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SPATIAL DIMENSIONS OF SOIL SEALING MANAGEMENT IN GROWING AND SHRINKING CITIES – A SYSTEMIC MULTI-SCALE ANALYSIS IN GERMANY

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With 6 figures and 4 tables
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Summary: The paper analyses and evaluates approaches to the management of urban soil sealing to support the implementation of guidelines and sustainability targets, such as the European Commission's soil sealing guidelines and the sustainability strategy in Germany which aims to reduce the daily land consumption and the associated soil sealing. Based on the assumption that only a mix of instruments can steer soil sealing the paper aims to answer the following questions: I) What are the spatial dimensions of urban soil sealing? II) Which strategies and management dimensions can control soil sealing on a macro-scale (regions, federal states, federal government), meso- (city level) and a micro-scale (urban structural units)? Spatial driving forces of and impacts of soil sealing are identified by urban structural units using a soil sealing gradient. Growing and shrinking cities in Germany were analyzed: Leipzig as a shrinking and Munich as a growing case study city. Results show that neither a growing nor a shrinking population drives the sealing development but the degree of re-use of urban brownfields. Overall, a holistic approach to soil sealing management comprises a multi-dimensional range of measures for the quantitative, qualitative and compensatory management of urban soil sealing and urban green areas, including basically the protection of soils. Economic and fiscal, planning and legal, informational and co-operative strategies have the potential to steer urban soil sealing. Further research is necessary to develop indicators to assess the efficiency of these strategies to achieve a holistic and efficient soil sealing management. This paper presents a framework showing how a set of instruments can be defined and their efficiency assessed by taking into account the identified spatial dimensions and strategies as well as their interconnections.

Zusammenfassung: Der Artikel analysiert und bewertet räumliche Dimensionen und Strategien zur Steuerung urbaner Flächenversiegelung, um Empfehlungen zur Reduzierung der Flächenversiegelung der Europäischen Kommission oder die Nachhaltigkeitsstrategie der deutschen Bundesregierung, welche die Reduzierung der Flächeninanspruchnahme durch Siedlung und Verkehr und der damit verbundenen Flächenversiegelung vorsieht, voran zu bringen. Basierend auf der Annahme, dass nur ein Bündel aus unterschiedlichen Maßnahmen Flächenversiegelung effizient zu steuern vermag, identifiziert der Aufsatz Ziele und Strategien, um solche Maßnahmenbündel auf einer Makro- (Bund, Bundesländer, Regionen), Meso- (Stadtebene) und Mikroebene (Stadtstrukturtypen) zu definieren. Folgende Forschungsfragen stehen im Mittelpunkt: I) Was sind räumliche Dimensionen der urbanen Flächenversiegelung? II) Welche Strategien und Managementdimensionen können Flächenversiegelung steuern? Räumliche Antriebsfaktoren und Auswirkungen der Flächenversiegelung wurden durch Stadtstrukturtypen in einem Versiegelungsgefälle analysiert. Untersucht wurden mit München und Leipzig eine wachsende und eine schrumpfende Großstadt. Die Ergebnisse zeigen, dass die Bevölkerungsentwicklung ein vernachlässigbarer Antriebsfaktor der Flächenversiegelung ist, sich aber das Maß der Revitalisierung von Brachflächen positiv auf die Versiegelungsentwicklung auswirken kann. Insgesamt ist ein holistisches Flächenversiegelungsmanagement multidimensional und umfasst eine quantitative und qualitative Steuerung der Versiegelung als auch urbaner Grünflächen und des Bodens und wird dabei von kompensatorischen Maßnahmen flankiert. Ökonomisch-fiskalische, planungsrechtliche, informatorische und kooperative Strategien haben das Potential, diese Dimensionen der Flächenversiegelung zu steuern. Jedoch ist noch weitere Forschung nötig, um die Effizienz dieser Strategien und der Maßnahmenbündel zu bewerten. Dieser Artikel präsentiert einen Bewertungsrahmen, wie Maßnahmenbündel definiert und deren Strategien hinsichtlich ihrer Effizienz zur Steuerung urbaner Flächenversiegelung evaluiert werden können.

Keywords: Urban ecology, urban landscape, Germany, urban planning, environmental policy

1 Introduction

Soil sealing has been recognized as a major threat jeopardizing the sustainable use of soils across the EU (EEA 2010; 2012). It is defined as the permanent covering of an area of land and its soil by completely or partly impermeable artificial material (Prokop et al. 2011). Soil sealing is closely related to land take, which is the conversion of open areas (mostly agricultural land) into settlement and transport areas. Talking about soil sealing therefore also addresses aspects of land take

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(EC 2012). Soil sealing as the most visible form of land take must be viewed as being particularly critical as exchanges between the pedosphere and atmosphere are strongly affected by the coverage of soils by artificial materials, determining an irreversible degradation of soil and its functions (Prokop et al. 2011).

Soil sealing and land take require intervention and regulation due to further increase across the EU which leads to a loss of ecosystem services; this is widely accepted by land use policy at EU and national level. In Germany, one of the countries with the highest percentage of sealed areas in the EU (Prokop et al. 2011), a target was formulated, which recommends the reduction of land take for settlement and transport areas from 129 ha/day in 2000 to 30 ha/day in 2020 (UMWELTBUNDESAMT 2003). In Germany settlement and transport areas are defined as built-up areas and open spaces related to buildings, holding areas, transport areas, recreational areas and cemeteries. According to estimates, the degree of sealing of settlement and transport areas lies between 43% and 50% (Breitenfeld 2009).

Main drivers of land take in Germany between 2006 and 2009 were, besides transport areas, also recreational areas (UMWELTBUNDESAMT 2010), which indicates that an increase in land take does not automatically lead to an increase in soil sealing. However, no standardized national monitoring on soil sealing is implemented in Germany although several studies have been conducted based on remote sensing or Corine Land Cover data (Esch et al. 2007; Prokop et al. 2011). Also on the basis of urban structural units, research has been done on the degree of soil sealing (e.g. Gill et al. 2008; Haase and Nuissl 2010; Pauleit and Duhme 2000). Therefore, urban structural units provide data for comparative studies of different cities and data on soil sealing where no spatial monitoring exists.

In Germany, data on land use show that a decrease in land take from 130 ha/day between 1997 and 2003 to 93 ha/day between 2006 and 2009 could be observed. However, the German Federal Environmental Agency assumes that these trends result from the global economic crisis and its effects on construction activities. Thus they demand the implementation of more intelligent methods in planning practice (UMWELTBUNDESAMT 2010). Scientific literature and policies suggest that an efficient soil sealing management approach can only be achieved by a mix of instruments addressing federal, provincial and municipal authorities (Arlt et al. 2001; DEUTSCHER BUNDESTAG 2004; Klemme 2009). In the course of the German REFINA program (Research for the Reduction of Land Consumption and Sustainable Land Management) instruments for managing land take have been developed and assessed in 45 sub-projects. These projects relate to separate or topic-specific aspects, such as brownfield development, regional co-operation or spatial information systems (Bock et al. 2011). For Germany and for Europe some other studies also exist which assess the efficiency of instruments for steering land take and soil sealing (e.g. EC 2012; Ulmer et al. 2007; UMWELTBUNDESAMT 2004). But all these studies and projects neither use an assessment framework to compare instruments nor do they define a set of useful instruments to specify how an efficient soil sealing management can be achieved. This paper aims to fill the gap in the literature by developing a framework to define sets of instruments for different management scales based on a spatial monitoring of soil sealing. This framework can be used in further studies to assess the efficiency of sets of instruments for steering urban soil sealing.

