Multiscale assessment of land use efficiency in functional urban areas of Munich and Augsburg

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Abstract

This study aims to understand the spatio-temporal variations in land use efficiency (LUE) estimations at different scales of assessment, focusing on the per-capita built-up area within the Functional Urban Areas (FUAs) of Munich and Augsburg, Germany. The analysis is done for the time epochs 1985, 1995, 2005, 2015 and 2020. FUAs are defined as the economic area of influence in each urban area, making the study of land consumption in FUAs crucial for spatial planning and policy analysis. Land use efficiency is computed using built up surface and population data extracted from the Global Human Settlement Layer. This is done at municipal level and 100 m grid level. Furthermore, the effects of using high resolution building footprints for LUE computations are assessed. The analysis shows that urban cores and the adjacent regions are densifying with lower per capita built surface consumption while smaller urban areas utlise more per capita built surface leading to inefficent land use. It is also observed that higher resolution assessments helps in identifying varying intra-regional LUE estimates for a focused urban planning strategy development. Our study concludes that land use efficiency has generally decreased over time in the commuting zones of FUAs while the urban cores have remained efficient.

1. Introduction

Climate adaptation and climate protection entail spatial demands (Roggema, 2009). These demands collide with increasing land use inefficiency, especially for housing (Schiavina et al., 2019). The United Nations estimated that by 2050, 70% of the global population will reside in major cities, increasing the urban population from 3.4 billion in 2009 to 6.3 billion. This surge in urban dwellers leads to an expansion of built-up areas, which then competes with land needed for agriculture, conservation, and other essential ecosystem services (Haberl et al., 2014).

Over the past century, rapid urbanization has become a significant driver of environmental change, profoundly affecting human impacts on the Earth (Grimm et al., 2008). Although urban areas currently occupy only about 0.5% of the Earth’s land surface (Florczyk et al., 2020), their influence extends far beyond their physical boundaries, influenced by the expanding activities of their inhabitants (Seto et al., 2012). The urbanization of land and population growth are closely linked, as cities expand their infrastructure to support increasing populations and their associated needs. However, sometimes these factors diverge, leading to different patterns in population growth and land consumption (Kroll and Kabisch, 2012).

Economic variables also play a role in shaping urban expansion and the distribution of activities within cities, influenced by factors such as transport accessibility and the costs associated with different locations. This leads to spatial disparities where central urban zones, due to better accessibility and higher property values, differ significantly from more distant areas (Suharsono and Candra, 2013); (Kocur-Bera and Pszenny, 2020).

While cities are growing, suburban areas are growing as well. The phenomenon of sub-urbanization is associated with the population shift from core cities to suburbs (Harris, 2015); (Koumparelou et al., 2023). This dynamic, surprisingly, does not densify these rural or suburban areas but to the contrary leads to even less efficient land use in these rural and suburban areas, as this research work shows. Together with the observation that low density neighbourhoods occur in cities as well (Frank, 2018) the term sub-urbanization might need to be reconsidered. In order to understand and manage residential sprawl better, land use efficiency needs to be measured on a more granular scale and shorter time cycles.

There is a notable disparity between the intensive land use in city centers and the inefficient, less developed peripheral zones that lack infrastructure that are often located near agricultural areas. To address these issues, it is crucial to monitor urban densities and land-use efficiencies to guide the sustainable development of cities in the future (Liu et al., 2014). This monitoring can be achieved by tracking changes in built-up areas and demographic trends over time, utilizing specific data and indicators (Wolff et al., 2018).

Land use efficiency is a fundamental concept within the framework of sustainable development. Various metrics have been employed to quantify this. Prior research has explored land use efficiency from an economic perspective, measuring the economic output per unit of land (Zitti et al., 2015); (Du et al., 2016). Additional research has linked land-use efficiency to the broader goals of sustainable development, considering both ecological and socioeconomic dimensions (Salvati, 2013); (Pili et al., 2017). In the context of urban planning, land-use efficiency has been associated with the ratio of new land developed to the number of people accommodated (Ceccarelli et al., 2014); (Colantoni et al., 2016).

