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INTEGRATING VISIBILITY GRAPH ANALYSIS (VGA) WITH CONNECTIVITY ANALYSIS IN LANDSCAPE ECOLOGY

META BERGHAUSER PONT
Chalmers University of Technology, Department of Architecture
meta.berghauserpont@chalmers.se

KARIN AHRNÉ
Swedish University of Agricultural Sciences, The Swedish Species Information Centre, Uppsala, Sweden
Karin.Ahrne@slu.se

ÅSA GREN
The Royal Swedish Academy of Sciences, The Beijer Institute of Ecological Economics, Stockholm, Sweden
asa.gren@beijer.kva.se

ANNA KACZOROWSKA
Chalmers University of Technology, Department of Architecture
lars.marcus@chalmers.se

LARS MARCUS
Chalmers University of Technology, Department of Architecture
lars.marcus@chalmers.se

ABSTRACT

Interest in urban green areas has rapidly increased in recent years as the world becomes increasingly urbanized (see e.g., McDonald, 2008, UN-habitat, 2016). This brings new demands for a deeper understanding of the morphology of green areas in cities that provide us with a range of important ecosystem services (ESS) such as evaporative cooling, water purification, micro climate regulation, recreation and even pollination (MA 2005; Andersson et al., 2007). If we also are to support or even enhance such services, we need to make this knowledge accessible for professionals in urban planning and design. In both regards we see the need to bring the fields of landscape ecology and urban morphology closer to each other. This papers addresses this, taking the ESS pollination as point of departure.

It has been acknowledged that besides the amount of green, also connectivity between green areas is important for most of these ESS (Alberti, 2008; Kindleman et al., 2008). The critical issue remains how connections are represented.

In this paper we propose an alternative approach inspired by space syntax where we introduce a method to capture urban form and their impact on movement behaviour of bumble bees. A first attempt to do so was discussed by Marcus et al. (2014) but instead of drawing connections using space syntax, we here propose to define the resistance to movement using visibility graph analysis (VGA). The level of visual integration can then be calculated based on the number of visual steps it takes to get from one point to any other point within the system. For species that navigate by sight this can be a rather simple and effective way to measure the cost or resistance

to move through an urban landscape. To test the method, observation data on bumble bees collected in 16 sites in Stockholm (Ahrné et al., 2009) are used.

KEYWORDS

Landscape ecology, connectivity, visibility graph analysis, least-cost-path analysis, nearest-neighbor-distance analysis

1. INTRODUCTION

Interest in urban green areas has rapidly increased in recent years as the world becomes increasingly urbanized (see e.g., McDonald, 2008; UN-habitat, 2016). This brings new demands for a deeper understanding of the morphology of green areas in cities that provide us with a range of important ecosystem services (ESS) such as evaporative cooling, water purification, micro climate regulation, recreation and even pollination (Millennium Ecosystem Assessment, 2005; Andersson et al., 2007). If we also are to support or even enhance such services, we need to make this knowledge accessible for professionals in urban planning and design. In both regards we see the need to bring the fields of landscape ecology and urban morphology closer to each other. This papers addresses this, taking the ESS pollination as point of departure.

It has been acknowledged that besides the amount of green, also connectivity between green areas is important for most of these ESS (Alberti, 2008; Kindleman et al., 2008). In landscape ecology, connections are often represented by straight lines although, in reality, these connections may have a quite crooked geometry. An alternative to the straight-line Euclidean distance is the more realistic least-cost path (LCP) length such as walking distance. However, LCP has proven to be of less importance than the LCP-accumulated-costs that also take into account impedances (i.e. resistance) along these paths due to, for instance, varying ground substrates (Etherington et al., 2013). Impedance can also be caused by built form and can be modelled by giving different paths a number representing the estimated impedance of the type of neighbourhood it crosses. The same metric distance from A to B will be larger if it traverses the city centre or an area of high rises in an open park setting.

However, from the point of view of urban design, these approaches are not really useful, since they translate built form from geometry to numbers, making it less accessible for design. It does not only seem difficult to estimate the impedance of built form in this manner, it also excludes creative design solutions. It are exactly these challenges this paper wants to address.

1.1 REPRESENTING GREEN CONNECTIVITY

This study aims to develop a method that includes real three-dimensional space into the measure of connectivity and accessibility in a LCP-accumulated-cost model. We propose a method inspired by space syntax following two papers by Marcus et al. (2014; 2017). There is reason to immediately clarify how one in landscape ecology does not find distinction between spaces for movement (i.e. streets) and spaces for occupation (i.e. plots and buildings) that is central in space syntax theory, in particular the notion of generic function (Hillier, 1996), and geometric representations of urban space, such as the axial map (Hillier and Hanson, 1984).

Landscape ecological descriptions structure the landscape into patches of different ecological content, primarily based on identified biotopes. Dependent on the agent, these can to different degrees be used for both movement and occupation. Flows between patches are here represented in more abstract manner based on geographical distance and impedances, as discussed above (Verbeylen et al., 2003).

The central question is, therefore, how the impedance created by built form, which is substantial in urban areas, can best be represented and measured so that it can inform professional urban designers. The originality of the axial map, is that it is not simply representing the physical environment, but rather its affordances (Gibson,1979), that is, what emerges in the meeting between properties of the physical environment and human abilities of both physical and

cognitive kinds (Marcus, 2015). It is therefore directly related to human activity in urban space, which seems to be the reason that it has proved so successful in capturing human movement in cities, for instance, correlating far better than metric distance (Hillier and Iida, 2005).

In parallel, what we aim for here, is a similar geometric representation that capture the affordances that emerge between the physical environment and central agents in need of connectivity between patches. This would allow us to better understand how to design the built environment as means to support such connectivity, which is essential for functioning ecosystems, which in turn is essential for many ESS. One clear example is the ESS pollination where pollinators such as bumble bees need to be able to fly between different resources found at different patches.

For humans, the axial map has proved successful, which basically is a network representation, where the components are geometric items in the form of straight lines representing the human affordances visibility and accessibility. For pollinators such as bumble bees, with their very different movement and visibility abilities, we suggest, that the visibility graph (Turner et al., 2001) is a better point of departure. Here all accessible space is divided into cells rather than lines, whereby the intervisibility and interaccessibility between these are calculated.

1.2 ESS POLLINATION AND CITIES

The ESS pollination is here chosen for two reasons. Firstly, pollination is highly dependent on the connectivity of green areas, especially where habitat comprises less than 30% of the total land cover, which is often the case in cities (Andren, 1994; Fahrig, 2001). Secondly, it is an essential ESS for the majority of food production in the world (Allen-Wardell et al., 1998; Klein et al., 2007) and therefore also representing a tremendous monetary value (Ricketts et al., 2004; Gallai et al., 2008).

Although cities are traditionally not the living environment for bees, due to increasing industrialization of agriculture, resulting in large rural monocultural areas, urban habitats have become more important for the survival of both bees and bumble bees (see e.g. Saure, 1996; Tommasi et al., 2004; Andersson et al., 2007; Matteson et al., 2008; Zetterberg, 2011). It is also pointed out how cities have a great potential to sustain pollinator populations if properly designed and managed (e.g. Andersson et al., 2007; Jansson and Polasky, 2010). Cities have even proven to act as source areas for surrounding landscapes in this respect (Saure, 1996; Tommasi et al., 2004; Matteson et al., 2008; Zetterberg, 2011).

