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Quantifying Landscape Connectivity: A GIS-based Approach

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***Abstract*—**Landscape connectivity combines a description of the physical structure of the landscape with special species' response to that structure, which forms the theoretical background of applying landscape connectivity principles in the practices of landscape planning and design. In this study, a residential development project in the southern United States was used to explore the meaning of landscape connectivity and its application in town planning. The vast rural landscape in the southern United States is conspicuously characterized by the hedgerow trees or groves. The patchwork landscape of fields surrounded by high hedgerows is a traditional and familiar feature of the American countryside. Hedgerows are in effect linear strips of trees, groves, or woodlands, which are often critical habitats for wildlife and important for the visual quality of the landscape. Based on geographic information system (GIS) and statistical analysis (FRAGSTAT), this study attempts to quantify the landscape connectivity characterized by hedgerows in south Alabama where substantial areas of authentic hedgerow landscape are being urbanized due to the ever expanding real estate industry and high demand for new residential development. The results of this study shed lights on how to balance the needs of new urban development and biodiversity conservation by maintaining a higher level of landscape connectivity, thus will inform the design intervention.

***Keywords*—**Biodiversity, Connectivity, Landscape planning, GIS

I. Introduction

Since the concept of landscape connectivity was formalized in landscape ecology in the 1990s, the meaning of "landscape connectivity" has become rather diffuse and ambiguous. Generally, human activities such as agricultural development, commercial conifer afforestation, infrastructure construction and urbanization have led to habitat fragmentation, namely loss of the original habitat, reduction in habitat patch size and increasing isolation of habitat patches and decreasing landscape connectivity[1]. Numerous scientific studies continue to ignore key elements of the original concept; many practical land development projects claim efforts are taken to enhance landscape connectivity. However, without understanding the meaning of landscape connectivity, these studies/projects might actually diminish its potential utility for land management and the conservation of biodiversity. As originally defined by Taylor et al [2], landscape connectivity is 'the degree to which the landscape facilitates or impedes movement among resource patches'[2]. This definition emphasizes that the types, amounts and arrangement of habitat or land use on the landscape influence movement and population dynamics and community structure. However, landscape connectivity should combine twofold of meaning: the description of the physical structure of the landscape (structural connectivity) with special species' response to that structure (functional connectivity), which forms the theoretical background of applying landscape connectivity principles in the practices of landscape planning and design. In this study, a GIS-based approach is used to quantify landscape connectivity. Furthermore, a residential development project in the southern United States was used to explore the meaning of landscape connectivity and its application in town planning [3-4][6-9].

As documented in the paper by Chen [3], hedgerow's primary function in the landscape is to serve as limits, marking boundaries and borders. But hedgerows can also provide products for human in his pursue of food, clothes and shelters. The improvement of the visual quality, authenticity of the rural landscape is another important function of hedgerow. Many of the functions of hedgerow can be assessed in the relationship one another. However, the most important function of hedgerows in biological conservation is that they are important habitat for wildlife such as bird, mouse, butterfly, etc. Meanwhile, hedgerows functioning as ecological corridors maintain and increase the connectivity of the landscape, maintaining the ecological variability, thus protect and improve the biodiversity of the landscape [10-15].

II. Site Context

The Hudson Farm project was used as the case study to demonstrate how landscape connectivity can be quantified [Newspaper-Chen]. Hudson Farm is located right on the Black Belt, which is a region of the southeastern U.S. Originally the term describes the prairies and dark soil of central Alabama and northeast Mississippi; however, it has long been used to describe a broad region in the American South characterized by a high percentage of African Americans. It is regarded that the Black Belt covers large areas of Central Georgia, North Florida, Western Mississippi, South Central Alabama, East Central Louisiana, Eastern North Carolina and Southeastern Virginia. Hudson Farm is right located on the black belt, a suburb to the southeast of Montgomery (Fig. 1), the capital city