Our study focuses on evaluating land use efficiency through the relationship between size of built surface area and the resident population (Schiavina et al., 2019). Although newer and more intricate indices have been introduced (Salvati et al., 2013);

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(Duvernoy et al., 2018), the per-capita built-up area continues to be an effective measure for longitudinal analysis of urbanization trends and land consumption at both local and regional levels (for instance, (Serra et al., 2014); (Quatrini et al., 2015); (Tomao et al., 2017)).

The contribution of this work are as follows:

1. understanding the spatial variations in land use efficiency between dense urban cores and other municipal regions within the functional urban areas of Munich and Augsburg.

2. showing the impact of different scales of assessment on LUE computations.

The next section presents a brief description about the study area, followed by datasets and methods outlining the datasets used and the methodology that is adopted in this research. Section 4 presents the findings and discussion based on the same. In section 6, concluding remarks are presented.

2. Study area

Functional Urban Areas (FUAs) aim to capture the essence of a metropolitan area by identifying a city and its surrounding commuting zone. This zone is characterized by areas from which at least 15% of the resident population travels to the central city for work (OECD, 2012a). The United Nations Statistical Commission designated FUAs as a key enhancement to the methodology recommended for defining urban regions for the purpose of international statistical comparisons (UnitedNations, 2020).

FUAs of Munich and Augsburg (Figure 1) represent key regions within Germany that highlight the inter-connectedness of urban centers and their surrounding areas, especially in terms of economic, social, and environmental dynamics. Munich and Augsburg are also the two largest cities in economically important official area called "Metropolregion München". Hence, these are chosen as study sites for this analysis.

Munich, being the capital of Bavaria and the third largest city in Germany, offers a vibrant urban core with extensive influence over surrounding regions. Augsburg, with its rich history and significant cultural heritage, complements Munich by contributing to the broader metropolitan network. These FUAs are crucial for understanding regional development, facilitating sustainable urban planning, and crafting policies that address the challenges and opportunities within these dynamic environments. The study of Munich and Augsburg's FUAs provides insights into the complexities of urban and peri-urban interactions in one of Europe's most economically significant areas.

3. Datasets and methods

This study utilizes a methodological framework that examines up-to-date, empirically-based geospatial data with a temporal dimension and global consistency, developed by the GHSL team. This framework facilitates the calculation of a spatially explicit land use efficiency indicator – the built-up area per capita as proposed by (Schiavina et al., 2019) – in our study area.

The approach employs an established metric to characterize land use efficiency across various time frames, aligning with the objectives of SDG 11.3.1 and explores additional methods (high resolution building footprint mapping) to enhance the LUE estimations. It evaluates the spatial and temporal patterns within FUAs and leverages precise, compatible spatial data to compare the performance in core areas against their commuting zones within the FUA at municipal as well as grid level.

Inorder to focus on the need for high resolution estimates for LUE computations, for the recent year, i.e 2020, high resolution building footprints are computed to calculate built-up surface area and compared with existing GHSL built surface estimates. A comparison of spatial-temporal variations in LUE at both municipal and 100m grid level and the need for higher resolution datasets for better LUE estimates is discussed in section 4 and 5 in the article. Details on datasets and methodology utilised for computing LUE is given below:

3.1 Land use efficiency (LUE)

This study measures land use efficiency by analysing the amount of built surface, BS (in m^2), with respect to the number of inhabitants, Population, at a given time period 't' in 1985, 1995, 2005, 2015, 2020 by

$$LUE = \frac{BS_t}{Population_t} \tag{1}$$

LUE is measured both at municipal level and 100 m grid level. We developed four classes of land use per person ranging from "efficient" to "inefficient". The efficiency classes are aligned with the "Weighted Urban Proliferation" (WUP) that defines land uptake per person under 100 m^2 as rather efficient (European Environmental Agency, 2016).

We utilise input datasets on a) the extent of built-up areas to quantify land consumption, b) demographic information to quantify population and c) delineation of FUAs. Datastes on a) and b) are acquired at 100 m spatial resolution from Global Human Settlements Layer (GHSL) owing to its consistent and multi-temporal geographical coverage.

