Ecological Indicators 36 (2014) 100–110

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

# The Theorized Urban Gradient (TUG) method—A conceptual framework for socio-ecological sampling in complex urban agglomerations

Salman Qureshi[a,b,*], Dagmar Haase[a], Richard Coles[b]

[a] Department of Geography, Humboldt University of Berlin, Rudower Chaussee 16, 12489 Berlin, Germany
[b] School of Architecture, Birmingham City University, Gosta Green, Birmingham B4 7DX, UK

ARTICLE INFO

*Article history:*
Received 16 November 2012
Received in revised form 7 June 2013
Accepted 11 July 2013

*Keywords:*
Ecological sampling
GIS
Landscape ecology
Land-use modelling
Megacities
Socio-ecological complexity
Urban ecological principles
Urban ecosystem

ABSTRACT

Mega-urbanization is a major driving force of environmental changes and sustainability because of its speed, scale and worldwide connectivity. Megacities, due to their spatial extent, multicultural demographic structure and multifunctional land-uses, demand new sophisticated scientific approaches to meet the challenges posed by these socio-ecological complexities. Scientists studying megacities are always confronted with the challenge of stratifying their sampling sites for in-depth field investigations particularly in developing countries where the urban landscapes do not expand in line with any predetermined plans – nevertheless with paradigmatic phenomena. This challenge becomes more complicated when considering socio-ecological studies because of the complexity of coupled human–environmental systems where multifunctional composites of land-uses and respective land cover interplay. This paper presents a conceptual framework for developing an urban gradient model, adapted from a set of scientific postulates to systematically hypothesize the selection of research/sampling sites in the field in large urban agglomerations. This framework, due to its scientific legitimacy, is named the Theorized Urban Gradient (TUG). It is based on the assumption that it would allow examination of field/data samples from a variety of urban structures incorporating different functional characteristics. An application of the framework is presented for the megacity of Karachi, Pakistan, comparing the TUG with other standard sampling methods to test and to show the value and the advantages of it. A systematic selection of samples in a compact and informally growing urban landscape is justified. Results corroborate urban gradient, being supported by deductive scientific postulates, as an important research method rather than merely a modelling approach.



## 1. Introduction

Megacities are unique ecosystems where humans inhabit a multi-functional and multi-attributed complex environment regulated by a composite of interacting land-use forms (Qureshi et al., 2010a,b). These ecosystems are derivatives of a dynamic coupling of human and natural systems where many land-use variables interplay (Haase, 2005), and form a complex mosaic of biological and physical patches within a matrix of infrastructure, social institutions, cycles and order (Machlis et al., 1997; Zipperer et al., 2000). The processes of urbanization have left a fragmented mosaic of habitat patches of varying size, shape, character and number where the quality of contact between patches varies considerably from location to location (Young and Jarvis, 2001). This situation makes it complicated for scientists to stratify their samples for field investigations, since the heterogeneous mosaics of such patches contain unique structural and functional attributes. It is even more difficult to characterize such complex mosaics in urban landscapes when considering social analyses.

Urban ecology has been seen as an anthropocentric approach to landscape ecology (Farina, 2006; Vink, 1982). Nevertheless, little work has been done in integrating ecology with sociology (Carpenter et al., 1999; Fry et al., 2007; Liu, 2001). However, integrated studies of coupled human and natural systems reveal new but typically complex patterns and processes (Grant et al., 2002) not evident when studied by social or natural scientists separately (An, 2012). The integration of ecology with socioeconomic and management practice has been strongly emphasized (Wu, 2008) – to promote interdisciplinary and transdisciplinary approaches to achieve sustainability (Wu and Hobbs, 2002; Wu, 2006). The debate, how this integration should be realized best, is already

* Corresponding author at: Department of Geography, Humboldt University of Berlin, Rudower Chaussee 16, 12489 Berlin, Germany. Tel.: +49 030 2093 6803; fax: +49 030 2093 6848.
*E-mail addresses:* salmanqureshi@uok.edu.pk, salman.qureshi@geog.hu-berlin.de, salman.qureshi@geo.hu-berlin.de (S. Qureshi).

1470-160X/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ecolind.2013.07.010

well established (Breuste et al., 1998; Daniels, 1988; Naveh, 1995; Termorshuizen and Opdam, 2009; Turner, 1988), but a sampling framework that could theoretically justify the selection of field samples supported by (landscape) ecological principles, systematized with social sciences' concepts, is acutely required. The urban gradient paradigm (McDonnell and Hahs, 2008; McDonnell and Pickett, 1990; McDonnell et al., 1993) has been widely applied in the urban environment as an important measure for studying varying types of samples in urban landscapes (Burton et al., 2005; Germaine and Wakeling, 2001; Hahs and McDonnell, 2006; McDonnell et al., 1997; Qureshi et al., 2010a, 2013; Niemelä et al., 2002; Pouyat et al., 1995), where the study samples are selected from different zones of urbanization. Often, the justification for selecting specific patch/landscape types has not been articulated systematically by the support of an appropriate theoretical explanation (e.g. Hedblom and Söderström, 2008; Kong and Nakagoshi, 2006; Magle et al., 2009). More specifically, the social dimension of an urban gradient concept has found to be missing during the site selection process; a process which should be an integral component of studies on human dominated ecosystems (Dow, 2002; Qureshi et al., 2010a, 2010b).

This paper presents a conceptual framework to rationalize the above discussion and to formulate a set of criteria for study site or sample selection in complex urban landscapes. The framework has been tested regarding its suitability for assessing the structural and functional characteristics of selected urban spaces. This paper reports on the interim results of the framework construct, its initial implementation and testing for on-going research and debate on the socio-ecological modelling of urban nature in megacities. The two main research questions being addressed are:

- How to develop an integrated sampling method which can select samples across different urban structural forms and functional units?
- What is the scientific framework to justify the selection of specific sample(s) – supported by systematized postulates which override mechanical (conventional) sampling methods?

### 1.1. Sampling – setting the scene for the TUG method

Sampling[1] is a method of selecting a subset of individuals from within a population or space to estimate the characteristics of the whole population or area. It is practically impossible to study the whole population or space within limited resources. Therefore, researchers always use and justify the use of different sampling techniques (Farina, 2006; Forman and Godron, 1986).

Landscape ecologists commonly use four major techniques for selecting field samples. Random sampling, being the simplest one has been widely used but criticized as being generalized in nature. It is usually carried out when the area under study is fairly uniform, very large, and or there is limited time available (cf. Yates et al., 2008 and an example for a city in Strohbach and Haase, 2012). When using random sampling techniques, large numbers of samples/records are taken from different positions within the habitat. Stratified random, being one of the widest used techniques, is used to take into account different areas (or strata) which are identified within the main body of a habitat. These strata are sampled separately from the main part of the habitat (cf. Strohbach et al., 2009, for the example of urban bird richness and social neighbourhood quality).

[1] This paper focuses only the ecological sampling techniques being used to study the landscapes in urban milieu whilst coupling human–natural systems or social-ecological systems per se.

Line transects are used when it is desired to illustrate a particular gradient or linear pattern along which communities of plants and/or animals change. They provide a good way of visualizing the changes taking place along the line. Depending on how detailed the line transect is, they can usually be accomplished fairly quickly (cf. Kroll et al., 2012 for assessing urban and peri-urban ecosystem services demand and supply). A line transect tells you what is there, but gives limited information on how much of it is present, for detailed density information a belt transect must be carried out. This is similar to the line transect method but gives information on abundance as well as presence, or absence of species. It may be considered as a widening of the line transect to form a continuous belt, or series of quadrats.

