

CAN SPATIAL FORM SUPPORT URBAN ECOSYSTEM SERVICES: Representing patches and connectivity zones for bees using space syntax methodology

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Abstract

Within the broad research field of sustainable urban development, we can identify a movement from a first generation of research and practice, primarily addressing mitigation strategies, to a second generation, broadening the field to also encompass strategies of adaptation. Most sustainable urban growth concepts (e.g. new urbanism, urban containment and smart growth) built on the findings from the first generation of research and have a strong focus on the transport-land use relation, aiming at reducing private (car) mobility and related CO₂-emissions and air pollution. Research shows that higher density, land-use diversity and pedestrian-friendly designs generally reduce trip rates and encourage non-car mobility, although the results are still ambiguous (Colding et al, forthcoming). Creeping global environmental changes, natural catastrophes and volatile financial markets, highlight the need to put emphasis also on strategies of adaptation as a complement to environmental mitigation strategies of cities (Vale et al 2005). This type of research concerns the understanding of the resilience of urban systems in which urban systems are seen as integrated social-ecological systems, bridging the ancient dichotomy between human and ecological systems. Research shows that green spaces and its fragmentation are crucial for biodiversity and other ecosystem services. One of the most relevant variables affecting landscape fragmentation is population density (Jaeger 2000). Indeed, urban sprawl causes directly land cover changes at the urban fringe and impacts indirectly on the rural landscape progressively further away from the urban fringe by fragmenting both agricultural areas and woodlands (Salvati et al 2012). However, city compactness and higher densities decrease the amount and access to green space within cities (Pauleit et al 2005, Burton 2000).

This paper especially focus on green space and its fragmentation and accessibility within cities and combine the human perspective on green space with the landscape ecological perspective in the aim to develop knowledge that opens for integration of eco-system design in urban design, moving towards an expanded professional practice of social-ecological urban design. To include the ecological perspective we use effective mesh density, which is a direct quantitative expression of landscape connectivity (Jaeger 2000) and biotope diversity (Marini et al 2010). To include the human perspective we build on the methods to measure cognitive accessibility developed within Space syntax research (Hillier 1996) and especially the measures proposed by Ståhle et al (2005, 2008) in which besides the measure of distance, also a measure of attraction is introduced. Through this we aim to include the described ecological measures in the framework of Space syntax, enabling us to use accessible green space both from a human and an ecological perspective. Important stepping-stone structures within the network (patches and links with more importance from one or both perspectives) can be traced and interventions can be proposed to improve (parts of) the system. This paper presents, firstly, a conceptual discussion on this topic and secondly, results from a study in Stockholm showing in principle the possibility of a spatial morphology of social-ecological urban systems.

Keywords: Design Synthesis, generative urban design, Neural Networks, Complex systems, GeoComputation, Space Syntax

Theme: Green Urbanism and Sustainable Developments

1. Introduction : Urban design for ecosystem services

Within the broad field of sustainable urban development, we can identify a movement from a first generation of research and practice, primarily addressing mitigation strategies, to a second generation, broadening the field to also encompass strategies of adaptation. Most sustainable urban growth concepts (e.g. smart growth, urban containment and new urbanism) build on the findings from the first generation of research and have a strong focus on the transport-land use relation, aiming at reducing private (car) mobility and related CO₂- emissions and air pollution. Research shows that higher density, land-use diversity and pedestrian-friendly designs generally reduce trip rates and encourage non-car mobility, although the results are still ambiguous (Colding et al, forthcoming). Incremental global environmental changes, natural catastrophes and volatile financial markets, highlight the need to put emphasis also on strategies of adaptation as a complement to environmental mitigation strategies of cities (Seto et al. 2012; UNEP 2012). This type of research needs to address the resilience of urban systems (Marcus and Colding, in review) and to understand cities as integrated social-ecological systems (Folke et al, 1999; 2003), bridging the ancient dichotomy between human and ecological systems.

For such a second generation of strategies in sustainable urban development the idea of ecosystem services (ESS) (Daily, 1997) is crucial, since it pinpoints how cities are dependent on local ecosystems and the wide range of services they provide for their welfare and survival (Elmqvist et al. in press; Deutsch et al. in press). Current processes of rapid global urbanization and growth present enormous challenges, but also opportunities to transform cities towards maintaining and developing urban ESS (Elmqvist et al. in press). However, our knowledge about how to uphold essential ESS in urban areas through urban planning and design is limited if not non-existent. This paper is a start to investigate how spatial form, here understood as urban space structured and shaped by built form and landscaping, can support urban ESS. More precisely, we propose to identify the spatial form needed for *pollination*, an ESS pointed out as critical for sustainable urban development (Gomez et al. in press).

Pollination is an essential ESS for the majority of food production in the world (Allen-Wardell et al. 1998) and therefore also represents a tremendous monetary value that is provided by ecosystems for free. That wild pollinators are facing increasing threats due to urbanization and habitat fragmentation is therefore a distressing development. At the same time, it is also pointed out how cities have a great potential to sustain pollinator populations if properly designed and managed (e.g. Ahrné 2009; Jansson and Polasky 2011). Cities have even proven to act as source areas for surrounding landscapes in this respect (Saure 1996; Tommasi et al 2004; Andersson et al. 2007; Matteson et al 2008; Zetterberg 2009).

