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Multifunctionality of Urban Green Spaces in the EU

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Dedicated to Delia
Aron
Pia
Erwin

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Acronyms

AOI	Area of interest
CICES	Common International Classification of Ecosystem Services
CLC	CORINE land cover
EEA	European Environment Agency
ES	Ecosystem services
EU	European Union
GDP	Gross domestic product
GI	Green infrastructure
IPBES	The Intergovernmental Platform on Biodiversity and Ecosystem Services
LF	Landscape functions
MA	The Millennium Ecosystem Assessment
MCA	Multi-criteria analysis
MESLI	Multiple ecosystem services landscape index
MF	Multifunctionality
NCP	Nature's contribution to people
OLS	Ordinary least square
SDG	Sustainable Development Goals
TEEB	The Economics of Ecosystems and Biodiversity
UGS	Urban green space
UN	United Nations
WGS	World Geodetic System

Abstract

Recently, there has been a global trend of people migrating from rural areas to urban centers, known as urbanization. While this process creates further dynamics in city planning, social services and many more professional or scientific fields, geographic research of recent years has had its focus inter alia on livelihood in urban areas (Jones & Newsome, 2015; Zhang et al., 2022). Closely connected to that are 'urban green spaces' (UGS), which are often defined as every green or blue surface area inside a city's borders. UGSs play a vital role in serving diverse landscape functions (LF), such as the critical task of water filtration, significantly influencing the well-being of urban residents as well as the overall ecological health of the city. As cities have experienced significant population density growth in recent decades, UGSs are tasked with fulfilling multiple LF responsibilities. In this thesis I want to measure the multifunctionality (MF) of UGSs in the European Union (EU), to provide valuable insight for decision-makers to identify areas for improvement in parks and other greenspaces. For this purpose, an indicator of MF was developed and applied to cities across Europe. By conducting case studies on selected cities, variations in MF can be observed and analyzed. Additionally, this thesis compares the MF with socio-economic factors to determine if correlations between these factors and the multifunctionality of UGS in the same area exist among different areas within a city.

1. Introduction

Today, over half of the human population worldwide live in urban areas (Leeuwen, Nijkamp & Noronha, 2009; Venditti, 2022; Zhang et al., 2022), while by 2050 urban dwellers will make up $^{2}/_{3}$ of society (United Nations, 2015b; United Nations, 2019; Zhang et al., 2022). Worldwide cities only constitute 2 - 4% of the total area, but they are responsible for 75% of resource consumption (UNEP, 2014; Venditti, 2022), which results in a loss of the non-human living world (Hill et al., 2021). While this growth is a worldwide phenomenon, in recent decades, western Europe experienced a significant rate of urbanization: expansion of cities at their borders (Zasada, 2011) as well as densification of the inner-city areas (Haaland & van den Bosch, 2015). The resources consumed by urban inhabitants must be produced on-site or elsewhere, but in any case, require more space with raising urban consumption. In any event, the urban inhabitants have a great impact on land transformation and environmental degradation within their habitat (Zhang et al., 2022). Cities have a considerable impact on local (and global) climate conditions, such as air pollution or rise in temperature (Zhang et al., 2022). One of the key solutions to improve the quality of life in urban areas is 'urban green space'[1] (UGS) (De la Barrera, Reyes-Paecke & Banzhaf, 2016; Guan et al., 2023). The United Nations (2015a) included as one of their Sustainable Development Goals (SDGs) to make cities "*safe, resilient and sustainable*" and has its focus on greenspaces that are open to the public, which are accessible and safe for vulnerable groups such as children (De la Barrera et al., 2023).