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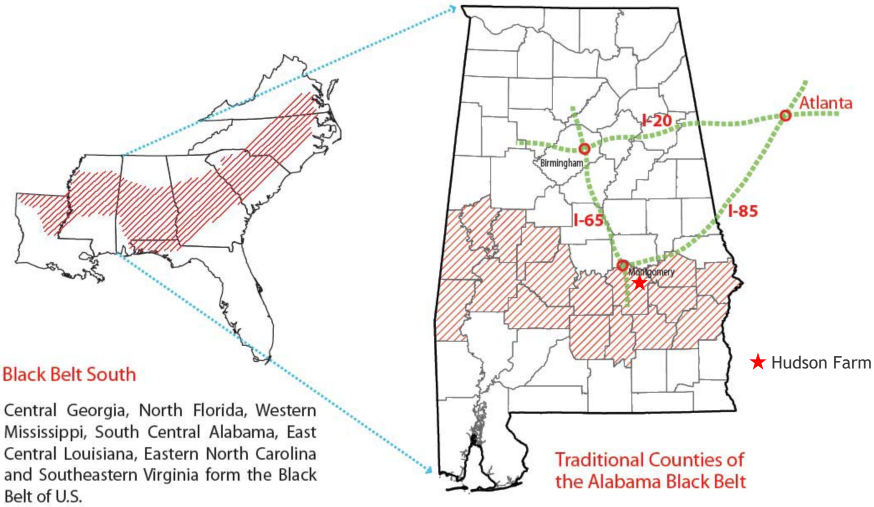


Fig. 1 Location and regional context of the Black Belt, traditional counties in the Alabama Black Belt, and location of Hudson Farm

of the state of Alabama (Fig. 1). The landscape of Hudson Farm is remarkably characterized by the hedgerow trees or groves. The hedgerows form a series of network of patchwork, creating a landscape of low fields surrounded by high hedgerows. As documented by Chen [3], hedgerow's primary function in the landscape is to serve as limits, marking boundaries and borders. However, hedgerows can also provide products for human in his pursue of food, clothes and shelters. The improvement of the visual quality and authenticity of the rural landscape is another important function of hedgerow. Many of the functions of hedgerow can be assessed in the relationship of one another [4][16-22]. Hedgerows are important habitat for wildlife such as bird, mouse, butterfly, etc. Meanwhile, hedgerows functioning as ecological corridors maintain the connectivity of the landscape; thus hedgerows are important to protect and improve the biodiversity. Hedgerows not only give a strong sense of place in the rural landscape but also invite an intimate emotional association with the American countryside [23][47].

III. Landscape Connectivity

A. Structural Connectivity

Common usage of the term 'connectivity' generally emphasizes the structural aspect, where landscape connectivity is simply equated with linear features of the landscape that promote dispersal, such as physically connected linear corridors. This connectivity allows route from *A* to *B*. In a network system, if there are more alternative routes to travel from *A* to *B*, then the network is considered more connected, or it has higher connectivity.

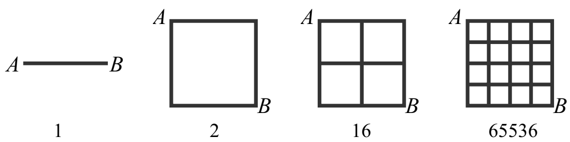
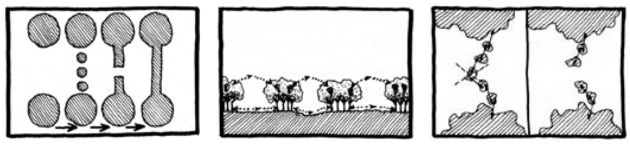


Fig. 2 Number of ways travelling from *A* to *B*, showing loop density and physical connectivity

B. Functional Connectivity

Physical connectivity is measured by the numbers of loops present in the network. However, in landscape ecology, commonly employed measures of connectivity focus not only on physically connected linear corridor, but also on patch area and how inter-patch distances affect movement in between; i.e. corridors not physically connected, for instance, the stepping stones that can be used by certain species as connected corridor (Fig. 3). This can be called as functional connectivity [49].



(a) (b) (c)

Fig. 3 Hedgerow corridor and connectivity: (a) stepping stone, (b) distance between stepping stone, (c) loss of stepping stone [49]

Width and connectivity are the primary controls on the five major functions of corridors, i.e., habitat, conduit, filter, source, and sink[4][30][50]. The effect of a gap in corridor on movement of a species depends on length of the gap relative to the scale of species movement, and contrast between the corridor and the gap. However, a row of stepping stones (small patches) is intermediate in connectivity between a corridor and no corridor, and hence intermediate in providing for movement of interior species between patches (Fig. 3a). For highly visually-oriented species, the effective distance for movement between stepping stones is determined by the ability to see each successive stepping stone (Fig. 3b). Loss of one small patch, which functions as a stepping stone for movement between other patches, normally inhibits movement and thereby increases patch isolation (Fig. 3c). The optimal spatial arrangement of a cluster of stepping stones between large patches provides alternate or redundant routes, while maintaining an overall linearly-oriented array between the large patches [30]. This structure facilitates wildlife movements as evidenced by many studies [4][31-36] [38-40][49].