However, the role of spatial form, as defined above, on the detailed scale in supporting ecosystems services has so far not been studied. This is unfortunate, since it is at this scale that urban designers need knowledge if they are to support ESS. Of course, there is a wide range of ESS that are critical for human well-being in cities, e.g. air and water cleaning, improved micro-climate, seed dispersal, pest regulation etc., and to support urban design in this respect, one in the end needs to investigate similarities in spatial demands among these ESS. We here propose a 'braiding' of such demands, so that spatial form simultaneously can support several ESS. This comes close to the idea of 'generic function' central to space syntax theory (Hillier, 1996). However, we are only at the beginning of a new and potentially large field of research, which is why we in this paper will focus on pollination as a both typical and critical example of ESS in cities, and the aim to identify its typical spatial demands, such as certain sets and sizes of biotopes as well as the particular spatial configuration and connectivity between these.

This paper presents, firstly, a conceptual discussion on the topic of spatial form of ecosystem

services and, secondly, a principal description of a methodological approach in which we propose to capture the spatial demands for pollination by developing descriptions and measures used in the framework of Space syntax. Thirdly, some preliminary results from a study in Stockholm (*Östermalm*) will be presented as the ground for a discussion about the principal potentials of a spatial morphology of urban ecosystems. *Östermalm* is chosen as a study area because it is a highly urbanised area with high levels of impervious surfaces. Such highly urbanised areas have a negative effect on the diversity of the primary pollinator in our study, different species of bees (Ahrné et al 2009), but for that very reason we think it an informative exercise. We aim to validate this in a later study.

The main research question is, first, whether we, drawing from the literature about biotope demands and the range of action for different species of bees, can formulate typical spatial forms and configurations necessary for bee abundance and, second, if such typical configurations are possible to identify in highly urbanized areas. In a second step of this preliminary study, we will attempt to empirically validate this.

2. Principal framework: analysing urban form for urban ecosystems

In principle, urban design is about using built form to structure and shape urban space so that it supports and directs different urban processes into certain politically sanctioned trajectories. Normally we identify these processes as typically social, including economic, cultural and technological processes. What is considered outside of this, most often, is natural systems and in particular ecosystems, due to the strongly established dichotomy between society and nature. However, evidence obviously point out how social and ecological systems typically are intertwined, not least in cities (Berkes et al, 1998; 2003). Given the current ubiquitous call for sustainable urban development, it therefore does not seem far to expand urban design into social-ecological urban design, in theory, simply by adding ecological processes in cities to the other processes addressed in urban design. This broader idea has already been extensively discussed, principally theorised and practically illustrated in a concrete case in Stockholm concerning a new campus area (Barthel et al, in press). However, for a successful practice of social-ecological urban design we clearly need more knowledge and it is exactly this that this paper aims to contribute to.

In a space syntax context, this implies an aim to develop knowledge about how the spatial configuration of cities, not only deeply influences a series of urban processes of a social kind, as listed above, but also a series of ecological processes, potentially aiming not only for a social logic of space but a social-ecological logic of space. A lot of ground has been covered in space syntax research concerning social systems (e.g. Koch et al, 2009; Greene et al, 2012), that we believe is useful when addressing this new challenge. One such concept we find extremely useful when addressing ecological systems is *generic function* (Hillier, 1996), which sorts a myriad of functions in urban systems into functions that truly carry spatial consequences. Another is the *axial map* (Hillier and Hanson, 1984), by which spatial configurations in cities are represented in what we interpret as geometry of high cognitive relevance, which is why, most likely, they have proven successful in predicting generic functions in cities, such as movement.

Expanding space syntax theory and methodology to comprise also ecosystems in cities is of course a tremendous task and in this paper we only aim at making some hints at how this could be accomplished. Addressing more specifically, the rapidly growing concept of urban ecosystems services (ESS), what we need to address is of course ecosystems that produce such services, in our case the ESS of pollination, which highlights ecosystems critical for pollinators such as different species of bees. Ecosystems are complex systems that incorporate all kinds of entities but what we more specifically aim for here are the spatial dimensions of such systems,

primarily the distribution and connectivity between different *biotopes* in cities. Such biotopes represent a very fine-grained description that often is aggregated into green *patches*, which will be the spatial unit worked with in this preliminary study.

In simple but rather robust terms, what we deal with are certain sets of green patches in cities and their spatial connectivity. Such a description is not far from the principal understanding of urban space in general in space syntax, where we typically analyse the configuration of urban spaces as, for instance represented by the axial map, and the connectivity or relative accessibility between these spaces. More specifically, what we are talking about is how urban space in space syntax is represented as a network, using graph theoretical descriptions (Newman, 2010). To represent ecosystems, or rather the distribution of green patches in cities as network is nothing new (see Pascual-Hortal et al 2006; Zetterberg, 2011). However, most such analyses are made specifically for ecosystems and do not account for the city as a social system and the typical barriers that these create for ecosystems, such as buildings and traffic arteries, in any effective way. This, however, is exactly what space syntax models do.

