakhtunkhwa, Pakistan, has raised serious ecological concerns owing to its invasive nature and strong competitive ability against native vegetation. This study integrates high-resolution Sentinel-2 multispectral imagery with Maximum Entropy (MaxEnt) species distribution modeling to assess habitat suitability and identify key environmental drivers governing the species' spatial spread. The results indicate that 76.9% of the landscape is unsuitable for paper mulberry establishment, whereas only 4.6% is classified as highly suitable. Agricultural land use contributed most strongly to the model (49%), followed by canopy height (21.3%) and total vegetation cover (14.1%), highlighting a pronounced association with disturbed and anthropogenically modified environments. Temporal analysis spanning 1990-2024 revealed substantial fluctuations in paper mulberry coverage, with an initial phase of relative stability followed by pronounced declines attributed to deforestation and urban expansion. Notably, a sharp increase in coverage was observed after 2020, likely driven by landscape disturbances and favorable climatic conditions. Between 2020 and 2024, a net gain of 0.0708 km^2 was recorded, indicating an accelerating expansion trend. Collectively, these findings emphasize the need for proactive management strategies to mitigate the ecological impacts of paper mulberry while judiciously balancing its commercial and agroforestry applications. Future research integrating high-resolution spatial modeling with extensive field-based validation will be critical for enhancing predictive accuracy and supporting evidence-based land-use planning in the region.

Corresponding Author: Manzoor Hussain
Email: manzoorhussain@hu.edu.pk

Introduction

The world's biodiversity is increasingly threatened by the introduction and spread of invasive plant species, which often result in significant ecological and economic consequences. Among these, *Broussonetia papyrifera*, commonly known as paper mulberry, has rapidly expanded into new regions, displacing native plant communities (Maan et al., 2021). Various physiological and ecological traits, including strong allelopathic interactions, high adaptability to diverse climatic conditions, and rapid growth, enable introduced species to quickly dominate novel ecosystems (Simberloff et al., 2013). Although paper mulberry was initially introduced for its economic value in ornamentation, afforestation, and papermaking, its unanticipated ecological impacts have raised serious concerns regarding ecosystem stability and biodiversity conservation (Maan et al., 2021). Originating from East Asia, *B. papyrifera* has now spread widely across tropical and subtropical regions, exhibiting invasive characteristics in many areas (Peng et al., 2019).

This species alters ecosystem structure and outcompetes native vegetation by thriving in disturbed environments such as agricultural lands, urban areas, forest edges, and roadside ditches. Its allelopathic potential, through the release of biochemical compounds into the soil, suppresses the germination and growth of local plants, making it a major driver of its invasiveness (Qureshi and Anwar, 2024). Furthermore, its vigorous vegetative propagation and extensive root system promote rapid expansion, leading to dense monocultures that exclude other species (Lowe et al., 2000). Such biotic aggressiveness disrupts native plant diversity, reduces habitat quality for herbivores and insect populations, and destabilizes trophic interactions across ecosystems. Invasions by paper mulberry are particularly problematic in regions with fragile ecological systems, where the loss of native vegetation can trigger cascading environmental effects. In Khyber Pakhtunkhwa (KPK) and Punjab, the species has emerged as a major invasive plant, especially in suburban and urban landscapes.

The notable spread of *B. papyrifera* in Haripur, Hazara Division of KPK, has raised concerns about its environmental implications in a region renowned for rich floral diversity and heterogeneous landscapes (Ullah and Khan, 2022). Its rapid expansion has resulted in decreased plant diversity, altered habitats for local wildlife, and degradation of native botanical communities. Furthermore, its proliferation has become a social and public health concern, as pollen from the species has been linked to allergic responses (Zhang et al., 2017). Understanding the spatial distribution and temporal progression of paper mulberry is essential for developing effective management and mitigation strategies.

Innovative remote sensing tools, such as LandTrendR, provide an efficient means for detecting vegetation changes and monitoring invasion dynamics over time (Kennedy et al., 2010). As a Landsat-based disturbance detection algorithm, LandTrendR offers valuable insights into the historical expansion patterns of *B. papyrifera* and facilitates the identification of past invasion pathways. In combination with forecasting tools like Maximum Entropy Modelling (MaxEnt), geographic distribution analysis allows researchers to predict the potential future spread of this aggressive species (Phillips et al., 2006). These approaches support conservation and management efforts by evaluating habitat conditions and assessing the current extent of invasion.