What is UGS? Derkzen (2017: 9) defines UGSs as all "*vegetation and water in cities*" regardless of their size and characteristics (e.g., natural or constructed, public or open). UGSs include parks, private gardens, single trees, cemeteries, ponds, rivers and more. A city can be seen as one ecosystem itself or as a network of many small ecosystems including all urban green and blue areas. Bolund and Hunhammar (1999) consider every green and blue area, regardless of their size as ecosystem. This might not be correct in case of single trees, since they do not function as an ecosystem by itself, but it serves a better understanding for the reader (Bolund & Hunhammar, 1999). Due to their restricted accessibility, I will follow Guan et al. (2023) in not considering private greenspace. Connected to their role as a compensation tool for the city's environmental pressures, UGSs have a great impact on human health and well-being (Baycan-Levent, Vreeker & Nijkamp, 2009; Leeuwen, Nijkamp & Noronha, 2009; Zasada, 2011). Functions of UGS, which contribute to human quality of life are often referred to as public goods, ecosystem services[2] (ES) or – as referred to in this thesis – landscape functions[3] (LF) (Bolliger & Kienast, 2010; Kadykalo et al., 2019). LF are composed of contrasting functions, such as recreational or habitat functions. The availability of LF has a

[1] subsequently referred to as UGS
[2] subsequently referred to as ES
[3] subsequently referred to as LF

direct impact on the human quality of live globally (Leeuwen, Nijkamp & Noronha, 2009). Nevertheless, they are appreciated and contextualized differently depending on the culture of people. Furthermore, LF, coming from a natural origin, are not distributed equally among the global human habitat, and the environment has been altered by human hand to extreme extents, which also endangers a lot of different species. The loss of diversity has a negative effect on food security and the availability of vital goods for people in different regions of the world. Most of the services provided through nature with an impact on the human quality of life deteriorate or decline in quality (IPBES, 2019).

There is a growing interest in not only analyzing UGS and LF, but also measure key elements of ecosystems and the functions they provide for humans (Christie et al., 2019). Due to densification, UGS available per resident is decreasing in most European cities (De la Barrera et al., 2023). This problem asks for more multifunctional green spaces, which means that multiple functions for a diverse group of people are provided by the same UGS (Charoenkit & Piyathamrongchai, 2019; Hölting et al., 2020). Human-dominated land always serves other functions apart from the purpose intended (Stürck & Verburg, 2017). But in the case of UGSs, their multifunctionality[4] (MF) should actively be promoted by decision-makers and related policies. With a constantly growing world population, there is a huge pressure on the landscape and the corresponding functions (The Royal Society, 2023), creating an intensified land use competition (De la Barrera et al., 2023; De la Barrera, Reyes-Paecke & Banzhaf, 2016). Therefore, a well-structured UGS planning and management becomes more important (Gugulica & Burghardt, 2023). A UGS is considered multifunctional if it provides "*high diversity and abundance of different functions and services within the same spatial unit*" (Hölting et al., 2019: 226).

The concept of UGS MF has been targeted by many political and scientific approaches in recent years, but there is no standardized assessment or definition of MF (Hölting et al., 2019). The 'Intergovernmental Platform on Biodiversity and Ecosystem Services'[5] (IPBES, 2019: 12) state that "*direct and indirect drivers of change have accelerated*" in the last decades. With a globalized economy and a consume-oriented society in the industrialized countries, sustainability goals can often not be met. Therefore, IPBES (2019) demand radical change in economics, politics, technologies, and social behavior.

The objective of this thesis is to make a meaningful contribution towards the mindful management of nature in light of the climate crisis and the rapid doubling of the global human population within the last 50 years (IPBES, 2019: 13). Additionally, this thesis aims to provide urban policymakers with a valuable tool for assessing the condition of their cities' UGSs and the corresponding LF. Although it is an important topic, which affects most people, authors of

[4] Subsequently referred to as MF
[5] Subsequently referred to as IPBES

LF indicators seem to be reluctant to apply it to urban study areas (La Rosa, Spyra & Inostroza, 2016). Additionally, studies to UGS MF and the surrounding factors that influence them are often limited to single city case studies (Pinto, Ferreira & Pereira, 2021). Therefore, there is a vast scientific gap in presenting a MF indicator that can be applied over a larger area, which allows a thorough investigation of small- to large-scale patterns.

