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Exploring the Relationship between Compact Urban Form and Green Infrastructure

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Abstract

Compact Urban Form (CUF) and Green Infrastructure (GI) are widely used in sustainability approaches. GI can be understood as a system of green components (e.g. parks, gardens, allotments, etc.) and has multiple benefits for the green and blue urban agendas. Alongside, CUF is an effective strategy used to address urban sprawl. The integration of the two approaches is challenging due to the limited availability of space in CUF and the lack of an analysis of existing and potential GI offerings in compact built environments. This paper looks at the relationship between urban form patterns and green space patterns at the urban scale. It seeks to identify the variables that can describe the compactness and greenness of CUF and the structure of GI, the typologies of CUF and GI, and their potential interrelationships. The method introduces selected variables for quantitative description of CUF and GI, and cluster-based typologies of CUF and GI based on the reproduced components. The three pattern variables are identified (using statistical analysis and spatial analysis) for CUF and GI respectively based on the degree of the greenness, density (e.g. Berghauser Pont and Haupt, 2007), landscape structure (FRAGSTATS) and space syntax measurements (e.g. connectivity). Subsequently, the clusters of CUF and GI are generated using fuzzy c-means clustering analysis (FCM). The method is applied to London, UK. Overall, this paper introduces a quantitative approach to understand CUF and GI as well as their relationship. The methods – which are reproducible because of the use of open-access data – take a fundamental step towards a deeper understanding of the way compact urban fabrics can become greener by activating and embedding green networks into the urban fabric.

Keyword: *Green Infrastructure, Compact Urban Form, typologies, Unsupervised Classification, Clustering Analysis, Compact Cities, UK*

Introduction

In the universal context of urban development, the World Bank elaborates the relationship between physical form, land use patterns, population, natural resources, and greenhouse gas emissions: "*Once a city is built, its physical form and land use patterns can be locked in for generations, leading to unsustainable sprawl. The expansion of urban land consumption outpaces population growth by as much as 50%, which is expected to add 1.2 million m^2 of new urban built-up area to the world in the three decades. Such sprawl puts pressure on land and natural resources, resulting in undesirable outcomes; cities consume two-thirds of global energy consumption and account for more than 70% of greenhouse gas emissions.*"[1] The description indicates that

[1] https://www.worldbank.org/en/topic/urbandevelopment/overview

the physical form and land use patterns have a significant influence on the complex and dynamic urban development process. The significant benefits brought by Compact Urban Form (CUF) should not be ignored as an effective way to slow the speed of urban sprawl, though there are also side effects, for instance, affording less green and open space, increasing congestion and segregation, reduced environmental quality (Holden and Norland, 2005). Alongside, Green Infrastructure (GI) is supported as a long-term method to solve environmental problems, such as air pollution and urban heat islands (Sun et al., 2019), as well as it provides cultural services for the public[2]. With the aim to provide a healthy urban environment based on the benefits brought by GI and CUF, two questions arose, namely: what are the characteristics of GI in the context of CUF? And how can we understand the relationship between GI and CUF?

Background

There are many ways to define compactness for the concept of the compact city, for example, high density built form, the high cover proportion of the land surface, mixed land use, the close arrangement of buildings and roads, and high population density (De Roo, 2000). However, in the perspective of urban morphology, how can we quantitatively understand compact urban form?

Green infrastructure is defined as "*a strategically planned network of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ecosystem services such as water purification, air quality, space for recreation and climate mitigation and adaptation*."[3] This research considers the following key qualities, which are (i) GI is *planned*, (ii) it comprises a *network of natural and seminatural areas,* and (iii) provides *ecosystem services*. In this research, all the planned green spaces that provide *ecosystem services* (function) are considered as GI components and the *network* is understood as the *structure* of GI. Then, how can we develop a quantitative understanding of GI in terms of function, structure and components in the context of CUF?