To set up an efficient approach to soil sealing, it is crucial to know the components of the "urban soil sealing management" system. One way to understand complex interactions within natural and urban environments is the use of system thinking. Systems are defined as groups of interacting components (such as policies, physical objects or people) that form a complex whole unit (Anderson and Johnson 1997). As an efficient management of soil sealing needs to be supported by a systemic approach to its monitoring, the purpose of the research was to identify spatial drivers of and impacts from urban soil sealing using the example of Germany. By doing so spatial system elements will be identified which need to be targeted by strategies and management dimensions as systemic responses. From the results, a multi-scale framework for defining set of instruments to control soil sealing will be developed.

The study aims to answer the following research questions:

1. What are the spatial dimensions of urban soil sealing? (spatial system elements)
2. Which strategies and management dimensions can control soil sealing? (systemic responses)

2 Methods and study area

2.1 The systemic multi-scale approach

To investigate which spatial system elements influence the system "urban soil sealing management" most and which responses can these steer, the research integrates three scales of investigations, the macro-, meso- and microscale. As the focus of this paper is on the spatial system elements referring to the spatial urban development of the case study cities and their relation to soil sealing, the investigations are carried out at the meso- and microscale. At the mesoscale at city level, quantitative and qualitative management of soil sealing within shrinking and growing cities over 100,000 inhabitants in Germany were investigated. Big cities were chosen since the challenges they face to reduce soil sealing and offer sufficient green and settlement areas for their residents are particularly complex. A distinction was made between growing and shrinking cities as the challenges they are confronted with in urban management differ from each other. Two case study cities, Leipzig as an example of a shrinking city and Munich as a growing city, were selected using specific selection criteria. First all cities over 100,000 inhabitants were differentiated into growing and shrinking cities according to investigations of the German Federal Institute for Building, Urban Affairs and Spatial Research. In a second step, the dynamics of settlement and transport areas between 1996 and 2008 were analyzed as the soil sealing data existing at the national scale in Germany is insufficient for comparative studies. On the basis of these criteria, the growing city with the highest increase in recreational area and the shrinking city with the highest increase in settlement and traffic area were selected. At the micro-scale, the research investigates urban structural units (as no comparable data on soil sealing exist) to identify drivers and impacts of soil sealing (see section 2.3). On the macroscale, the management competences in policy and decision making of regions, federal states and the federal government were analyzed. These aspects of management addressees and authorities will be investigated in further studies and are not part of this paper.

To analyze and assess urban development and its spatial impact on soil sealing, a soil sealing gradient was applied based on the urban-rural gradient approach. The urban-rural gradient can be a suitable tool to investigate land use changes due to urbanization and its impacts on the urban ecosystem and can help to integrate ecological features into urban planning (Niemelä 1999). Urban development and its densification do not take place concentrically from inside to the outside; however, peri-urban and rural areas can be described well by their degree of impermeable surfaces (Haase and Nuissl 2010). Following these assumptions the districts of the case study cities have been classified according to their percentage sealing degrees in three classes: little sealed (Munich: 16–35%; Leipzig: 9–31%), medium sealed (Munich: 36–54%; Leipzig: 33–53%) and strongly sealed (Munich: 60–72%; Leipzig: 59–76%) (see Fig. 1).

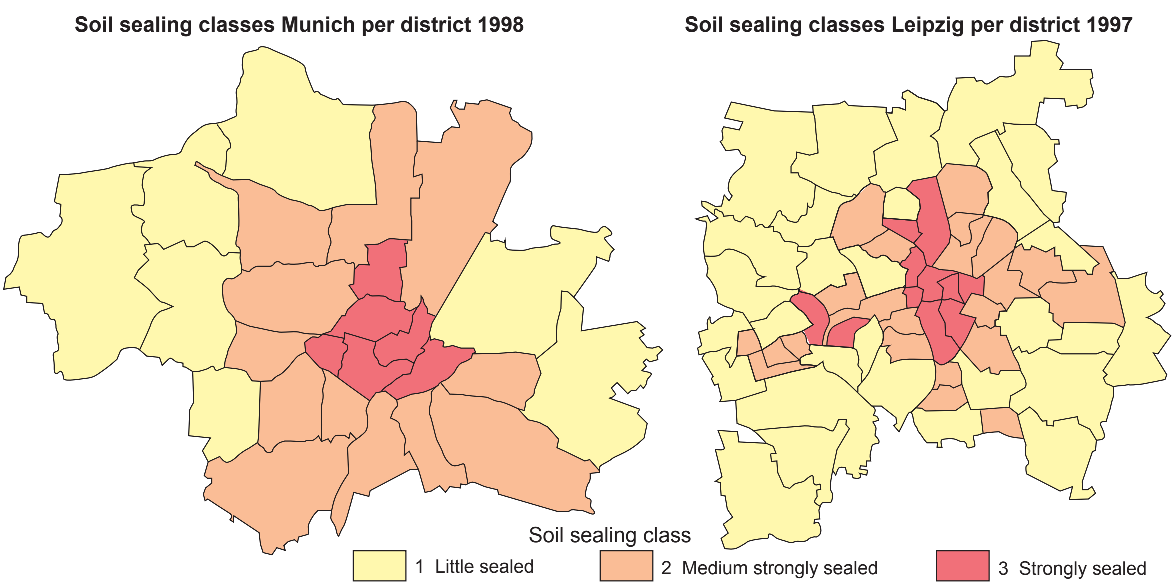


Fig. 1: Soil sealing classes in Munich and Leipzig at a sealing gradient

2.2 The case study cities Leipzig and Munich

The analysis of the spatial development of soil sealing refers in each case study city to two different periods of time. The reasons for this are, on the one hand, pragmatical as maps of urban structural units were used that already existed. On the other hand, the spatial analysis of the respective time steps refers to specific development steps within the cities; these will be described in this section.

Leipzig is situated in eastern Germany in the north-western part of Saxony and has a population of 531,809 (2011) in 63 districts extending over an area of 298 km². From the beginning of the 1960s Leipzig's population declined due to the loss of its economic importance and administrative functions. In the course of the post-socialist transition a process of suburbanization and urban sprawl began. This process reached its peak in the late 1990s. Today, parallel processes of population shrinkage in the urban periphery on the one hand and re-urbanization, especially in the inner-city, on the other hand can be observed (Haase and Nuissl 2010). These trends of suburbanization are contradictory to targets set in the city's zoning plan, which aims for a compact city achieved by the reduction of further land take at the city fringes and the reuse of urban brownfields. As long-term investigations concerning the land cover change have already been conducted (Haase and Nuissl 2010) the investigations in Leipzig include two time steps between 1997 and 2003 to investigate impacts of de-densification (Haase and Nuissl 2010) and decline of population (-4.5% between 1995 and 2004) (Rössler 2010) on the soil sealing development. For the spatial analysis urban structural unit maps of 1997 and 2003 are used on the basis of Haase and Nuissl (2007), which also include percentage sealing degree classes for each structural unit.