Introduced species such as paper mulberry pose direct threats to native ecological diversity by altering habitat characteristics, disrupting environmental interactions, and reducing the availability of essential resources (Jian et al., 2012). Therefore, the widespread expansion of *B. papyrifera* in Haripur Hazara necessitates a detailed assessment of its ecological impacts and habitat-level effects. By applying MaxEnt and LandTrendR, this study aims to comprehensively analyze the spatial and temporal patterns of paper mulberry invasion to determine its potential range expansion and dispersal behavior. Furthermore, the study evaluates the ecological impacts of paper mulberry on native plant communities, including competitive interactions, habitat alterations, and potential reductions in biodiversity resulting from invasion. Through the integration of ecological modeling and advanced remote sensing, this research seeks to generate valuable scientific insights that can guide management practices and support the development of effective conservation strategies to mitigate the environmental risks posed by this invasive species in Haripur Hazara and other vulnerable regions.

Materials and Methods

Study area

Haripur, located in the Hazara region of Khyber Pakhtunkhwa (KPK), Pakistan, covers approximately 1,725 km^2. The landscape primarily consists of plains interspersed with rocky mountains and rolling foothills. Elevations range from 500 to over 1,500 meters above sea level, situated between 33°44′N and 72°55′E. The region experiences a humid subtropical climate, with average temperatures ranging from 25°C in winter to 38°C in summer and an annual precipitation of approximately 1,200 mm (Luqman et al., 2017). These conditions support diverse vegetation, including dry subtropical evergreen forests and cultivated agricultural land. Native flora such as *Dodonaea viscosa*, *Pinus roxburghii*, *Quercus incana*, and *Acacia modesta* provide essential ecological support for various plant and animal species (Fazal et al., 2010). Hydrological features, including seasonal streams and the Haro River, contribute to sustaining regional biodiversity. However, anthropogenic pressures, such as deforestation, agricultural expansion, and rapid population growth, have facilitated the spread of invasive species like paper mulberry, posing significant threats to native species diversity and overall ecosystem resilience.

Environmental preprocessing and data collection

High-quality multispectral data from Sentinel-2 imagery were employed to assess environmental suitability. Surface reflectance values were corrected to minimize atmospheric interference and ensure spectral fidelity (Sola et al., 2018). Ecologically relevant variables for modelling paper mulberry distribution were selected based on their significance, including vegetation cover, land accessibility, and agricultural canopy structure (Zayani et al., 2023). Sentinel-2 spectral bands utilized included the visible bands blue (B2), green (B3), red (B4); coastal aerosol (B1); water vapor absorption (B9); vegetation red-edge bands (B5, B6, B7); and short-wave infrared bands (B11, B12) (Drusch et al., 2012). These spectral inputs facilitated accurate characterization of land surface features, water availability, and vegetation condition (Claverie et al., 2018).

Vegetation and landscape indices were derived to quantify ecosystem processes and topographic characteristics, enhancing the precision of environmental classification. The Normalized Difference Built-Up Index (NDBI) detected built-up areas (Teillet et al., 1997), the Green Normalized Difference Vegetation Index (GNDVI) estimated chlorophyll content, and the Modified Normalized Difference Water Index (MNDWI) quantified water availability. Plant health was assessed using the Normalized Difference Vegetation Index (NDVI), and the Soil-Adjusted Vegetation Index (SAVI) accounted for soil brightness in sparsely vegetated areas. Collectively, these indices provided a comprehensive evaluation of land-cover variability and vegetation status.

Temporal vegetation changes were examined using the Global Tree Cover Change (GTCC) dataset (Fick and Hijmans, 2017) alongside advanced remote-sensing products to evaluate canopy height dynamics. Within Google Earth Engine (GEE), the LandTrendR algorithm detected temporal shifts in vegetation cover, reconstructed disturbance patterns, identified land-use transitions, and assessed long-term forest changes. This approach facilitated insights into habitat stability and ecosystem dynamics, enabling the validation of both rapid and gradual vegetation shifts, thereby improving ecological relevance and predictive accuracy in distribution modelling (Turner et al., 2015).

Selection of environmental predictors

To assess statistical interdependence among variables, the corrplot package was used to visualize correlation structures (Zuur et al., 2010). A multicollinearity analysis was conducted using pairwise Pearson correlations in R. Variables exceeding a correlation coefficient threshold of r = 0.8 were considered highly collinear, and the one with lower predictive contribution was removed to maintain statistical independence and model accuracy (James et al., 2013).