GHS-BUILT represents a global, multi-temporal grid level data that illustrates the density of built-up areas. This grid is generated by analyzing vast quantities of Earth Observation (EO) data through a machine learning technique applied to collections of Landsat data, in addition to learning sets GlobeLand30 datasets. The GHS-POP dataset, which quantifies population density, is created by refining the harmonized estimates of resident populations from the Global Population of the World (GPW) project by the Center for International Earth Science Information Network (CIESIN) at Columbia University. This refinement involves downscaling globally collected census data. These datasets were obtained at 100m grid level and were then aggregated at municipal level for multiscale computations and FUA boundaries are acquired from OECD database.

3.2 Building footprint generation

In order to have access to the information about the temporally accurate state of the buildings present in the year 2020, we derive the building footprints out of *Sentinel-2* imagery. We follow closely the procedure in (Prexl and Schmitt, 2023) which leads to a binary map of buildings on a 2.5 m ground sampling distance grid. This increase of resolution is done by computing model (UNet) features on a upsampled version of the input signal and is proven to reliably increase the resolution of

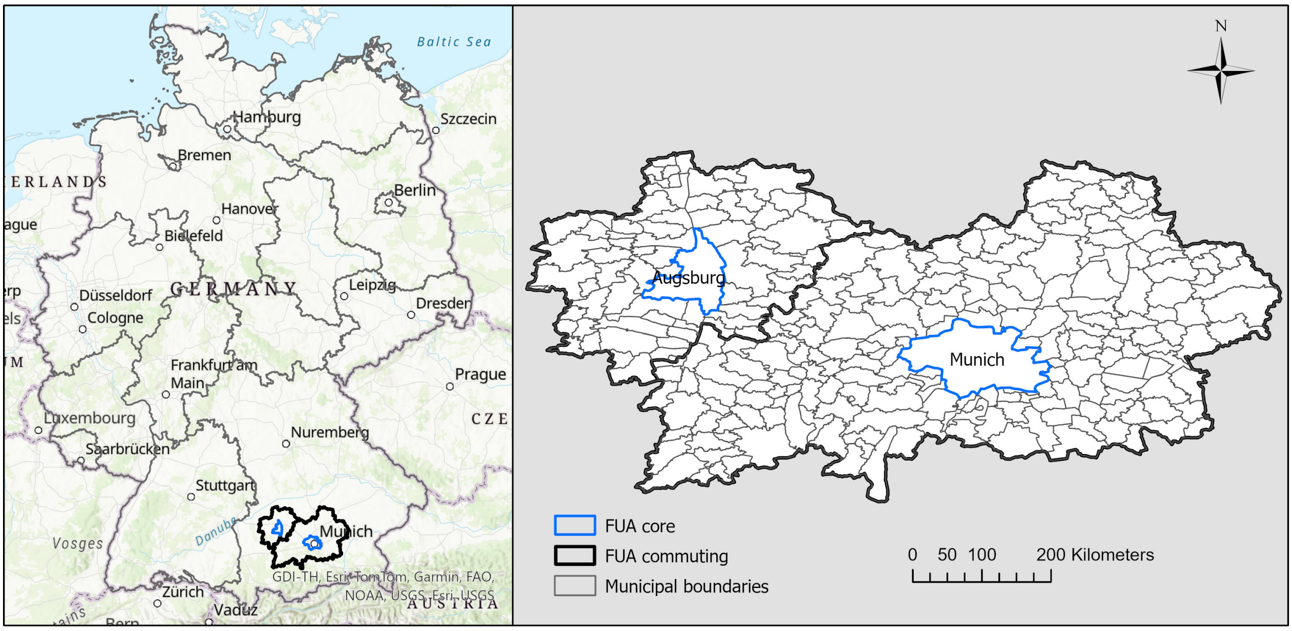

Figure 1. shows geographical location of the study area in Germany and the municipal regions contained within FUAs of Munich and Augsburg.