1.3 EARLIER FINDINGS OF BUMBLE BEES IN STOCKHOLM

The impact of the urban environment on the abundance and diversity of bumble bees in cities has proven relevant in an earlier study from 2009, conducted in the Stockholm region (Ahrné et al., 2009). The study concludes that for the amount of bumble bees, local quality of sites, such as flower diversity, is most important, while the amount of green in surrounding neighbourhoods is not. The study also shows that the amount of impervious surface in the direct surroundings of the observation sites (radius up to 1 km), negatively affects the diversity of bumble bees. Since the amount of impervious surface also was strongly negatively related to the amount of green areas, this means that diversity of bumble bees increases with increasing amount of green areas in the surroundings. Bumble bee diversity is important because the different bee species are active during different parts of the season and will, hence, also contribute to pollination during different 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).

What the earlier study by Ahrné et al. (2009) does not give an answer to, is the question whether or not it is important how these green areas are distributed. In other words, it demonstrates that the amount of green is important, but not whether the configuration of these green areas matters. A study by Andersson et al. (2009) in Stockholm showed that "groups of well-placed small habitat patches can, together, be sufficient to attract birds in intensively developed areas".

This supports our hypothesis that urban form and the configuration of green areas matter.

1.4 OUTLINE

In this study a method to measure connectivity of urban green areas, based on the visibility graph, will be proposed and empirically tested using observation data on bumble bees collected by Ahrné et al. (2009).

In the following, we will, first, introduce the key elements of bumble bee behaviour in space (e.g. navigation of bumble bees, barriers, scales of operation). Second, we will introduce the distance measures tested in the model, present characteristics of the land cover data and introduce the 16 sites. Third, we present the findings from these tests and, fourth, discuss the implications for both research and practice.

2. BUMBLE BEES AND THEIR BEHAVIOUR IN SPACE

2.1 NAVIGATION OF BUMBLE BEES

It is mainly the search for nectar and pollen as well as nesting sites that generates movement of bumble bees through the landscape. They use visual range and flower scent to find food and navigate the landscape (McFredrick et al., 2008). In controlled experiments bumble bees and honey bees were found to rely on visual cues, rather than magnetic pass information, to locate the correct corner of a rectangular box where they had previously been rewarded with a sugar solution (Dittmar et al., 2014). The same experiment shows that bumble bees rely more on visual (colours) than on geometric cues, and more on distant visual cues than on local ones.

Bumble bees are central place foragers meaning that they start from a specific site (their nest) and need to return to that site to unload their collected nectar and pollen. Individual bumble bees are also known to return to the same foraging locations that they have previously visited (Osborne and Williams 2001). Bumble bees do not communicate the direction and location of food sources to fellow bees (as do e.g., honey bees). However, they seem to communicate the scent of the plant they foraged on to their nest mates, the odour helps recruits to find the food source used by a successful forager (Dornhaus and Chittka, 1999). There is also evidence that individual bumble bees are more likely to return to plants with higher rates of nectar secretion implying a relatively developed spatial memory when searching for food (Cartar, 2004).

2.2 BARRIERS THAT MIGHT GENERATE IMPEDANCE

Altitude (building height) – It has been shown that bees can fly at air pressure equivalents exceeding 7,4km above sea level (Dillon and Dudley, 2014). However, they typically don't, if there are no resources up high. Although there are few studies directly investigating the regular flight height above ground for foraging bees, it has been suggested that about 2m above ground is a common altitude (Riley et al., 1999). Hence, buildings may act as a barrier, forcing bees to navigate around it, unless there is some resource attached to the building, e.g., a green roof, a green wall, or flowers on balconies, which will make the trip worthwhile.

Paved areas and roads – Paved areas might not necessarily generate a resistance towards movement, but they have been shown to have a negative impact on nesting densities (Jha and Kremen, 2013) and landscapes with large amounts of paved roads and impervious construction have fewer species and lower nesting densities of bumble bees that mainly nest in the ground (Jha and Kremen, 2012; Ahrné et al., 2009). While bumble bees have the ability to cross a road and railroad, these human structures may restrict bumble bee movement and act to fragment plant populations because of the innate site fidelity displayed by foraging bumble bees (Bhattacharya et al., 2003).

Water – Since water bodies do not provide food nor nest sites, they can, depending on the size of the water body and the quality and quantity of the surrounding matrix, form a barrier to bumble bees.

Wind – It has been shown that bees can maintain direct routes between the forage areas and their nests even in winds with a strong cross-track component (Riley et al., 1999). Furthermore, Riley et al. (ibid) suggest that a simple strategy to keep on track in cross-winds would be for the bumble bees to use a sun compass for navigation.

Air pollution – Floral hydrocarbons provide essential signals to attract pollinators. As soon as they are emitted to the atmosphere, however, hydrocarbons start to decompose due to chemical reactions involving pollutants, such as ozone. It is therefore likely that increased air pollution interferes with pollinator attracting hydrocarbon signals. For highly reactive volatiles the maximum downwind distance from the source at which pollinators can detect the scents may have changed from kilometres during pre-industrial times to less than 200m during the more polluted conditions of present times (McFredrick et al., 2008). When patches of flowers are further apart than the visual range of pollinators, as in fragmented landscapes, the loss of scent signals may mean that pollinators spend more time searching for patches and less time foraging, which will make them more dependent on other visual cues, such as the depth of the environment and the sun compass.

2.3 SCALE OF OPERATION BASED ON FORAGING RANGE

Landscape connectivity is important on two scales: 1) day-to-day movement and 2) population dynamics (Dyck and Baguette, 2005). In this study, we focus on day-to-day movement. Foraging range, which is the day to day flight range for bumble bees, is known to vary among species and has been explained by nest size (Rundlöf et al., 2008) and mean body size of individuals within species (Westphal et al., 2006). However, the drivers of foraging range among bumble bees are still debated (Goulson, 2003). Different methods have been used to estimate foraging distance among bumble bees. Osborne et al. (1999) studied bumble bee foraging range using harmonic radar and found a bumble bee mean foraging distance of 275m and a range of 70-631m. In recent years microsatellites have become an established method to estimate foraging distances in bumble bees. The results of studies using this method have found a range of 449-758m (Knight et al., 2005)[1]. Based on the review of foraging distances for different bumble bee species we will test three foraging distances with a maximum of 1km.

3. METHOD

As discussed earlier, we will compare the straight-line Euclidean distance to measure green accessibility with a LCP accumulated-cost model, based on built form using visibility graph analysis (VGA). VGA enables us to measure variations of visible integration across urban environments without having to draw lines that connect the green areas. Instead, the green areas will get a weight based on the VGA that reflects its spatial position in the network of open spaces. The visibility graph is derived from a map where all buildings in the urban landscape are regarded as barriers. The resources for bees (green areas, forest and arable land) are defined in a similar way as in the earlier study of Ahrné (2009).

The study areas and observation data in this paper are identical to those in the study of Ahrné et al. (2009): 16 allotment gardens in Stockholm region (figure 1). These gardens are generally intensively managed, flower rich, green areas, thus potentially good habitats for bumble bees.

3.1 VISIBILITY GRAPH ANALYSIS

Instead of including all green areas within the distance threshold of 300m, 500m or 1km, as was used by Ahrné et al. (2009), the VGA allows us to include a distance weight to the green areas defined by intervisibility and interaccessibility. ´Visual step depth' is a measure that can be derived from VGA and calculates distance in terms of visual steps instead of metric distance.