The final set of environmental descriptors included MNDWI, NDVI, canopy height (canHt), SAVI, tree cover (tCov), and Euclidean distance to agricultural areas (dAgri), selected based on ecological relevance (Table 1). These variables effectively capture vegetation patterns, habitat structure, and resource availability (Pettorelli et al., 2014). Integration of LandTrendR outputs further accounted for long-term habitat dynamics, ensuring that the model reflected recent ecological changes rather than relying solely on static datasets (Kennedy et al., 2010).

Table 1. Correlation matrix of selected environmental variables (standard and correct).

	NDVI	SAVI	canHt	dAgri	tCov	MNDWI
NDVI	1	0.540857	0.278393	0.11839	-0.41278	-0.41281
SAVI	-0.5303	1	0.121338	0.249687	-0.5753	0.563892
canHt	0.398931	-0.34519	1	-0.37991	-0.23491	0.029708
dAgri	-0.08167	-0.25053	0.134223	1	-0.24943	-0.16037
tCov	-0.05272	0.342211	-0.36039	0.017081	1	-0.54426
MNDWI	0.129054	-0.39537	-0.52194	0.538663	0.558758	1

Variable influence analysis and habitat suitability modeling

Using an optimally selected set of ecological predictors, the Maximum Entropy (MaxEnt) algorithm was employed to estimate habitat suitability. MaxEnt version 3.4.4 was applied with advanced regularization settings to minimize overfitting and enhance model reliability (Elith et al., 2011). A presence-background approach was implemented, with background points randomly distributed across the study area to ensure an unbiased representation of environmental conditions (Kramer-Schadt et al., 2013).

To assess the contribution and importance of each predictor, MaxEnt's built-in permutation importance, response curves, and jackknife tests were conducted. These methods provided a robust evaluation of each variable's independent influence, ensuring that only ecologically relevant factors were emphasized in the final model (Fourcade et al., 2018).

Environmental data preprocessing, including Sentinel-2 image preparation and spectral index computation, was performed using Google Earth Engine (GEE), enabling efficient handling of large-scale remote sensing datasets. Habitat suitability outputs were visualized in QGIS 3.22, an open-source geographic information system with advanced analytical and modeling capabilities, facilitating accurate mapping and interpretation of predicted habitat distributions.

The integration of LandTrendR into the preprocessing workflow allowed for a comprehensive assessment of long-term vegetation dynamics. By capturing both gradual and abrupt ecological changes, this approach strengthened the ecological robustness of the model, enhancing its utility for habitat management, conservation planning, and monitoring of invasive species.

Results

Ecological suitability and main drivers of paper mulberry

The predictive performance of the MaxEnt model demonstrated acceptable accuracy, yielding an AUC value of 0.701 (Figure 1). Habitat suitability modeling revealed distinct spatial patterns of paper mulberry distribution across Haripur District. Although the administrative area of Haripur encompasses approximately 1,725 km^2, the total assessed region extended to 2,362.87 km^2, accounting for potential species spread beyond district boundaries. The analysis indicated that 1,816.71 km^2 (76.9%) of the landscape is unsuitable for paper mulberry establishment, whereas 282.05 km^2 (11.9%) exhibits low suitability. Moderately suitable areas cover 155.59 km^2 (6.6%), and highly suitable zones, critical for potential species expansion, comprise 108.51 km^2 (4.6%).

Among the predictor variables, agricultural land (dAgri) exerted the strongest influence, contributing 49% to model gain with a permutation importance of 41.2%, reaffirming the species' preference for disturbed and human-modified habitats. Canopy height (canHt) contributed 21.3% with a permutation importance of 23.5%, indicating its significant role in defining suitable habitat structure. Total vegetation cover (tCov) accounted for 14.1% of the contribution with a permutation importance of 16.8%, demonstrating the effect of forest density on distribution patterns.

Spectral indices, including the Soil-Adjusted Vegetation Index (SAVI) (8.2% contribution, 5.1% permutation importance) and the Normalized Difference Vegetation Index (NDVI) (7.8%, 6.3%), showed moderate influence, reflecting the species' dependence on vegetation health. Although the Modified Normalized Difference Water Index (MNDWI) contributed only 2.9%, its relatively high permutation importance (12.7%) suggests an indirect yet notable effect of hydrological features (Table 2).