The case study city Munich is the capital of Bavaria. The city covers 311 km² and has 25 districts. Munich is the largest city in Bavaria and the third biggest in Germany. The city of Munich experienced high immigration rates: between 1990 and 2010 the population increased from 1.2 million inhabitants to 1.4 million and a further increase to 1.5 million inhabitants by 2020 is projected. These developments put pressure on the city of Munich to secure sufficient land for new settlement areas. Between 1990 and 2010 115,000 new residential units were built through further densification and the re-use of brownfields (LANDESHAUPTSTADT MÜNCHEN 2011a). This trend will continue although Munich's city development plan "Perspektive München" (Munich's Prospects) aims to reduce further sealing and to protect urban green areas. For the spatial analysis, maps made by the City of Munich (Department of Health and Environment) of urban structural units of two time steps (1998 and 2011) are used based on the block level and include degrees and type of sealing per block. This urban development step reflected the impact by high population growth and densification on soil sealing.

2.3 Analyzing and assessing soil sealing

The selection of indicators to assess drivers for and impacts of soil sealing was based on approaches to monitor soil sealing and land take, e.g. by the Leibnitz Institute of Ecological and Regional Development (www.ioer-monitor.de) and Esch et al. (2009). The indicators have been grouped according to the Driver-Pressure-State-Impact-Response (DPSIR) model, which is used in policy and science to evaluate impacts on environment by human activities (Nuissl et al. 2009). The pressure indicators describe soil sealing and land take at the mesoscale. As the German Federal Government's national sustainability strategy differs between a quantitative and qualitative goal to reduce daily land take, the indicators are grouped to describe quantitative and qualitative dimensions of management (see Tab. 1). According to the German Federal Government's national sustainability strategy, the qualitative goal stands for the promotion of infill development to reduce land take on greenfield sites (UMWELTBUNDESAMT 2003). At the microscale, the quantitative driver indicators refer to the percentage change of soil sealing degree per urban structural unit of the built-up areas, and the impact indicators to the percentage change of recreational and open space structural types.

In this paper the qualitative management of land take and sealing is understood in general as a goal for increasing efficient use of space. The qualitative indicators are derived from local planning documents, so that the connection between planning targets and sealing development can be evaluated. For instance, the indicator "compactness" (Esch et al. 2009) is included, as a compact city is demanded which should reduce sealing at the urban fringes (STADT LEIPZIG 2007). The impact on quality of life is described by the supply per capita and average size of green areas. This includes a sufficient supply of green spaces and the possibil-

Tab. 1: Indicators of the spatial system elements of soil sealing

Indicators	Scale	Indicator sealing	Indicator land take/use**	Driver/Pressure/ Impact
		Quantitative management dimension		
Settlement and transport areas	Meso	% p.d.	% p.d.	Pressure
Transport areas	Micro	% p.d.	–	Driver
Low density/little sealed residential units	Micro	% p.d.	–	Driver
High density/highly sealed residential units	Micro	% p.d.	–	Driver
Commercial, industrial buildings/warehouses	Micro	% p.d.	–	Driver
Recreational areas	Micro	–	% p.d.	Impact
Forest	Micro	–	% p.d.**	Impact
Agricultural areas	Micro	–	% p.d.**	Impact
		Qualitative management dimension		
Land take /Soil sealing efficiency	Meso	resi./ha p.d.	resi./ha p.d.	Pressure
Vacancy*	Micro	–	% p.d.	Driver
Compactness (ratio between surface area of low density units and high density units)	Micro	–	Dimensionless (p.d.)	Driver
Recreational areas supply	Micro	–	m²/res. p.d.	Impact
Forest supply**	Micro	–	m²/res. p.d.	Impact
Agricultural areas supply**	Micro	–	m²/res. p.d.	Impact
Recreational areas mean patch size	Micro	–	ha p.d.	Impact
Forest mean patch size**	Micro	–	ha p.d.	Impact
Agricultural areas mean patch size**	Micro	–	ha p.d.	Impact
Sealing of high quality soils	Micro	ha p.d.	–	Impact

% p.d., percentage of surface area per district; p.d., per district; resi./ha, resident/ha; m²/resi., m²/resident, * just for Leipzig, ** according to the definition of land take for settlement and transport areas, indicators referring to agricultural areas and forest relate to land use

Tab. 2: Grouping of urban structural units into low density/little sealed residential units (LD) and high density/highly sealed residential units (HD)

	Floor areal density[1)]	Gross density standard[2)]	Living space per capita[3)]	Sealing degree[4)]	Sum of classes[5)]	Group
Multi-storey tenement blocks	1.00	0.50	0.75	0.75	3.00	HD
Prefabricated housing estate	1.00	0.75	1.00	0.50	3.25	HD
Terraced houses	1.00	1.00	1.00	0.50	3.50	HD
Residential park after 1990	0.50	0.50	0.50	0.75	2.25	HD
Single family (densely built-up), semi-detached houses	0.25	0.00	0.00	0.50	0.75	LD
Single family houses (lightly built-up), villas	0.00	0.00	0.00	0.25	0.25	LD

[1)] Classes for floor areal density (dimensionless): 1:1.0-1.1; 0.75: 0.8-0.9; 0.5: 0.6-0.7; 0.25: 0.4-0.5; 0: 0.2-0.3;
[2)] Classes for gross density standard: 1: 85-103; 0.75: 66-84; 0.5: 47-65; 0.25: 28-46; 0: 8-27;
[3)] Classes for living space (m²) per capita: 1: 26.4-28.7; 0.75: 28.8-31; 0.5; 31.1-33.3; 33.4-35.6; 35.7-37.9;
[4)] Classes for sealing degree (in %): 1: 81-100; 0.75: 61-80; 0.5: 41-60; 0.25: 21-40; 0: 0-20;
[5)] HD: Sum of classes > 2; LD: Sum of classes < 2;

ity of nature-oriented recreation (REGIONALER PLANUNGSVERBAND MÜNCHEN 2012; STADT LEIPZIG 2006). To analyze the impact of soil sealing on highly fertile soils, the soil protection concept of the Department of Environmental Protection of the City of Leipzig was used. This concept assesses the soil quality according to five classes. For Munich, an overview soil map (TK25 map sheet) by the Bavarian Federal Office for Environment was used and classified according to soil qualities, based on Goetzke (2010).

The indicators were calculated using urban structural unit maps. As the urban structural unit typology differs between the cities, the units were grouped into traffic areas (streets, railways), commercial and industrial areas/warehouses (including fairgrounds), recreational areas (parks, allotment gardens, cemeteries), agricultural areas (grassland, arable land) and forest (deciduous and conifer forests). Units of settlement areas were grouped into low density/little sealed residential units and high density/highly sealed residential units based on sealing rates and degree of density. Freestanding structural types (such as free standing single houses or small freestanding multi-storey buildings in Munich which were predefined by the City of Munich) were assigned to low-density built up areas. The degree of density and space efficiency of the other urban structural types were grouped using living space per capita, floor areal density and gross density standard per urban structural unit (Siedentop et al. 2006) (see Tab. 2).