A critical dimension here is that such models, for instance, the MatrixGreen developed at KTH Stockholm (Bodin and Zetterberg, 2010), do not deal with distance in a life like manner. Normally, such models represent a system of patches, constituting the vertices in the network, and the links between these as edges in the network. The edges are drawn as straight lines between the patches avoiding only major obstacles, such as large buildings and waters. Clusters of patches are then identified by setting limits to the length of edges based on the range of operation for the particular species under investigation. To this can be added different distance measures, which are calculated as weighted impedance in the network, based on conditions, such as character of terrain or different barriers. Such impedances are naturally often very difficult to estimate.

This problem is directly addressed for humans in space syntax models by the representative technique of axial maps. This technique represents distance in its very geometry in two ways, and has proven to do so in a quite life-like manner (Hillier, 2004). First, by defining urban space as accessible open space primarily defined by buildings (Hillier, 1996), second, by representing such accessible open space with the least amount of straight lines that cover it, where, in principle, these lines comes to represent the least amount of lines of sight and access for a human being. Whether the axial map in this sense can be defined as a cognitive map can be discussed, but it certainly captures some basic dimensions of the conditions for human perception and as such can be argued to capture certain basic prerequisites for human cognition of urban space.

This is a large discussion that certainly needs to be readdressed in detail if an extension of space syntax modelling into ecosystems is to be imagined. However, in this paper we only aim to show how this approach, in principle, seems likely to be useful in such an extension. The challenge here is to construct an 'axial map', which we here define as a model of urban space particularly designed for the point of view of human cognition, that instead is designed from the point of view of the cognition of other species; in our case bees. This needs to concern what spaces are to be included in the model, given that bees read barriers differently than humans; the definition of the basic spatial units used, since axial lines are not necessarily relevant for bees; and, finally, the limits of the analysis given by the range of operation for the particular species. To this comes also a need for a deeper analysis of particular substrates of the ground that here will play a critical role in facilitating movement of different species and, finally, the mapping of biotopes relevant for different species.

While this might sound complicated, we need to remember how urban systems already are complex and that humans through history have seemed able to cope with this complexity

through rather simple but sophisticated spatial solutions. As far as ecosystems goes, we might also note that these used to be a natural part of cities, often carefully maintained by humans, for instance, in urban agricultures of different kinds. Also, we do not imagine a future urban design that specifically deals with spatial forms specific for every species, but rather representative key species or species groups that can work as generic demands for design. Finally, we see the basic notion of generic function as highly applicable in this context, as a conceptual support in sorting the great variety of potential demands presented by different species to those that are genuinely relevant for the design of spatial form.

In the following we will attempt some first steps by looking closer at the presence of bees in a highly urbanised area and attempt to identify characteristic spatial configurations in relation to such presence, which in the future could be made to inform the practice of urban planning and design in support of urban ESS, in this case more particularly the ESS of pollination.

3. Bees in cities and resilience

Wild bees (bumblebees and solitary bees) are the most important pollinators and as such a key resource for sustainable (urban) agriculture (Linkowski et al, 2004). There has been a documented decline in diversity and abundance of wild bees in Europe and the United States during the last decades. The main causes of this decline are considered to be habitat destruction and landscape fragmentation as a consequence of human activity, such as urbanization and increase in specialised and intensive agricultural uses (Buchmann et al 1996, Biesmeijer et al 2006, Linkowski et al, 2004). In Sweden, almost one third of the species of wild bees are red listed (Gärdenfors, 2000).

In a study on the response of bumblebees to increasing urbanization, Ahrné et al (2009) show, however, that urban areas can also harbour a high diversity and abundance of wild bees. They found that this is, however, depending on the degree of urbanization, e.g. the diversity of bumblebees is lower in allotment gardens located in more urbanised areas than in allotment gardens located in less urbanized settings. In other words, diversity was negatively affected by urbanization, here measured by an increasing proportion of impervious surface within the surrounding landscape (radius 300, 500, 1000 m). The variation in bumblebee abundance in this study was found to mainly be the result of flower cover (i.e. proportion of flowering plants within study plots) and not so much of the degree of urbanization. In other words, local qualities are important for the presence of wild bees, but contextual qualities explain the diversity of bee species on these sites.

Diversity is important because the different bee species are active in different periods in spring and summer. They can roughly be divided into four groups, spring, early summer, summer and late summer flying species and will, hence, also contribute to pollination in these periods. A lack of diversity will thus affect the reliability and efficiency of pollination. Furthermore, diversity is important for the *resilience* of the ecosystem as a whole (Holling, 1973). Resilience in interlinked social-ecological processes has three interrelated characteristics: (1) the amount of change a system can undergo and still retain the same controls on function and structure; (2) the degree to which the system is capable of self-organization; and (3) the ability to build and increase the capacity for learning and adaption (<http://www.resalliance.org/>). Climate change or changes in flower cover can affect certain bee species harder than others. The presence of a diversity of bee species in an area creates redundancy that can help safeguard pollination even in the case of temporary or permanent loss of one or more bee species, so called *response diversity* (Elmqvist, 2003). In other words, diversity is a critical attribute of resilient systems (Folke et al, 2003). Similarly, disturbances to an ecosystem can be handled more effectively if allowing for recuperation through self-organization, for instance, by being well connected with other green

areas so that bees can migrate.