1 In this study in an arable landscape in the UK foraging distances of four bumble bee species, also common in Sweden, were estimated: Bombus terrestris (758m), B. pascuorum (449m), B. lapidarius (450m) and B. pratorum (674m).

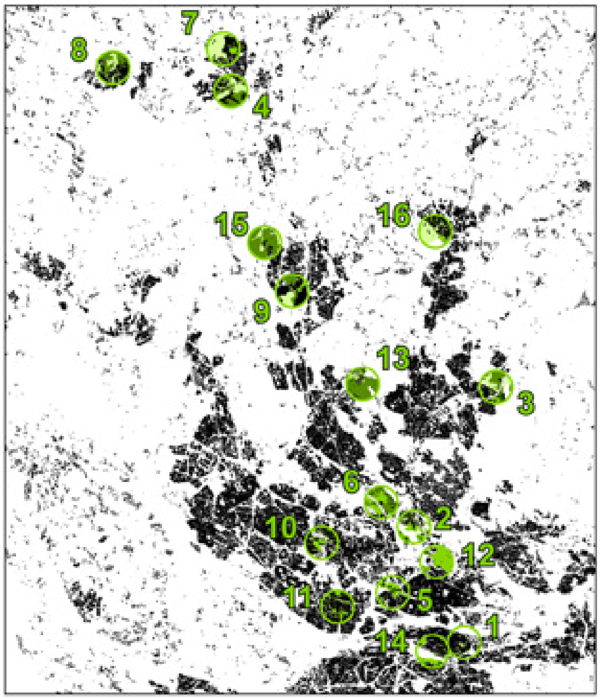

Figure 1 - Position of the 16 allotment gardens in Stockholm

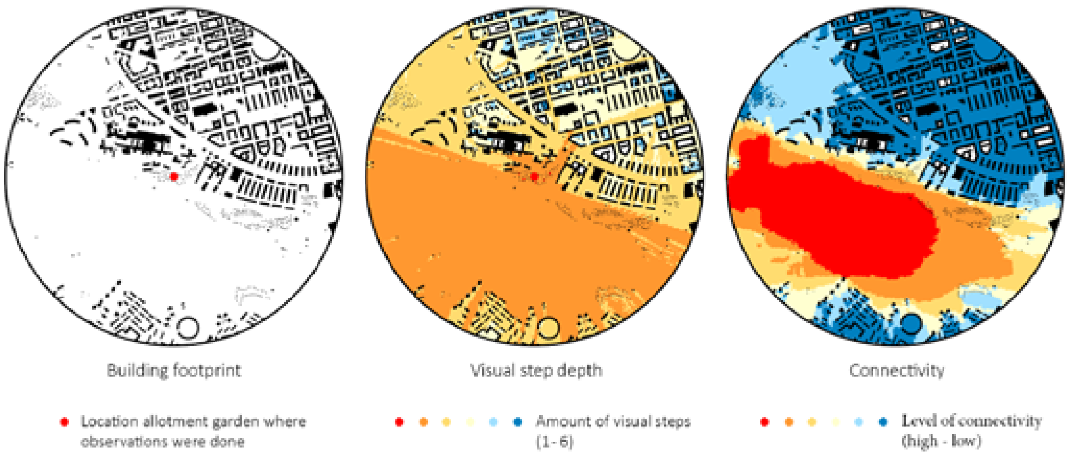

Figure 2 - Two methods to weigh the LCP accumulated-cost model using VGA: visual step depth and connectivity.

The map in figure 2 shows in orange the open space that can be overseen from the points of origin (in red); in yellow, the open spaces that can be seen in the second step and in blue we find areas that are located furthest away in terms of visual distance. This analysis can be repeated for every location in the urban landscape resulting in a measure of 'connectivity'[2]. A low connectivity (in blue) indicates that little of the context is visible in one step; high connectivity is shown in red (figure 2).

2 We even tested the measure 'integration' which calculates how many visual fields one has to move through to reach the whole area and multiplied this value with the area of green. However, this is not a distance measure in the same manner as visual step depth is. We therefore do not report this further in this paper. Results were not significant either, see appendix.

3.2 LAND COVER DATA AND MODEL

We used the land cover dataset CadasterENV (http://www.cadasterenv.se/), which is a Swedish land cover dataset with a resolution of 10m and compare this to the Corine dataset[3] with a resolution of 25m. This finer grained dataset has the advantage that the distribution of green and impervious surfaces is better capturing reality (figure 3). In other words, the modifiable areal unit problem (MAUP) [4] is less of a problem in the CadasterENV dataset than in the Corine dataset.

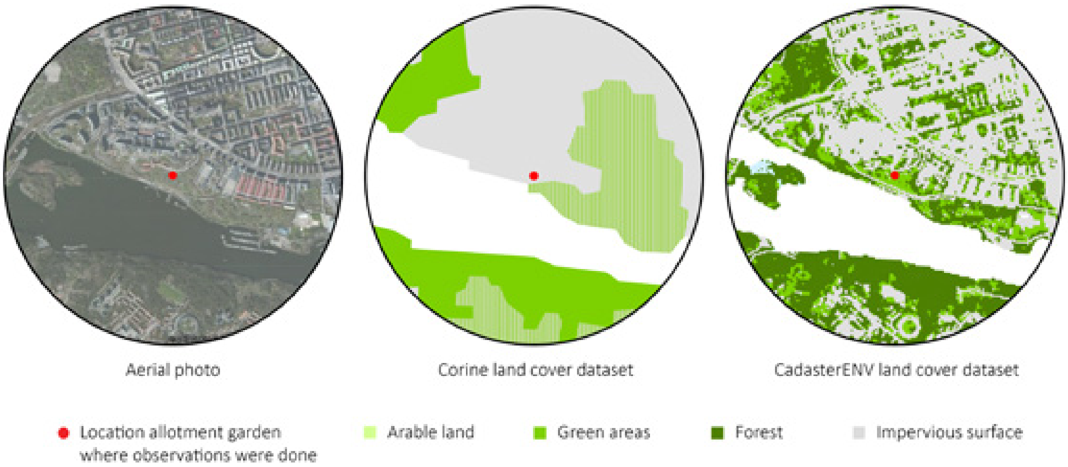

Figure 3 - Comparison of Corine and CadasterENV land cover dataset

The land cover categories defined in CadasterENV (Metria, 2015) are used and grouped according to the study of Ahrné et al. (2009) with four categories: impervious (I), green areas (G), forest (F) and arable land (A). Class 41 is defined as "other open land with less than 10% vegetation cover" and the areas of this class are therefore included for 95% in category impervious (I) and for 5% in category green areas (G)[5]. Class 42 has more than 10% vegetation: 45% of the area is included in category impervious (I) and 45% in category green areas (G). An overview of all cases with the spatial distribution of these categories is shown in figure 4.

Besides the land cover dataset, a building density model is used to map buildings that we know are one of the main barriers for bumble bees. The footprint of buildings are the barriers in the VGA. Besides the footprint of buildings, a height model is used to calculate the built volume (3D-coverage). This also allows us to specify the building density of the cases along the urban-periurban gradient. The Spacematrix method developed by Berghauser Pont and Haupt (2010) will be used to calculate Floor Space Index (FSI) and Ground Space Index (GSI).[6]

3 Also referred to as Corine Land Cover, CLC (Coordination of Information on the Environment *Land* Cover).

4 MAUP is a source of statistical bias that can radically affect the results of statistical hypothesis tests. It affects results when point-based measures of spatial phenomena (e.g. population density) are aggregated into districts.