All indicators of table 1 were calculated for the separate time steps (Munich: 1998 and 2011; Leipzig: 1997 and 2003) and their changes between the time steps. Spatially the indicators were analyzed per district where the districts have been grouped in three classes from a soil sealing gradient (see Fig. 1). The analysis was carried out per district as data on population or land use are mostly publicly available per district. The data on population and vacancy were provided by the Statistical Offices of the cities of Munich and Leipzig. The analyses of the mean patch sizes and impact on soil quality were conducted using ArcGIS 10 software. To assess the distribution of soil sealing and its drivers and impacts spatially for a soil sealing gradient, the significance of differences between the city districts within the three sealing classes were calculated using a Kruskal-Wallis test. This test was used as a Kolmogorov-Smirnov test and showed that the data are mostly not normally distributed (Bühl 2008). To analyze the degree and the direction of association of changes on soil sealing and land take caused by the drivers and to identify impacts of sealing at the microscale, the significance of changes were calculated using the Spearman rank order correlation. The statistical analyses were conducted using SPSS (version 16). Based on the results of this analysis, strategies and management dimensions to steer urban soil sealing are discussed, based on a review of literature and planning documents in the case study cities.

3 Results

On the mesoscale, land take for settlement and transport areas and degree of sealing in Munich (73% and 36% of the total area) are higher than in Leipzig (49% and 27% of the total area)[1)] (see Fig. 2). However, soil sealing increased more strongly in Leipzig (2.8%) during the short observation period than in Munich within the longer study period (0.4%). The high increase in sealing in the north east of Leipzig was driven by a strong growth in sealing by commercial and industrial areas (23.2%). The slight decrease of sealing in some districts in Munich is caused by de-structuring activities of brownfields such as of barracks where, for instance in the south of Munich, the demolition of warehouses led to a reduction in sealing.

3.1 Quantitative spatial dimensions of soil sealing

Almost all drivers and impacts of sealing differed within the three sealing classes and between Munich and Leipzig (see Fig. 3).

In Munich transport areas held the greatest proportion in soil sealing, especially in the sealing class-

[1)] According to statements by the Department of Health and Environment of the City of Munich the degree of sealing is estimated at 43% in 1994 and 44.3% in 2006. The differences between these data occur as, besides the sealing rates of the sealing maps on block level, they integrated additional sealing data for public transport areas derived from statistical yearbooks, which are not integrated into the blocks. But as roads, railways and large parking spaces are already integrated into the urban structural unit maps at least at block level, no statistical data on public transport areas were available per district for 1998 and since other research also analyzed the sealing rate of Munich as being about 35% (Pauleit and Duhme 2000) the data used seems appropriate. However, these differences in data show that standardized methods for analyzing sealing degrees have yet been insufficiently developed.

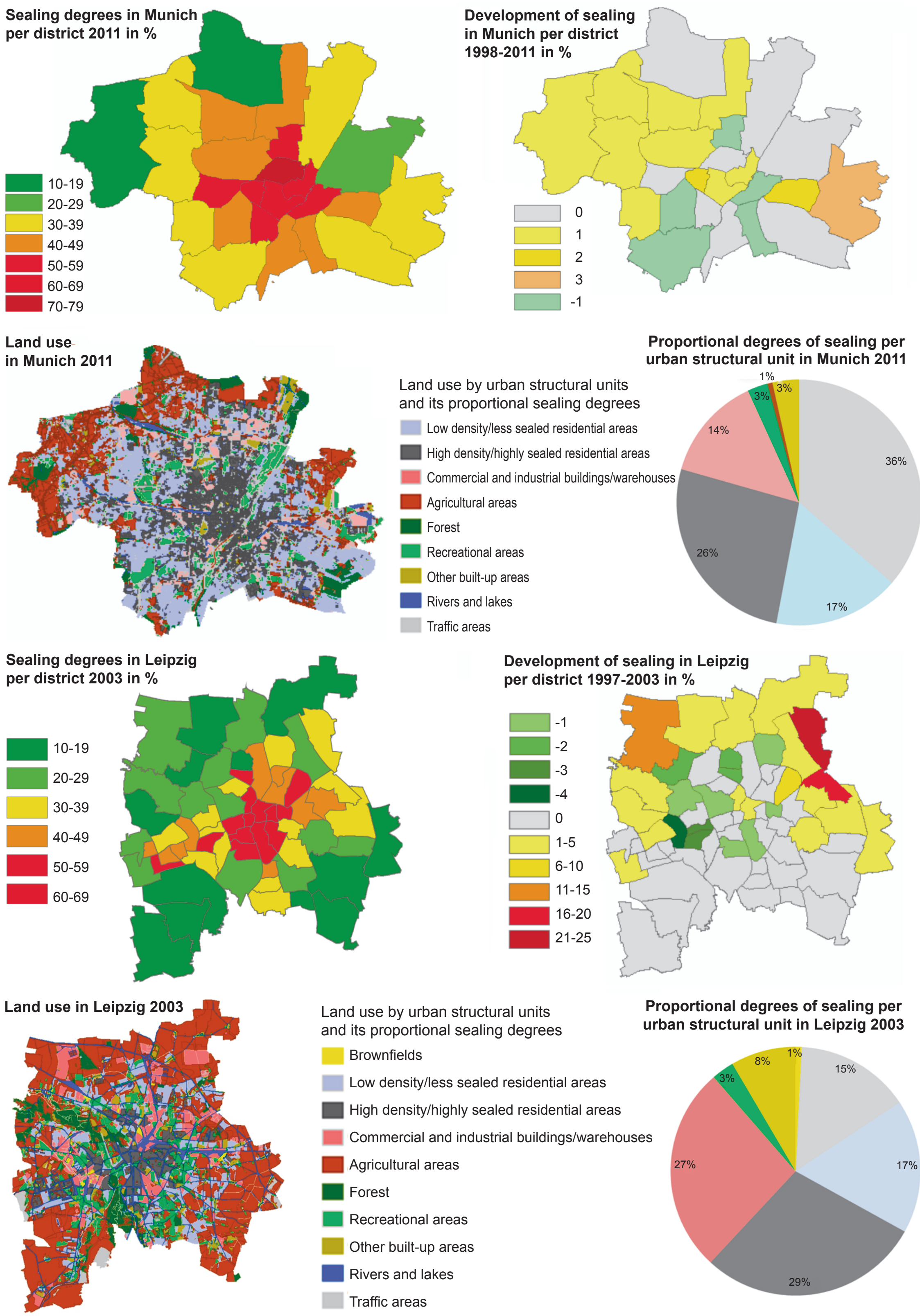
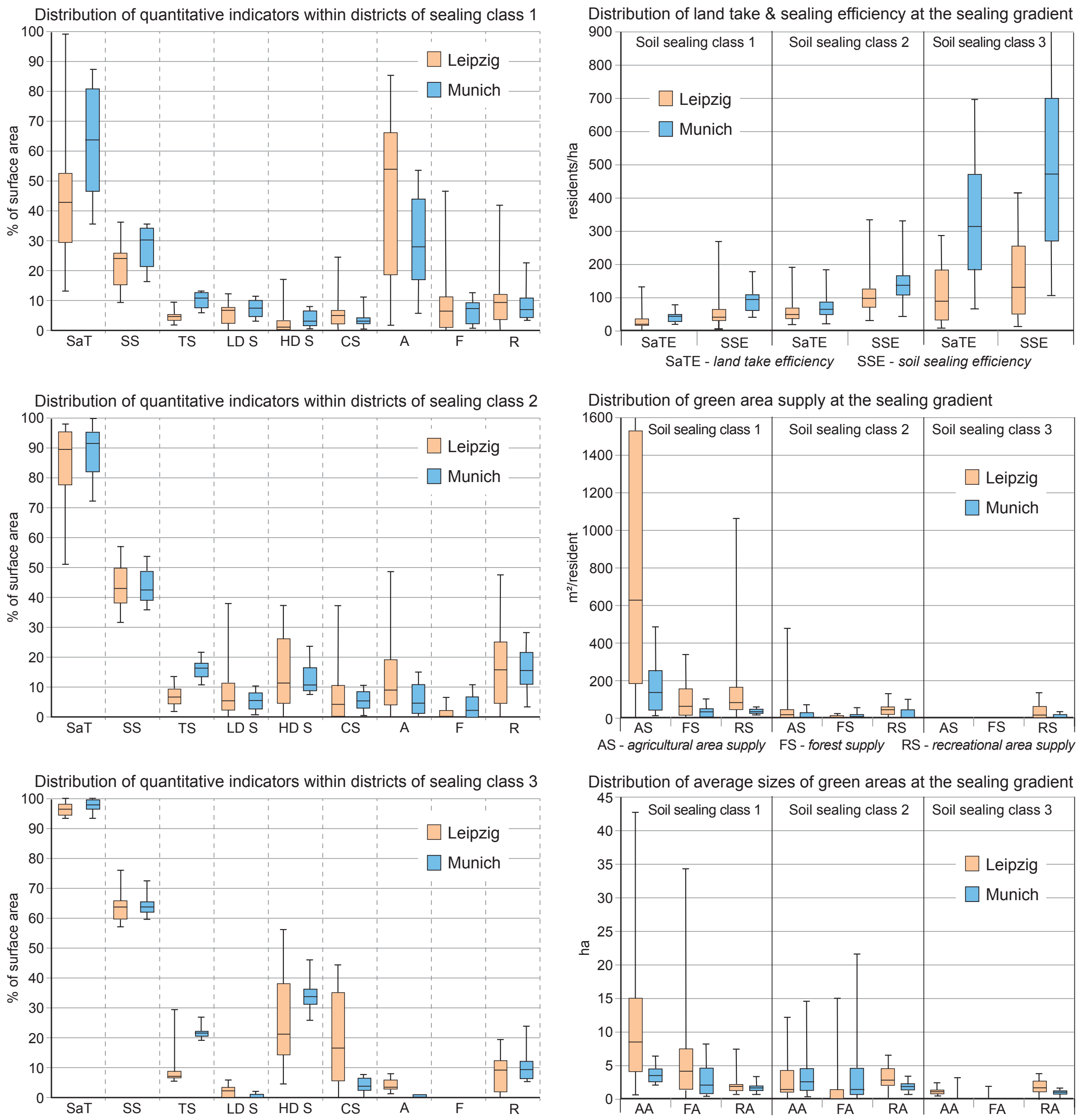


