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Applying and exploring a new modeling approach of functional connectivity regarding ecological network: A case study on the dynamic lines of space syntax

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ABSTRACT

The construction of ecological network or other continuous habitat is essential for urban eco-system; however, to quantify the heterogeneous functional connectivity for eco-network is academically attractive and challenging. The dynamic lines of space syntax, tenable to simulate perception and navigation flows in network-configured human settlements, is introduced to inspire idea and approach to modeling connectivity in eco-network, while the classical graphic notions and variables are assumed functional to new relationship between other species and eco-network. After mapping continuous functional components among land layout into free space and then into dynamic lines that influence bio-flows, the paper conducts an exploration on functional connectivity of Singapore's green network. Conclusions involves the distribution heterogeneity of basic variables, *Connectivity*, *Control*, *Mean Depth* and *Integration*, demonstrating each meaning for functional connectivity in the network, with a step-wise *Integration* further comparing the connectivity patterns under different behavioral ranges. Moreover, a scale robustness determined via linear regression between *Integration* and *Connectivity* reveals network functionality as behavioral scale varying. The analogical modeling of space syntax raised in this paper is adaptive and instructive, particularly if original essential traits remain valid between the substituted species and space, because several principles and characteristics of conventional connectivity models can be logically inherited, while the graphic notions of dynamic line shares unique advantages.

1. Introduction

Since the end of the 20th century, researchers began to find out the importance of ethology in animal protection (Feró et al., 2008). A rational conservation strategy should consider organism's behavior (including migration, feeding, mating, reproduction, prey and evasion) according to habitat states (With and Crist, 1995; Tischendorf and Fahrig, 2000b; Goodwin and Fahrig, 2002; Brooks, 2003; Jordán et al., 2003; Bélisle and Fortin, 2005; Vuilleumier and Metzger, 2006; Buchholz, 2007; Estrada et al., 2008; Berger-Tal et al., 2011). Ignoring the movement of species is incorrect and can even be potentially devastating to bio-conservation (Taylor et al., 1993). The ethological activity of species, which is tremendously complex (Lima and Zollner, 1996; Sutherland, 1998; Baguette and Van Dyck, 2007), includes both the procedures and the modes of movements. The interaction of the bio-flows with the landscape structure consists of the combined effects of dispersal, detection, migration and settlement (Tischendorf and Fahrig, 2000b). Currently, the modeling methods employed to quantify how the nature of relationship patterns influences landscape functions are a subject of debate in academic literature (Goodwin and Fahrig, 2002; Liu et al., 2012; Shanthala Devi et al., 2013).

Remarkable endeavors have been made in spatially explicit models of functional connectivity (Chen et al., 2014). Some integrate the artificial intelligence of individual-based modeling, whose operation emphasizes the dynamic interaction between multi-agent behavior and functional space that influences landscape connectivity and eco-network functionality (Schippers et al., 1996; Lima and Zollner, 1996; Hargrove et al., 2004; Heinz et al., 2007; Feró et al., 2008; Pe'er et al., 2011; Vincenot et al., 2011; Haythorne and Skabar, 2013), some rely on general graph theory to forge bio-flows and network, the attention of which is majorly attached to the conceptualization on empirical patterns of organism behavior and the calibration and validation of the connection rules in and between landscape elements (Tischendorf and Fahrig, 2000a,b;

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Goodwin and Fahrig, 2002; Jordán et al., 2003; Bélisle and Fortin, 2005; Heinz et al., 2007; Estrada et al., 2008; Palmer et al., 2011; Tremblay and St. Clair, 2011). However, several conventional approaches feature specific common weaknesses, especially the limitations in simulating how landscape elements dynamically or directly affect the space selecting behavior of species (Hargrove et al., 2004; Vuilleumier and Metzger, 2006; Shanthala Devi et al., 2013), either from variant fitness or up to larger scale (Lima and Zollner, 1996; Tischendorf and Fahrig, 2000b; Wu et al., 2009). This paper addresses a novel approach concerning these defects to inspire new solutions, because by corporation and communication, some framework in other discipline is probably of substantial use in landscape ecology study (Chen et al., 2014), and even the agent-based connectivity modeling.

Since the birth time of the 1970s, space syntax has amazed the study of human settlement sciences, because it offers a tenable perspective in physical and social dynamics of space functions; dozen years later, its efficiency was scaled up to the analysis of urban morphology (Steadman, 1983; Peponis et al., 1990; Turner, 2003; Hillier, 2007). Predictably, space syntax may have no less potential to further facilitate the studies of functional heterogeneity that are integrated with substituted agents. Moreover, the landscape connectivity study can take unique advantages of the graphic notions and algorithmic deductions of space syntax, which stand on dynamic configuration, systematic topology and scale variability. Considering the configuration of ecological network is applicable to the dynamic lines of space syntax, while the perception and navigation behavior of certain species is inherited by the sociological activity of *Homo sapiens*, this paper attempts to introduce the line-based space syntax under the same logic and discipline, to quantify the functional connectivity without a loss of generality and integrate it with the behavior of certain species. Then the ecological network of Singapore is investigated deductively to demonstrate how the framework could be implemented, which involves the variable calculation for graphic notions obtained by space division and the further exploration of scale influence. The paper also focuses on consulting several conventional models, together with empirical knowledge, to disclose the practicability of the analogical model.