In grid/quadrats, samples are arranged in a regular pattern such as lines, rectangular arrays, and hexagonal patterns (cf. again Strohbach et al., 2009). Depending on sample size and the distribution of samples, this sampling pattern may be inadequate, e.g. misrepresenting heterogeneity. An alternative approach is the use of Plotless Methods, these do not use a defined area (like a quadrat), nor are they arranged linearly as in transect methods, rather, they use distances between a point and an individual, or between two individuals, the nearest neighbour method. The plotless method is particularly useful in areas where carrying out large quadrats would be difficult to manage such as dense forest, also being suited to habitats that are relatively uniform.

## 2. Methodology framework

### 2.1. Study area and justification

The megacity of Karachi, the business capital of Pakistan, has been selected as the study area (Fig. 1). It is a mushroom-form-like city, expected to accommodate 27.5 million people in 2020 (MPGO-CDGK, 2007), one of the fastest growing megacities of the World (Hasan, 1999). With its suburbs, Karachi spreads over 3530 km$^2$; having an estimated population of 21 million (Khan, 2012). The city is responsible for generating around 65 percent of the country's economic GDP.

The main reasons for selecting Karachi as a case study area are:

(i) Enormous population explosion, high urbanization rate, underestimated and wrong projection of population statistics internationally (see UNPD (2012) for current estimates; Khan (2012) and MPGO-CDGK (2007) for local/official estimates).
(ii) Karachi has an estimated backlog of 90,000 housing units per year; half of the city's population lives in squatter or informal settlements (MPGO-CDGK, 2007; GOP, 2000).
(iii) Karachi has six independent cantonments areas (controlled by the military administration) in addition to 18 administrative towns (controlled by the CDGK); having a 135 km long coast line within its administrative control proving a unique and geostrategically important city.
(iv) Fourteen out of fifteen of the largest megacities in the world have been studied at least once by major international organization – Karachi unfortunately lacks attention from the scientific community (Qureshi, 2010).
(v) In the consequence of environmental changes, Karachi is a city under proven stress of climate change (cf. Sajjad et al., 2009).

Karachi is particularly well suited for testing the Theorized Urban Gradient (TUG) as it is extremely heterogeneous, provides highly complex land-use and socioeconomic patterns and is dynamically developing. Karachi is typified by its heterogeneity and thus demonstrates the difficulties presented when sampled by homogeneous raster schemes or linear gradients; random


**Fig. 1.** Study area: Karachi with administrative settings.

sampling, would require a high number of sites which by far exceeds the budgets of most landscape planning departments. Socio-cultural aspects and public perception vary significantly throughout the city (Qureshi et al., 2013), thus, studies at local scale (site level) remain a challenge due to firstly – their limited spatial extent and secondly – due to the fact that patterns of socio-cultural settings within a small neighbourhood cannot be generalized for the whole city with 20 million inhabitants.

## 2.2. Selection of indicators and urban gradient development

In the first phase of the study, the major objective was to conduct a land-use and land-cover (LULC) classification of the city to gain a general overview about the cityscape with special emphasis on classifying the urban green spaces. A cognition network, adopting the approaches of diagnostic and semantic views offered by Lang et al. (2006), was used for extracting the net coverage of the natural areas. In the absence of the most recent satellite image, an extensive GPS based field mapping exercise was conducted to give updated information of selected areas which showed abjection in their shape and/or area and which were to be mapped using TUG.

For site-level investigations, the urban gradient model of Karachi was used where six major urban indicators (Table 1) were selected in respect of their importance and representativeness during the process of urbanization. A growing body of literature helps to justify the selection of such indicators. Impervious surfaces (Lu and Weng, 2006), urban green (Hahs and McDonnell, 2006), porous/pervious surfaces, population distribution (Du Toit et al., 2009), road network (Cilliers and Bredenkamp, 2000) and socio-economic conditions (Dow, 2000; Cilliers et al., 2009) were selected as the major drivers of urbanization and urban land-use change. The requirement of multi-scale indicators of urban gradient requires the use of a wide range of datasets. Table 2 presents the details of the data sources used to extract the various layers (in raster grid format) for multivariate aggregation. Population density index, road density index, urban forest cover (including all green/vegetated structures), sealed surfaces and socio-economic status of the population in Karachi were ranked and summed-up using map algebra in GIS framework. A Gradient Index was developed using five classes; the first showing the 'highly urbanized areas' and the last the 'least urbanized areas'.

Each of these indicators was extracted following a different procedure so as to improve accuracy and to reduce complexity. In the first stage, the urban land-use/land-cover (LULC) was classified using the Landsat ETM+ image for the year 2003; topographic

**Table 1**
Selected indicators of urbanization used to characterize the urban gradient.

| Measure | Description |
|---|---|
| Impervious | Generally built-up structures where most of the land is covered by sealed surfaces like buildings, roads and artificially surfaced area covering almost all the ground. Technically these areas are surfaces with concrete, asphalt, tamacadam, or stabilized, e.g. beaten earth. An average amount of impervious surface calculated at the pixel level from the impervious surface fraction image created using image data mentioned in Table 2. |
| Pervious/porous | Herein a collective term for bare soil, brown fields, abandoned land, hilly areas including rocks, etc. |
| Green cover | Herein a collective term for areas with vegetation within urban fabric including urban parks, playgrounds, trees, forest, agricultural land (see Qureshi et al., 2010b for full definition of concept). |
| Population | Total number of people in census collection district, expressed as the number of people per hectare. |
| Road network | Length of existing public roads, ranging from local roads to national freeways. |
| Socio-economic status | Indicated by income, education, house type/ownership and mode of transportation, etc. |

**Table 2**
Datasets used for LULC classification and development of urban gradient model.

| Data | Stand | Scale/resolution | Publisher/source |
|---|---|---|---|
| *Image data* | | | |
| Landsat TM | 1990, 1992, 1998 | 30 m | Downloaded from Global Land Cover Facility programme website, University |
| Landsat ETM+ | 2000, 2003 | 15 m | of Maryland, USA. http://glcfapp.umiacs.umd.edu |
| QuickBird image | 2006 | 61 cm | Digital image archive, Remote Sensing Lab. Department of Geography, University of Karachi, Pakistan |
| *Land use* | | | |
| Topographical maps | 1992, 1996 | 1:50,000 | Geographical Survey of Pakistan |
| Karachi guide map | 2003 | 1:40,000 | Geographical Survey of Pakistan |
| Karachi land use map | 1991 (Projected for 2000) | 1:250,000 | Karachi Development Authority, Master Planning and Environmental Control Department |
| *Vector maps* | | | |
| Road network | 2006 | 1:10,000 | Developed using high resolution satellite images; processed and digitized in Remote Sensing lab., Department of Geography, University of Karachi, Pakistan |
| *Statistical data* | | | |
| Population | 1998 | (i) Town level; (ii) UC level; (iii) Charges/circles level. | Statics from the Census Department, Govt. of Pakistan Initial vectorization by Arsalan, 2002; updated and adjusted by author for this study |
| Socio-economic | 2005 | Town level | Socio-economic study conducted by Japan International Cooperation Agency Pakistan (2005) |

*Note:* Landsat images were used for temporal LULC classification and feature extraction like settlements, open spaces (e.g. urban green), sealed surfaces and unused land.

maps of the city assisted substantially to cope with the challenge faced because of the size of the study area (ca. 1300 $km^2$). We preferred to use a pre-monsoon satellite image data so that inconsistency of classification results can be controlled, as the monsoon brings enormous but short-term changes to the landscape of the City (Pithawalla et al., 1946). Later follows the feature extraction of selected indictors; urban built-up structures, urban green and urban pervious/porous locations were extracted from the classified LULC of Karachi. A very high resolution QuickBird image was used for developing a comprehensive road network where all major and minor roads were digitized on-screen. Adjustment of this data layer was done using a GPS survey so as to have an accurate and detailed road map of the city.