5 See for a detailed overview how the Corine data and CadasterENV data is grouped, the appendix.

6 GSI is calculated by dividing the total amount of built up area with the total area of land reached within a 1 km radius; FSI is calculated by dividing the total amount of floor space with the total area of land reached within a 1 km radius. For more details see Berghauser Pont and Haupt (2010).

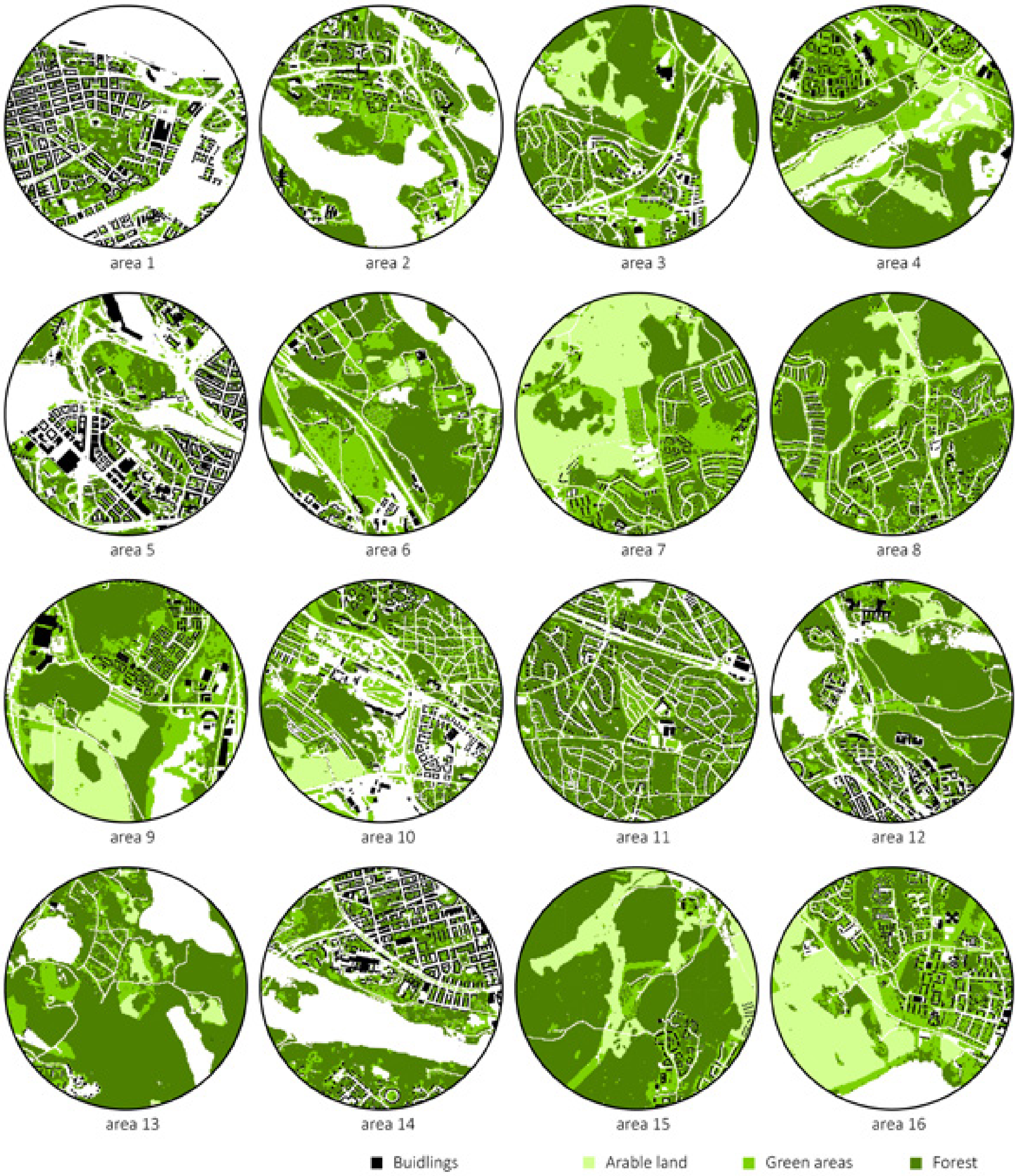

Figure 4 - 16 allotment gardens in Stockholm with the amount of green divided in green areas (G), forest (F) and arable land (A) using the CadasterENV dataset (radius 1km).

3.3 SPATIAL ANALYSIS

The software used is Mapinfo 15.0 for the accessibility analysis within 300m, 500m and 1km and Depthmap for the VGA. The following spatial analysis were conducted:

- For the straight line distance model we calculated the sum of the area of each land cover group (I, G, F, A) separately and all green combined within the radii 300m, 500m and 1km. To compare our results with Ahrné et al. (2009) we used both the Corine dataset and the CadasterENV dataset.

- For the LCP accumulated-cost model we used visual step depth and divided the area of each land cover group by this distance (i.e. average amount of visual steps). An area 3 steps away from the origin counts for 33 % and an area within the first visual field counts 100 %.

Figure 5 shows the results of the VGA analysis using visual step depth where especially the more urban cases show large variation in visual distance. Areas very close to the sites of observation can be visually far away. The observation data is shown in table 1 and include bumble bee abundance and bumble bee diversity. Diversity is measured as amount of species, Simpson Index of diversity (1-D) and rarefaction. The latter is used when discussing results as it corrects the outcome by sample size; for more details see Ahrné et al. (2009). In total 1937 bumble bee individuals of 13 species were observed. The number of species observed per allotment garden ranged between 5 and 11.

ID	Area name	Municipality	Abundance	Diversity	Simpson Index of Diversity (1-D)	Rarefaction species
1	Barnängen	Stockholm	107	7	0,72	5,74
2	Bergshamra	Solna	139	9	0,80	6,48
3	Gröna Hägern	Täby	190	11	0,87	8,47
4	Kaprifolen	Sigtuna	72	8	0,85	7,15
5	Karlbergs Bro	Stockholm	39	5	0,61	4,28
6	Kvarnvreten	Solna	123	10	0,80	6,40
7	Lupinen	Märsta	108	7	0,83	6,29
8	Sigtuna	Sigtuna	25	8	0,81	8,00
9	Smedby	Upplands Väsby	105	8	0,81	6,66
10	Solvalla	Stockholm	39	7	0,75	6,49
11	Stora Mossen	Stockholm	170	9	0,81	6,36
12	Söderbrunn	Stockholm	208	10	0,87	7,75
13	Södersättra	Sollentuna	172	10	0,88	8,59
14	Södra årstalunden	Stockholm	196	9	0,69	5,16
15	Vaxmyra	Upplands Väsby	141	11	0,83	7,22
16	Väsby	Upplands Väsby	103	9	0,76	6,20

Table 1 - Observation data 16 allotment gardens (Ahrné et al. 2009)

The observation data is correlated with the results from the spatial analysis using IBM SPSS Statistics 22. The table with all correlations can be found in the appendix, but the most relevant findings will be presented in the next section.

