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Research Paper

Landscape Ecology Modelling Through Graph Theory

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Abstract
This study applies network-based mathematical concepts to examine landscape organization by modelling selected areas of the Nilgiris district in Tamil Nadu as spatial graphs. A systematic modelling strategy is introduced to convert highly heterogeneous landscape mosaics into uniform graph structures, allowing detailed identification and comparison of spatial arrangements involving patches, corridors, and matrix elements. Quantitative graph indices related to connectivity and accessibility are employed to measure spatial interactions and evaluate functional cohesion within the landscape. The proposed framework offers a rigorous analytical basis for investigating spatial structure, connectivity dynamics, and landscape organization.

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I. Introduction

Landscape ecology focuses on understanding how biophysical processes and anthropogenic activities collectively shape landscape composition, spatial structure, and temporal dynamics. A fundamental principle within this field is the concept of landscape stability, which emphasizes that spatial heterogeneity strengthens resistance to disturbances, enhances recovery potential, and supports long-term ecological sustainability. Landscapes are commonly described as spatial assemblages comprising patches, corridors, and a surrounding matrix, each playing a distinct role in shaping ecological processes and spatial interactions.

As highlighted in [1], landscapes form the spatial setting in which physical, biological, and socio-economic processes interact and evolve. Landscape ecology aims to interpret these interactions and develop conceptual as well as analytical frameworks to assess human-induced environmental change. Such insights are essential for formulating evidence-based environmental management practices and sustainable land-use policies. Consequently, landscape studies involve examining interactions among components of the geosphere, including vegetation systems, wildlife habitats, and human land-use activities.

Graph theory provides a well-established mathematical framework for analysing relationships among interconnected entities [3]. When applied to landscape ecology, it enables the abstraction of complex spatial arrangements into simplified yet informative network structures. In this representation, landscape components such as habitat patches, corridors, and matrix areas are modelled as nodes and links, facilitating the identification of central elements, highly connected regions, and isolated spatial units. Quantifying connectivity, developing formal measures to describe it, and evaluating the contribution of individual components to overall landscape cohesion are particularly relevant for planners and land managers.

In this work, graph-theoretic principles are used to model landscape configurations in selected regions of the Nilgiris. A structured methodology is developed to transform intricate landscape patterns into standardized graph forms, allowing comparative evaluation of spatial structures. Connectivity and reachability metrics derived from graph theory are then applied to demonstrate the usefulness of this approach in analysing landscape organization. By integrating ecological concepts with network-based quantitative analysis, this study investigates how habitat connectivity, fragmentation, and landscape resilience vary under different land-use scenarios.

Landscape mosaics from the Nilgiris are represented through graph models using a consistent transformation framework. This approach simplifies complex spatial arrangements, enabling systematic identification and comparison of structural patterns involving patches, corridors, and matrix elements. Graph-based indicators of connectivity and accessibility are employed to assess spatial interactions, confirming the effectiveness of this methodology in landscape structural analysis.

By combining mathematical network modelling with ecological theory, this research demonstrates that landscape graphs provide a powerful interpretative tool for understanding spatial patterns and ecological processes. The proposed framework supports informed decision-making in regional planning and environmental management and offers an integrated approach for monitoring landscape change and guiding sustainable land-use practices.

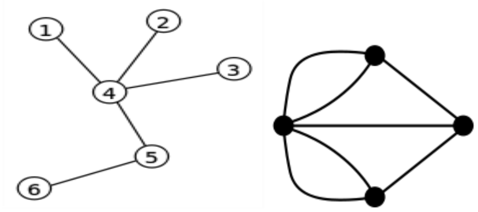
The subsequent section introduces essential concepts from graph theory and landscape mosaic analysis. Further theoretical background can be found in [2] and [3].