Table 2. Relative contribution and importance of environmental variables influencing paper mulberry distribution.

Variable	Percent Contribution	(%)Permutation Importance
dAgri	49	41.2
canHt	21.3	23.5
tCov	14.1	16.8
SAVI	8.2	5.1
NDVI	7.8	6.3
MNDWI	2.9	12.7

Overall, these findings highlight the selective establishment of paper mulberry across diverse environmental gradients, particularly within anthropogenically modified landscapes. Considering its invasive potential, proactive management strategies are essential to mitigate ecological and socioeconomic impacts. In Haripur Hazara, future studies integrating high-resolution modeling with field validation are recommended to improve predictive accuracy and support conservation-oriented land-use planning.

Paper mulberry coverage dynamics

In Haripur Hazara, temporal analysis of paper mulberry coverage from 1990 to 2024 reveals a dynamic pattern driven by complex interactions between environmental conditions and anthropogenic activities (Figure 2). During the initial decade (1990-2000), mulberry coverage remained relatively stable, with modest gains and minimal losses. This trend suggests a largely undisturbed landscape in which natural regeneration processes were maintained under favorable environmental conditions.

A pronounced shift became evident in the early 2000s, when losses increased substantially despite sporadic gains, indicating escalating pressure on natural habitats. This accelerated decline is closely associated with widespread deforestation, rapid agricultural expansion, and urban encroachment, which collectively led to habitat fragmentation and depletion of ecological resources. During this period, total mulberry loss reached approximately 0.0891 km², whereas gains were limited to 0.0414 km².

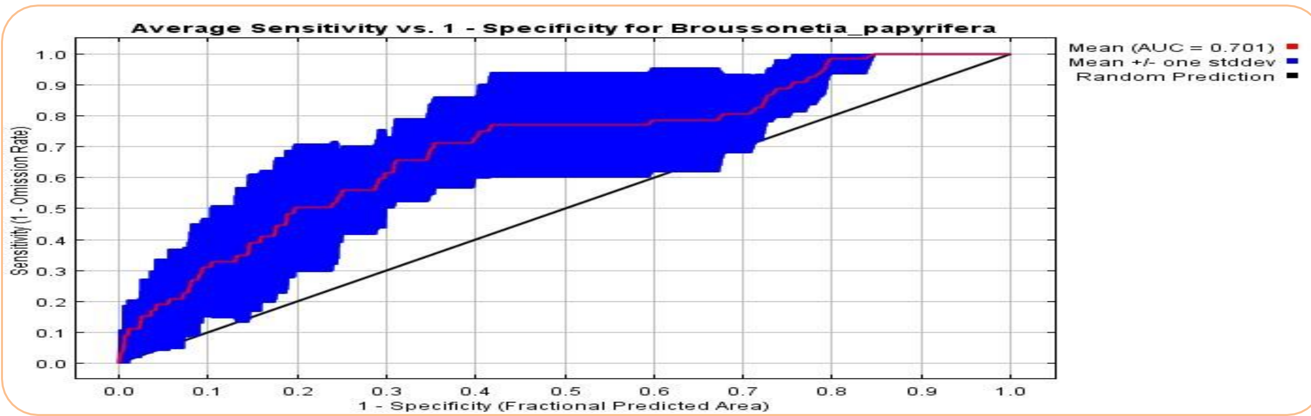

Figure 1. Receiver operating characteristic (ROC) curve of the paper mulberry habitat suitability model.