4. FINDINGS

4.1 COMPARING THE CORINE AND CADASTERENV DATASET

Our findings correspond to those presented by Ahrné et al. (2009) which confirms that our model is reliable and can be used to test the other models and measures. The main result is that the amount of impervious surface in the direct surroundings of the observation sites (radius up to 1 km) negatively affects the diversity of bumble bees. The amount of forest is positively associated with the diversity of bumble bees, but green area and arable land are not (table 2). [7] The latter might be explained by the fact that green areas, being mostly grasslands, and arable land, where all vegetation is taken away to provide space for growing crops, are very monotonous and that this does not provide a good foundation for diversity. The abundance of bumble bees does not correlate with any of the spatial measures, which corresponds to earlier findings that showed that the amount of bees is most affected by site-specific characteristics such as flower abundance or plant species richness and not contextual factors (Ahrné et al. 2009).

7 For all correlations, see appendix.

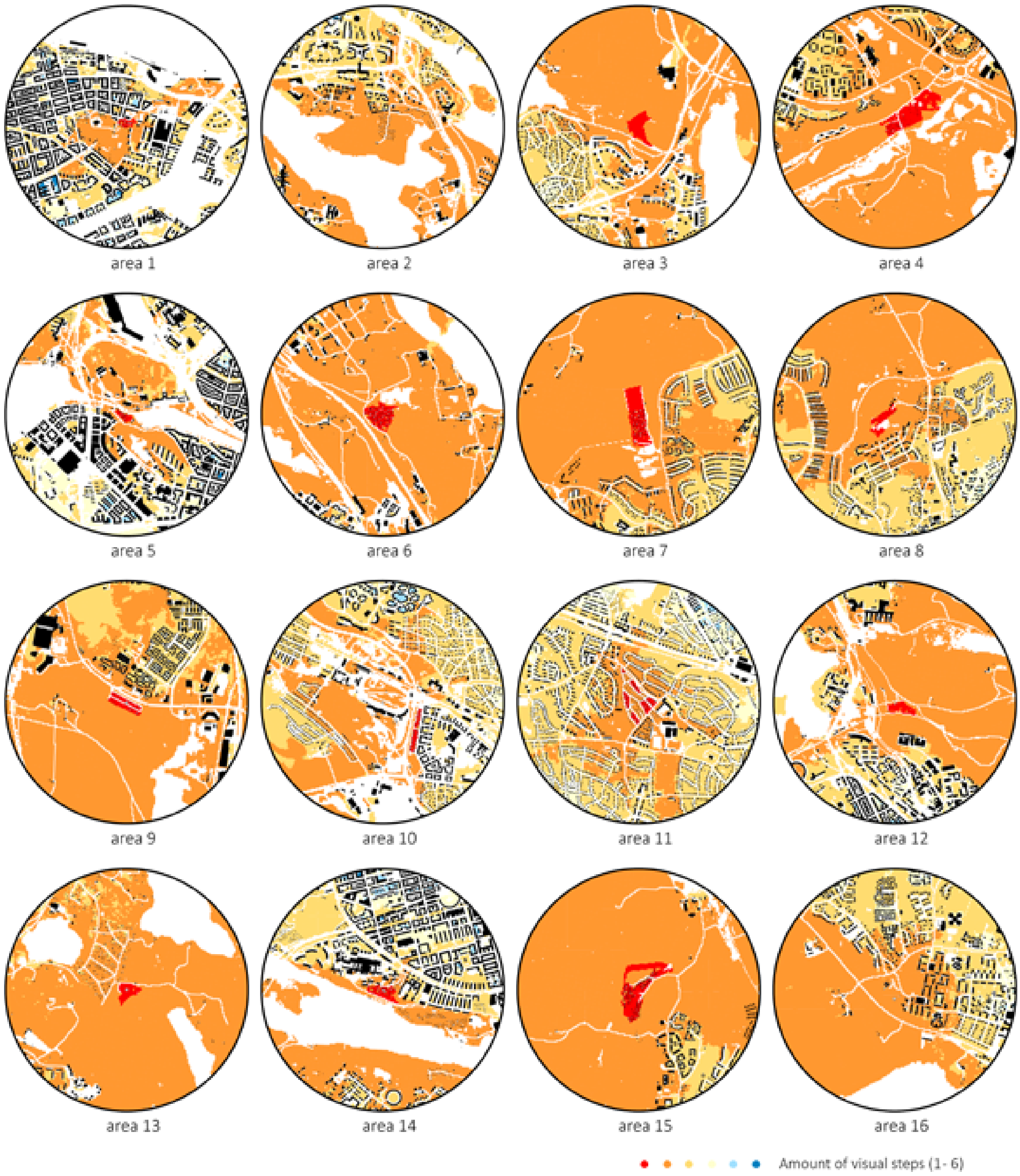

Figure 5 - 16 allotment gardens in Stockholm showing the results of the VGA using visual step depth with the location of observation as origin (radius 1km)

The same results are found with the CadasterENV dataset where we find slightly higher correlations for bumble bee diversity, both when we relate to the amount of impervious surface (negative correlation) and the amount of forest (positive correlation). Further, the trend is significant at the 0.01 level for all radii which was not the case when using the Corine dataset. This is probably due to higher resolution of the CadasterENV dataset making the calculations more accurate.

Area *m2*	Land cover category I	 G	 F	 A	 G+F+A
Corine 300m	-,542*	not sig	,617*	not sig	,537*
Corine 500m	not sig	not sig	,610*	not sig	,549*
Corine 1km	-,628**	not sig	,608*	not sig	,637**
CadasterENV 300m	-,664**	not sig	,705**	not sig	,774**
CadasterENV 500m	-,609*	not sig	,753**	not sig	,715**
CadasterENV 1km	-,702**	not sig	,724**	not sig	,654**

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Table 2 - Correlation bumble bee diversity and spatial analysis (straight line distance model), comparing the two land cover datasets: Corine and CadasterENV (I=impervious, G=green areas; F=forest; A=arable land)

Forest *Radius 1km*	ALL	11 cases
Green area (CadasterENV)	,724**	,670*
Green area / VGA depth	,707**	,693*
GSI	-,785**	not sig

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Table 3 - Correlation bumble bee diversity and spatial analysis, comparing the straight line distance model to the LCP accumulated-cost model

4.2 COMPARING THE STRAIGHT LINE DISTANCE AND LCP ACCUMULATED-COST MODEL

When moving from the straight line distance model to the LCP accumulated-cost model, we find slightly lower correlations when using the distance measure 'visual step depth' (table 3).[8] We could thus conclude that the simple straight line model is sufficient.

However, as our cases are located along an urban-periurban gradient it might be so that more subtle differences are overshadowed by the differences in urban density. We found that the 16 cases can be divided in three groups: high dense, medium dense (or suburban) and rural (figure 6). By marking the points by their level of bumble bee diversity, we can see that especially the three urban cases stand out with low diversity . Two interesting things can be concluded from this. Firstly, we know that FSI and GSI in combination describe building types in an efficient way (Berghauser Pont and Haupt, 2010): combined higher values of FSI and GSI describe closed building blocks and combined low values are associated with more permeable building patterns. These measures show high correlations with bumble bee diversity and demonstrate that the permeability of the urban landscape is important. This brings us to the second interesting issue. If indeed the built pattern plays an important role, it can be interesting to look at the relation between access to green and diversity in each cluster separately. However, we do not have enough cases in each category, but can look into the correlations for the suburban cases alone, thus excluding the most urban and rural cases.

8 We even tested the impact of heavy trafficked roads and large open water areas by excluding the green areas on the "wrong" side of the barrier, but none of the correlations were significant. Traffic flow of more than 40.000 cars daily (yearly mean, source Trafikverket) were considered as barrier. For water we used a threshold of 200m.