All the feature layers were predominantly developed to comprehend the density indices of respective urbanization indicators. This was done in ESRI's ArcGIS© where each density index was classified into five classes. Density indices of impervious surfaces, urban green, road network, population and socio-economic status were developed; each of these five classes were assigned a weight from 1 to 5 (e.g. 1 = no vegetation, 2 = less vegetation, 3 = moderate vegetation, 4 = dense vegetation, 5 = completely covered with green with no other land use). Using these weights, the classes were then added using Map Algebra. Subsequently, all indices were integrated to produce the urban gradient of Karachi having five zones of urbanization, later reclassifying the combined layers into three broader classes which helped to identify growth corridors from the central commercial area (e.g. City centre or Central Business Area). Classes were systematically adjusted involving further reduction by a process of manual interpretation to avoid redundancy and being overwhelmed by spatial subdivisions of the megacity. This involved examining the transition (fuzzy) areas between two immediate/neighbouring zones, checking the structural and functional aspects demonstrated; based on the resemblance of these urban structure/functions these fuzzy areas were reallocated to the closest resembling or nearest class so that the broader, city-wide and overall urbanization zones could be conceptually created (for sample selection and targeting specific neighbourhoods). It should be noted that the original five zones were kept intact for visualization (see Fig. 3) but three clearly demarcated, obvious and readily visible zones were needed to identify the most, least and moderately urbanized areas which effectively helped identifying on-ground samples.

### *2.3. Principles of site selection in urbanizing landscape – the TUG method*

The core message of landscape ecology is understanding how the landscape functions and how the pattern of the landscape influences its function (Termorshuizen and Opdam, 2009). It validates one of the basic principles of landscape ecology, i.e. the continuous interaction between structure and function (Forman and Godron, 1986). Since the spatial pattern of selected urban structures is investigated by the remote sensing methods, the functional assessment of the urban structures can be adapted to the framework presented by Zipperer et al. (2000), see also Flores et al. (1998) (see Table 3) i.e. to study the landscapes based on

(i) content,
(ii) context,
(iii) dynamics,
(iv) connectivity,
(v) heterogeneity and
(vi) hierarchy.

**Table 3**
Definition of key ecological principles applicable to ecological research and land-use decisions in urban landscapes (Zipperer et al., 2000).

| Principle | Definition |
|---|---|
| Content | The structural and functional attributes of a patch where "structure" is the physical arrangement of ecological, physical and social components, and "function" refers to the way the components interact. |
| Context | The patch's location relative to the rest of the landscape as well as the adjacent and nearby land units that are in direct contact or linked to a patch by active interactions. |
| Dynamics | How a patch or patch mosaic changes structurally and functionally through time. |
| Connectivity | How spatially or functionally continuous a patch, corridor, network or matrix of concern is |
| Heterogeneity | The spatial and temporal distribution of patches across a landscape. Heterogeneity creates the barriers or pathways to the flow of energy, matter, species, and information |
| Hierarchy | A system of discrete functional units that are linked but operate at two or more scales. Proper coupling of spatial and temporal hierarchies provides a key to simplifying and understanding the complexity of urban landscapes |

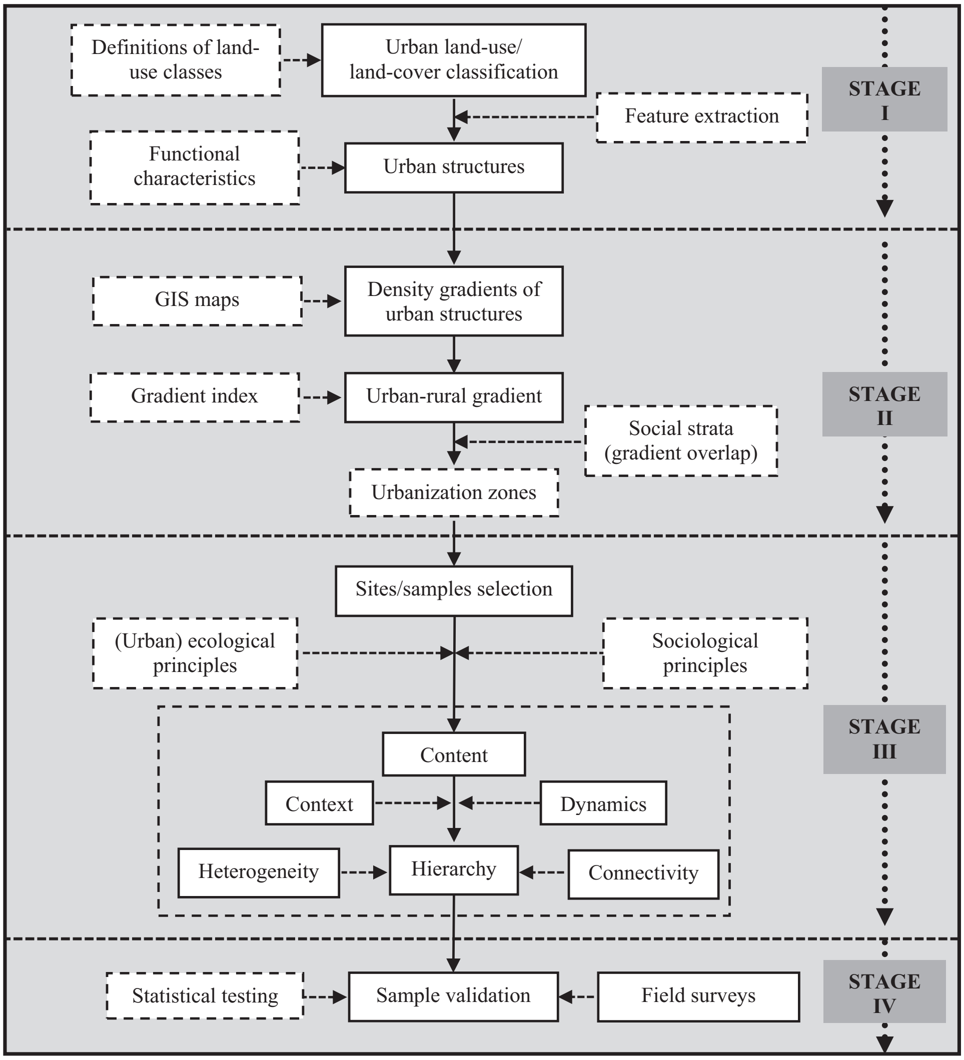


**Fig. 2.** TUG conceptual model and stages of execution.

Dow (2002) stated that, through a landscape ecology approach urban areas can be visualized as mosaics composed of discrete urban spaces, such as parks, called 'patches'. Urban green spaces (parks, street trees and landscape, playgrounds, etc.) are lungs of the city (Grahn and Stigsdotter, 2003). Each type of urbanized zone in Karachi bears more than 300 green spaces. Karachi has more than 1250 green spaces (patches). In this study, it is attempted to integrate the approaches of ecosystem-gradient and patch-dynamic as suggested by Dale et al. (2000), utilizing the structural assessment by remote sensing, their integrated gradient development and the functional assessment of patches through standard ecological principles. The selection of study sites utilized a classification of urban green spaces based on the functional characteristics of natural spaces in Karachi (Qureshi and Breuste, 2010). Accordingly, three sites, each from highly urbanized, moderately urbanized and least urbanized areas of Karachi were selected to test the practical implications of the framework. The overall approach is summarized in Fig. 2 which identifies the underpinning concept, its execution including the trans-disciplinary components.

### 2.4. Comparative analyses

It was necessary to compare the TUG method results with some existing sampling methods (especially the raster based methods). The comparative analyses were done in two steps: (i) initially on the maps then (ii) comparing the merits of all sampling methods. A test exercise was conducted and three other sampling procedures were implemented in ArcGIS software to select the samples in the gradient raster image of Karachi. The three sampling methods, viz. random sampling, social strata sampling and equidistant raster were selected for this comparison and maps were produced.

For comparing the merits of each sampling methods a preconfigured balanced scale (similar to a Likert scale; Trochim, 2006) was developed having values from 0 to 4 (0 as the lowest and 4 being the highest). All sampling methods were checked for their suitability against each ecological principle discussed in the earlier section. The results were illustrated using spider diagrams.