Fig. 2: Degree of sealing, land use types and proportional degree of sealing in Leipzig and Munich at the mesoscale



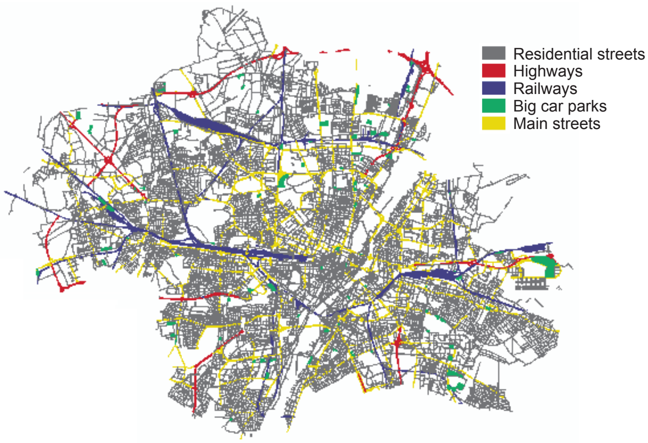
L: Leipzig (N=126); M: Munich (N=50); SaT: settlement and transport areas (land take);
SS: soil sealing; TS: transport areas (sealed); LD S: low density/little sealed (sealed);
HD S: high density/highly sealed (sealed);
CS: commercial and industrial buildings/warehouses (sealed);
A: agricultural areas; F: forest; R: recreational areas

Significance of differences of quantitative indicators within soil sealing classes 1-3 in Leipzig (L) and Munich (M) (Kruskal-Wallis-Test, α=0.05, NS: not significant): SaT(L): 0.000; SaT(M): 0.000; SS(L): 0.000; SS(M): 0.000; TS(L): 0.000; TS(M): 0.000; LD S(L): 0.000; LD S(M): 0.000; HD S(L): 0.000; HD S(M): 0.000; CS(L): 0.001; CS(M): NS; A(L): 0.000; A(M): 0.000; F(L): 0.000; F(M): 0.000; R(L): 0.003; R(M): 0.008

Significance of differences of qualtitative indicators within soil sealing classes 1-3 in Leipzig (L: N=126) and Munich (M: N=50) (Kruskal-Wallis-Test, α=0.05):
SaTE(L): 0.000; SaTE(M): 0.000; SSE(L): 0.000; SSE(M): 0.000;
AS(L): 0.000; AS(M): 0.000; FS(L): 0.000; FS(M): 0.000; RS(L): 0.000; RS(M): 0.001;
AA(L): 0.000; AA(M): 0.001; FA(L): 0.000; FA(M): 0.000; RA(L): 0.002; RA(M): 0.003

Fig. 3: Boxplots showing the distribution of quantitative (left) and qualitative (right) indicators within districts at the sealing gradient

es 1 and 2. Transport areas had an average sealing degree of 83 % (2011). According to analysis at the microscale residential streets had the biggest share of sealing within the transport areas (see Fig. 4). In Leipzig, big contributors to soil sealing at the microscale were low density built-up areas at the urban fringe. However, most of the sealed surfaces were concentrated in high density residential areas where



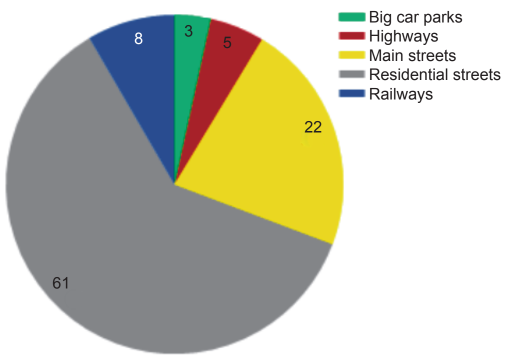


Fig. 4: Transport areas and their share of sealing in Munich

multi-storey tenement blocks had the biggest share of sealing (76%), followed by prefabricated housing estates (17%) and residential parks created after 1990 (7%) (2003). No significant differences were found in the percentage share of commercial and industrial areas in the three classes of soil sealing in Munich. In Leipzig, commercial and industrial areas contributed to sealing, especially in the urban core areas. Analyzing the impact indicators a more equal allocation within the three sealing classes could be found for recreational areas. But these had a high variance within the sealing classes, especially in peri-urban areas which indicate their unequal distribution in sealing class 1 and 2.