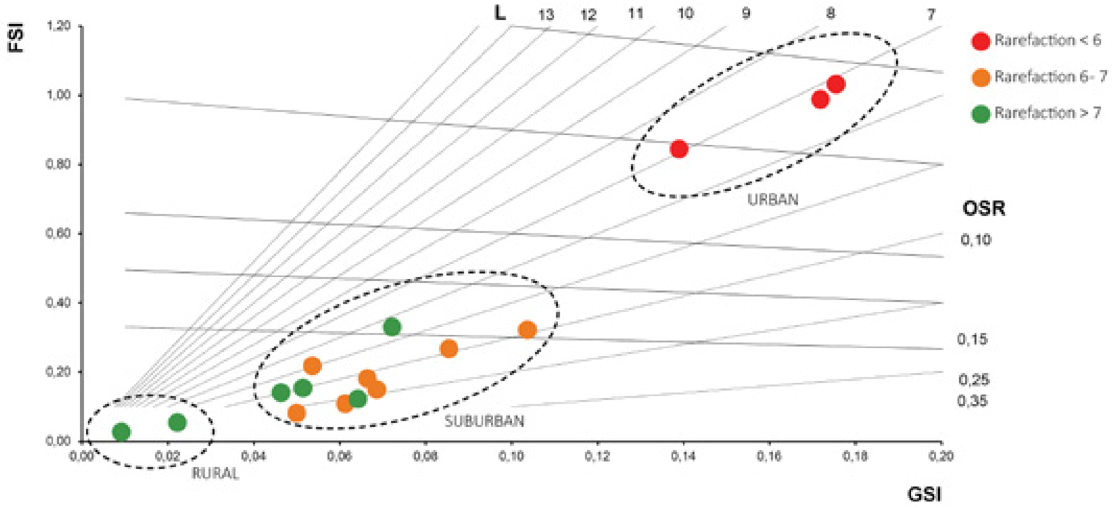

Figure 6 - Spacematrix showing the 16 cases and their built density values GSI on the x-axis and FSI on the y-axis, marked with the level of bumble bee diversity using different colours.

The statistical analysis with only the 11 suburban cases, shows that GSI and the amount of impervious surface do not play a significant role anymore. In other words, these variables cannot explain the variety in bumble bee diversity for these 11 cases. The only two measures that show a significant relation to diversity are amount of forest (F), measured with straight line distance, and weighted with the visual step depth distance measure. The latter is slightly higher than the first indicating that visual distance starts playing a more important role for the diversity of bumble bees when looking at the suburban cases alone. We expect this trend to be even stronger when only studying urban cases. However, with only three cases in this group, we cannot prove this hypothesis.

5. DISCUSSION

We have shown in this paper that the spatial distribution of green areas and buildings is important for managing pollinator diversity. We have further shown that using too rough datasets can be misleading when predicting this diversity. We have also presented that GSI can be used as a good first indicator for bumble bees´ diversity without considering green areas at all. The more urbanized and the higher GSI the less diversity can be expected. Further, we have shown that within one and the same density category, in our case suburban, we start to see that the visual distance to natural green (i.e. forest) starts to play a more important role. This indicates that built density limits the movement of bumble bees through the urban landscape, but within this limitation, the distribution of green can improve or worsen movement potential, depending on the visual distances between green areas, especially forest. Forest in this case does not consist of large forested areas, rather smaller patches with trees. Thus, including a lot of edge habitat between forest and other landscape types which could potentially provide nesting sites for bumble bees.

Our suggestion to use the visibility graph (Turner et al., 2001) to calculate the intervisibility and interaccessibility between green spaces has shown to be a promising way forward, especially within urban areas of the same type, that is, level of urbanization. This is important for urban design because when working in urbanized area, it is often the distribution of green that can be influenced and less the amount of green. We have shown that this is of importance for the diversity of bumble bees.

Although these are exciting findings and we see them as a start of a novel approach for finding a representation of the affordances of the physical environment that are central for green connectivity and ecosystem services (ESS) that depend on flows of species between locations, it is important to be transparent about the limitations of the study. Hence, based on those limitations, in order to arrive at a better understanding of the performance of our cities in terms of ecosystem services, we sum up the most important next steps:

- The test of a higher resolution land cover dataset showed how important it is to be precise. The categories green area, forest and arable land are, however, still very crude and the results showed that especially forest in urbanized areas is important. We presumed that these areas are the least disturbed by people, but we do not know this for a fact. Looking into the qualities of the green areas is therefore an important next step.
- Highly trafficked roads did not seem to form a barrier, but we only tested this for roads with more than 40.000 cars daily and this should obviously be tested for various thresholds. The same can be said about water as a barrier, where we now only tested 200 m.
- The way we weighted the green areas using the results of the VGA could be done in several ways and should be elaborated more on. We simply divided the area by the visual distance (step depth) where all green areas were treated equally, but other options should be tested such as adding a metric distance decay to let both metric distance and visual distance play a role.

Apart from the above mentioned methodological issues, maybe the most important next step would be to set up a study in highly urbanized areas. We did show that visual distance played a more important role when looking into the suburban cases alone and we assume that this will be even more so in the very urban cases. However, we only had three urban cases and could not use this data to proof our hypothesis.

Further, until now we only looked at bumble bees and it would of course be interesting to test if we can find similar results when looking at other species that might be impacted by visual impedances when moving through the urban landscape. It is only then that we can start to formulate some general findings for urban designers and how the design of our cities can in general stimulate biodiversity and not only bumble bee diversity.

Then, these results should be linked back to the how human beings use our cities as we do not built cities for bumble bees, but hopefully we can start building them so that all species can co-exist in cities.

Also, biodiversity is an essential parameter for building resilience. Hence, it would be most interesting and urgent to apply and test this methodological lens for building resilient cities.

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APPENDIX

ID	Corine *3 digits*	Corine *5 digits*	Beskrivning
1	111	111	Tät stadstruktur
2	112	11211	Orter >200 invånare och mindre omr av grönt
3	112	11212	Orter >200 invånare och med större områden av grönt
4	112	1122	Orter <200 invånare
5	112	1123	"Enstaka hus och gårdsplaner"
6	121	121	Industri, handelsenheter, offentlig service, mm
7	122	122	Väg och järnvägsnät med kringområden
8	123	123	Hamnområden
9	124	124	Flygplats
14	141	141	Urbana grönområden
18	142	1424	Golfbana
19	142	1425	Ej urban park
30	211	211	Åkermark
31	222	222	Frukt och bärodling
32	231	231	Betesmark
40	311	3111	Lövskog ej på myr eller berg i dagen
41	311	3112	Lövskog på myr
42	311	3113	Lövskog på berg-i-dagen
43	312	31212	Barrskog på lavmark
44	312	312121	Barrskog ej på lavmark 7-15 meter
45	312	312122	Barrskog ej på lavmark > 15 meter
46	312	3122	Barrskog på myr
47	312	3123	Barrskog på berg-i-dagen
56	312	31212	Barrskog, ej på lavmark
48	313	3131	Blandskog ej på myr eller berg i dagen
49	313	3132	Blandskog på myr
50	313	3133	Blandskog på berg-i-dagen
54	324	3242	Hygge
55	424	4243	Ungskog