The goal of this thesis is to create a UGS MF indicator to quantify multifunctionality in Urban Greenspaces in the EU. The UGS MF indicator, which will serve as a fundament of this thesis, will consist of different environmental factors based on LF from corresponding literature related to the concept of 'natures' contribution to people'[6] (NCP) included in the framework of the IPBES (Hill et al., 2021), which will be thoroughly introduced later. After developing an UGS MF indicator, different comprehensive maps are created for case studies of European cities that show MF values in UGSs. The geographical spread will hopefully result in a socioeconomic distinction, which will make the analysis of differences more important. After, the structural causes of the contrasts in within the selected case studies and between cities will be explored by including surrounding factors of UGS.

The phenomena of social injustice in urban areas are entangled with the availability of UGS. Different studies found that socio-economic factors such as income, origin or education levels have an influence on availability and access to greenspaces in cities (Dai, 2011, Xu et al., 2018), with socially deprived areas having restricted access to UGS (Guan et al., 2023). This social injustice of uneven distributed UGSs is often measured with spatial proximity calculations or the GINI coefficient. Furthermore, the spatial pattern, size and shape of UGS distribution can be measured (Guan et al., 2023). Guan et al. (2023: 4) defined every green space with public access as UGS and combined four landscape metrics (*class area, patch density, largest patch index, mean Euclidian nearest neighbor distance*) with four control variables (*minority, income, household unit, education*). Additionally, to income and distance to the nearest UGS, Pinto, Ferreira and Pereira (2021) emphasize sociodemographic factors, such as age of residents, and transportation characteristics, such as available means of transport. All these factors are what subsequently will be called surrounding factors and will be further examined in this thesis to see their influence on UGS MF.

[6] Subsequently referred to as NCP

My master's thesis will address the following research question:

RQ1: How does the multifunctionality vary between different urban greenspaces of selected European cities?

RQ2: How do surrounding socio-economic factors have an influence on urban greenspace multifunctionality?

Usually, MF studies related to UGS concentrate on a quite limited spatial extension (e.g., city level). The resulting indicator and the demonstrated inequities of UGS MF are of a high scientific relevance. Firstly, the resulting maps give a great overview of the state of UGSs in regard to their MF in Europe. Since the UGS MF indicator is applied to the largest cities all over the EU-27_2007 territory[7], policymakers and city planners can use it to analyze the desired area of interest and compare it to other areas. The Royal Society (2023) recently published an interdisciplinary report on MF of the United Kingdom's landscapes. Thereby, they aim to create a guide on a sustainable and versatile land use in the UK, which helps to cover the needs for different LF. With this thesis and the resulting UGS MF indicator, I anticipate that my work will serve as a crucial foundation for future policies regarding the MF of UGSs, which could help to reduce environmental injustice in Europe's cities. Secondly, policymakers can identify inequities inside their area of interest in comparing the MF values for the corresponding green spaces. By comparing the indicator values to socio-economic and demographic data, path-breaking conclusions regarding their correlations can be drawn. Policymakers can therefore conduct and direct needed structural changes in deprived neighborhoods. Especially in these areas a UGS MF indicator could be of great use for city planners to create missing LF for local residents.

[7] For a list of the EU-27_2007 member states see Appendix 1

2. State of the Art

2.1. Urban Green Spaces

It is undisputed that green areas in cities add value to urban residential areas and their inhabitants, given the UGS phenomena is readily evident in all major cities worldwide. UGS is inseparably connected to the urban quality of life (Leeuwen, Nijkamp & Noronha, 2009). UGSs are defined as "*all urban land covered by vegetation*" (Pinto, Ferreira & Pereira, 2021: 2) and are also called 'urban green and blue' (Leeuwen, Nijkamp & Noronha, 2009), where every green surface or water in urban areas are included in the concept (Derkzen, 2017). As such, the corresponding land covers are urban parks, street trees, residential lawns, roof gardens, urban forests, sporting fields, community gardens nature conservation areas, streams, ponds, lakes and more (Bolund & Hunhammar, 1999; Guan et al., 2023; Kabisch et al., 2016; Pinto, Ferreira & Pereira, 2021). Why are UGSs so important to urban areas, and why do they have such an immense scientific focus in the corresponding field on them?