## 3. Results

### 3.1. Pattern of urban gradient and finger-like structure

Karachi is divided into highly urbanized, moderately urbanized and least urbanized zones instead of using independent gradients of each urban indicator (Fig. 3). These zones of urbanization form an integrated urban gradient of Karachi which served as the foundation for strengthening the theoretical framework. Growth corridor C1 (highlighted with an arrow directing towards the NNE of Karachi) represents the expansion of residential areas; the corridor C2 (highlighted with an arrow directing towards the ESE of

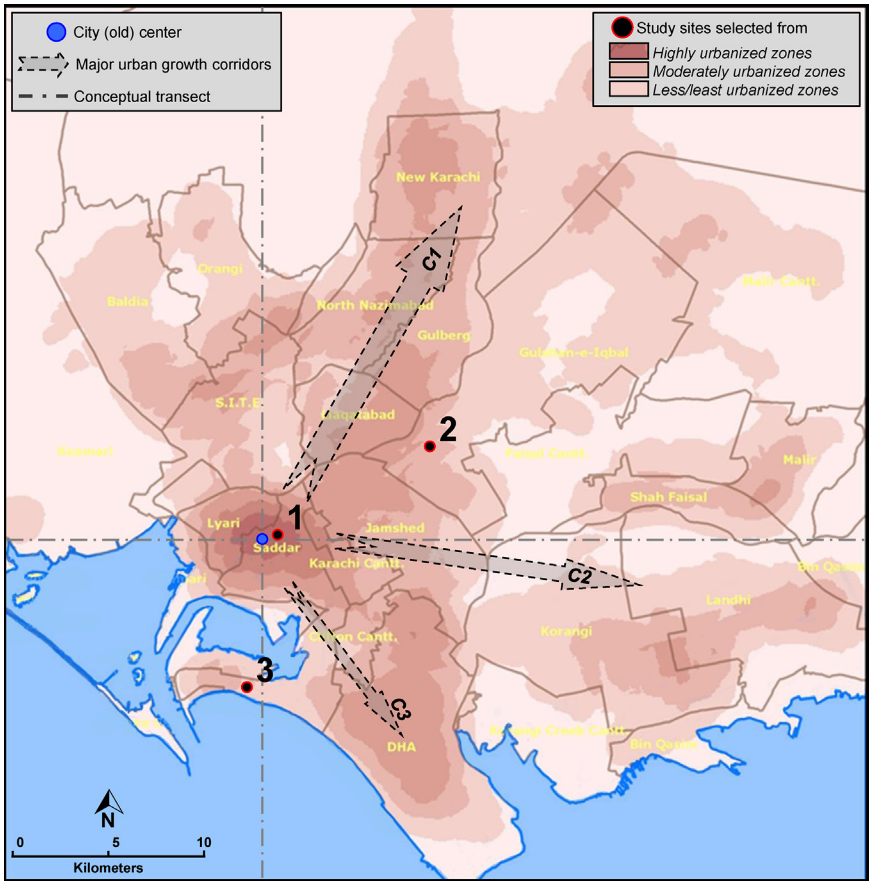


**Fig. 3.** Urban gradient of Karachi with example of site selection from different urbanization zones.

Karachi) mostly consists of industrial occupancy amalgamated with dense residential areas serving the neighbouring industries. The corridor C3 (highlighted with an arrow directing towards the SSE of Karachi) is a planned residential area which is administrated by the cantonment authorities and presents a model of sophisticated urban planning. The history of spatial growth proves that the city has followed different growth corridors in different eras and the development priority of the city administration has shifted from area to area and from service to service (see Kazmi et al., 2008; Qureshi, 2010; Hasan, 1999; Bredsdorff et al., 1947; Jørgensen, 2004). These growth corridors collectively portray a situation of finger-like patterns combined with the mushroom shaped expansion of the city making this area a challenge for classical sample and plotting techniques.

### 3.2. Postulates for hypothesizing the site selection and selected sites

Selected research sites, each located in different urbanization zones are identified (Fig. 3). A set of postulates (Table 4) was developed to select individual sites for in-depth investigations. It is comprehended that the urban natural spaces of megacities have very specific spatial and physical characteristics. It is a challenging task to study these megacities at such a scale it is more effective to study larger ecosystems in smaller fragments where each ecosystem type should specifically be classified according to its respective spatial, structural and functional details.

The criteria set above were implemented and three study sites satisfying the criteria were selected (and later used for in-depth investigations in other studies). Table 5 is presented to further explain the implementation of the method, including the social ecological and physical dimensions of the areas selected.

### 3.3. Head to head – sampling methods

The result of comparing the merits of different sampling methods revealed that each method is limited in its capacity to perform against each ecological principle (Fig. 4). The maximum performance that can be achieved by any method is satisfying up to four out of six principles. For example, random sampling performs better when the connectivity and hierarchy of different indicators is the focus, however, it completely overrules the principles of content, dynamics and heterogeneity. Similarly, equidistant raster sampling is also suitable for connectivity but overrides the hierarchy of a system. Nevertheless, it is a suitable technique for uniform homogenous study areas with minimum variety within the samples. Sampling in the social strata (especially for questionnaire based social studies) focusses more on the heterogeneity of the study area. It weakly supports the hierarchy of the systems but completely overrules context, dynamics and connectivity of the indicators (Fig. 5).

The TUG method has its advantages and disadvantages as well. This method performs strongly against the principles including content, context and dynamics. It is slightly weaker for hierarchy and heterogeneity but does not consider the connectivity to any great extent, however, it is intentionally designed to do this, since for urban landscapes the content within the patch, the surrounding land use, i.e. context and temporal changes, viz. dynamics, needs

**Table 4**
The TUG approach – postulates and principles underpinning site selection.

| Principle | Postulate | Application of principle and/or remarks |
|---|---|---|
| Content | Each site should be located in a neighbourhood demonstrating multi-functional land-use, i.e. not be limited to uni-functional land use. | Ensure that each site provides multiple (functional) services achieved using the defined land use categories, e.g. residential, commercial. |
| Context | Neighbouring land use defines the content of a patch, it should be different from others regarding its functional and physical characteristics. | A concept of spaces along a gradient is used rather than identifying discrete physical site boundaries applying ecological sampling principles, plus ecological and social indices. |
| Dynamics | Historical patterns, trends and functionalities are included to help to portray dynamics and future development, scenarios/trends. | Spatio-temporal LULC change was used to quantify and highlight the most dynamic patches. GPS surveys further validate and update current status. |
| Connectivity | Every site should have a different administrative structure, which ensures that the functional effectiveness of site is fully sampled. | Sites (patches) were selected to ensure their distinct identity as functional, linking components of a continuum. (Qureshi, 2010) |
| Heterogeneity | Selected sites should represent a specific patch type (e.g. urban park or playground) that exists within the wider region being sampled. | A standardized classification of urban nature spaces was used to select specific functional categories. (Qureshi and Breuste, 2010) |
| Hierarchy | Urban structures have varying service scales where they can function to their optimum. Service/functional scale of spaces should be considered. | A hierarchal, analytical approach was used to develop a typology of urban spaces at different spatial scales. (Qureshi and Breuste, 2010) |

to be considered earlier before the other three principles. This is because with megacities like Karachi which are growing very fast and where the content of urban structure changes rapidly, study is only possible when the dynamics of the urban system are understood appropriately and integrated into the sampling technique. The hierarchy of the system remained the second priority which is justified because of the fact that a city like Karachi has over 1250 formal green spaces and that all urban structures (specifically green spaces) have multiple ecosystem services and functions to perform at multiple scales. Therefore it is given lesser priority as the services scales are overlapping. Similarly the heterogeneity of urban structures in a compact urban milieu is very difficult to study – the integration of all indicators is the ultimate objective. Integration and connectivity need to be understood and identified