Land cover classes Corine dataset

Kod/Code	Klass/Class
0	Oklassificerat/Unclassified
1	Skog/Forest
2	Öppen våt mark/ Open wet land
3	Jordbruksmark/ Arable land
4	Övrig öppen mark/ Other open land
41	*Övrig öppen mark utan vegetation/ Non-vegetated other open land*
42	*Övrig öppen mark med vegetation/ Vegetated other open land*
5	Exploaterad merk/Artificial non-vegetated surfaces
51	*Byggnader/ Built-up areas*
52	*Exploaterad mark, ej hus /Non Built-up areas*
6	Vatten/ Water
61	*Sjöar och vattendrag/ Inland water surfaces*
62	*Hav/ Marine water surfaces*
254	Moln/Clouds/No data

Land cover classes CadasterENV dataset

	Corine 5 digits
I - Impervious surface	1 + 0,65*2 + 0,4*3 + 0,4*4 + 0,55*5 + 6 + 7 + 8 + 9
G - Green areas	0,35*2 + 0,6*3 + 0,6*4 + 0,45*5 + 14 + 18 + 19 + 31 + 32
F - Forest	40 + 41 + 42 + 43 + 44 + 45 + 46 + 47 + 48 + 49 + 50 + 54 + 55 + 56
A - Arable land	30

	TRANSLATION 5 digits to 3 digits
I - Impervious surface	111 + 0,5*112 + 121 + 122 + 123 + 124
G - Green areas	0,5*112 + 141 + 142 + 222 + 231
F - Forest	311 + 312 + 313 + 324 + 424
A - Arable land	211

	CadasterENV
I - Impervious surface	51 + 52 + 0,95*41 + 0,45*42
G - Green areas	0,05*41 + 0,55*42
F - Forest	1
A - Arable land	3

Translation of the datasets to the classes used in the paper: impervious surface (I), green areas (G), forest (F) and arable land (A)

Correlations

		Abundance	Diversity	Rarefaction species	1-D
Abundance	Pearson Correlation	1	,730**	,283	,398
	Sig. (2-tailed)		,001	,289	,127
	N	16	16	16	16
Diversity	Pearson Correlation	,730**	1	,654**	,676**
	Sig. (2-tailed)	,001		,006	,004
	N	16	16	16	16
Rarefaction species	Pearson Correlation	,283	,654**	1	,905**
	Sig. (2-tailed)	,289	,006		,000
	N	16	16	16	16
1-D	Pearson Correlation	,398	,676**	,905**	1
	Sig. (2-tailed)	,127	,004	,000	
	N	16	16	16	16

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

Correlations

		Abundance	Diversity	Rarefaction species	1-D
Abundance	Pearson Correlation	1	,762**	,193	,579
	Sig. (2-tailed)		,006	,569	,062
	N	11	11	11	11
Diversity	Pearson Correlation	,762**	1	,449	,469
	Sig. (2-tailed)	,006		,166	,145
	N	11	11	11	11
Rarefaction species	Pearson Correlation	,193	,449	1	,709*
	Sig. (2-tailed)	,569	,166		,015
	N	11	11	11	11
1-D	Pearson Correlation	,579	,469	,709*	1
	Sig. (2-tailed)	,062	,145	,015	
	N	11	11	11	11

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

Correlations bumble bee abundance, diversity, rarefaction species and Simpson Index of diversity, for all sites (left) and suburban sites (right).

Correlations

		Cor_R300_I	Cor_R300_G	Cor_R300_F	Cor_R300_A	Cor_R300_GFA	Cor_R500_I	Cor_R500_G	Cor_R500_F	Cor_R500_A	Cor_R500_GFA	Cor_R1000_I	Cor_R1000_G	Cor_R1000_F	Cor_R1000_A	Cor_R1000_GFA
Abundance	Pearson Correlation	,120	-,130	,114	-,206	-,259	,081	-,065	,132	-,254	-,157	-,199	,243	,080	-,139	,159
	Sig. (2-tailed)	,658	,632	,675	,444	,332	,764	,812	,626	,342	,562	,461	,365	,769	,608	,556
	N	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
Diversity	Pearson Correlation	-,289	-,284	,555*	,014	,277	-,334	-,227	,557*	-,063	,342	-,612*	,028	,535*	-,004	,611*
	Sig. (2-tailed)	,277	,286	,026	,959	,299	,206	,398	,025	,816	,195	,012	,917	,033	,987	,012
	N	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
Rarefaction species	Pearson Correlation	-,542*	-,324	,617*	,236	,537*	-,448	-,290	,610*	,159	,549*	-,628**	-,161	,608*	,104	,637**
	Sig. (2-tailed)	,030	,220	,011	,375	,032	,082	,276	,012	,555	,028	,009	,551	,012	,702	,008
	N	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
1-D	Pearson Correlation	-,633**	-,317	,495	,337	,517*	-,576*	-,258	,501*	,287	,578*	-,746**	-,059	,503*	,271	,717**
	Sig. (2-tailed)	,008	,231	,051	,202	,040	,020	,334	,048	,281	,019	,001	,827	,047	,310	,002
	N	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

Correlations

		Cad_R300_I	Cad_R300_G	Cad_R300_F	Cad_R300_A	Cad_R300_GFA	Cad_R500_I	Cad_R500_G	Cad_R500_F	Cad_R500_A	Cad_R500_GFA	Cad_R1000_I	Cad_R1000_G	Cad_R1000_F	Cad_R1000_A	Cad_R1000_GFA
Abundance	Pearson Correlation	-,257	-,081	,376	-,095	,229	-,251	-,403	,374	-,180	,118	-,353	-,448	,348	-,185	,091
	Sig. (2-tailed)	,336	,767	,151	,725	,395	,349	,121	,153	,505	,662	,180	,082	,187	,494	,737
	N	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
Diversity	Pearson Correlation	-,604*	,049	,643**	,092	,597*	-,591*	-,121	,670**	-,004	,525*	-,702**	-,172	,695**	-,032	,510*
	Sig. (2-tailed)	,013	,856	,007	,735	,015	,016	,656	,005	,988	,037	,002	,523	,003	,906	,044
	N	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
Rarefaction species	Pearson Correlation	-,664**	,001	,705**	,322	,774**	-,609*	-,065	,753**	,182	,715**	-,702**	,036	,724**	,110	,654**
	Sig. (2-tailed)	,005	,996	,002	,224	,000	,012	,812	,001	,500	,002	,002	,896	,002	,685	,006
	N	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
1-D	Pearson Correlation	-,707**	,281	,564*	,416	,794**	-,714**	,115	,666**	,351	,781**	-,778**	,190	,663**	,282	,732**
	Sig. (2-tailed)	,002	,292	,023	,109	,000	,002	,672	,005	,182	,000	,000	,482	,005	,290	,001
	N	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

Correlations

		VGA_Int_I	VGA_Int_G	VGA_Int_F	VGA_Int_A	VGA_Int_GFA	VGA_Dep_I	VGA_Dep_G	VGA_Dep_F	VGA_Dep_A	VGA_Dep_GFA	CON_mean	GSI	FSI
Abundance	Pearson Correlation	-,240	-,114	,242	-,056	,167	-,422	-,306	,339	-,161	,141	,283	-,200	-,066
	Sig. (2-tailed)	,371	,675	,366	,837	,536	,104	,249	,200	,550	,602	,287	,457	,807
	N	16	16	16	16	16	16	16	16	16	16	16	16	16
Diversity	Pearson Correlation	-,101	,296	,587*	,180	,526*	-,582*	,027	,718**	-,022	,561*	,613*	-,638**	-,546*
	Sig. (2-tailed)	,709	,263	,017	,504	,036	,018	,921	,002	,937	,024	,012	,008	,029
	N	16	16	16	16	16	16	16	16	16	16	16	16	16
Rarefaction species	Pearson Correlation	-,118	,273	,455	,157	,415	-,550*	,115	,707**	,108	,630**	,504*	-,785**	-,726**
	Sig. (2-tailed)	,663	,307	,077	,562	,110	,027	,672	,002	,691	,009	,047	,000	,001
	N	16	16	16	16	16	16	16	16	16	16	16	16	16
1-D	Pearson Correlation	-,013	,467	,446	,321	,463	-,550*	,313	,662**	,289	,716**	,624**	-,856**	-,824**
	Sig. (2-tailed)	,961	,068	,084	,226	,071	,027	,238	,005	,278	,002	,010	,000	,000
	N	16	16	16	16	16	16	16	16	16	16	16	16	16

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

Correlations all sites (16): Corine dataset (above), CadasterENV dataset (middle) and VGA (below).