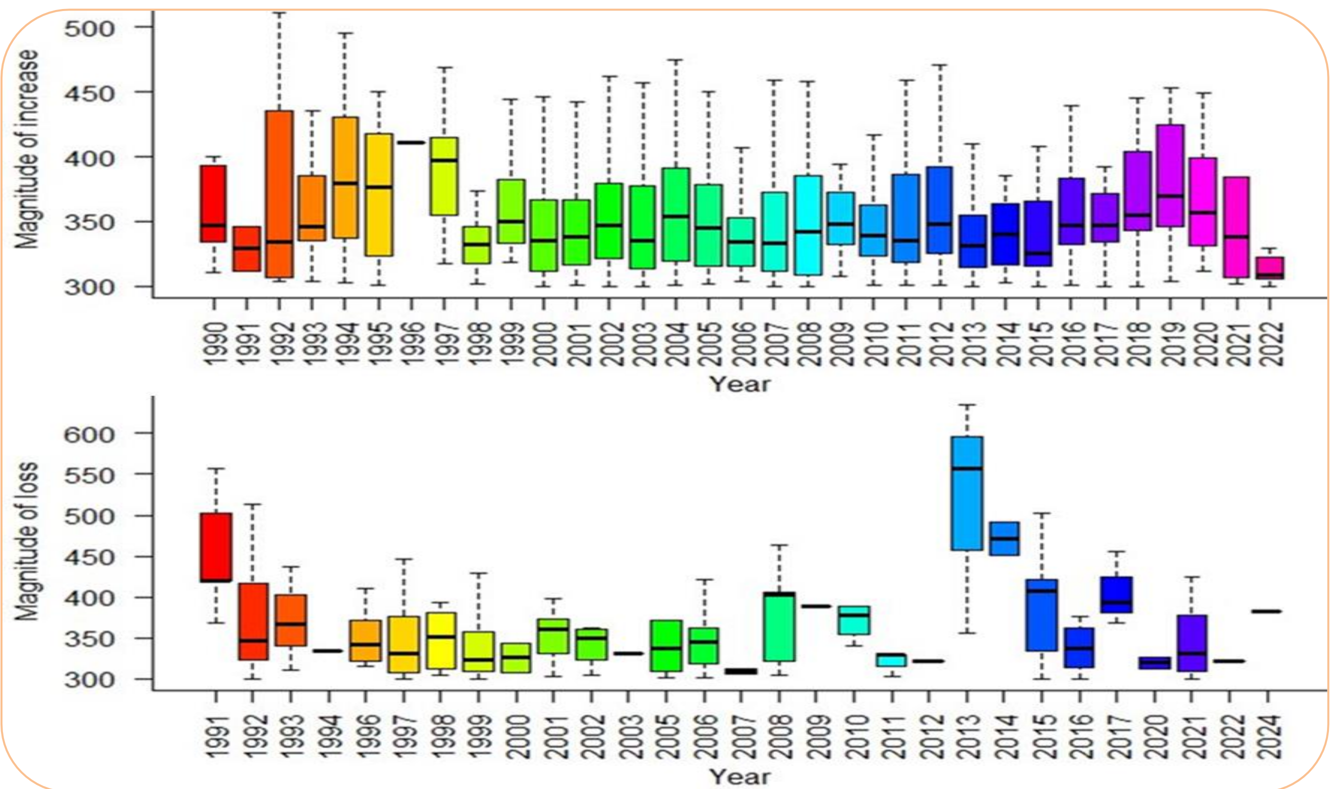

Figure 2. Habitat gain and loss of paper mulberry: (A) Annual magnitude of habitat gain from 1990 to 2022, with no additional gain observed after 2022; (B) Annual magnitude of habitat loss from 1990 to 2024.

Between 2010 and 2020, trends in paper mulberry coverage exhibited marked variability. This decade was characterized by intermittent recovery phases during which temporary gains exceeded losses, primarily driven by climate-mediated regeneration, afforestation programs, and localized planting initiatives. Despite these episodic improvements, recovery remained inconsistent, with recurrent declines attributed to anthropogenic pressures and environmental variability. Over this period, cumulative gains totaled 0.1983 km^2, whereas total losses reached 0.2106 km^2. This pattern highlights the pronounced sensitivity of paper mulberry distribution to external disturbances and underscores the unstable and fluctuating nature of its spatial extent in the Haripur Hazara region.

Acceleration of paper mulberry expansion and land transformation

Following 2020, a pronounced shift in paper mulberry dynamics was observed, characterized by a substantial acceleration in expansion rates and increased spatial dominance. Beyond intentional plantation for silvicultural and commercial purposes, this rapid spread reflects intensified landscape disturbances, climatic conditions conducive to species proliferation, and changes in land-use practices. The continued expansion of paper mulberry across Haripur Hazara indicates heightened adaptability and a progressively aggressive invasion pattern, with significant implications for long-term ecological stability.

Between 2020 and 2024, total losses in paper mulberry coverage were estimated at 0.1752 km^2, while gains reached 0.2460 km^2, resulting in a clear net increase in spatial extent. This substantial expansion raises critical environmental concerns, including intensified competition for water resources, suppression of native vegetation, alterations in soil nutrient dynamics, and displacement of local biodiversity. These trends emphasize the urgency of assessing the long-term ecological consequences of continued proliferation.