**Table 5**
Selected research sites and the TUG criteria they satisfied to be selected.

| Ecological principle | Site 1 – Karachi Zoological (Gandhi) Garden | Site 2 – Askari Park | Site 3 – Beach View/Bin Qasim Park |
|---|---|---|---|
| | A representative sample from highly urbanized area | A representative sample from a moderately urbanized area | A representative sample from the least urbanized area |
| Content | An established zoological garden, containing six botanical gardens including protected plant species. | A newly developed model landscape park. | A 1.6 km narrow belt along the Karachi beach, the only green space located adjacent to the beach including an amusement park. |
| Context | Located in the central business and commercial core of Karachi and within the old city boundary. The connecting plots are used for a range of mixed commercial and residential activities. | Adjacent land use includes a squatter settlement, particularly important as a home to many people working in the fruit and vegetable market. Opposite is a high-quality residential area. | The unusual juxtaposition of contrasting land uses makes it one of the most unique green spaces not only in the City but in the whole country. |
| Dynamics | The oldest park of the City dating back to 1861 originally used by the British East India Company as their headquarters now changed to a neighbourhood park and zoological garden. | A site formerly occupied by a wholesale fruits and vegetable market which encroached on government land, leading to illegal slum development. CDGK Karachi with the Pakistan Army forcibly moved the market to develop a public park (2005) improve the sanitary conditions to change it from a barren and disputed piece of land to a park within a short period of 9 months. | Developed as a recreational place in 1920 by Mr. Jahangir Kothari, who constructed the Jahangir Kothari Parade at the site of his bungalow and gifted it to the citizens of Karachi. Beach View Park (19 ha) runs along a 3.7 km coastal driveway. Both parks are part of the 'grand recreation project' approved by the Governor of the Sindh province in 2005. Development involved freeing 73 acres of land from illegal control. |
| Connectivity | Intermingled with heavily commercial areas. The only zoological garden in Karachi owned by the provincial government and run by the City District government (in cooperation with private consultants) making it a unique representative sample. | Adjacent to unauthorized squatter settlement. The park remains under the administration of the Pakistan Army (in agreement with local government) and is considered as one of the most important sites for citizens. | Located along Karachi's famous beach and including an amusement park, connected to the whole city by its location and size, i.e. a unique location to be selected as study area. Situated within the Defence House Authority Area, administrated by military and the City District Government in collaboration with a private consultant. |
| Heterogeneity | Being a zoological garden it stands out as a unique sample of the greenspace hierarchy within the city limits, with a diverse structure and function attracting a range of visitors. | A model park presenting a new face of Karachi as it undergoes a new phase of regeneration. Its unique administrative structure and professionally designed landscape identify it as an explicit case for study. | The only park in Karachi which is similar to smaller neighbourhood parks (see Qureshi and Breuste, 2010 for definitions) but due to its context, location and size it has a unique structure. |
| Hierarchy | Attracting heavy patronage from metropolitan Karachi and the surrounding villages. One of the most popular picnic places for low-income groups with a specific child/family focus. | An integral part of the Greener Karachi Plan with a unique development history designed to improve the local area regarding its social environmental and health conditions. | A unique coastal area and key component of the urban landscape with a distinct history, properties and patronage forming part of the Grand Recreation Project and a model for a future Karachi. |

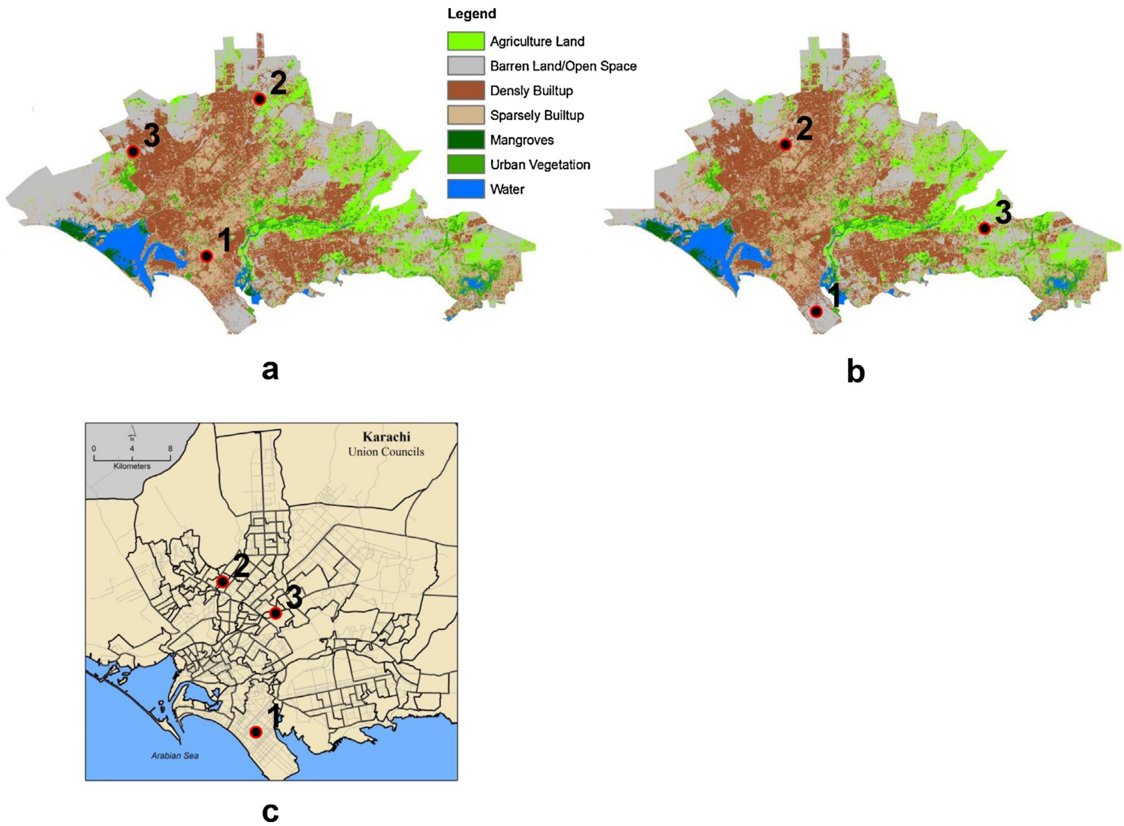


**Fig. 4.** Selecting three study sites/samples using (a) random sampling method, (b) equidistant raster sampling and (c) social strata. *Note:* In figure (a) and (b) the samples have been shown on the land cover map of Karachi so that the actual context/neighbourhood of the selected samples can be understood. Whereas, in figure (c) the samples are shown on the administrative boundary map of the city, so that the social strata classes can be identified within the city. The land cover map shown in (a) and (b) were developed using the Landsat TM image of the year 2009.

as the most potent and legitimate of the characteristics since sites do not function independently, all urban functions operate simultaneously near and around study sites (selected using the selection criteria).

Fig. 4 is a conceptual representation of the weightage of each sampling method and its relevance to the selected ecological principals. This weightage method was developed based on the expert knowledge approach and relevance of each sampling method whilst it is applied specifically in the context of megacity Karachi. Its application was tested for individual cases to validate its suitability. For example, it can be observed that equidistant raster sampling, being too technical (image based method) in nature poorly addresses the issues relevant to social science aspects. They, unintentionally, aggregate socio-demographic differences in neighbourhoods in summing up the different social strata and demographic properties of inhabitants and can be criticized for producing "mean values" which are not very meaningful. In this situation the relevance of content, context and system hierarchy gets weaker. Similarly, social strata sampling is inappropriate being developed for studies focusing on animal species looking weaker when applying principles such as connectivity or dynamics, already identified as key issues. Further testing was undertaken by selecting samples based on classified maps of Karachi (Fig. 4) This proved that most of the automated sampling techniques (raster based sample grids/plots, etc.) select samples regardless of the ground realities, i.e. land use, structures and functions, while the social strata across the city are mostly overridden due to certain presumptions made by the researchers surpassing ground reality.