Further sealing by an increase in land take could especially be observed for the soil sealing class 1 (see Tab. 3) where sealing increased by 3.6% in Leipzig between 1997 and 2003 and by 0.8% in Munich between 1998 and 2011. In Leipzig further sealing at the town periphery was strongly driven by land take of less sealed low density settlement areas and commercial and industrial buildings. A decrease in sealing in areas within the sealing classes 3 of -0.8% could be shown due to slight de-sealing measures of traffic, commercial and industrial areas. In Munich the slight increase in sealing was driven by transport areas which increased by 0.3%, especially in the soil sealing class 1 and 2.[2)] In districts at the urban fringes where sealing increased a rise in land take by recreational areas due to compensation measures was be recorded. But due to densification recreational areas were lost in the core areas, like in Altstadt-Lehel where an increase of sealing by 1.4% between 1998 and 2011 to a total sealing degree of 61.2% could be shown. The main drivers for this increase are the development of high density built-up areas (1.6%) and transport areas (0.4%). At the same time 1.6% of recreational areas were lost in Altstadt-Lehel.

3.2 Qualitative spatial dimensions of soil sealing

Within the three sealing classes most of the qualitative indicators differed for the sealing gradient. The land take efficiency increased from the classes 1 to 3 in both case study cities (see Fig. 3). In general, the sealing and land take efficiency is higher in Munich as more people live in more densely built-up areas. Significant differences were found in Leipzig between the sealing classes and the degree of vacancy where the median was highest in sealing class 3 (25.0%) and lowest in sealing class 1 (9.8%). The analysis of changes by qualitative indicators of the mesoscale showed a decrease in land take efficiency and more significant in sealing efficiency in Leipzig between 1997 and 2003 (see Tab. 4). However, in the districts where land take efficiency increased, agricultural areas could be protected. This indicated the positive correlation shown in table 4. In Munich almost no significant correlation by change of land take and sealing efficiency could be proven, only a significant decrease in sealing efficiency by an increase in transport areas within districts in the peri-urban area was observed.

[2)] According to estimates by the Department of Health and Environment of the City of Munich the increase in sealing by transport for the whole city is even higher as they also added public transport like sidewalks and squares to the monitoring. Transport areas increased by 0.5% between 1994 and 2006.

Tab. 3: Significant changes of quantitative indicators of soil sealing at the mesoscale

Indicator	City	Sealing class 1		Sealing class 2		Sealing class 3		Change significance over all classes[a]	
		SaT	SS	SaT	SS	SaT	SS	SaT	SS
SaT	L	1	0.880**	1	0.981**	1	-0.662*	1	0.573**
	M	1	0.857*	1	0.720**	1	–	1	0.654**
T S	L	–	-0.426*	–	–	–	–	–	-0.251*
	M	–	0.857*	–	0.811**	–	–	–	0.718**
LD S	L	0.686*	0.525**	–	–	–	–	0.298*	0.508**
	M	–	–	–	–	–	–	–	–
HD S	L	–	–	–	–	–	–	0.341**	0.261**
	M	0.786*	0.786*	–	–	–	–	–	0.455*
C S	L	0.814**	0.763**	0.455*	0.501*	0.968**	–	0.465**	0.750**
	M	–	–	–	–	–	–	–	0.447*
A	L	-0.958**	-0.846**	-0.733**	-0.457*	–	–	-0.853**	-0.651**
	M	–	-0.857*	-0.797**	-0.888*	–	–	-0.710**	-0.773*
R	L	–	–	–	–	–	–	–	–
	M	–	0.757**	–	–	–	–	–	0.488*
V	L	-0.473*	-0.466*	–	–	–	–	-0.290*	-0.329**
AS	L	-0.525**	-0.422*	–	–	–	–	-0.372**	-0.347**
	M	–	–	-0.692*	-0.818**	–	–	-0.597**	-0.587**
AA	L	-0.453*	-0.569**	–	–	–	–	-0.490**	-0.517**
	M	–	-0.821*	–	–	–	-0.841*	–	–
SQ	L	–	–	–	–	–	–	0.257*	–
	M	–	–	–	–	–	–	–	–

L, Leipzig (N=63); M, Munich (N=25); SaT, settlement and transport area (land take); SS, soil sealing; T S, transport areas (sealed); LD S, low density/little sealed (sealed); HD S, high density/highly sealed (sealed); C S, commercial and industrial buildings/warehouses (sealed); A, agricultural area; R, recreational area; V, vacancy; AS, agricultural area supply; AA, agricultural area average size; SQ, soil quality; [a]Spearman correlation (* = 0.05; ** = 0.01); –, not significant

4 Discussion

4.1 On the development of sealing facing demographical and structural changes

The results indicate that growth or shrinkage of urban populations is not a driver of sealing on a mesoscale in the two case study cities. Sealing was driven more by the degree of re-use of brownfields and densification. Also investigations of 202 European cities showed an increase of residential areas in growing and shrinking cities and especially a decline of urban green spaces in East European cities which were characterized by population shrinkage (Kabisch and Haase 2013). The development step investigated in Leipzig stood for a period of de-densification which could be confirmed by monitoring soil sealing in a qualitative manner. Between 1997 and 2003 land take by low density built-up areas and commercial and industrial sites at the urban fringes led to a decrease of sealing efficiency. Moreover, land take by low density built-up areas led to a decrease in compactness (rS = 0.531*). This might be a result of urban sprawl following its definition based on urban forms (Song and Knaap 2004). In Munich the decrease of sealing efficiency due to the increase of transport areas was interlinked with a decrease of compactness in the urban fringes (rS = 0.786*) where land take by low density built-up areas increased by 1.0% over the entire investigation period. In general, urban sprawl increases the distances between working and living and therefore the need for streets which, in turn, leads to an increase in the use of cars and therefore in energy consumption and associated emissions by traffic (de Ridder et al. 2008). Therefore, land take by densely built-up areas should be promoted by planning practice on the microscale as these increase sealing efficiency at the mesoscale, as could be shown in Leipzig (rS = 0.698**) and Munich (rS = 0.660**). Moreover, reducing sealing at the urban fringes from low-density built-up and transport

Tab. 4: Significant changes of qualitative indicators of soil sealing at the mesoscale

Indicator	City	Sealing class 1		Sealing class 2		Sealing class 3		Change significance over all classes[a]	
		SaTE	SSE	SaTE	SSE	SaTE	SSE	SaTE	SSE
SaT	L	-0.693**	-0.751**	-0.535**	–	–	–	-0.387**	-0.360**
	M	–	–	–	–	–	–	–	–
SS	L	-0.677**	-0.761**	–	–	–	–	-0.361**	-0.351**
	M	–	–	-0.601*	-0.629*	–	–	–	–
T S	L	0.600**	0.583**	–	–	–	–	–	–
	M	–	–	-0.622*	-0.783**	0.829*	–	–	–
LD S	L	-0.473**	-0.554**	–	–	–	–	–	–
	M	–	–	–	–	–	–	–	–
HD S	L	–	–	–	–	–	–	0.619*	–
	M	–	–	–	–	–	–	–	–
C S	L	-0.496**	-0.574**	-0.526*	–	–	–	-0.347**	-0.363**
	M	–	–	–	–	–	–	–	–
A	L	0.697**	0.743**	–	–	-0.607*	-0.607*	–	–
	M	–	–	–	–	–	–	–	–
RS	L	-0.546**	-0.489**	-0.485*	-0.621**	–	–	-0.420**	-0.457**
	M	–	–	–	–	–	–	–	–

L, Leipzig (N=63); M, Munich (N=25); SaTE, settlement and transport area (land take efficiency); SSE, soil sealing efficiency; SaT, settlement and traffic area (land take); SS, soil sealing; T S, traffic (sealed); LD S, low density/little sealed (sealed); HD S, high density/highly sealed (sealed); C S, commercial and industrial buildings/warehouses (sealed); A, agricultural area; RS, recreational area supply; [a]Spearman correlation (* = 0.05; ** = 0.01); –, not significant

areas on the microscale might also have positive impacts on the environment at a macroscale as it reduces traffic and therefore energy consumption.