2. Methods

2.1. Inspirations from the space syntax

The space configuration (or "space syntax"), which includes various essential messages of spatial geometrical logic, can reveal the "deep-seated structure" beneath human settlements. The theory of "space syntax", which was established by Hillier et al. (1970s), integrates correlations of basic-element in graph theory with physical and social dynamics (Steadman, 1983) to describe the functional space with the navigation flows of humans. This behavior, which is primarily referred to as "natural movement", has been empirically proven capable of manifesting subtle correlations between the space configuration and the frequency heterogeneity of informal moving flows internal (Peponis et al., 1998; Penn, 2003; Turner, 2003; Hillier, 2007). After the adaptation and evaluation in the following decades, the urban topological model derived from space syntax has been proved to coincide well with Kevin Lynch's cognition map of agent individuals, if the attracting force and other factors in the city are excluded. Evidently, this framework can quantify the influence of surroundings on individual's actions both locally and generally (Jiang et al., 2000; Turner, 2003). Furthermore, replacing roads and squares in human settlements with corridors and patches in eco-space, while adjusting human behavior to that of other species, is inspirable both to the approach itself and the ecological modeling. This paper proposes to analogize space syntax to modeling functional connectivity.

Considering the geometry deviations from spatial functional unit or the "convex space", it is believed that the adaptable approaches of space syntax depend on the configurations of landscapes (Turner, 2003; Hillier, 2007). For example, a finger- or grid-shaped landscape on a certain scale is more suitable for a line-based approach. The ecological network, which generally provides moving conduits for species as network-configured elements, can therefore be transferred with similar principles, which allows the subsequent parameters to reveal its functional patterns.

2.2. How space syntax works

The core ingenuity of space syntax is based on dividing the space into systematic graphic notions. Following the "Spatial Dichotomy Phenomenon", larger divisions first define the space that is only composed of "spatial obstacles" (inaccessible by perception and navigation) and the "free space" remaining among those physical obstacles, which is to be defined as species' preferable space (Tischendorf and Fahrig, 2000b; Hargrove et al., 2004) in this paper. The method then divides the free space into a group of spatial elements with graphical notations to symbolize individual's spatial behavior. Specifically, the fewest and fattest convex space is first used to cover the entire free space; a net of "dynamic lines" is then constructed to penetrate each convex space. The dynamic lines are conceptualized from the strategic breaking perception or navigation of boundaries, which can be defined as a set of lines tangent to at least 2 apexes of obstacles that extend until reaching any boundary. Assisted by numerous lines of different lengths (or "all-line map"), the graphical approach can represent an accurate and detailed Euclidean geometry of the interacting behavior of agents within the free space (Jiang et al., 2000; Hillier, 2007). After transferring each line into a node (the symbol of a unit) and their intersections into links, we can obtain a topological network parameterized by the indices of "*Connectivity*", "*Control*", "*Depth*" and "*Integration*", etc.

(1) *Connectivity*: $C_i = \sum_l R_{il}$, where R_{il} presents the direct bridge between units i and l. In classical theory, C_i can positively quantify the permeability of unit i together with its aggregation degree with neighbors; the number of communication routes to assemble moving flows positively correlates with the value of C_i.
(2) *Control*: $\mathrm{ctrl}_i = \sum_{j=1}^{k} \frac{1}{C_{ij}}$, where C_{ij} is the *Connectivity* of the jth neighbor to unit i. In classical theory, ctrl_i concerns the dominance degree of unit i allocated from its directly linked units. Thus, it can positively estimate the control (or influence) of unit i over neighbors or its selectable dynamic units in ideal situations.
(3) *Depth*: $D_i = \sum_{d=1}^{s} (d \times N_d)$, $MD_i = \sum_{d=1}^{s} (d \times N_d)/(m-1)$, where d is the shortest topological distance from unit i to any other unit, ranging from 1 to s (the longest shortest step); N_d is the number of traversed nodes (by "Breadth First Search") at a d, and m is the number of units in a system. In classical theory, D_i (and the normalized MD_i) negatively quantifies the location convenience and ability to link unit i by counting the least tracking (or topological) steps outwards. D can be calculated under varying domain which depends on d.
(4) To avoid the unit number interference in the system, *Depth* can be normalized into *Relative Asymmetry i* (Steadman, 1983): $RA_i = 2(MD_i - 1)/(m-2)$. To eliminate structural interference, this expression can be further normalized into *Real Relative Asymmetry*: $\mathrm{RRA}_i = \mathrm{RA}_i / D_m$, where $D_m = \frac{2m\left[\log_2\left(\frac{m+2}{3} - 1\right) + 1\right]}{(m-1)(m-2)}$ is a

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