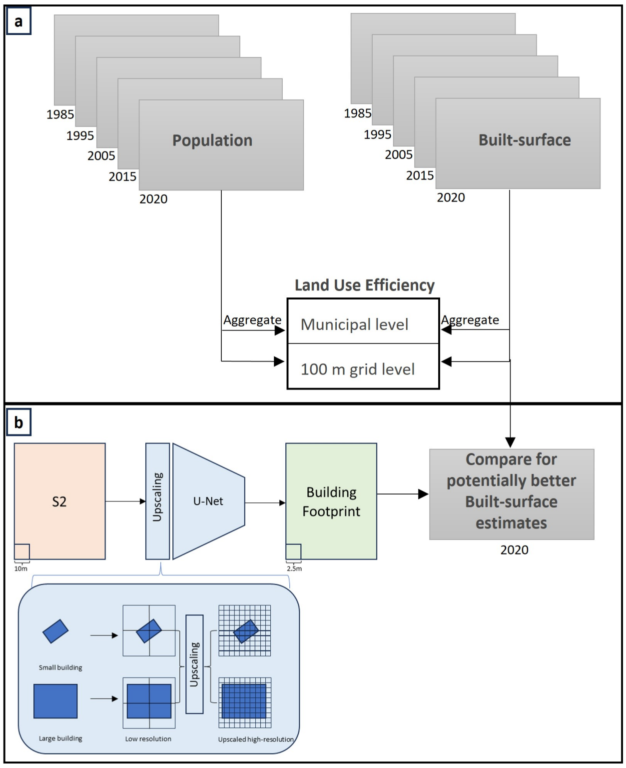

Figure 2. Methodological framework showing a) the datasets and computation of LUE at municipal and grid level and b) building footprint generation at 2.5 m resolution for calculation and comparison with GHSL Built surface estimates.

the obtained building masks. Here, the models from (Prexl and Schmitt, 2023) were retrained on a local dataset that includes 26 *Sentinel-2* tiles (covering nine locations every three months), encompassing Munich and Augsburg capturing a variety of urban settings and accounting for seasonal changes in surface reflection throughout the year. Labels were obtained by the OSM layer. The model reaches an IoU score of 0.73 on a random validation set, which indicates a sufficient performance for a underlying information product in our study.

A detailed methodological framework is presented in Figure 2.

4. Results

This section presents the results showing long-term spatio-temporal variations in LUE in the urban core and commuting zones of the FUAs in Munich and Augsburg. This is presented at municipal level and 100m grid level for the time periods 1985, 1995, 2005, 2015 and 2020. Furthermore, impact of the scale of assessment is discussed while highlighting the need for higher resolution datasets for LUE computations.

4.1 Multi-scale assessment of spatial variations in LUE from 1985 to 2020

4.1.1 At municipal level Figure 3 shows that the urban core of Munich has been consistently performing well on the LUE metric with the lowest (below 50 m^2) built up area consumption per person from 1985 to 2020, while urban core of Augsburg consistently falls in the second most efficient category (i.e. 50 to 100 m^2). Interestingly, most of the municipalities adjacent to the urban core of Munich and Augsburg falls in the second most efficient LUE category, while those farther away are shown to be less efficient implying a larger land consumption per person in these regions. It is also interesting to note that the number of municipalities with LUE in the range 200 to 500 m^2 was only 1 in Munich FUA in 1985, which increased to 24 in Munich FUA and 17 in Augsburg FUA in the year 2020.

This signifies that Land Use Efficiency has decreased over time in both the FUAs in the commuting zone. Nearly all these municipalities have changed into 200 to 500 m^2 per person class (orange color) from 100 to 200 m^2 per person class (yellow color) and not from the more efficient ones (represented in green color).