C. Habitat Connectivity of Hudson Farm

Hudson Farm, is a family-owned 2,600 acre property at the suburb of Montgomery, Alabama. The land was used primarily for cattle grazing or hay harvesting. Landscape elements such as trees, hollows, hedgerows, barns, and fences serve as unique landmarks in the Montgomery urban-rural interface. A deep knowledge and understanding of the site will serve as the foundation for planning and design. The preservation and enhancement of distinctive landmarks such as trees, hollows, hedgerows, barns, and fences will maintain the site's unique character. The development of the property is to create a new community with pedestrian-oriented, compact, and mixed-use neighborhoods, in contrast to the single-use conventional suburban development. Creating whole neighborhoods and towns, rather than pockets of suburban development, is a vital step towards creating a sustainable development footprint [41].

Fig. 4 Hedgerow corridors on Hudson Farm

On Hudson Farm, hedgerows always exist in the landscape in the form of corridor (Fig. 4). Before development, Hudson Farm is used exactly for cattle grazing and hay harvesting. The aerial photography of Hudson Farm area shows the landscape structure of the site (Fig. 4). Hudson farm is surrounded by large stream corridors and wetlands, which provide critical wildlife habitats for migrating birds and other wildlife. The landscape elements that make Hudson Farm unique are big patches of forests, open fields, corridors in the form of hedgerows, large 'landscape rooms' enclosed by high hedgerows. The hedgerows and tress on the farm enhance the sense of place by providing refreshing long views across the open field dotted or enclosed by high hedgerow trees and groves (Fig. 4).

IV. Quantifying Connectivity at Landscape Scale

As per Forman, connectivity (*con*) can be calculated through the equation (Forman, 1995, p.282)

$$con = L / 3\,(V\text{-}2) \tag{1}$$

where L = number of linkages; V = number of nodes [4][30].

However, this approach may be easy to use at a very fine scale where landscape linkages nodes are easily identified. At landscape scale, where the site condition is highly diversified and complicated (e.g. with different forms of connectivity), a new method based on GIS is needed to quantify connectivity.

A. GIS-based Landscape Metrics

Many GIS-based landscape metrics are developed by landscape ecologist and scientists and provided for public use [5]. FRAGSTATS is one of these applications designed to compute a wide variety of landscape metrics (including landscape connectivity) for categorical map patterns. This program is developed by the Landscape Ecology Lab at the University of Massachusetts. The original software (version 2) was released in the public domain during 1995 in association with the publication of a USDA Forest Service General Technical Report [5]. The latest version 3.3 is available for download at the lab's website and the program is currently undergoing a major revamping, which will result in the release of version 4.0 sometime in 2011.

FRAGSTAT calculate connectivity based on connectivity metrics (Table 1).

TABLE I
CONNECTIVITY METRICS

Type	Code	Metric	Acronym
Class Metrics	*C121*	Patch Cohesion Index	COHENSION
	C122	Connectance Index	CONNECT
	C123	Traversability Index	TRAVERSE
Landscape Metrics	*L121*	Patch Cohesion Index	COHENSION
	L122	Connectance Index	CONNECT
	L123	Traversability Index	TRAVERSE

For example, the Connectivity Index (*con*) is calculated as

$$con = \left[\frac{\sum_{i=1}^{m} \sum_{j=k}^{n} C_{ijk}}{\sum_{i=1}^{m} \left(\frac{n_i (n_i - 1)}{2} \right)} \right] \tag{2}$$

where

c_{ijk} = joining between patch j and k (0 = unjoined, 1 = joined) of the same patch type, based on a user-specified threshold distance.

n_i = number of patches in the landscape of each patch type i.

In this matrix, connectivity equals the number of functional joinings between all patches of the same patch type (sum of c_{ijk} where c_{ijk} = 0 if patch j and k are not within the specified distance of each other and c_{ijk} = 1 if patch j and k are within the specified distance), divided by the total number of possible joinings between all patches of the same type, multiplied by 100 to convert to a percentage. Therefore the connectivity ranges between 0 and 100. Connectivity = 0 when either the landscape consists of a single patch, or all classes consist of a single patch, or none of the patches in the landscape are connected (i.e., within the user-specified threshold distance of another patch of the same type). Connectivity = 100 when every patch in the landscape is connected [5].