Based on the description above, we can conclude that for bee abundance and bee species diversity, it is crucial to study both local characteristics of urban green areas, for instance, the presence and configuration of particular biotopes, as well as contextual conditions, such as, the connectivity to and biotope composition of surrounding green areas. This seems, in principle, possible to describe as a network of vertices of varying characteristics and edges of varying impedance, that is, representing such a configuration of urban biotopes as graph (Newman, 2010).

4. Method and application

To identify the configuration of urban biotopes in the real world that, in principle, are appropriate for pollinators, we mapped the key biotopes for wild bees and bumblebees, necessary for *spawning*, *foraging* and *overwintering*, in a centrally located area in Stockholm (*Östermalm*). There is an extensive study on wild bees in Sweden, published within the framework of the project “The wild bee project - restoration of an ecological key resource” (Swedish: *Svenska vildbiprojektet - Restaurering av en ekologisk nyckelresurs*) (Linkowski et al. 2004), that gives a good overview of both the important biotopes for wild bees (Ibid.: table 4, p. 16) and the scale of operation of bees (Ibid.: table 3, p. 11). For the mapping of bee biotopes in *Östermalm*, using GIS (Arc View), this overview of key bee characteristics was used together with an existent detailed inventory of biotopes in the Stockholm region (Löfvenhaft et al, 2002).

The terminology here is easy to confuse due to the interdisciplinary character of this paper which is why some clarification is necessary. In this paper the term *network*, *patch* and *connectivity zone* will be used as was proposed by Zetteberg et al (2009). *Network* is used in the general meaning applied in network analysis, and more specifically in geometric representations of networks using graph theory (Newman, 2010), which fundamentally is identical to how the concept is used in space syntax theory (Hillier, 1996). *Patch* is used when referring to a spatially explicit, geographically defined component of the network. A patch is composed of one or more neighbouring urban *biotopes*, relevant for bees. *Connectivity zone* is introduced as a general term defining a spatially explicit area corresponding to the functional link between two patches. These again are composed of one or more neighbouring biotopes relevant for bees. The areas that are not a patch nor a connectivity zone are *barriers*. For instance, it is known that dense vegetation with a width of only 5 meter can stop bees from navigating to an attractive patch at the other side of it, hence this constitutes a barrier. *Green area* refers to the categorisation used in urban planning and land-use maps, such as parks and natural areas.

Patches are composed of the following biotopes important to bees for spawning, foraging and overwintering:

- Open grassland with 0-20% bush or tree coverage (dry - moist conditions)
- Half open grassland with a leaf tree coverage of 20-50% or needle tree coverage of 20-70% (dry - moist conditions)
- Allotment gardens
- Urbanised land with 10-30% vegetation
- Urbanised land with 30-50% vegetation

For the biotope categories 'Urbanised land with 10-30% vegetation' and 'Urbanised land with 30-50% vegetation', the footprint of the buildings are cut out (using the command 'splitting' in GIS) as these area are not accessible for bees. The courtyards that are the result of this splitting are treated as isolated patches. All patches are divided into cells of similar size using a grid-overlay of 100x100 meter in order to be able to show differences in performance within the larger patches.

Connectivity zones are composed of the biotopes grouped under the name 'Forests with more than 70% tree coverage'. These biotopes are not appropriate for spawning, foraging and overwintering, but the edges are used to navigate from one patch to the other.

In Figure 1 the patches (solid light green) and connectivity zones (dotted dark green) are shown for *Östermalm* in Stockholm. Three types of green area can be distinguished: park (a), green urbanized area (b) and natural area (c).



Figure 1: Map of *Östermalm* with patches (solid light green) and connectivity zones (dotted dark green). Three types of green area can be distinguished: park (a), green urbanized area (b) and natural area (c).

The scale of operation for solitary bees is 250 meters and for bumblebees 750 meters, as for honeybees this can be up to 3 km (Steffan-Dewenter et al. 2002). The mean distance flown by wild bees is 500 meter but to include the capacity of bees that occasionally fly longer, we also use the distance of 3 km in this study.

The accessibility of patches in *Östermalm* is measured using metric distance (measured in meters) and topological distance (the latter combined with a metric distance threshold) that relates to the scale of operation of wild bees. The axial lines do not follow the street network as is usually done in space syntax research, but include the longest visual lines in the patches and the longest visual lines along the edges of the connectivity zones. Only the aforementioned patches and the edges of the connectivity zones are included in the drawing of axial lines, resulting in a map with disconnected clusters of axial lines (see figure 2). As can be seen in figure 2 are the streets that are part of the biotopes 'Urbanised land with 10-30% vegetation' or

‘Urbanised land with 30-50% vegetation’ included in the axial map. Here, a series of trees, or other green linear element, can make even a street habitable for bees. Isolated patches (e.g. courtyards), as a result of splitting, explained earlier, are not connected with the surrounding patches since it is assumed that bees cannot fly over buildings.