The research presented in this paper integrates aspects from extant research about green infrastructure, urban morphology, landscape ecology and space syntax theory (Forman, 1995; Hillier, 1997; Berghauser Pont and Haupt, 2007; Mashall, 2009; Kropf, 2014; Çalışkan and Mashhoodi, 2017; Marcus et al., 2019; Whitehand, 2019) and takes London as an example to exemplify the approach. CUF is defined through the indicators of density and intensity (Çalışkan and Mashhoodi, 2017; Pont and Haupt, 2021) and GI is defined by the structural variables based on the indications of FRAGSTATS (McGarigal and Marks, 1995). The data for the research is obtained from online portals: Edina Digimap[4] and Space Syntax OpenMapping[5]. The green space

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[2] www.cices.eu
[3] https://ec.europa.eu/environment/nature/ecosystems/
[4] https://digimap.edina.ac.uk/roam/download/os
[5] https://spacesyntax-openmapping.netlify.app/#16/52.7589/-1.2289

data from OS Open Greenspace of Edina Digimap will be used to generate the clusters of GI. The datasets, e.g. *Greenspace*, *Building Height Attribute*, and *Boundary and Location Data* from Edina Digimap-Ordnance Survey, are used to obtain the variables for CUF clusters.

Methodology

The approach contains two steps which are first, a selection of variables and second, clustering analysis. A set of potential variables for quantifying the CUF and GI are selected (in this research, six potential variables are selected for GI and five for CUF). The values for variables are processed through ArcGIS and statistical software (e.g. SPSS and Excel). The attribute variables for clustering analysis are identified through correlation analysis. The number of clusters for GI and CUF is defined through the elbow method and average silhouette method. The Membership Value (m) of Fuzzy c-means clustering analysis (FCM) are tested and defined through the identified three attribute variables. Finally, six clusters of GI and seven clusters of CUF are generated through FCM. The relationship between the clusters of GI and CUF is processed through spatial analysis by using the *intersect* function in ArcGIS.

GI and CUF Components

The research presented here is an investigation on 'socio-ecological spatial morphology' introduced by Marcus et al. (Marcus and Berghauser Pont, 2015; Marcus et al., 2019). We are proposing a GI-CUF model that can be used to examine GI and CUF and their relationship (see Figure 1). The GI components are green spaces from the OS Open Greenspace database. Each polygon in the OS Open Greenspace database represents one GI component. The CUF components are defined by using the street network lines from *Space Syntax Open Mapping*, i.e. using the *split* function of ArcGIS to split the area of inner London into polygons (i.e. sites) by using road centre lines.