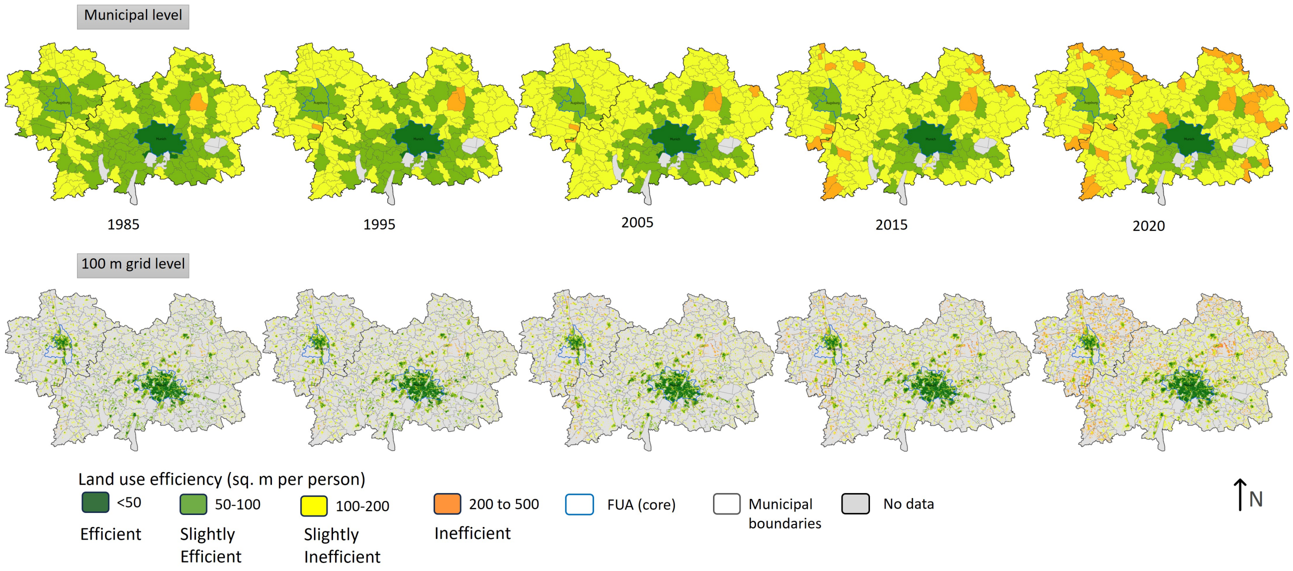

Figure 3. shows the variations in land use efficiency from 1985 to 2020 at municipal and 100 m grid level in the functional urban areas of Munich and Augsburg.

4.1.2 At 100 m grid level When analysing the LUE patterns at grid level, a comparatively detailed picture can be seen with similar observations. Urban core of both Munich and Augsburg is seen to be in the efficient category (below 50 m^2) as at the municipal scale. However, further LUE variations within municipal regions can be observed at 100 m grid scale. For instance, in the urban core of Munich most of it is in the efficient category however there are still some regions in the slightly inefficient category (yellow color). Similarly, while most of the region in Augsburg can be observed in slightly efficient (light green) category, as in the municipal level computation, the centre of the urban core is in the land use efficient category (below 50 m^2).

It is also observed that the municipalities farther away from the urban core seems to undertake more inefficient land consumption with a larger area covered in 100-200 m^2 per person category.

4.2 Need for high resolution datasets for better LUE estimates

This study presents a first set of experiments to show the potential of *Sentinel-2* derived building footprints at 2.5 m spatial resolution for calculating built surface estimates for computation of sustainability indicators like LUE. Figure 4a and b shows the qualilty of building footprints at 2.5 m resolution for the municipal region of Ismaning. Figure 4c highlights comparison of OSM building layer and our building footprints at 2.5 m resolution in 100m grids as used in GHSL data. As clearly visible, building footprints generated using *Sentinel-2* looks reliable and accurate comparing it with OSM building footprints. Figure 4d shows the built surface estimates in each 100m grid using GHSL data (in blue) and using our building footprints (in pink).

Evidently, in most of the grids GHSL data is seen to slightly overestimate the built surface. This could be because GHSL built surface is estimated using Landsat data with 30 m spatial resolution and due to the problem of mixed pixels built surface areas could be over or under estimated. This highlights that higher resolution and temporally consistent datasets for estimation of built surface are needed.