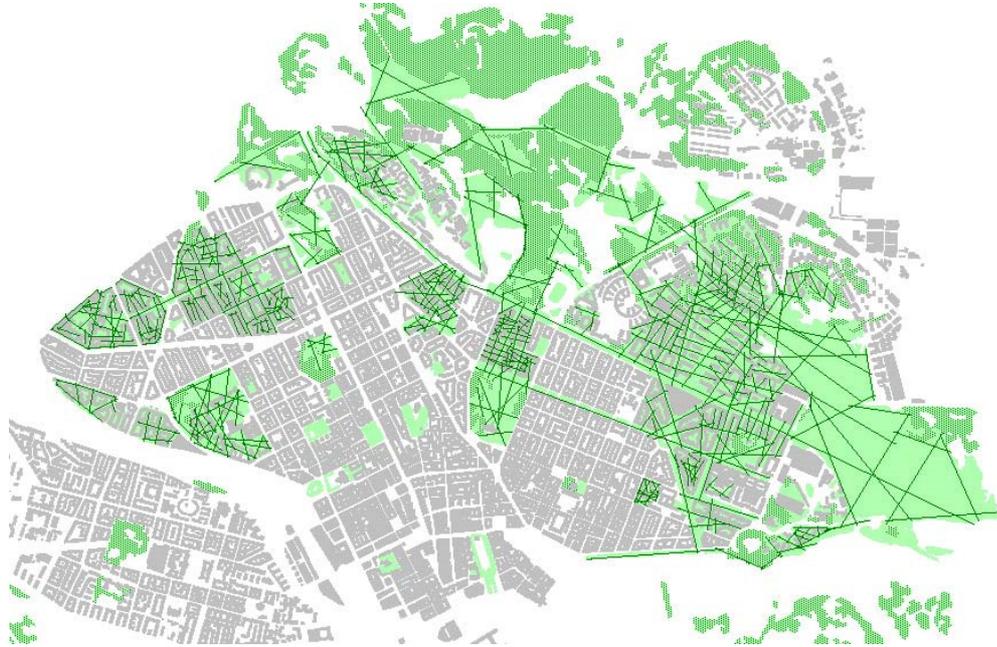


Figure 2: Axial lines in the green patches

As discussed in section 2, the cognitive character of the axial map clearly poses a challenge for the type of analysis proposed here. At the same time, geometric representation of spatial cognition typical for different species or species groups clearly presents a theoretically well-supported approach (Dolins and Mitchell, 2010). As a matter of fact, this sets the axial map into perspective as exactly such geometric representation, however, till now, specific to the particular species of humans. What we propose in this paper is to take this as a starting point and ask how the axial map could be developed or be made to inspire geometric representations of the spatial cognition also of other species in network analyses. The actual geometry of such ‘axial maps’ for bees certainly presents a challenge, but generalised descriptions of scale of operation and similar limitations poses a way forward, at least in principle. Future research is therefore aimed at, where we hope to arrive at more precise and accurate geometric descriptions.

To measure the connectivity of the patches we will use the location density (LD) measure, specifically adapted for space syntax methodology by Stähle (2008). This is a common measure in both spatial analysis and urban planning that calculates the number of opportunities accessible within a fixed cost limit (distance based) (Breheny, 1978). To measure LD, distance contours are drawn and the number of relevant opportunities, in this case patches, within each contour are counted, expressed, for patch i and contour distance c_{ij} , as follows:

$$LD_i = \sum_j B_j h(c_{ij}) \quad (1) \quad \text{where}$$

B_j = the number of opportunities in zone j

$$h(c_{ij}) = \begin{cases} 1 & \text{if } c_{ij} \leq C \\ 0 & \text{if } c_{ij} \geq C \end{cases}$$

c_{ij} = distance from origin i to destination j

C = contour

LD increases if more opportunities can be reached due to infrastructural improvements (i.e. you reach patches at *further* distance) and/or land-use changes (i.e. you reach *additional* patches within the same distance).

LD, however, is not specifically developed to measure landscape connectivity in the context of the ecological functions of the landscape. A review of graph based landscape connectivity indices by Pascual-Hortal et al (2006) shows that the most effective measure for this purpose is the Integral Index of connectivity (IIC). The expression is as follows:

$$ICC_i = \sum_j (a_j a_i) / (1 + nl_{ij}) \quad (2) \quad \text{where}$$

a_i = the area of the patch of origin (i)

a_j = the area of the patches in zone j

nl_{ij} = the number of links in the shortest path between patches i and j

The difference between the two expressions (LD and ICC) is twofold. Firstly, IIC includes the size of the patch of origin in the calculation of connectivity, resulting in a higher connectivity in cases with a larger patch of origin, but with similar catchment (see Figure 3). Secondly, in IIC the number of opportunities (patch area) in zone j is divided by the number of links needed to connect these to the patch of origin. This is important to be able to make a distinction between cases where the same amount of patch area can be reached in three steps (case A and B in figure 3) or in only one step (case C). It can be argued that for a wild bee, example C is better since more patches can be reached in a shorter distance.

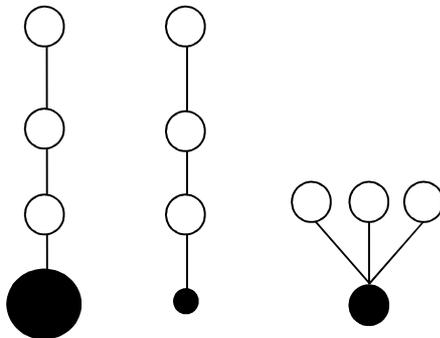


Figure 3: Three different cases (A-B-C) with patches (represented as circles) and links between the patches (represented as lines).