## 4. Discussion and conclusion

### *4.1. Surpassing the classical sampling*

In megacities social and ecological processes do not fit within administrative boundaries. That is why it is extremely difficult to study a socio-ecological phenomenon interlaced with certain administrative unit(s) Qureshi (2011). In urban areas, the overlap in ecological and administrative boundaries results in losses of either social or bio-habitat. The presented TUG framework helps to transgress the challenge put forward under the theory of ecological boundaries to better characterize coupled human–environmental systems via sampling (Cadenasso et al., 2003a,b); it speculates the adoption of ontological approaches to study heterogeneous and complex landscapes in urban landscapes.

Accordingly, the results of this study exemplify the need to address and identify a methodology for addressing the socio-ecological complexities which characterize modern urban environments making it possible to model tightly coupled human–environmental systems (Alessa et al., 2008; Liu et al., 2007; Berkes et al., 2008), easy-to-understand, easy-to-interpret and utilize methods which are cost effective in terms of personnel and budget. Hence, the approach/methodology strongly supports the idea of Vink (1982) which argues urban ecology as an anthropocentric approach of landscape ecology. Further, it fosters the idea of better introducing landscape ecological knowledge and principles to land-use planning in cities.

For example, this proposed method surpasses the idea of studying landscape patches along transects of urban gradients

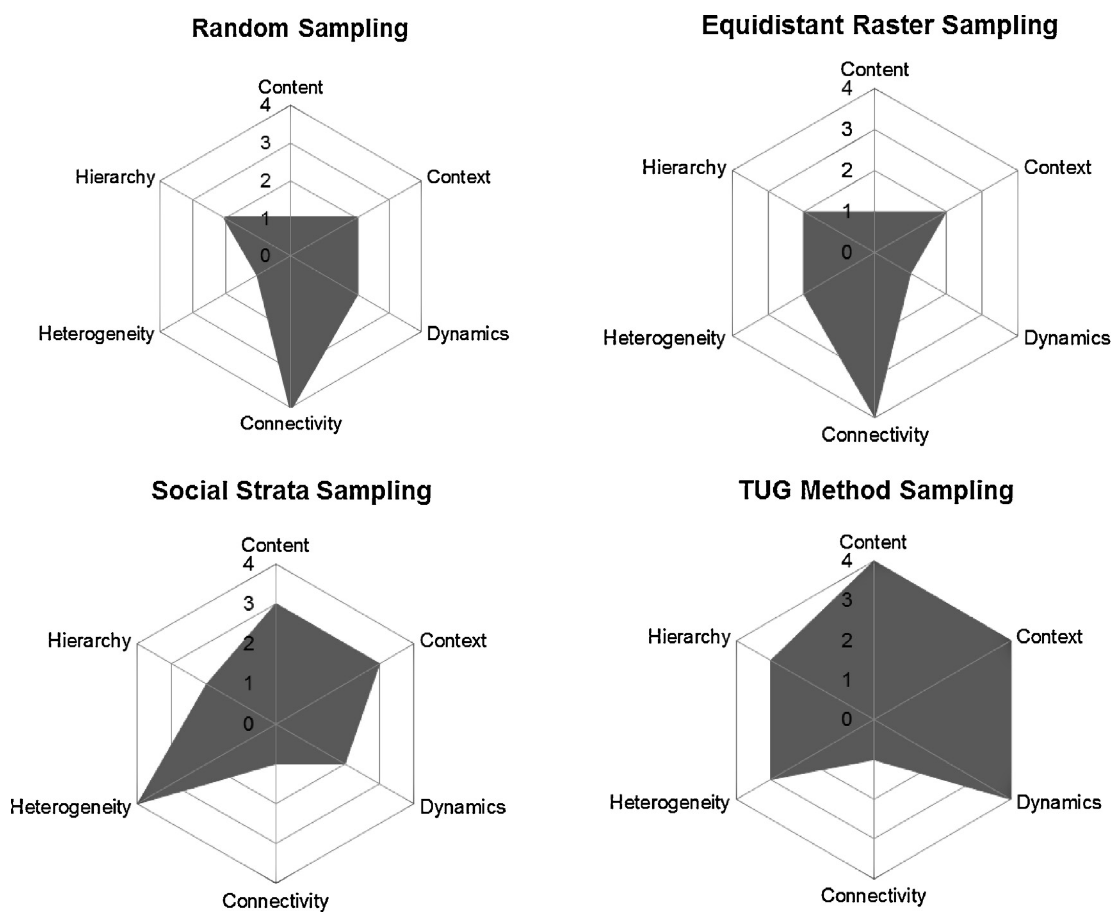


**Fig. 5.** Comparing the performance of each sampling method in the context of selected ecological principles.

as suggested by, e.g. Haase and Nuissl (2010). In addition, the disadvantages of being correlative (Felson and Pickett, 2005) can be nullified using this approach because the landscape patches can be studied independent of the forces which seems to push them for interaction among each other. This is suggested as being ideal when the studies have social and ecological dimensions.

### 4.2. Outlook – the bigger picture

The paper seeks to consider the multiple prospects of the TUG framework and the following major conclusions are made in support of existing literature and approaches:

(1) The knowledge base of (landscape) ecologists has proven to be a problem for land-use and landscape planners and has frequently resulted in the communication gap between both planners and scientists. Planners need reliable typically quantitative answers and readymade practical tools adaptable to any condition at varying spatial scales (Wu, 2004); the proposed TUG method using multiple indictors across different subject domains could help simplify this complexity.
(2) This study is an effort to simplify the complex ecological analyses, which can be difficult for social scientists to understand, which results in a traditional separation of ecological and social sciences. The main reason for the separation has been the different language that natural and social scientists use (Rosa and Dietz, 1998; Antrop, 2000b). Thus, the TUG approach is considered useful in building bridges between social and natural sciences as it integrates the biophysical and social aspects of urban landscapes (Fischer-Kowalski and Weisz, 1999; Haberl et al., 2004). It helps in creating a mutual understanding by involving expert knowledge from both – avoiding highly quantitative aggregation or disaggregation procedures which are often denied by social scientists. Thus one of the research questions has been addressed to a larger extent.
(3) Most of the ecological studies, being objective and socio-economic studies being subjective could be practiced using such methods where a trans-disciplinary pluralistic framework is required (Wu, 2006). This method also helps in identifying the unique landscape patches/structures required to conduct social surveys. It indulges Forman and Godron (1986) by examining the functionality of certain urban structures which can be further assessed, e.g. by examining public perception. The TUG-gradient approach helps to address studies which require sampling at different spatial scales. In our case the hierarchy of urban green spaces developed by Qureshi and Breuste (2010) was used to select the scale at which any specific site functions. Three different sites were selected each with a required different service scale as some green spaces in urban areas only serve the immediate neighbourhoods while others have a stronger influence on larger areas – sometimes the whole city or even surrounding villages and towns. Therefore, the results here successfully find a logical answer to the central question of this study.
(4) Hence the TUG approach proves its suitability to guide land use decisions by attesting to the full use of ecological principles but also assimilating the concept of integrating different

approaches of urban landscapes. It does so by selecting a very limited number of study sites, strongly supported by theoretical arguments thus minimizing the financial requirements of such sampling. It could further help in the in-depth study of the selected yet complex samples. This approach is adaptable across different urban scales/regions and thus applicable for different urban steering/planning levels and processes.

## Acknowledgements

This research is supported in part by the funding through the Alexander von Humboldt Foundation, Germany, and the Leverhulme Trust, UK. The first author is indebted to Prof. Jürgen Breuste (University of Salzburg, Austria) for his support and brainstorming during initial phase of this research. The constructive comments of two anonymous reviewers are appreciated which lead to the substantial improvement in the paper.