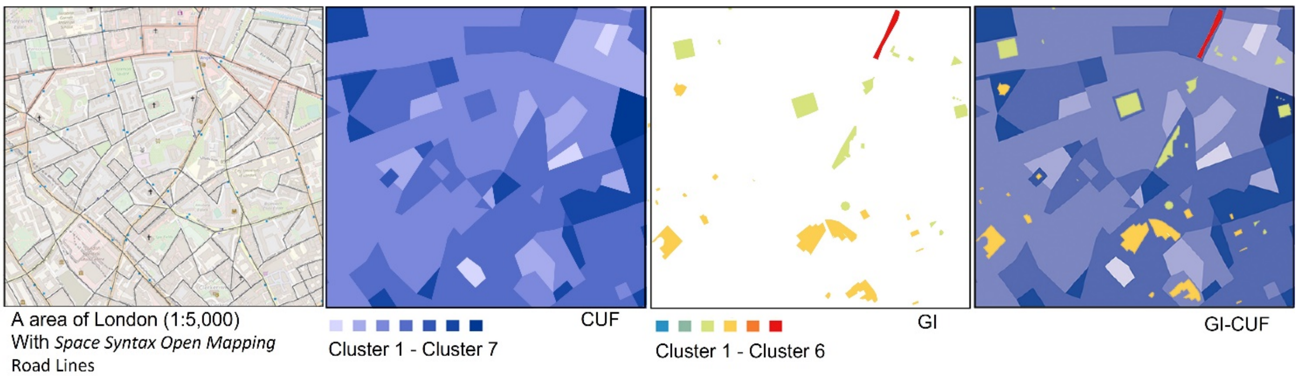

Figure1. *GI- CUF model*

GI and CUF Variables

The selection of structure-related variables for GI was based on the similarities between two models, which are (i) Hubs-Links-Sites, HLS (Benedict and McMahon, 2006) which considers a landscape scale, and (ii) Patches-Corridors-Matrix, PCM (Ahern 2007) which focuses on the urban context. In an urban area, the elements of HLS and PCM could be considered the same, e.g. parks or rivers (Ahern 2007, Whitehand 2019). Moreover, standing on the landscape scope, HLS indicates a relationship between patches (i.e. hubs and sites) and corridors (i.e. links) of PCM. Overall, the similarities of the two models are concluded in two properties, connectivity (i.e. links and corridors) and components (i.e. hubs, sites, patches, and matrix). Based on the two properties, the connectivity of GI is presented by using the *Choice* and *Integration* values from space syntax, considering the priority function of GI is cultural services in the human settlement, despite GI having other significant ecosystem services (e.g. provisioning services and regulating services[6]). The other variables for GI are selected from a critical understanding of landscape structure metrics from FRAGSTATS. Overall, the six potential variables for GI are selected in Table 1.

The five potential variables for CUF contain four variables selected from *Spacemate* (Berghauser Pont and Haupt, 2007; Pont and Haupt, 2021) and one 'greenness' variable introduced by this research – we call this Site Green Spaces Index (SGI). Berghauser Pont and Haupt (2007) proposed four variables (i.e. floor space index, ground space index, open space ratio, and layer) to quantify urban form which is widely used for indicating urban built form density. For instance, Wei et al. (2016) considered the four variables as urban built form density parameters for discussing the relationship between urban morphology and urban heat islands. SGI is generated from the green spaces that do not contain the GI components considering that GI components are just selected from the OS Open Greenspace database and there are more types of green spaces of London that can be found in the Greenspace database of OS data from Edina Digimap.

Table 1. The potential variables for GI and CUF

GI Variables		CUF variables
Attributes	Area of each green space; The perimeter of each green space; Shape Index of each green space	The average number of floors (Layer); Ground Space Index; Floor Space Index; Open Space Ratio; Site Green spaces Index
Connectivity	Integration; Choice	
Density	Number of GI components within 800 meters of each GI component	

Clustering Analysis

The initial step of clustering analysis is to select three variables from the six potential variables of GI and five potential variables of CUF. To do so, a correlation analysis is adopted for identifying the three non-correlated variables (i.e. attribute variables), which are Shape Index (SI), Density (D) and Integration (I) for GI; and Average Number of floors (L), Open Spaces Ratio (OSR) and Site Green spaces Index (SGI) for CUF. The two basic steps for FCM clustering are: 1) selecting the number of clusters and; 2) define the membership value. The Elbow method indicates the range of the number of clusters, and then, the number of clusters with the

[6] www.cices.eu

highest average silhouette value is defined. The membership value (e.g. m=1.1, m=2, m=3 and m=4) are tested using the three attribute variables.

Results

Clusters

The visualization of the clusters is processed in ArcGIS, for example, Figure 2 shows the six GI clusters and the number of components of each cluster. The abbreviation, for example, GI-C1, GI-C2, CUF-C1 and CUF-C2 in this paper refers to the Green Infrastructure Cluster 1, Green Infrastructure Cluster 2, Compact Urban Form Cluster 1, and Compact Urban Form Cluster 2. The characteristics of each cluster can be described through the composition of the three attribute variables (e.g. 100% stacked Bar Diagrams) and their comparable spatial locations. For example, in Figure 2, the composition of variables indicates that Cluster 1 for GI (GI-C1) is well connected to the urban system, the components in this cluster tend to be more circular and fewer components are located within 10 minutes walking distance for each component. Based on the composition of GI-C2, the integration is lower than GI-C1, but still contains a large number of medium-level integration components. The composition of the Shape Index is similar to GI-C1. The density of GI-C2 is higher than GI-C1, which shows that GI-C2 could get access to the surroundings easier than GI-C1. In addition to the spatial location, we can see that GI-C1 is located near the edge of the city, and GI-C2 is closer to the centre of the city.