B. Data Input and Parameterization

The FRAGSTAT requires GIS data to be arranged in a recognizable file as input to the program to calculate the landscape metrics. Besides this, the program has to be properly parameterized before it can be run to produce the output statistics (Fig. 5).

C. Case Study: Hudson Farm

Maintaining networks of corridors is a principle in the design of functional and healthy landscape so as to allow wildlife movement through the landscape and enhance biodiversity. During the master plan making process of the Hudson project, hedgerows are connected, with a continuous tree cover. This

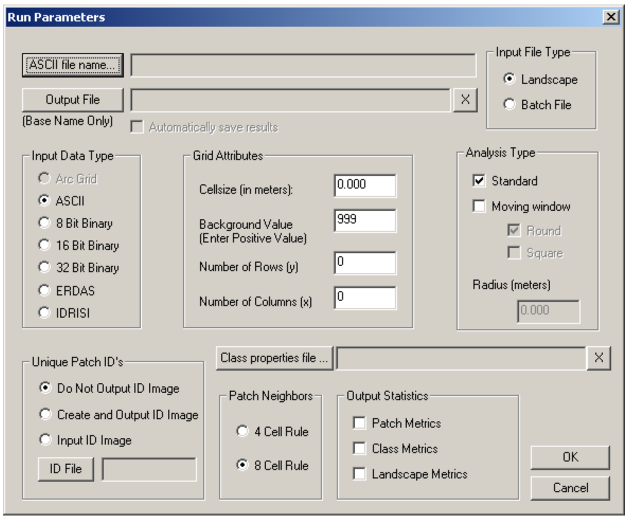


Fig. 5 Parameterization interface of the FRAGSTAT program

concept is generally advocated by many landscape ecologists[52]. This network is superimposed on the ditch network and based on the existing hedgerows. Its spatial arrangement is related to historical factors, such as landlord-worker relationship [19]. Based on this idea, the existing hedgerows are studied (Fig. 6).

To increase connectivity, some hedgerows are proposed to connect the existing hedgerow to create a hedgerow network. Basic ideas are to show why they should be connected and how should they be connected. The left diagram (Figure 6a) shows the existing hedgerow, the diagram in the middle (Figure 6b), the red color area, shows the proposed hedgerows. The diagram