Evidence showing that the promotion of compact cities and higher sealing efficiency reduces the fragmentation of larger connected green areas (Haase and Nuissl 2007) was also revealed in this paper. The increase in sealing at the urban fringes in Leipzig for instance was mostly at the expense of agricultural land in a quantitative and also in a qualitative manner, as soil of high quality has been sealed and the average field size has decreased. To protect sealing of fertile soils at the urban fringes the re-use of brownfields should be promoted since in Leipzig 697 ha of agricultural land were converted to commercial and industrial areas between 1997 and 2003, at the same time 114 ha of commercial and industrial areas became wastelands.

The fact that periods of urban re-organization can be a chance to reduce soil sealing in a quantitative manner could be shown for Munich. In Munich, due to the privatization of German railways and the closing of barracks, 650 ha of railways, barracks and industrial areas have been re-used for new residential areas within the last two decades (LANDESHAUPTSTADT MÜNCHEN 2011b) which has led to a low increase of sealing. Even more, the Department of Health and the Environment in the City of Munich recorded in some districts a decrease in sealing between 1994 and 2006. An example of this is shown in the new urban district Messestadt Riem which was developed on an abandoned airport in the east of Munich where parks were developed as part of urban development measures and the sealing degree decreased from 40% to 37% (unpublished data). However, after the period of re-organization no further wastelands are available for the development of residential areas in Munich and further efforts to steer urban green and urban grey, which is understood as being all forms of paved areas and buildings (Breuste 2011), in a qualitative manner is necessary (see Fig. 5).

Also in Leipzig, where today a trend of re-urbanization can be observed in the inner city, such a qualitative management of urban grey and green is crucial to improve the quality of life in the highly sealed urban core and thus support re-urbanization.

Munich, as a compact city, has a high sealing efficiency which is crucial due to lack of space. That a shortage of green areas is characteristic

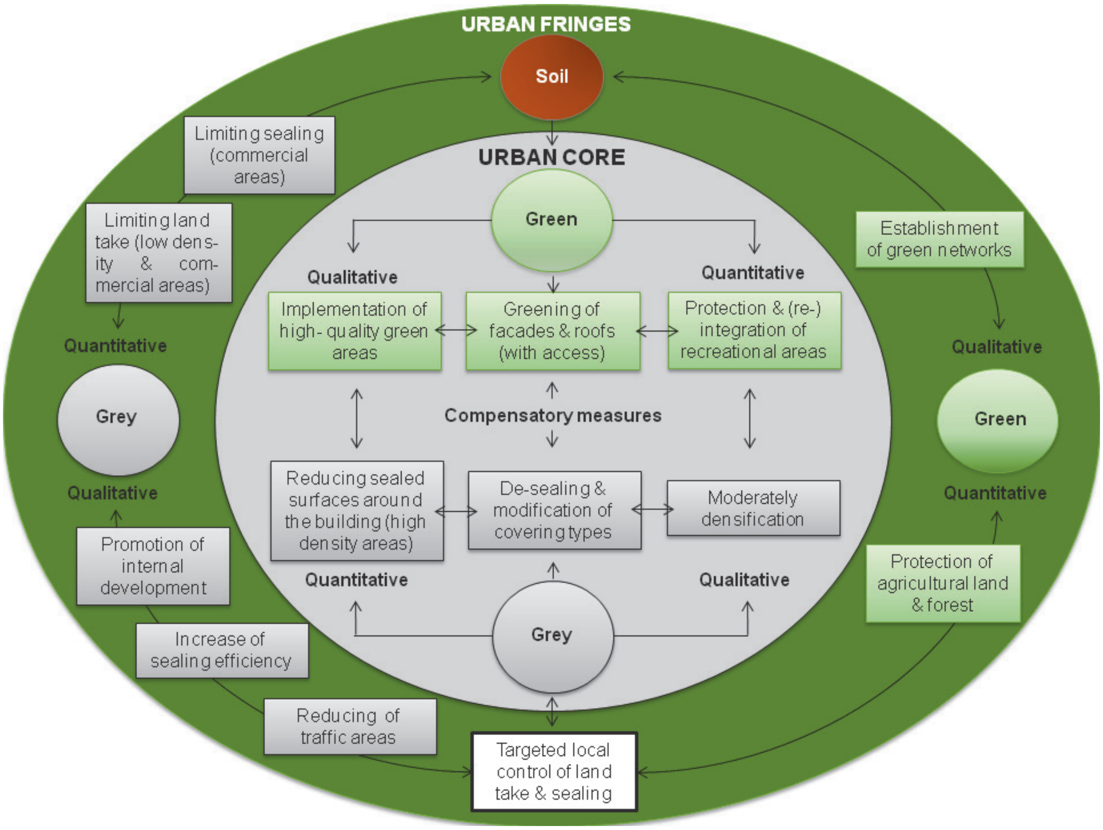


Fig. 5: Management dimensions of a holistic approach to urban soil sealing management

for compact cities (Jim 2004) was also shown for Munich where recreational areas tend to be lacking, the more compact a district is (rS = -0.295*); forest areas also decrease the higher the sealing degree is (rS = -0.700**). High sealing degrees therefore could reduce the living quality due to a lack of recreational areas and also due to negative impacts on heat stress as part of climate change (Lafortezza et al. 2009). But according to the zoning plan in Munich new settlement areas should be developed in part by further densification as no further wastelands are available. To protect recreational areas a moderate densification and reduction of urban grey around buildings should be promoted in Munich. For highly sealed core areas, such as in Munich, pocket parks can support the management of urban green in highly sealed and densely built-up areas. Studies of pocket parks in Scandinavian cities have shown that some of the smallest parks (<3000 m^2) have the highest restorative values including physical, environmental and psychological variables depending on the design and components used for park development (Nordh et al. 2009).

4.2 On the management of soil sealing

To steer urban green as part of soil sealing management informal and legal planning strategies such as the landscape plan of Leipzig or the zoning plan of Munich include goals to protect urban green for climate adaptation, and for recreational and environmental protection. Because of high degrees of sealing and high pressure on recreational areas in urban areas, it has to be proven whether the 30-ha target is useful for cities as this target can also be reached by a reduction of recreational areas as these are included as part of settlement and transport areas. The results suggest that it would be useful to implement a separate goal for reducing soil sealing at least at the mesocale. Furthermore, the promotion of inner development recommended by the German sustainability strategy needs to be supplemented for cities as results of the sealing gradient show that an adoption of the concept of "dual inner development" of cities by planning is crucial if a moderate densification is to occur whilst protecting sufficient high quality green areas (DRL 2006).