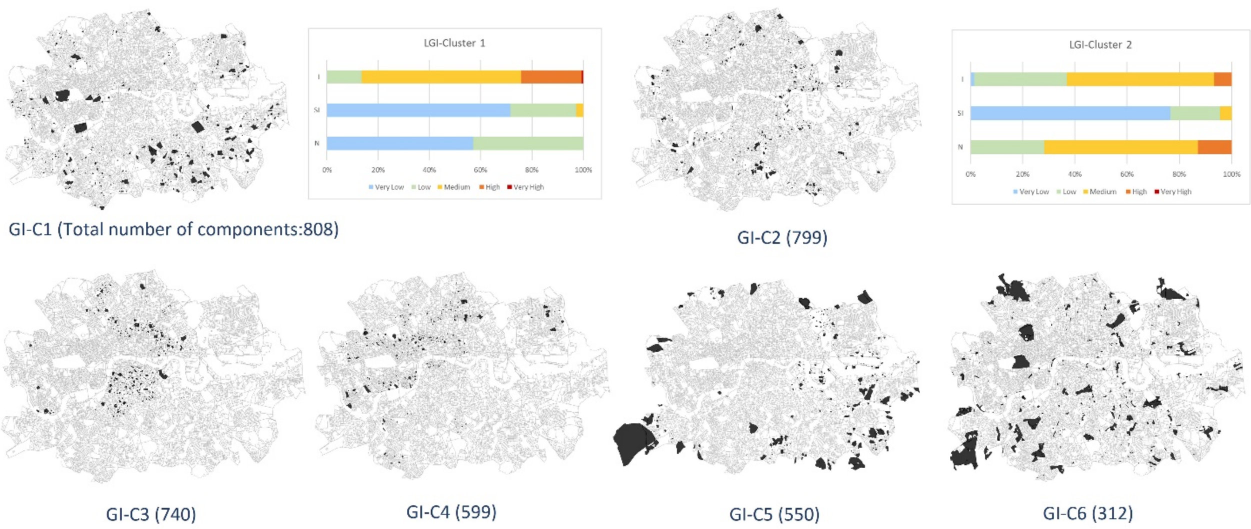

Figure 2. *The Six GI clusters of London*

GI and CUF Relationship

The GI-CUF relationship will be examined through the *intersect* function in ArcGIS. There are three main objectives for presenting the relationship: 1) to find which CUF clusters are provided more services by GI; 2) which GI clusters provide more CUF components of CUF clusters and CUF clusters services; 3) which CUF clusters can be provided more types of services from GI clusters. For **objective 1**, the ratio in Table 2 indicates that GI provides more components of CUF-C3 services since the ratio of C3 is the highest (i.e. 23.67%), then C2, C4, C6, C5, C1, and C7.

Table 2. The table for Objective 1

The number of CUF components of each CUF cluster in CUF components that intersects with GI components (A1)								
C1 = 376; C2 = 581; C3 = 543; C4 = 257; C5 = 125; C6 = 99; C7 = 17								
Total number of CUF components that intersect with GI components (A) = 1998								
The number of CUF components of each CUF cluster (B1)								
C1 = 3339; C2 = 2954; C3 = 2294; C4 = 1503; C5 = 897; C6 = 642; C7 = 202								
Total number of CUF components (B) = 11831								
A(1)/B(1) (%)	C1 = 11.26	C2 = 19.67	C3 = 23.67	C4 = 17.10	C5 = 13.94	C6 = 15.42	C7 =8.42	Total = 16.89

For objective 2, Figure 3 shows 1) the ratio *between the number of CUF components that intersect with each GI cluster* and *the total number of CUF components*. The ratio indicates which GI clusters contribute more services to CUF. 2) the ratio between the *number of CUF components of each CUF cluster in the CUF components that intersects with each GI cluster* and *the number of CUF components that intersected with each GI cluster*. This ratio indicates which GI clusters provide services to more components of which CUF clusters. For instance, combing 1) and 2), GI-C1 contributes more services to CUF, especially to CUF-C2.

		GI-C1	GI-C2	GI-C3	GI-C4	GI-C5	GI-C6
2)	CUF-C1	29.94%	17.67%	5.46%	10.10%	32.18%	21.90%
	CUF-C2	39.29%	36.51%	24.47%	19.21%	36.02%	33.58%
	CUF-C3	17.26%	29.77%	44.42%	26.35%	20.69%	18.73%
	CUF-C4	6.65%	11.16%	16.63%	23.89%	5.36%	8.76%
	CUF-C5	2.08%	2.79%	3.56%	8.13%	3.45%	13.14%
	CUF-C6	3.74%	1.86%	4.75%	10.84%	1.53%	3.89%
	CUF-C7	1.04%	0.23%	0.71%	1.48%	0.77%	0.00%
1)		4.07%	3.63%	3.56%	3.43%	2.21%	3.47%

__Figure 3.__ Heatmap Diagram for Objective 2

For **objective 3,** for example, the CUF components that intersect with GI-C1 and GI-C2 have the same CUF components, i.e. overlapping components. Based on the spatial processing targeting objective 2, the overlapping CUF components are identified according to the unique object ID of CUF components. In Figure 4, there are more CUF components of CUF-C2 (i.e. 141) that can be provided more types of services from GI clusters.