Correlations

		Cor_R300_I	Cor_R300_G	Cor_R300_F	Cor_R300_A	Cor_R300_GFA	Cor_R500_I	Cor_R500_G	Cor_R500_F
Abundance	Pearson Correlation	,130	,212	-,224	-,232	-,388	,269	,338	-,203
	Sig. (2-tailed)	,703	,531	,509	,492	,239	,424	,310	,549
	N	11	11	11	11	11	11	11	11
Diversity	Pearson Correlation	,147	,130	,277	-,247	,163	,207	,244	,286
	Sig. (2-tailed)	,667	,703	,410	,464	,633	,542	,470	,394
	N	11	11	11	11	11	11	11	11
Rarefaction species	Pearson Correlation	-,285	-,313	,639*	,098	,340	,122	-,246	,559
	Sig. (2-tailed)	,395	,349	,034	,774	,306	,721	,466	,074
	N	11	11	11	11	11	11	11	11
1-D	Pearson Correlation	-,499	-,378	,397	,176	-,073	-,187	-,259	,365
	Sig. (2-tailed)	,118	,251	,226	,606	,832	,581	,443	,269
	N	11	11	11	11	11	11	11	11

		Cor_R500_A	Cor_R500_GFA	Cor_R1000_I	Cor_R1000_G	Cor_R1000_F	Cor_R1000_A	Cor_R1000_GFA
Abundance	Pearson Correlation	-,296	-,201	,029	,521	-,297	-,160	,046
	Sig. (2-tailed)	,377	,553	,932	,100	,376	,638	,894
	N	11	11	11	11	11	11	11
Diversity	Pearson Correlation	-,359	,123	-,106	,359	,206	-,322	,222
	Sig. (2-tailed)	,278	,718	,756	,278	,544	,334	,511
	N	11	11	11	11	11	11	11
Rarefaction species	Pearson Correlation	-,038	,146	-,056	-,110	,456	-,145	,208
	Sig. (2-tailed)	,911	,667	,871	,749	,159	,670	,540
	N	11	11	11	11	11	11	11
1-D	Pearson Correlation	,082	,121	-,301	-,008	,259	,062	,386
	Sig. (2-tailed)	,810	,723	,369	,981	,442	,856	,241
	N	11	11	11	11	11	11	11

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Correlations

		Cad_R300_I	Cad_R300_G	Cad_R300_F	Cad_R300_A	Cad_R300_GFA	Cad_R500_I	Cad_R500_G	Cad_R500_F
Abundance	Pearson Correlation	-,226	-,111	,514	-,219	,355	-,129	-,455	,551
	Sig. (2-tailed)	,505	,744	,106	,518	,284	,704	,160	,079
	N	11	11	11	11	11	11	11	11
Diversity	Pearson Correlation	-,412	-,323	,780**	-,334	,478	-,189	-,296	,715*
	Sig. (2-tailed)	,208	,333	,005	,316	,137	,579	,377	,013
	N	11	11	11	11	11	11	11	11
Rarefaction species	Pearson Correlation	-,487	-,705*	,767**	-,057	,559	-,216	-,676*	,697*
	Sig. (2-tailed)	,129	,015	,006	,867	,074	,524	,022	,017
	N	11	11	11	11	11	11	11	11
1-D	Pearson Correlation	-,659*	-,358	,617*	,076	,637*	-,544	-,611*	,614*
	Sig. (2-tailed)	,028	,279	,043	,823	,035	,084	,046	,044
	N	11	11	11	11	11	11	11	11

		Cad_R500_A	Cad_R500_GFA	Cad_R1000_I	Cad_R1000_G	Cad_R1000_F	Cad_R1000_A	Cad_R1000_GFA
Abundance	Pearson Correlation	-,268	,154	-,185	-,681*	,248	-,251	-,186
	Sig. (2-tailed)	,426	,652	,586	,021	,462	,457	,584
	N	11	11	11	11	11	11	11
Diversity	Pearson Correlation	-,419	,215	-,262	-,582	,435	-,450	-,188
	Sig. (2-tailed)	,200	,525	,437	,060	,181	,165	,581
	N	11	11	11	11	11	11	11
Rarefaction species	Pearson Correlation	-,192	,321	-,278	-,506	,670*	-,260	,250
	Sig. (2-tailed)	,571	,336	,408	,112	,024	,440	,458
	N	11	11	11	11	11	11	11
1-D	Pearson Correlation	,034	,498	-,519	-,522	,588	-,068	,365
	Sig. (2-tailed)	,921	,119	,102	,100	,057	,841	,270
	N	11	11	11	11	11	11	11

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Correlations

		VGA_Int_I	VGA_Int_G	VGA_Int_F	VGA_Int_A	VGA_Int_GFA	VGA_Dep_I	VGA_Dep_G	VGA_Dep_F	VGA_Dep_A	VGA_Dep_GFA	CON_mean	GSI	FSI
Abundance	Pearson Correlation	-,113	-,250	,223	-,202	-,008	-,232	-,452	,238	-,220	-,082	,120	,026	,400
	Sig. (2-tailed)	,740	,459	,509	,551	,981	,493	,163	,481	,516	,812	,724	,939	,223
	N	11	11	11	11	11	11	11	11	11	11	11	11	11
Diversity	Pearson Correlation	,014	-,099	,415	-,458	,003	-,166	-,273	,501	-,430	-,013	,220	-,132	,129
	Sig. (2-tailed)	,967	,773	,204	,157	,993	,625	,417	,117	,187	,969	,515	,699	,705
	N	11	11	11	11	11	11	11	11	11	11	11	11	11
Rarefaction species	Pearson Correlation	-,106	-,241	,493	-,243	,151	-,286	-,405	,693*	-,256	,269	,126	-,324	-,020
	Sig. (2-tailed)	,756	,474	,123	,471	,657	,394	,216	,018	,448	,424	,711	,331	,954
	N	11	11	11	11	11	11	11	11	11	11	11	11	11
1-D	Pearson Correlation	,045	,042	,682*	,076	,509	-,379	-,230	,686*	-,038	,480	,442	-,428	,004
	Sig. (2-tailed)	,896	,902	,021	,823	,110	,250	,496	,020	,912	,131	,174	,189	,991
	N	11	11	11	11	11	11	11	11	11	11	11	11	11

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Correlations suburban sites (11): Corine dataset (above), CadasterENV dataset (middle) and VGA (below).