## References


Alessa, L., Kliskey, A., Brown, G., 2008. Social–ecological hotspots mapping: a spatial approach for identifying coupled social–ecological space. Landscape Urban Plan. 85, 27–39.

An, L., 2012. Modeling human decisions in coupled human and natural systems: Review of agent-based models. Ecol. Model. 229, 25–36.

Antrop, M., 2000b. Changing patterns in the urbanized countryside of Western Europe. Landscape Ecology 15, 257–270.

Arsalan, M.H., 2002. Monitoring Spatial Patterns of Air Pollution in Karachi Metropolis: A GIS and Remote Sensing Perspective. University of Karachi, Pakistan, Available from: http://eprints.hec.gov.pk/279/ (last accessed on 20.01.12) (Ph.D. Dissertation).

Berkes, F., Colding, J., Folke, C. (Eds.), 2008. Navigating social-ecological systems: building resilience for complexity and change. Cambridge University Press, Cambridge, 416 pp.

Bredsdorff, P., Boertmann, M., Draiby, R., Lyager, P., Nyvig, A., Rasmussen, D., Teisen, F., 1947. Skitseforslag til Egnsplan for Storkøbenhavn. Teknisk kontor for udvalget til planlægning af Københavnsegnen (In Danish).

Breuste, J., Feldmann, H., Uhlmann, O. (Eds.), 1998. Urban Ecology. Springer Verlag, Berlin, Germany.

Burton, M.L., Samuelson, L.J., Pan, S., 2005. Riparian woody plant diversity and forest structure along an urban–rural gradient. Urban Ecosyst. 8, 93–106.

Cadenasso, M.L., Pickett, S.T.A., Weathers, K.C., Bell, S.S., Benning, T.L., Carreiro, M.M., Dawson, T.E., 2003a. An interdisciplinary and synthetic approach to ecological boundaries. Bioscience 53, 717–722.

Cadenasso, M.L., Pickett, S.T.A., Weathers, K.C., Jones, C.G., 2003b. A framework for a theory of ecological boundaries. Bioscience 53, 750–758.

Carpenter, S., Brock, W., Hanson, P., 1999. Ecological and social dynamics in simple models of ecosystem management. Conserv. Ecol. 3 (2), 4 http://www.consecol.org/Journal/vol3/iss2/art4/index.html

Cilliers, S.S., Bouwman, H., Drewes, J.E., 2009. Comparative urban ecological research in developing countries. In: McDonnell, M.J., Hahs, A.K., Breuste, J. (Eds.), Ecology of Cities and Towns: A Comparative Approach. Cambridge University Press, Cambridge, UK, pp. 90–111.

Cilliers, S.S., Bredenkamp, G.J., 2000. Vegetation of road verges on an urbanisation gradient in Potchefstroom, South Africa. Landscape Urban Plan. 46, 217–239.

Du Toit, M.J., Cilliers, S.S., de Klerk, T.C., 2009. Grassland ecology along an urban-rural gradient using GIS techniques in Klerksdorp, South Africa. South Afr. J. Bot. 75, 399.

Dale, V.H., Brownm, S., Haeuberm, R.A., Hobbsm, N.T., Huntlym, N., Naiman, R.J., Riebsame, W.E., Turner, M.G., Valone, T.J., 2000. Ecological principles and guidelines for managing the use of land. Ecol. Appl. 10, 639–670.

Daniels, R.E., 1988. The role of ecology in planning: some misconceptions. Landscape Urban Plan. 15, 291–300.

Dow, K., 2000. Social Dimensions of Gradients in Urban Ecosystems. Urban Ecosystems 4, 255–275.

Dow, K., 2002. Social dimensions of gradients in urban ecosystems. Urban Ecosyst. 4, 255–275.

Farina, A., 2006. Principles and Methods in Landscape Ecology: Toward a Science of Landscape, 2nd ed. Springer, Dordrecht.

Felson, A.J., Pickett, S.T.A., 2005. Designed experiments: new approaches to studying urban ecosystems. Front. Ecol. Environ. 3, 549–556.

Fischer-Kowalski, M., Weisz, H., 1999. Society as hybrid between material and symbolic realms, toward a theoretical framework of society–nature interrelation. Advances in Human Ecology 8, 215–251.

Flores, A., Pickett, S.T.A., Zipperer, W.C., Pouyat, R.V., Pirani, R., 1998. Adopting a modern ecological view of the metropolitan landscape: the case of a greenspace system for the New York city region. Landscape Urban Plan. 39, 295–308.

Forman, R.T.T., Godron, M., 1986. Landscape Ecology. John Wiley, New York.

Fry, G., Tress, B., Tress, G., 2007. Integrative landscape research: facts and challenges. In: Wu, J., Hobbs, R. (Eds.), Key Topics in Landscape Ecology. Cambridge University Press, Cambridge, pp. 246–268.

Germaine, S.S., Wakeling, B.F., 2001. Lizard species distributions and habitat occupation along an urban gradient in Tucson, Arizona, USA. Biol. Conserv. 97, 229–237.

Government of Pakistan (GOP), 2000. District Census Report of Karachi, Pakistan. Demographic Survey 1998. Federal Bureau of Statistics, Statistics Division, Government of Pakistan, Islamabad.

Grahn, P., Stigsdotter, U.A., 2003. Landscape planning and stress. Urban Forest. Urban Green. 2, 1–18.

Grant, W.E., Peterson, T.R., Peterson, M.J., 2002. Quantitative modeling of coupled natural/human systems: simulation of societal constraints on environmental action drawing on Luhmann's social theory. Ecol. Model. 158, 143–165.

Haase, D., Nuissl, H., 2010. The urban-to-rural gradient of land use change and impervious cover: a long-term trajectory for the city of Leipzig. Land Use Sci. 5 (2), 123–142.

Haase, D., 2005. How spatial explicit models contribute to explain processes and support decision making in changing urban landscapes? In: Proceedings of the Conference Life in the urban landscape, Gothenborg, Germany.

Haberl, H., Wackernagel, M., Wrbka, T., 2004. Land use and sustainability indicators. An introduction. Land Use Policy 21, 193–198.

Hahs, A.K., McDonnell, M.J., 2006. Selecting independent measures to quantify Melbourne's urban–rural gradient. Landscape Urban Plan. 78, 435–448.

Hasan, A., 1999. Understanding Karachi: Planning and Reform for the Future. City Press, Karachi, Pakistan.

Hedblom, M., Söderström, B., 2008. Woodlands across Swedish urban gradients: status, structure and management implications. Landscape Urban Plan. 84, 62–73.

JICA, 2005. Per Person Trip Study of Karachi. Japan International Cooperation Agency (JICA), Karachi, Pakistan.

Jørgensen, J., 2004. Evolution of the finger structure. In: Dubois-Taine, G. (Ed.), European Cities: From Helsinki to Nicosia – Insights on Outskirts Eleven Case Studies and Synthesis. , pp. 187–197, www.qub.ac.uk/ep/research/costc10/findoc/cs08-cope.pdf

Kazmi, S.J.H., Mehdi, R., Arsalan, M.H., 2008. Karachi: environmental challenges of a mega city. In: Misra, R.P. (Ed.), South Asian Mega Cities. Cambridge University Press, New Delhi, India, pp. 23–36.

Khan, A.S., 2012. Sindh population surges by 81.5 pc, households by 83.9 pc. The News International, http://www.thenews.com.pk/Todays-News-13-13637-Sindh-population-surges-by-81.5-pc,-households-by-83.9-pc (last accessed on 19.07.2012) (Lahore issue published on 02.04.12).

Kong, F., Nakagoshi, N., 2006. Spatial–temporal gradient analysis of urban green spaces in Jinan, China. Landscape Urban Plan. 78, 147–164.