Although paper mulberry offers notable commercial and agroforestry benefits, its increasing dominance necessitates careful evaluation of its impacts on native flora and fauna, hydrological processes, and overall land productivity. Future research should focus on identifying ecological thresholds beyond which mulberry expansion transitions from beneficial to ecologically disruptive. Such insights are essential for formulating balanced land-management strategies that integrate environmental sustainability with socioeconomic objectives.

Discussion

In the Haripur district of the Hazara Division, environmental suitability modeling revealed a spatially structured distribution of paper mulberry, primarily shaped by anthropogenic land-use patterns and ecological adaptability. Although the MaxEnt model demonstrated moderate predictive performance (AUC = 0.701), this level of accuracy indicates that further refinement using higher-resolution spatial data and additional ecological predictors could enhance model robustness (Phillips et al., 2006). Comparable AUC values have been reported in studies on invasive plant species, highlighting that predictive performance often varies with data availability, species traits, and environmental complexity (Merow et al., 2013).

Agricultural land cover emerged as the most influential predictor, contributing 49% to model performance, underscoring the strong role of human-mediated landscape modification in facilitating the expansion of paper mulberry. This pattern is particularly evident in peri-urban areas and intensively managed agricultural landscapes. These findings are consistent with previous studies showing that human-altered ecosystems provide favorable conditions for invasive species establishment due to reduced competition from native flora, frequent disturbance, and increased nutrient availability (Pyšek and Richardson, 2010; Shackleton et al., 2020).

Owing to its rapid vegetative growth and aggressive root-sprouting capacity, paper mulberry readily colonizes disturbed habitats such as plowed fields, roadside verges, and fallow lands, which act as highly suitable establishment zones (Cui et al., 2020). Total vegetation cover (14.1%) and canopy height (21.3%) were also identified as important predictors, emphasizing the influence of forest structure on species establishment. Similar trends have been observed in other invasive tree species, where open-canopy conditions, forest fragmentation, and reduced competition enhance seedling establishment and dispersal (Basnou et al., 2015). The ability of paper mulberry to tolerate a wide range of light conditions, thriving in both open and semi-shaded environments, further reflects its ecological plasticity, as reported in earlier studies (Klaus et al., 2017).

Vegetation indices, including the Normalized Difference Vegetation Index (NDVI) and Soil-Adjusted Vegetation Index (SAVI), also exerted measurable influence on habitat suitability. High SAVI values, indicative of productive and moisture-retentive soils, corroborate previous findings that paper mulberry preferentially invades nutrient-rich agricultural lands, urban green spaces, and riparian zones (Maan et al., 2021; Mehal et al., 2023). Moreover, the Modified Normalized Difference Water Index (MNDWI), with a permutation importance of 12.7%, suggests that hydrological conditions indirectly influence species distribution, likely through effects on vegetation structure, soil moisture, and nutrient dynamics (Castro-Díaz et al., 2019a). Collectively, these results highlight the broad ecological tolerance of paper mulberry, enabling it to exploit both semi-natural and heavily disturbed habitats. Such adaptability aligns with global invasion patterns, where human-modified environments create ecological opportunities for rapid species proliferation (Seebens et al., 2018; Zhang and van Kleunen, 2019).

Temporal analysis revealed distinct phases of paper mulberry expansion from 1990 to 2024. During the period from 1990 to 2000, expansion remained relatively stable, indicative of an initial establishment phase. Similar invasion lag phases have been documented in woody invasive species such as *Prosopis juliflora* and *Ailanthus altissima* before rapid population growth occurs (Essl et al., 2011). A notable shift was observed in the early 2000s, when losses exceeded gains, largely attributable to accelerated urbanization, deforestation, and infrastructure development. Such land-use changes can temporarily suppress invasive populations before facilitating renewed expansion once landscape conditions stabilize (Lembrechts et al., 2017; Pauchard et al., 2018).

Between 2010 and 2020, fluctuations in paper mulberry coverage reflected the combined influence of land-use policies, conservation initiatives, and interannual climate variability. Comparable invasion dynamics have been reported for *Acacia dealbata*, where management interventions temporarily reduced population growth but failed to prevent subsequent resurgence due to incomplete eradication (Richardson et al., 2011). Afforestation programs also contributed to slowing the spread of *B. papyrifera*, although their effectiveness varied, consistent with outcomes reported in other regions where such interventions have produced mixed results (Meyerson et al., 2022).