Fig. 6 Existing and Proposed Hedgerow connection on Hudson Farm

TABLE II
COMPARISON OF THE LANDSCAPE CONNECTIVITY INDEX OF HUDSON FARM BEFORE AND AFTER THE PROPOSED HEDGEROW

	LID	Defintion	unitype_2_utm	unitype_utm	Change%
Area/Density/ Edge	TA	Total Area (CA/TA)	216.6415	191.5492	13.1%
	NP	Number of Patches	365	330	10.6%
	PD	Patch Density	168.4811	172.2795	-2.2%
	LPI	Large Patch Index	39.2358	44.3668	-11.6%
	TE	Total Edge	2231.1405	2139.7003	4.3%
	ED	Edge Density	10.2988	11.1705	-7.8%
	LSI	Landscape Shape Index	23.2981	18.6337	25.0%
	AREA_MN	Mean Patch Area	0.5935	0.5805	2.2%
	AREA_AM	Area Weighted Mean Patch Area	35.5972	39.9073	-10.8%
	AREA_MD	Median Patch Area	0.0585	0.0502	16.5%
	AREA_RA	Patch Area Range	84.9927	84.976	0.0%
	AREA_SD	Patch Area Standard Deviation	4.5581	4.7778	-4.6%
	AREA_CV	Patch Area Coefficient of Variation	767.9494	823.1162	-6.7%
Shape	SHAPE_MN	Mean Shape Index	1.4889	1.37	8.7%
	SHAPE_AM	Area Weighted Mean Shape Index	2.7105	2.4998	8.4%
	SHAPE_MD	Median Shape Index	1.2	1.1667	2.9%
	SHAPE_RA	Shape Index Range	5.7667	4.434	30.1%
	SHAPE_SD	Shape Index Standard Deviation	0.8561	0.6855	24.9%
	SHAPE_CV	Shape Index Coefficient of Variation	57.5004	50.0372	14.9%
	PAFRAC	Perimeter-Area Fractal Dimension	1.4551	1.3941	4.4%
Core Area	TCA	Total Core Area	83.7469	83.7469	0.0%
	NDCA	Number of Disjunct Core Area	23	23	0.0%
	DCAD	Disjunct Core Area Density	10.6166	12.0074	-11.6%
	CORE_MN	Mean Core Area	0.2294	0.2538	-9.6%
	CORE_AM	Area Weighted Mean Core Area	27.212	30.7708	-11.6%
	CORE_RA	Core Area Range	68.0276	68.0276	0.0%
	CORE_SD	Core Area Standard Deviation	3.5757	3.7598	-4.9%
	CORE_CV	Core Area Coefficient of Variation	1558.4413	1481.5153	5.2%
	CAI_MN	Mean Core Area Index	0.9139	1.0109	-9.6%
	CAI_AM	Area Weighted Mean Core Area Index	38.6569	43.7208	-11.6%
	CAI_RA	Core Area Index Range	80.0315	80.0472	0.0%
	CAI_SD	Core Area Index Standard Deviation	6.9111	7.2621	-4.8%
	CAI_CV	Core Area Index Coefficient of Variation	756.2592	718.403	5.3%
Contagion/ Interspersion	CONTAG	Ciontagion	61.9249	63.8536	-3.0%
	PLADJ	Proportiono f Like Adjacencies	85.2875	87.422	-2.4%
	AI	Aggregation Index	86.1895	88.3833	-2.5%
	IJI	Interspersion Juxtaposition Index	56.1931	54.8214	2.5%
	DIVISION	landscape Division Index	0.8357	0.7917	5.6%
	MESH	Effective Mesh Size	35.5972	39.9073	-10.8%
	SPLIT	Split	6.0859	4.7999	26.8%
Connectivity	CONNECT	Connectance Index	0.622	0.4421	40.7%
	COHESION	Patch Cohesion Index	95.2263	95.6507	-0.4%
Diversity	PR	Patch Richness	4	4	0.0%
	PRD	Patch Richness Density	1.8464	2.0882	-11.6%
	SHDI	Shannon's Diversity Index	1.0165	0.9616	5.7%
	SIDI	Simpson's Diversity Index	0.5799	0.5298	9.5%
	MSIDI	Modified Simpson's Diversity Index	0.8672	0.7547	14.9%
	SHEI	Shannon's Evenness Index	0.7332	0.6937	5.7%
	SIEI	Simpson's Evenness Index	0.7731	0.7064	9.4%
	MSIEI	Modified Simpson's Evenness Index	0.6255	0.5444	14.9%

on the right (Figure 6c) shows the overlay of existing hedgerow and the proposed hedgerow. The benefits of doing this is, from a landscape ecology point of view, that the connectivity is increased by 40% without losing much of the core habitat (Table 2).

V. DISCUSSION

The information showed in Table 2 above are the results of applying GIS to calculate connectivity together with other parameters at landscape scale. However, the results in Table 2 must be interpreted with caution. For instance, connectivity is measure in 'CONNECT' and 'COHENSION' (Table 1-2); even the overall 'CONNCET' as measured use equation (2) is increased by 40.7%, however, the landscape 'COHENSION' does not increase as the same magnitude. On the contrary, it decreases slightly [5]. This example illustrates that design interventions can change the ecology of the site; therefore,