Kroll, F., Müller, F., Haase, D., Fohrer, N., 2012. Rural-urban gradient analysis of ecosystem services supply and demand dynamics. Land Use Policy 29 (3), 521–535.

Lang, S., Jekel, T., Hölbling, D., Schöpfer, E., Prinz, T., Kloyber, E., Blaschke, T., 2006. Where the grass is greener–mapping of urban green structures according to relative importance in the eyes of the citizens. In: Hostert, P., Schiefer, S., Damm, A. (Eds.), Workshop of the EARSeL Special Interest Group on Urban Remote Sensing "Challenges and Solutions". (CD-ROM).

Liu, J., 2001. Integrating ecology with human demography, behavior, and socioeconomics: needs and approaches. Ecol. Model. 140, 1–8.

Liu, J., Dietz, T., Carpenter, S.R., Alberti, M., Folke, C., Moran, E., Pell, A.N., Deadman, P., Kratz, T., Lubchenco, J., Ostrom, E., Ouyang, Z., Provencher, W., Redman, C.L., Schneider, S.H., Taylor, W.W., 2007. Complexity of Coupled Human and Natural Systems. Science 317 (5844), 1513–1516.

Lu, D., Weng, Q., 2006. Use of impervious surface in urban land use classification. Remote Sens. Environ. 102, 146–160.

Machlis, G.E., Force, J.E., Burch Jr., W.R., 1997. The human ecosystem. Part I: the human ecosystem as an organizing concept in ecosystem management. Soc. Nat. Resour. 10, 347–367.

Magle, S.B., Theobald, T.M., Crooks, K.R., 2009. A comparison of metrics predicting landscape connectivity for a highly interactive species along an urban gradient in Colorado, USA. Landscape Ecol. 24, 267–280.

McDonnell, M.J., Hahs, A.K., 2008. The use of gradient analysis studies in advancing our understanding of the ecology of urbanizing landscapes: current status and future directions. Landscape Ecol. 23, 1143–1155.

McDonnell, M.J., Pickett, S.T.A., 1990. Ecosystem structure and function along urban–rural gradients: an unexploited opportunity for ecology. Ecology 71, 1232–1237.

McDonnell, M.J., Pickett, S.T.A., Groffman, P., Bohlen, P., Pouyat, R.V., Zipperer, W.C., Parmelee, R.W., Carreiro, M.M., Medley, K., 1997. Ecosystem processes along an urban-to-rural gradient. Urban Ecosyst. 1, 21–36.

McDonnell, M.J., Pickett, S.T.A., Pouyat, R.V., 1993. The application of the ecological gradient paradigm to the study of urban effects. In: McDonnell, M.J., Pickett, S.T.A. (Eds.), Humans as Components of Ecosystems: Subtle Human Effects and the Ecology of Populated Areas. Springer-Verlag, New York, pp. 175–189.

MPGO-CDGK, 2007. Karachi Strategic Development Plan 2020. Master Plan Group of Offices, City District Government Karachi, Pakistan.

Naveh, Z., 1995. Interactions of landscapes cultures. Landscape Urban Plan. 32, 43–54.

Niemelä, J., Kotze, D.J., Venn, S., Penev, L., Stoyanov, I., Spence, J., Hartley, D., Montes de Oca, E., 2002. Carabid beetle assemblages (Coleoptera, Carabidae) across urban–rural gradients: an international comparison. Landscape Ecol. 17, 387–401.

Pithawalla, M.B., Kaye, P.M., Wadia, D.N., 1946. Geology and geography of Karachi and its neighbourhood. Daily Gazette Press, Karachi., pp. 18–30.

Pouyat, R.V., McDonnell, M.J., Pickett, S.T.A., 1995. Soil characteristics of oak stands along an urban–rural land-use gradient. J. Environ. Qual. 24, 516–552.

Qureshi, S., 2011. Boundary crossing by transregional practice of governance to address sustainability issues. Landscape Ecol. 26 (3), 455–456.

Qureshi, S., Breuste, J., Lindley, S.J., 2010b. Green space functionality along an urban gradient in Karachi, Pakistan: a socio-ecological study. Human Ecol. 38 (2), 283–294.

Qureshi, S., Breuste, J.H., 2010. Prospects of biodiversity in the megacity Karachi, Pakistan: potentials, constraints and implications. In: Müller, N., Werner, P., Kelcey, J. (Eds.), Urban Biodiversity and Design – Implementing the Convention on Biological Diversity in Towns and Cities. Wiley-Blackwell, Oxford, pp. 497–517.

Qureshi, S., 2010. The fast growing megacity Karachi as a frontier of environmental challenges: Urbanization and contemporary urbanism issues. J. Geogr. Regional Plan. 3 (11), 306–321.

Qureshi, S., Breuste, J.H., Jim, C.Y., 2013. Differential community and the perception of urban green spaces and their contents in the megacity of Karachi. Pakistan. Urban Ecosyst, 1–18, http://dx.doi.org/10.1007/s11252-012-0285-9.

Qureshi, S., Kazmi, S.J.H., Breuste, J.H., 2010a. Ecological disturbances due to high cutback in the green infrastructure of Karachi: analyses of public perception about associated health problems. Urban Forest. Urban Green. 9 (3), 187–198.

Rosa, E.A., Dietz, T., 1998. Climate Change and Society: Speculation. Construction and Scientific Investigation. International Sociology 13, 421–455.

Sajjad, S.H., Hussain, B., Khan, M.A., Raza, A., Zaman, B., Ahmed, I., 2009. On the rising temperature trends of Karachi. Climate Change 96, 539–547.

Strohbach, M.W., Haase, D., 2012. Estimating the carbon stock of a city: a study from Leipzig, Germany. Landscape Urban Plan. 104, 95–104.

Strohbach, M., Haase, D., Kabisch, N., 2009. Birds and the city–urban biodiversity, land-use and socioeconomics. Ecol. Soc. 14 (2), 31.

Termorshuizen, J.W., Opdam, P., 2009. Landscape services as a bridge between landscape ecology and sustainable development. Landscape Ecol. Landscape Ecol. 24, 1037–1052.

Trochim, W.M., 2006. Likert Scaling. Research Methods Knowledge Base, 2nd Edition.

Turner, T., 1988. The role of ecology in planning: a comment by Tom Turner on R.E. Daniels. Landscape Urban Plan. 15, 301–302.

UNPD, 2012. World Urbanization Prospects: The 2011 Revision. Department of Economic and Social Affairs, Population Division, United Nations, New York.

Vink, A.P.A., 1982. Anthropocentric landscape ecology in rural areas. In: Tjallingii, S.P., de Veer, A.A. (Eds.), Perspectives in landscape ecology: contributions to research, planning and management of our environment, Proceedings of International Congress, Veldhoven, April 6–11, 1981. Centre for Agricultural Publishing and Documentation, Wageningen, pp. 87–98.

Wu, J., 2004. Effects of changing scale on landscape pattern analysis: scaling relations. Landscape Ecol. 19, 125–138.

Wu, J., 2006. Cross-disciplinarity, landscape ecology, and sustainability science. Landscape Ecol. 21, 1–4.

Wu, J., 2008. Making the case for landscape ecology: an effective approach to urban sustainability. Landscape J. 27 (1), 41–50.

Wu, J., Hobbs, R., 2002. Key issues and research priorities in landscape ecology: an idiosyncratic synthesis. Landscape Ecol. 17, 355–365.

Yates, D.S., Moore, D.S., Starnes, D.S., 2008. The Practice of Statistics, 3rd ed. W. H. Freeman and Company, New York.

Young, C.H., Jarvis, P.J., 2001. Measuring urban habitat fragmentation: an example from the Black Country, UK. Landscape Ecol. 16, 643–658.

Zipperer, W.C., Wu, J., Pouyat, R.V., Pickett, S.T.A., 2000. The application of ecological principles to urban and urbanizing landscapes. Ecol. Appl. 10, 685–688.