	CUFC1	CUFC2	CUFC3	CUFC4	CUFC5	CUFC6	CUFC7	Total
2GIclusters	55	113	56	28	8	9	0	269
3GIclusters	12	21	11	6	0	1	0	51
4GIclusters	1	6	5	0	0	0	0	12
6GIclusters	0	1	0	0	0	0	0	1
Total	68	141	72	34	8	10	0	333

__Figure 4.__ Overlapping Components for Objective 3

Discussion

The research presents an approach to find GI and CUF clusters, how to describe and discover their characteristics and relationship. The results could benefit urban planners to improve land use patterns with the consideration of services that GI clusters can provide. For instance, based on the results of objective 3, CUF-C2 has access to all types of services from GI clusters. As such, can the land patterns of CUF-C2 influence the equity of accessibility of green infrastructure? Furthermore, it could benefit landscape designers to develop the Hubs-Links-Sites (HLS) structure in compact cities, for instance, based on the relationship from objective 2, GI-C1 can provide services to more components of CUF-C2 (see Figure 5). If the function of GI-C1 is planned with high vegetation that can provide more regulating services, does it mean that CUF-C2 could get more environmental benefits from GI-C1?

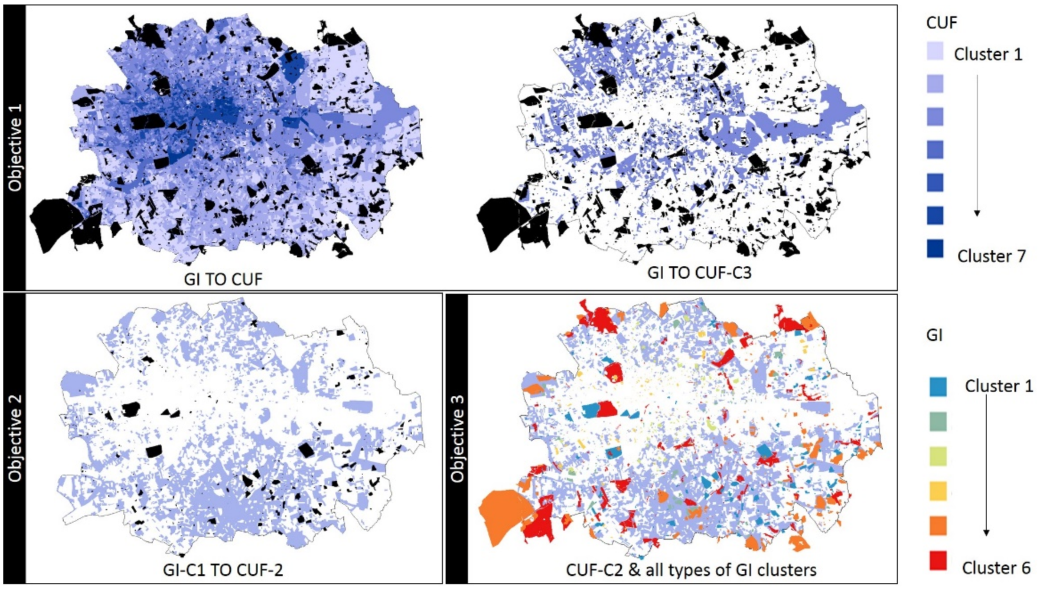

Figure 5. *Parts of the Relationships Mapping*

There are some limitations to the research. 1) The number of potential variables could be selected following the researchers' interests. The attribute variables defined by correlation analysis for clustering analysis could be more than three, though this research adopts three. 2) For the relationship between two systems, i.e. GI and CUF, this research just shows how to understand the relationship by using one spatial function, *intersect*, in ArcGIS, while many other types of spatial functions could be used to indicate the relationship between GI and CUF. 3) The functions, ecosystem services, are an important part of GI, though this research focuses on the physical structure. The combination between the structure and functions could be interesting. For instance, in objective 2, GI-C3 and GI-C4 can provide services to more components of CUF-C3, then, which types of services the GI clusters (i.e. the functions of green spaces in GI clusters) could be designed for the CUF-C3? And what the urban services of the CUF-C3 could be? Finally, the paper focused on presenting the methodology (i.e. the statistical processing, clustering and spatial analysis steps) but, due to space constraint, it did not present a qualitative understanding of the results which will follow in subsequent publications.

Conclusions

This research is based on significant previous research about GI in the urban context and quantitative methods for urban morphology to generate potential variables that relate to attributes of GI and CUF and then select the variables for FCM clustering analysis. It also shows how to understand GI and CUF in the context of compactness and explore the relationship between GI and CUF based on FCM, spatial analysis and statistical analysis. The approach presented in this paper could be applied to other compact or non-compact cities. In the end, the exploration of GI and CUF and their relationship still have many aspects underexplored, for example, comparing the results between multiple variables and three variables to define the significant variables for further policymaking on an urban scale; and combing the ecosystem services with HLS structure to the clusters to make an in-depth understanding about green infrastructure in the urban context.