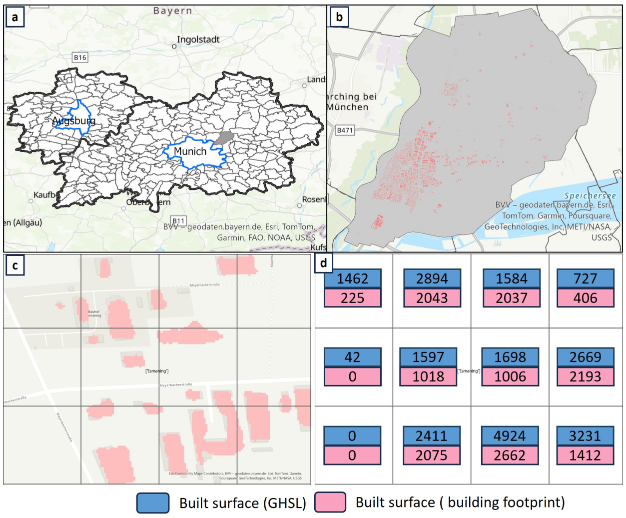

Figure 4. shows a comparison between bulit surface estimates using GHSL data and building footprint data generated using *Sentinel-2* data at 2.5 m spatial resolution.a) shows the gegraphical location of test site ’Ismaning’ in the study area, b) shows the building footprints from *Sentinel-2* data in Ismaning,c) shows a comparison of building footprints from OSM and those generated using *Sentinel-2* at 100 m grid level and d) shows the built surface estimates in m^2 in each 100 m grid cell using GHSL (in blue) data and *Sentinel-2* building footprints (pink).

5. Discussion

Section 4 shows the long-term variations in LUE at municipal and 100 m grid level. It also highlights the challenges in computing LUE at higher resolutions and the need for the same. It brings to light that the regions that are efficient are closer to the urban core and maintain a higher LUE with low built up area per person consumption while the ones that are already consuming more space are becoming more inefficient. It can be attributed to the fact that overtime urban cores tend to become saturated and suburbs are seen as the primary reserve of future urban developments.

This indicates that sustainable urban development and planning policies need to focus more on the sub-urban areas and smaller cities in terms of efficient land consumption than the urban core. Overall, it is also observed that the LUE patterns at 100 m grid scale is similar to that at municipal level where only inter-municipal differences in LUE can be seen while intra-municipal region variations can be observed at 100 m grid level analysis making it suitable for focused urban planning approach.

Section 4.2 highlights the challenges and need for higher resolution built surface estimates using modern machine learning algorithms for LUE computations. Another limitation to compute LUE at higher resolution are population estimates which are collected at municipal level once in 10 years and down-scaled to meet the analysis criterion. This analysis also highlights the need for higher resolution and temporal frequency in population datasets. Results on multiscale estimation of LUE in this study also highlights the importance of assessing sensitivity of LUE to the spatial scale of assessment. This should be considered while using LUE estimates in regional urban planning.

Keeping these challenges in mind, for long-term monitoring of LUE, GHSL is considered to be the most notable dataset with consistent database. However, considering the ongoing housing crisis globally, it is essential to monitor LUE at granular scales for better spatial urban planning.

6. Conclusion

Recent studies on the dynamics of land use due to the expansion of human settlements show that globally, there is a trend towards ongoing depletion of natural resources. Specifically, it has been noted that the rate at which land is consumed often surpasses population growth rates. Our findings suggest that urban cores tend to densify (therby becoming more efficient), whereas the efficiency in commuting zones diminishes, in line with the general theory that larger agglomerations operate more efficiently in terms of land consumption. However, this overall trend varies across different spatial extents.

As observed in our research focusing on different spatial scales of assessment, more granular observations are capable of revealing patterns that otherwise go unnoticed. While per capita land consumption has increased over time implying a decrease in land use efficiency, these changes do vary within administrative boundaries and on neighbourhood scale. Consequently, this study reflects that the quality of monitoring tools is greatly influenced by the availability of suitable input data. For continuous monitoring of land use efficiency, it is crucial to have access to high-resolution and temporally consistent datasets on built surfaces and demographics. These detailed efficiency assessments are vital for spatial and territorial planning aimed at regulating urban development. Policymakers can benefit significantly from this analysis, which can assist in identifying specific areas, such as commuting zones, where efforts should be focused and successful strategies can be replicated.

This work is also intended to contribute to the ongoing discussion regarding sustainable development indicator 11.3.1, facilitated by the European Work Group on Data Integration under the United Nations Initiative on Global Geospatial Information Management (UN-GGIM: Europe). Given that indicator 11.3.1 is linked to certain indicators suggested by the European Commission for tracking the impact of EU policies on achieving the Sustainable Development Goals (SDGs)—specifically the EU SDG indicators 15.21 (Artificial land cover per capita)—this work is also expected to aid the working groups tasked with calculating these indicators.

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