The denominator in IIC measures the amount of links in the shortest path between patch i and j . We propose to use the average Real Relative Asymmetry (RRA) at the patch of origin i instead of nl_{ij} because this includes more information of the configurational system as a whole. RRA numbers below 1 are integrated, and above 1 more segregated. Commonly, in contemporary Space Syntax studies, the reciprocal of RRA is taken so that the numbers are reversed to make it easier to understand and discuss the numerical data. We can use (1) to reformulate (2) as follows:

$$ICC_i = a_i LD_i / (1 + RRA_i) \quad (3) \quad \text{where}$$

a_i = the area of the patch of origin (i)

LD_i = Location Density (1)

RRA_i = average Real Relative Asymmetry at i

5. Results

(a) When comparing the LD numbers of the cells within a distance of 250 meter (the scale of operation for solitary bees) and 750 meter (the scale of operation for bumblebees), we see, not surprisingly, that the LD number increase in the larger parks and especially in the large natural area Ladugårdsgärdet. In other words, the conditions for bumblebees are better here than in the parks of Östermalm. For bees, also the park Humlegården and Vasaparken seem to perform well. This is not only due to their size, Vasaparken is actually rather small, but also and maybe foremost due to the location of these parks next to green urbanized areas. LD numbers are higher here than in the more isolated parks (e.g. Vanadislunden, Observatorielunden).

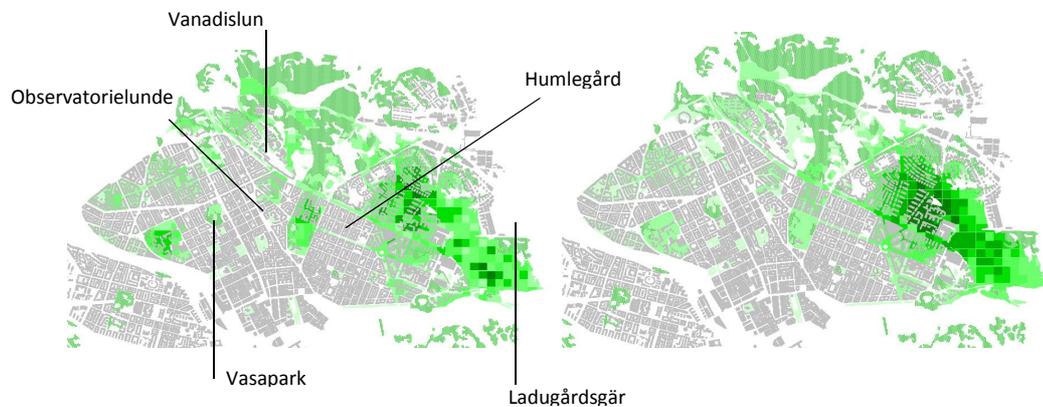


Figure 4: LD measured at a distance of 250 meter (left) and 750 meter (right).

A comparison of the LD and ICC numbers for the topological distance of 6 axial steps with a metrical limit of 500 meter resp. 3 km is shown in figure 5. It should be noted that the LD and ICC values are normalized by dividing each column by the column sum, creating a new variable whose values add to 1. This allows interpretation of the rescaled values as proportions or shares of the whole. This process of normalization shows first of all that LD* and ICC* numbers differ and they thus measure something substantially different. A comparison of the general statistics of LD and ICC calculation with a metrical limit of 3 km, show further that the ICC* numbers vary more than the LD* numbers (δ^2 is 3 resp. 1). More important, however, is that the LD map shows the presence of a set of good performing cells with higher LD numbers as the ICC map merely shows high numbers in the natural area Ladugårdsgärdet.

The presence of a network of good performing cells (i.e. high LD or ICC values) is important for the survival of bees in the long run. Ahrné (2004) has shown that less impervious surface, or a lack of green links, negatively impacts bee diversity. This means that more isolated patches (i.e. patches with less accessible patch area) are more vulnerable to the loss of whole bee populations due to e.g. climate change, severe winters or diseases. In other words, for the resilience of the system, the connectivity of patches is most important. We can thus conclude that for showing the network of patches, the LD measure is more effective than the ICC measure. In a later study we aim to validate this with observations in strategically chosen sites.