The post-2020 period marks a renewed and intensified expansion phase, with gains (0.2460 km^2) exceeding losses (0.1752 km^2). This trend mirrors the global increase in invasive species prevalence driven by land-use intensification and climate change (Early et al., 2016). Rising temperatures and altered precipitation regimes have been shown to enhance the growth and dispersal of invasive plants, particularly those with broad ecological tolerances such as paper mulberry (Storch et al., 2018). Its capacity to rapidly colonize disturbed habitats suggests that future expansion may accelerate under projected warmer and wetter climate scenarios (Walther et al., 2009).

The continued spread of paper mulberry poses significant ecological and management challenges. Invasive tree species are widely recognized for disrupting ecosystem functions, suppressing native plant diversity, and altering soil microbial communities (Castro-Díez et al., 2019b). Paper mulberry, in particular, has been shown to form dense monocultures that outcompete native vegetation, disrupt trophic interactions, and reduce overall biodiversity (Zhou and Zhang, 2023). Given its aggressive colonization ability, the implementation of integrated management strategies is imperative.

Conventional control measures, such as mechanical removal and herbicide application, have demonstrated limited long-term success due to the species' strong resprouting capacity (Kowarik and Säumel, 2007). More effective outcomes have been achieved through integrated approaches combining targeted removal with ecological restoration using native species (Flory and Clay, 2010). Public awareness and community participation can further reduce spread, while policy-driven land-use planning that incorporates invasion risk assessments is essential for minimizing introduction pathways during urban and agricultural development (Wilson et al., 2009). Future research should focus on refining predictive models by integrating climatic, ecological, and anthropogenic variables. Genetic studies exploring population structure and dispersal pathways would also enhance understanding of invasion dynamics (O'Donnell et al., 2012). Moreover, remote sensing, combined with ground-based validation, will remain critical for long-term monitoring and evaluation of management effectiveness (González-Moreno et al., 2015).

Conclusion

This study assessed the habitat suitability and temporal expansion of paper mulberry in district Haripur, Hazara division, highlighting its increasing ecological significance. The MaxEnt model demonstrated acceptable predictive accuracy (AUC = 0.701), indicating that 76.9% of the study area is currently unsuitable for the species, while 4.6% is classified as highly suitable. Temporal analysis spanning 1990-2024 revealed a dynamic pattern of gains and losses largely driven by urbanization, agricultural expansion, and deforestation. Although the early decades exhibited relative stability, the period from 2020 to 2024 showed a marked acceleration in species spread.

Agricultural land cover (49%), canopy height (21.3%), and total vegetation cover (14.1%) emerged as the strongest predictors of habitat suitability, reflecting the species' preference for disturbed and human-modified environments. The continued expansion of paper mulberry raises substantial environmental concerns, including altered ecosystem processes and displacement of native biodiversity. Given its invasive potential, proactive and integrated management strategies are essential to mitigate long-term ecological impacts. Future research should emphasize coordinated land-use planning, sustained monitoring, and the development of management approaches that balance any potential economic benefits of the species with the imperative of maintaining ecosystem stability and ecological sustainability.

Authors' Contributions

MN, a PhD scholar, conducted the fieldwork and laboratory research, collected data, and contributed to the initial interpretation of results. MH, the supervisor of MN, conceptualized and designed the study, provided overall supervision, and guided the research framework. ZS, as co-supervisor, contributed to data analysis and assisted in drafting the initial manuscript. SA provided critical scientific guidance, constructive feedback, and valuable suggestions to strengthen the study. NS contributed to manuscript compilation and substantially improved the content, structure, and clarity of the manuscript. MAK performed the statistical analyses and enhanced the clarity and rigor of data presentation. GW assisted in manuscript compilation, critically reviewed the draft, and contributed to improving its scientific coherence. FM carried out the GIS and remote sensing analyses, conducted field-based spatial assessments, and compiled the geospatial data. All authors reviewed and approved the final version of the manuscript and agreed to be accountable for all aspects of the work, ensuring the accuracy, integrity, and transparency of the reported research.

Research Funding

This research did not receive any grant from funding agencies.

Conflict of Interest

The authors declare no conflict of interest.

Sustainable Development Goals Targeted

SDG 11: Sustainable Cities and Communities

SDG 13: Climate Action

SDG 15: Life on Land

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