II. Graph Theory

Graph theory deals with mathematical structures known as graphs, which serve as abstract representations of relational systems [3,4]. A graph consists of a collection of nodes representing entities and a set of links representing relationships between them. Graphs are commonly visualized using schematic diagrams. Within geographic information systems (GIS) and spatial analysis, graphs offer a structured mechanism for translating spatial features and their relationships into network form.

In landscape applications, spatial units such as habitat patches, land-use zones, or urban regions are represented as vertices, while adjacency, proximity, or functional interactions are modelled as edges. This abstraction enables the use of network metrics to evaluate connectivity, fragmentation, and accessibility, thereby integrating spatial data with quantitative analytical tools [8]. In ecological contexts, habitat patches can be treated as nodes and corridors as links, facilitating the identification of well-connected habitats, isolated fragments, and critical corridors that require conservation or restoration.

Definition 1:
A graph $G$is defined as an ordered pair (V, E), where Vrepresents a set of vertices and Erepresents a set of edges connecting pairs of vertices. Two edges are said to be adjacent if they share a common vertex.
Graphs are typically represented diagrammatically as shown below.



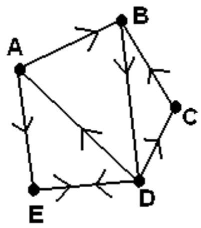
Definition 2:
The degree of a vertex is the number of edges incident to that vertex.
Definition 3:
A walk is an ordered sequence of vertices where consecutive vertices are connected by edges. A path is a walk in which no vertex is repeated. The length of a walk or path equals the number of edges it contains.
Definition 4:
A graph is termed connected if a path exists between every pair of vertices. If this condition is violated, the graph is disconnected and consists of multiple components.
Definition 5:
A component of a graph is a maximal connected subgraph in which all vertices are mutually reachable.
Definition 6:
Vertex-connectivity refers to the minimum number of vertices whose removal results in a disconnected graph.
Definition 7:
Edge-connectivity is defined as the smallest number of edges that must be removed to disconnect a graph.
Definition 8:
The adjacency matrix $A$of a graph with $n$vertices is an $n \times n$binary matrix defined by

$$a_{ij} = \begin{cases} 1, & \text{if vertices } i \text{ and } j \text{ are adjacent} \\ 0, & \text{otherwise} \end{cases}$$

The m^{th}power of the adjacency matrix, A^m, gives the number of walks of length $m$between pairs of vertices.
Definition 9:
Two vertices $v_i$and $v_j$are considered reachable if at least one path exists between them. The reachability matrix $R$is obtained by summing the adjacency matrix and its successive powers:

$$R = A + A^2 + A^3 + \cdots + A^n$$

where $n$denotes the maximum path length required to traverse the graph.



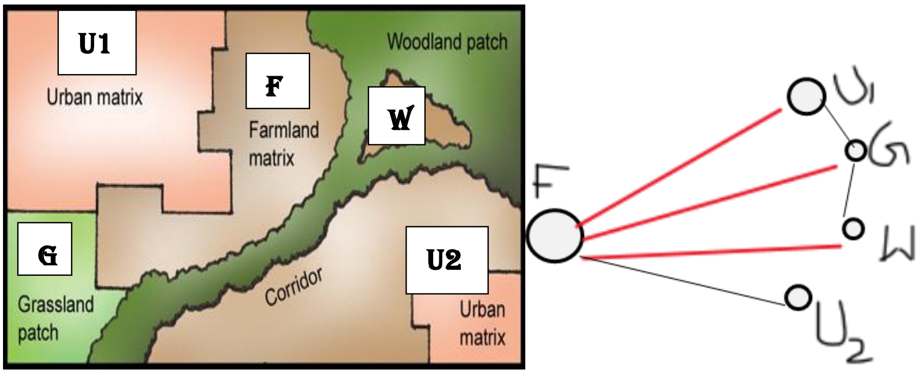
$$A(G) = \begin{pmatrix} 0 & 1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 \end{pmatrix}$$

Graph G Adjacency Matrix A (G)

III. Landscape Mosaics and Graph Models

Landscape mosaics are composed of three fundamental elements: patches, corridors, and the matrix. Common configurations include a dominant matrix containing embedded patches, corridors that subdivide space, and interconnected corridor networks forming integrated systems [5,6]. Patches represent discrete spatial units such as agricultural plots, forest remnants, or wetlands. Corridors are elongated features that facilitate the movement of organisms, materials, and energy between patches. The matrix forms the background landscape, typically occupying the largest area and exhibiting high internal connectivity.