To (re-)integrate green areas, the City of Munich, for instance, promotes de-sealing and greening roofs through financial subsidies and awareness-raising measures. As part of the biennial competition "More Green for Munich" best practice examples of green courtyards and green roofs of settlement and commercial areas by residents and investors are honored. Leipzig, as a shrinking city, or as a city in transition, is especially affected by quantitative land take through low density built-up and commercial and industrial areas in the suburban areas which have increased sealing and meant a loss of agricultural land. Reasons for this development can be economic and fiscal drivers. Shrinking cities use spatial development to improve the local budget (Klemme 2009) and to overcome competition with neighboring municipalities. Therefore, monetary and fiscal incentives are necessary to promote more efficient settlement types as well as regional co-operation to reduce the competitions between cities (EC 2012).

4.3 On the use of urban structural units for monitoring soil sealing

As the spatial analysis was carried out by using already existing structural unit maps and data on population per district, such analysis could also have been carried out in other big cities where these data are usually available. Thus, the analysis supports the planning practice (Larondelle and Haase 2012). However, for comparative studies the use of the urban structural unit approach can be tricky when data are used that already exist as the data differs between the cities. Differences especially occurred between structural types of residential areas which had to be grouped to obtain comparable data. It should be noted that the indicators used for grouping are mean values based on literature. However, further studies showed that mean values such as floor areal density can clearly be assigned to typical urban structural units (such as compact-closed development/ loosened-open development) (Böhm et al. 2010). Moreover, as correlations between the decrease of sealing efficiency and increase in low density built-up areas could be found it seems that the grouping was meaningful.

Also the method of monitoring sealing based on urban structural units differed between the cities. In Munich the sealing degrees have been exactly defined within construction blocks which support the sealing monitoring more precisely; however this is only used for building blocks and does not integrate public streets, places and railways. Also the separate sealing monitoring by the City of Munich identifies sealing per building block assigning the blocks to the degree of sealing within 10% steps. The analysis of the development of sealing between 1994 and 2006 by the City of Munich showed that especially blocks of the sealing class 8 (70–80%) and 9 (80–90%) decreased (unpublished data). These decreases can be explained by the decline in big warehouses which have a mean sealing degree of 82% and decreased by 46 ha between 1998 and 2011. Analysis of soil sealing development using urban structural units therefore has the strength to show up the sources of such changes, which are also not included in detail in the sealing monitoring by the European Commission (EC 2012; Prokop et al. 2011). In Leipzig the sealing degrees based on the urban structural units are less precise than in Munich as the sealing degrees are only estimated per structural unit type, but these do include the whole city area, not just blocks.

Finally, sealing monitoring using urban structural units supported the assessment of spatial qualitative driving forces of soil sealing as it allowed analyzing relationships between de-densification, sealing efficiency and urban form and therefore complemented the quantitative study on urban sprawl by Haase and Nuissl (2007). In the urban structural unit maps of Munich rough degrees on type of coverage (built-up, asphalt, pavement) are included per block and can be analyzed in further in-depth studies. However, the data analyzed in both cities lack on qualitative statements such as on the potential of de-sealing and greening roofs which would be crucial to assess the ecological performances of the structures precisely and to develop compensation strategies for soil sealing management.

5 Conclusion

This paper analyzed spatial drivers of urban soil sealing on a meso- and mircoscale and identified planning, economic-fiscal, co-operative and informational strategies for steering soil sealing. By using a multi-scale approach including quantitative and qualitative indicators the paper contributes to a clearer understanding on the sources and

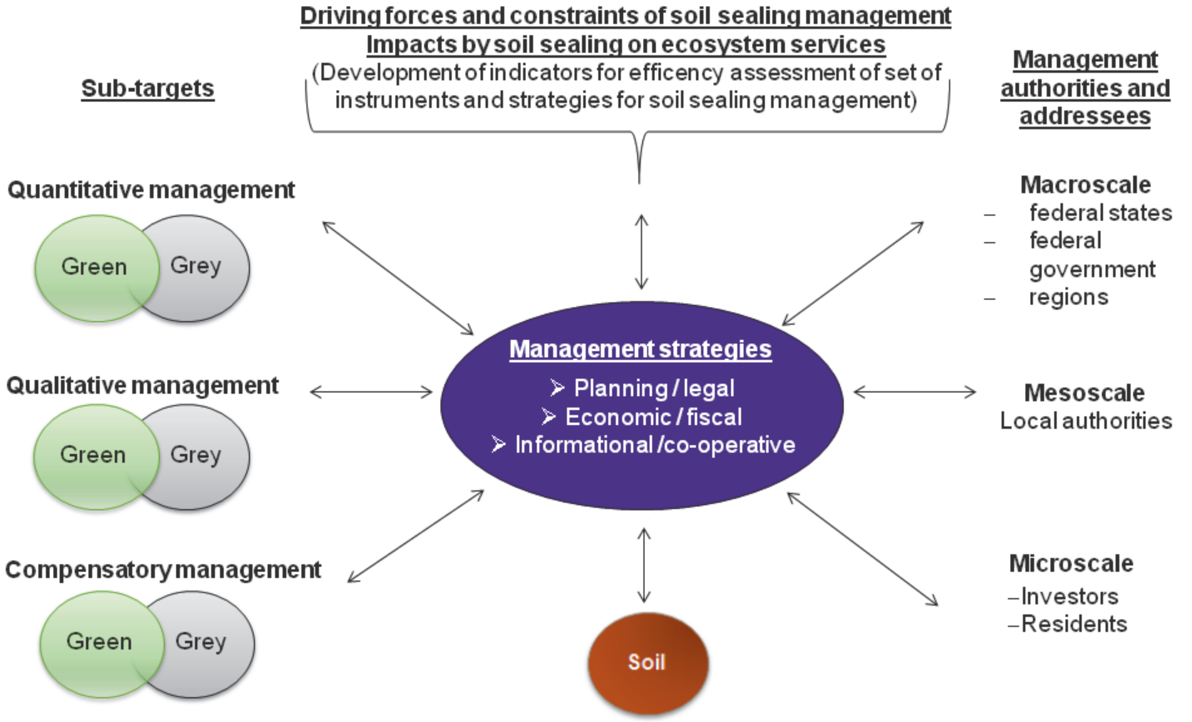


Fig. 6: Framework for defining a set of instruments and efficiency assessment of soil sealing management

spatial distribution of the development of urban soil sealing. In particular relations between soil sealing development and urban sprawl and the re-use of urban wastelands are discussed. By analyzing impacts of soil sealing the paper shows in an illustrative way that soil sealing management also includes the integration of urban green as an antagonist of urban grey. The results showed that a holistic soil sealing management comprises a two-by-three dimensional range of tasks (see Fig. 5). The management dimensions include quantitative, qualitative and compensatory management (three dimensions) of urban soil sealing and urban green areas (two dimensions) with different main tasks in the core districts (focus on soil sealing) than at urban fringes (focus on land take). As the basis of urban grey and urban green areas is the soil, sealing management includes basically the protection of soils in terms of land protection as well as a substrate. The study further showed that the achievement of these management dimensions can include a range of strategies. In further research sets of instruments can be defined by allocating specific instruments of the strategies to the sub-targets (Fig. 6). These can then be assessed in their efficiency including stakeholders of different scales. This paper developed a multi-scale framework on how to define a set of instruments based on spatial soil sealing monitoring and therefore supports the current political soil sealing debate on how to steer soil sealing efficiently. The study further responds to the increasing need for comparable data on soil sealing.

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