References

1. Ahern, J. (2007), Green infrastructure for cities: the spatial dimension in 'Cities of the future: towards integrated sustainable water and landscape management. IWA Publishing', Citeseer.
2. Benedict, M. A., McMahon, E. T. et al. (2006), *Green infrastructure: linking landscapes and communities,* Island press.
3. Berghauser Pont, M. and Haupt, P. (2007), 'The spacemate: Density and the tpomorphology of the urban fabric'*, Urbanism laboratory for cities and regions: progress of research issues in urbanism.*
4. Çalışkan, O. and Mashhoodi, B. (2017), 'Urban coherence: a morphological definition'*, Urban Morphology* 21 (2), 123-41
5. DeRoo, G. (2000), 'Environmental conflicts in compact cities: complexity, decisionmaking, and policy approaches', *Environment and Planning B: Planning and Design* 27(1), 151–162.
6. Forman, R. T. T. (1995), 'Land Mosaics: The Ecology of Landscapes and Regions', *Cambridge University Press*.
7. Hillier, B. (1996), 'Cities as movement economies'*, Urban design international* 1(1), 41-60.
8. Holden, E. and Norland, I. T. (2005) 'Three Challenges for the compact city as a sustainable urban form: household consumption of energy and transport in eight residential areas in the greater oslo reigon', *Urban studies* 42(12),2145-2166.
9. Kropf, K. (2014), 'Ambiguity in the definition of built form'*, Urban morphology* 18(1),41–57.
10. Marcus, L. and Berghauser Pont, M. (2015), 'Towards a social-ecological urban morphology: integrating urban form and landscape ecology', *in 'international Seminar on Urban Form ISUF'*, pp.1-13
11. Marcus, L., Pont, M. B. and Barthel, S. (2019), 'Towards a socio-ecological spatial morphology: integrating elements of urban morphology and landscape ecology', *Urban morphology* 23(2), 115-124.
12. Marshall, S. (2009), *Cities Design and Evolution*, Routledge.
13. McGarigal, K. and Marks, B. J. (1995), 'Spatial pattern analysis program for quantifying landscape structure', *Gen. Tech. Rep. PNW-G351. US Department of Agriculture, Forest Service, Pacific Northwest Research Station* pp.1–122.
14. Sun, R., Lü, Y., Yang, X. and Chen, L. (2019), 'Understanding the variability of urban heat islands from local background climate and urbanization', *Journal of cleaner production* 208,743–752.
15. Pont, M. B. and Haupt, P. (2021), *SPACEMATRIX*, nai101 publishers/Marcel Witvoet.
16. Wei, R., Song, D., Wong, N. H. and Martin, M. (2016), 'Impact of urban morphology parameters on microclimate', *Procedia Engineering* 169,142-149
17. Whitehand, J. W. R. (2019), 'Green space in urban morphology: an historico-geographical approach', *Urban morphology* 23(1), 5-17.