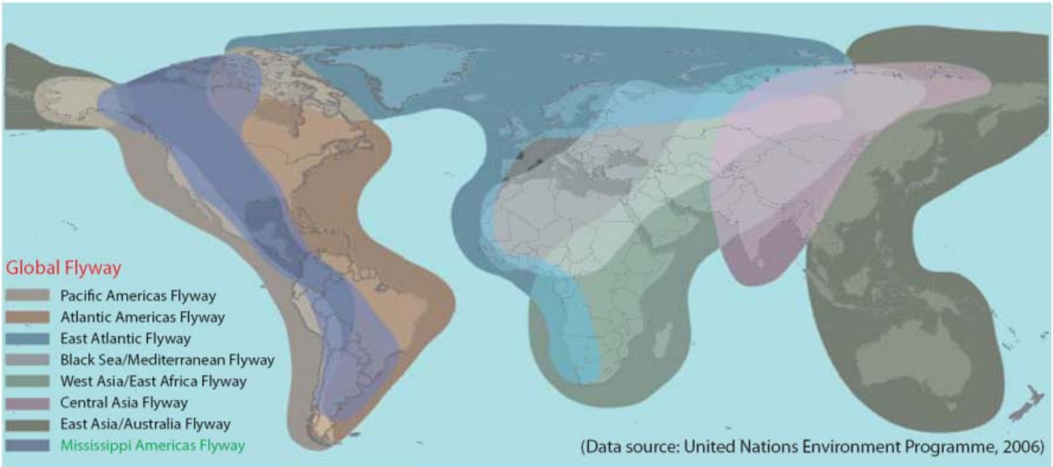


Fig. 7 The global migrating flyway. Hudson Farm is located on the Mississippi-Americas Flyway

design intervention must be informed by appropriate analysis of the eco-regional context of the site.

The proposed hedgerows reconnect the broken corridors and increase the overall landscape connectivity dramatically. This indicates the importance of maintaining the intactness of the landscape and its natural vegetation corridor. A further look at the regional and global context reveals how important the corridor is in terms of maintaining the ecological variability of the site.

Biodiversity is another important issue that has critical influence of the sustainability of our planet. Hudson Farm is located on the Mississippi Americas Flyway [51] in the global context (Fig. 7) as well as on the Mississippi flyway in the American continental scale (Fig. 8). The forest patches, hedgerows and wetlands within Hudson Farm should receive careful consideration where development should not eliminate or degrade these habitats but maintain or improve them in order to keep its ecological function in the global flyway [51].

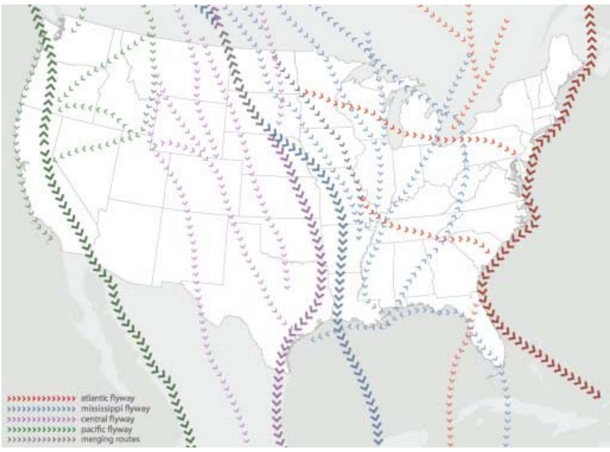


Fig. 8 The Mississippi Flyway in the continental United States. Hudson Farm is located on the Mississippi Flyway

These two images serve as strong arguments that the site is ecologically sensitive, not only at the national scale, but also at the global level. Further analysis at the Alabama state level and local scale also reveals the ecological significance of the site, which requires the design team to exercise integrated decision making in the plan-making process. Sustainable development is only possible when consensus is reached among different groups defending their own interests without neglecting the common long-term benefits of biodiversity preservation.

In this study, a general distance of 30 m (a gap below this distance is still considered connected) is used to calculate the connectivity. However, assessing landscape connectivity requires a species-centered approach [53]. A connected structure may serve as a corridor for one species, but a barrier for another. Meanwhile, habitat does not necessarily need to be structurally connected to be functionally connected. Some organisms, by virtue of their gap-crossing abilities, are capable of linking resources across an uninhabitable or partially inhabitable matrix, while other species can not cross gaps therefore requires higher structure connectivity. Therefore, the study of connectivity requires information on species' movement responses to landscape structure (e.g., movement rates through different landscape elements, dispersal range, mortality during dispersal, boundary interactions, etc.) and how those responses differ as a function of broader-scale influences. Such information is typically quite difficult to obtain, as very limited study is carried out on a species to species basis. Therefore, the assessment of the overall connectivity at landscape scale is but a big-picture overview of the connectance of different landscape elements present.

VI. Conclusions

Connectivity is an important concept in landscape ecology and landscape architecture. Landscape connectivity can be measured in different ways. The practical way is to use GIS data as input layers to calculate connectivity. This is efficient when GIS data are available. Significant difference when comparing the landscape connectivity of the existing site with that of proposed development can be easily used to assess the impact of the modified landscape after proposed development, thus negative impacts on connectivity can be avoid in real urban development projects. Instead, measures can be taken to maintain or improve landscape connectivity during the master plan making process. This study proves GIS as an efficient and useful tool in connectivity study at landscape scale.

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