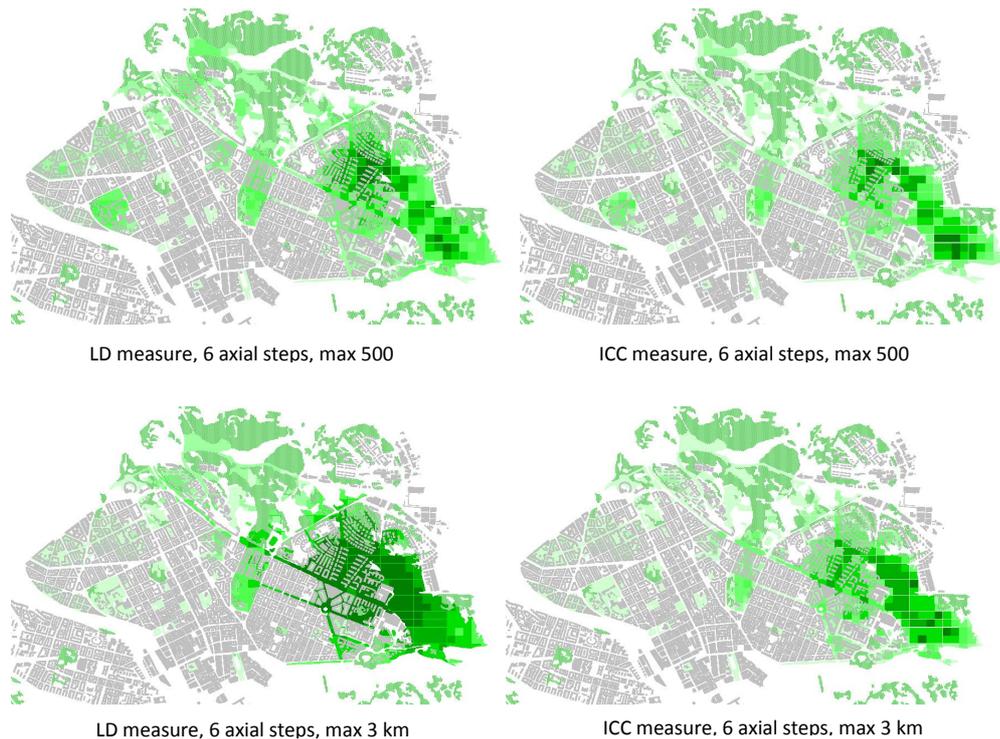


Figure 5: LD and ICC measured at a distance of 6 axial steps and with a limit of 500 m resp. 3 km.

6. Discussion

The next step will be to correlate the two measures, using different radii, to bee counts by observing solitary bees and bumblebees in various carefully selected sites in Östermalm. The main selection criteria are twofold: firstly, the local conditions (e.g. type of biotope, flower cover) should be similar and secondly, the LD numbers should differ so that we can conclude whether the measures capture bee abundance and diversity.

The observation will help us to find the right resolution for drawing the axial maps and further develop the method described in part 5. Only after validation can we start to discuss the impact this can have for urban planning and design. What we can say is that the results of the here proposed method to describe and measure the configuration of urban biotopes could be an important contribution to the more and more applied tool Biodiversity Area Factor (BAF) (Kazmierczak & Carter 2010). BAF as it is developed and used now focuses on local qualities only (mostly courtyards) and ignores the existence, or absence, of a network of patches.

References

- Ahrné, K., J. Bengtsson, and T. Elmqvist. 2009. "Bumblebees (*Bombus* spp) along a gradient of increasing urbanization." *PLoS ONE* 4 (5): e5574
- Alberti, M. 2008. *Advances in Urban Ecology: Integrating Humans and Ecological Processes in Urban Ecosystems*, Springer.
- Andersson, E., and Ö. Bodin. 2009. "Practical tool for landscape planning? An empirical investigation of network based models of habitat fragmentation." *Ecography*, 32, 123-132.

- Andersson, E., S. Barthel, and K. Arhné. 2007. "Measuring socioecological dynamics behind the generation of ecosystem services." *Ecological Applications* 17:1267-1278.
- Barthel, S., J. Colding, H. Erixon, H. Ernstson, S. Grahn, C. Kärsten, L. Marcus, and J. Torsvall (in print). *Principles of social-ecological urbanism – the case of Albano sustainable campus*. KTH.
- Berkes, F., and C. Folke. 1998. *Linking Social and Ecological Systems*. Cambridge University Press. Cambridge UK.
- Berkes, F., J. Colding, C. Folke. 2003. *Navigating Social-ecological systems*. Cambridge University Press, Cambridge, UK.
- Biesmeijer, J. C., S. P. M. Roberts, M. Reemer, R. Ohlemüller, and M. Edwards, et al. 2006. "Parallel declines in pollinators and insect-pollinated plants in Britain and the Netherlands." *Science* 313: 351–354.
- Bodin, Ö, and A. Zetterberg. 2010. *MatrixGreen v 1.6.4 User's Manual: Landscape Ecological Network Analysis Tool (www.matrixgreen.org)*. Stockholm: Stockholm Resilience Centre and KTH Royal Institute of Technology.
- Bolund, P., and S. Hunhammar. 1999. "Ecosystem services in urban areas." *Ecological Economics* 29: 293–301.
- Brito, L., and M. Stafford Smith. 2012. "State of the Planet Declaration." *Planet under Pressure: New Knowledge Towards Solutions*, International Council for Science.
- Buchmann, S. L., and G. P. Nabhan. 1996. *The forgotten pollinators*. Washington, DC: Island Press.
- Burton and Elizabeth. 2000. "The Compact City: Just or Just Compact? A Preliminary Analysis" *Urban Studies* 37: 1969.
- Colding, J. 2011. "The role of ecosystem services in contemporary urban planning." In *Urban Ecology. Patterns, Processes and Applications*, edited by J. Niemelä. 228-237. Oxford University Press. Oxford.
- Colding, J., L. Marcus, A. Gren, and M. Berghauser Pont (forthcoming). How smart is Smart Growth?
- Constanza, R., R. D'arge, R. de Groot, S. Farber, M. Grasso, B. Hannon, K. Limburg, S. Naeem, R. O'Neill, J. Paruelo, R.G. Raskin, P. Sutton, and M. van den Belt. "The value of the world's ecosystem services and natural capital." *Nature* 387: 253-260.
- Daily. 1997. *Nature's Services: Societal Dependence on Natural Ecosystems*. Island Press.
- Elmqvist, T., C. Folke, M. Nystrom, G. Peterson, J. Bengtsson, B. Walker, and J. Norberg. 2003. "Response Diversity, Ecosystem Change, and Resilience." *Frontiers in Ecology and the Environment* 1(9): 488-494.
- Greene, M., J. Reyes, and A. Castro. 2012. "Proceedings of the 7th International Space Syntax Symposium." Pontefica Universidad Catholica de Chile.
- Holling, C. 1973. "Resilience and Stability of Ecological Systems." *Annual Review of Ecology and Systematics* 4 1-23
- Hillier, B., and J. Hanson. 1984. *The Social Logic of Space*. Cambridge University Press, Cambridge.
- Hillier, B., A. Penn, J. Hanson, T. Grajewski, and J. Xu. 1993. "Natural movement: or, configuration and attraction in urban pedestrian movement." *Environment and*