In graph-based landscape representations, individual landscape elements are mapped to vertices, while shared boundaries or functional interactions are represented as edges. Node sizes may be scaled according to spatial extent, and edges indicate adjacency or interaction. The matrix is also represented as a node within the network.



Formally, a landscape can be expressed as a graph $G = (V, E)$, where Vdenotes the set of vertices corresponding to patches, corridors, and matrix units, and $E \subseteq V \times V$represents adjacency relations. The degree of a vertex v, denoted deg (v), equals the number of neighbouring elements connected to it. Nodes with higher degree values play a crucial structural role, as they contribute disproportionately to maintaining network connectivity. The shortest path distance between two vertices provides an indicator of movement efficiency or interaction potential, while reachability expresses whether such a connection exists.

IV. Graph Patterns

Distinct spatial configurations of landscape elements generate characteristic graph topologies. Frequently observed patterns include necklace, graph cell, satellite, candelabra, and spider forms, each reflecting specific spatial organizations derived from GIS-based landscape data.

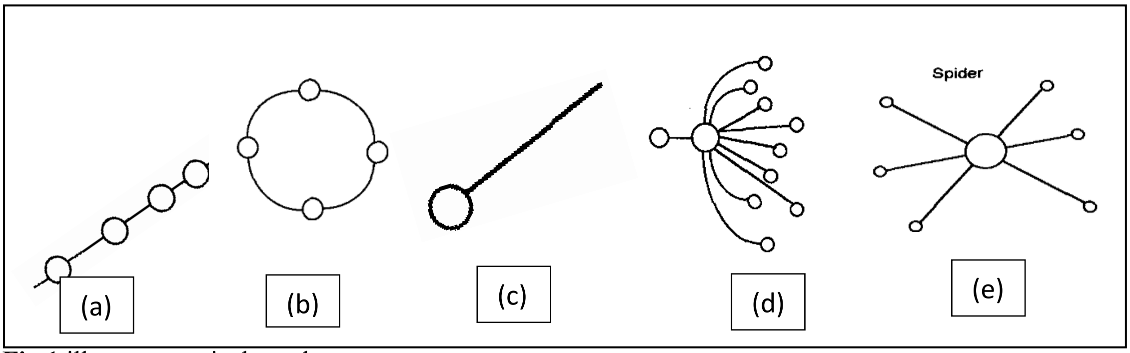


Fig.1 illustrates typical graph patterns:
(a) Necklace pattern—linear chains of patches aligned along corridors such as roads or rivers;
(b) Graph cell pattern—clusters of landscape units with strong internal connectivity;

(c) Satellite pattern—small isolated patches surrounding a dominant central element;
(d) Candelabra pattern—branching corridor systems typical of drainage or transport networks;
(e) Spider pattern—highly centralized structures where multiple corridors converge on a single core node.
Necklace patterns commonly correspond to linear infrastructures, graph cell patterns arise from intersecting corridors forming enclosed regions, satellite patterns indicate spatial isolation, candelabra patterns reflect hierarchical branching, and spider patterns denote centralized connectivity often associated with dominant matrix elements.

V. Ecological and Management Implications

Graph-derived landscape patterns provide important insights into ecological functioning and management priorities. Necklace configurations often support directional movement and exhibit relatively low resistance. Reductions in graph cell size are frequently linked to increased anthropogenic pressure and landscape fragmentation, making these units suitable for targeted management. From a network perspective, vertices with degree one are weakly connected and highly vulnerable, as the loss of a single edge results in complete isolation. Ecologically, such nodes typically represent small patches embedded within a dominant matrix and therefore warrant focused conservation efforts.