Planning B: Planning and Design 20: 29-66.

Hillier, B. 1996. *Space is the machine*. London. Cambridge University Press.

Hillier, B., and S. Lida. 2005. "Network effects and psychological effects: a theory of urban movement." In *Spatial Information Theory, Lecture notes in computer Science 3603*, edited by A. Cohn and D. Mark (Springer Verlag, Berlin), 473-490.

Jaeger, J. A. G. 2000. "Landscape division, splitting index, and effective mesh size: new measures of landscape fragmentation." *Landscape Ecology* 15(2): 115–130.

Jansson, Å., and S. Polasky. 2010. "Quantifying biodiversity for building resilience for food security in urban landscapes: getting down to business." *Ecology and Society* 15(3):20

Kazmierczak, A., and J. Carter. 2010. *Adaptation to climate change using green and blue infrastructure*. A database of case studies.

Kearns, C. A., D. W. Inouye, N. M. Waser. 1998. "Endangered Mutualism: The Conservation of Plant-Pollinator Interactions." *Annu Rev Ecol Syst* 29: 83–112. doi:

Koch, D., L. Marcus., and J. Steen. 2009. "Proceedings of the 7th International Space Syntax Symposium." Trita-Ark-Research publication 1, KTH.

McFrederick, Q. S., and G. Le Buhn. 2006. "Are urban parks refuges for bumblebees *Bombus* spp. (Hymenoptera: Apidae)?" *Biol Conserv* 129: 372–382.

Marcus, L., and D. W. Colding. In review. "Towards an integrated theory of spatial morphology and resilient urban systems".

Marcus, Lars, and Johan Colding. 2011. "Towards a Spatial Morphology of Urban Social-Ecological Systems." Presented at the Montréal, Canada, 2011: *Urban morphology and the post-carbon city*, ISUF 2012 (the 19th International Seminar on Urban Form)

Matteson, K. C., J. S. Ascher, and G. A. Langellotto. 2008. "Bee richness and abundance in New York City Urban Gardens." *Ann Entomol Soc Amer* 101: 140–150.

Marini, Lorenzo, Bommarco Riccardo, Fontana Paolo, and Battisti Andrea. 2010. "Disentangling effects of habitat diversity and area on orthopteran species with contrasting mobility." In *Biological Conservation*.

Pauleit, Stephan, Ennos Roland, and Golding Yvonne. 2005. "Modeling the environmental impacts of urban land use and land cover change—a study in Merseyside, UK." *Landscape and Urban Planning* 71: 295–310.

Salvati, Luca, Munafo Michele, Gargiulo Morelli Vittorio, and Sabbi Alberto. 2012. "Low-density settlements and land use changes in a Mediterranean urban region." *Landscape and Urban Planning* 105: 43– 52.

Saure, C. 1996. "Urban habitats for bees: the example of the city of Berlin." *The Conservation of Bees*, edited by A. Matheson, S. L. Buchmann, C. O'Toole, P. Westrich, and I. H. Williams. pp. 47–54. New York: Academic Press.

Seto, K. C., et al. 2012. "Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools." *PNAS* 109(40): 16083-8.

Ståhle, A. 2008. *Compact Sprawl: Exploring Public Open Space and Contradictions in Urban Density*. Stockholm: KTH.

Ståhle, Alexander, Marcus Lars, and Karlström Anders. 2005. "Place Syntax - Geographic Accessibility with Axial Lines in GIS." In *Proceedings of the 5th International Symposium*

in Space Syntax.

- Tommasi, D., A. Miro, H. A. Higo, and M. L. Winston. 2004. "Bee diversity and abundance in an urban setting." *The Canadian Entomologist* 136: 851–869.
- UNEP. 2012. 21, J., Leonard, S.A. (Eds.), (UNEP), Nairobi, Kenya, 56pp.
- Vale, L. J, and T. J. Campanella. 2005. *The resilient city: How modern cities recover from disaster*. New York: Oxford University Press, NY, USA.
- Zetterberg, A., U. Mörtberg, and B. Balfors. 2010. "Making graph theory operational for landscape ecological assessments, planning and design." *Landscape and Urban Planning* 95(4): 181-191.
- Zetterberg, A. 2011. "Connecting the dots: Network analysis, landscape ecology, and practical application." Trita-LWR. PhD, KTH, Royal Institute of Technology. ISSN 1650-8602; 1062.