Spider patterns usually indicate dominant matrix elements connecting multiple patches, suggesting strong patch–matrix interactions but potentially low habitat diversity. Satellite patterns highlight ecological vulnerability due to isolation, while candelabra structures identify critical transitional zones influencing movement, accessibility, and landscape performance.

VI. Connectivity of Landscape Elements

Connectivity refers to the degree to which landscape units are linked, enabling organism movement and material flows. In graph-theoretic terms, connectivity is quantified using node degree and adjacency relations. Adjacency and reachability matrices offer systematic tools for assessing both direct and indirect interactions among landscape components. Nodes with higher degrees are more influential within the network and play a key role in sustaining overall connectivity.

From the graph representation, an adjacency matrix $A$is constructed to evaluate spatial relationships quantitatively [7,9]. Higher powers of Acapture indirect connections involving intermediate units, supporting a comprehensive analysis of reachability and interaction potential across the landscape network.

VII. Methodology

Using the proposed graph construction framework, landscape graphs are derived from aerial imagery and land-use data for selected regions of the Nilgiris. Analysed land-cover classes include forests, lakes, agricultural areas, roads, degraded lands, and residential clearings. This approach enables comparative assessment of spatial connectivity across different landscape contexts.

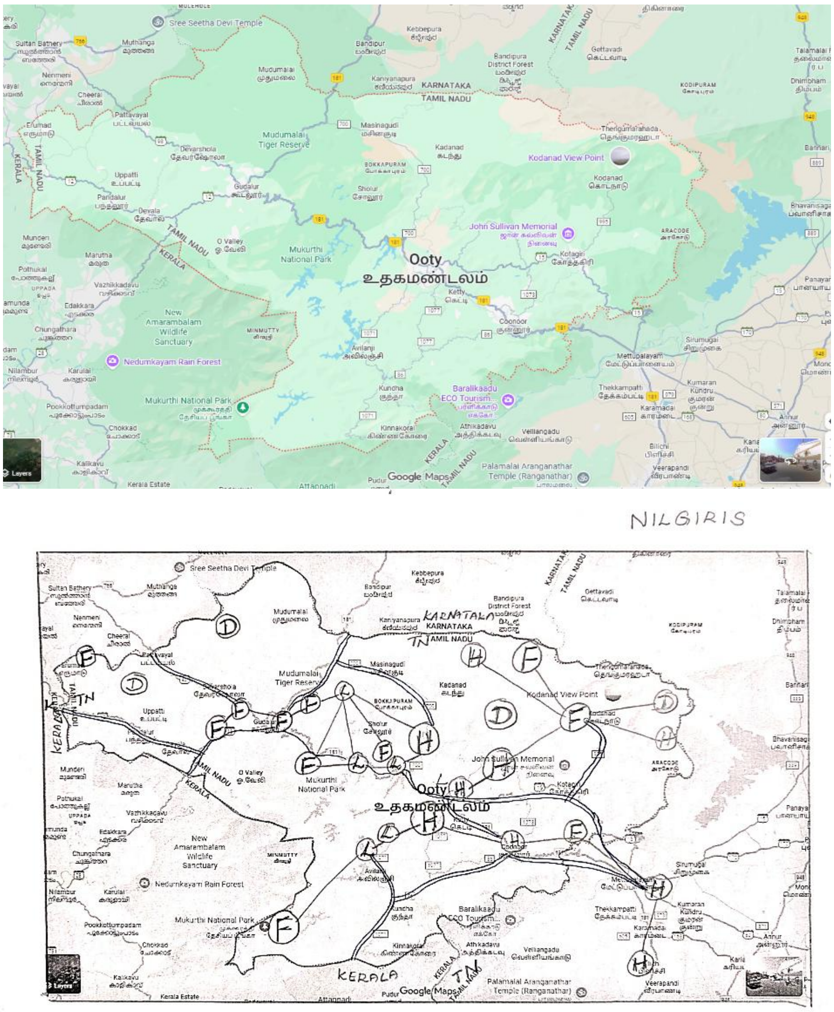


Fig. 2 presents the landscape mosaic graph of the Nilgiris, where L denotes lakes, F forests, D dry lands, and H house clearings. Observed graph patterns include necklace and graph cell structures formed by roads, satellite patterns associated with forests and settlements, candelabra configurations linked to lakes, and spider patterns associated with forest areas.

The resulting graphs indicate that residential zones, forest patches, and agricultural lands serve as the most structurally integrated components. Each graph exhibits a distinct topological arrangement, with recurring necklace and spider configurations. These patterns provide valuable insights for land-use planning, ecological assessment, and resource management [10].

VIII. Graph-Theoretical and Ecological Interpretation

In the graph representations, nodes depicted as circles correspond to small or spatially isolated landscape units. A single connecting edge indicates one direct link to a larger dominant component, usually part of the matrix. Nodes with degree one contribute minimally to overall connectivity and are highly prone to isolation. The removal of their sole connecting edge completely disconnects them from the network.

Such configurations typically describe minor landscape features, such as small wetlands within cropland, compact residential areas near extensive forests, or fragmented woodlands connected by a single corridor. The Nilgiris landscape graph demonstrates this analytical approach by examining interactions among forests (F), lakes (L), residential areas (H), and degraded lands (D).

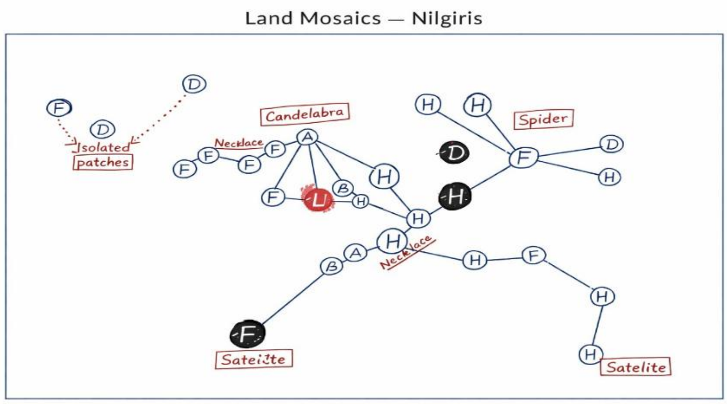


Fig. 3 shows the corresponding landscape graph model.

The adjacency and reachability matrices reveal that dry land (D) remains isolated and unreachable from other elements, indicating limited ecological interaction.
The adjacency matrix for this graph is given as follows:

$$A = \begin{array}{c} \\ F \\ L \\ H \\ D \end{array} \begin{array}{c} \begin{array}{cccc} F & L & H & D \end{array} \\ \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \end{array}$$

Reachability matrix for this graph
F L H D

$$R = \begin{array}{c} F \\ L \\ H \\ D \end{array} \begin{pmatrix} 1 & 1 & 1 & 0 \\ 0 & 1 & 1 & 0 \\ 1 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

which indicates that the Dry land D is not reachable from other elements and vice-versa.

IX. Discussion

Analysis of the adjacency and reachability matrices highlights weak interactions between non-adjacent landscape elements, such as animal movement between forest patches separated by agricultural fields. The reachability matrix further indicates high landscape resistance, limiting dispersal of flora and fauna across the region.

X. Conclusion

The graph-based analysis demonstrates that residential areas, forests, and agricultural lands often function as highly connected landscape components, with necklace and spider configurations recurring across study sites. In contrast, satellite patterns reveal poor connectivity of forests and dry lands. These spatial structures significantly influence ecological flows and interactions. Overall, the graph-theoretic approach presented here offers a flexible and rigorous framework for analysing landscape dynamics and supports sustainable land-use planning and environmental management.

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