Depending on (lifestyle) trends and contemporary topics, types of green spaces in cities and user groups that benefit from it change (Derkzen, 2017). UGSs contribute to a sustainable development of cities, since they provide crucial benefits to the urban population (Baycan-Levent, Vreeker & Nijkamp, 2009; Guan et al., 2023). Urban green policy gained a great deal of attention recently. Policymakers seem to have understood the importance of the availability of sustainable urban green and blue for human well-being (Leeuwen, Nijkamp & Noronha, 2009). A higher population density in cities often causes a reduction of UGS per capita since the pressure of densification leaves no room for new UGS (De la Barrera et al., 2023). Therefore, it is eminently important to consider the needs of the urban population relating to different UGSs. Urban nature is in direct competition with other land uses, mainly residence or public buildings (Andersson et al., 2015). This discord calls for a strict policy in favor of a healthy proportion of UGS and needs the support of the public to actively stand up for their rights of availability to UGS (Andersson et al., 2015). Additionally, as mentioned before, social injustices are present due to the inequality of distribution of UGS (Guan et al., 2023). To promote equity in this regard, a comprehensive study of spatial distribution and influential processes is crucial in the scientific field.

Kabisch et al. (2016) showed that there is a great variation between different European cities in availability of UGS. While they found a high availability in terms of spatial proximity for northern European cities, especially Scandinavian countries, they pointed out a low access level for southern European cities. This spatial pattern can be attributed to historical city planning decisions (e.g., lacking room for UGSs in ancient Mediterranean cities), land cover conditions (e.g., high proportion of rock surface in southern European cities) as well as differences in policy prioritization (e.g., environmental, and social sustainable focus in northern European cities) (Kabisch et al., 2016). In these cities, a threshold of 300 m or 500 m is often mentioned as maximum distance to the next UGS for every inhabitant (Kabisch et al., 2016; Pinto, Ferreira & Pereira, 2021).

Although the importance of UGS for the urban population is undisputed, degradation endangers the viability of those places. This means that urbanization can lead to certain parks or other greenspaces to be neglected, since neither the authorities nor the residents feel obligated to look after, maintain and develop the area (Derkzen, 2017). In such circumstances, the budget for maintenance and development of UGSs is low (Kabisch et al., 2016). The opposite process is restoration, which often arises as a response to climate change by city planners, given UGSs have a positive impact on the local climate. During restoration, apart from coming up with a climate sensitive design, the recreational purposes of city parks is and additional focal point (Derkzen, 2017; Kabisch et al., 2016).

UGSs have always been part of city planning, however, the focus changed over time. Initially, UGS related studies focused on the recreational aspect of UGS. Different scientists looked at human behavior around UGS and which socio-economic impacts UGSs have on different user groups (e.g., Tzoulas and James, 2010; Adinolfi, Suárez-Cáceres & Cariñanos, 2014). Subsequently, the focus switched to a more health orientated research. Questions about green spaces in cities and human physical and mental health were given a lot of attention (e.g., Brown, Schebella & Weber, 2014; Hunter et al., 2015; Raaschou-Nielsen et al., 2013). Also, the economic aspects of UGS were discussed, as for example, the relation between higher house prices and the scenic view were found corresponding (Sander & Haight, 2012; Tu, Abildtrup & Garcia, 2016).

Another topic concerning UGS is related to their biophysical aspects. The processes taking place in an urban ecosystem and how they are connected to their environment, especially to the human environment, has been tried to understand and quantify in various attempts (e.g., Baró et al., 2016; Conedera et al., 2015; Dobbs, Kendal & Nitschke, 2014). Given the current climate crises and the pivotal role of green spaces in mitigating its impact, UGSs are recognized as a vital toll in environmentally conscious planning (e.g., Derkzen, Teeffelen & Verburg, 2017; Geneletti & Zardo, 2016; Matthews, Lo & Byrne, 2015). Another topic related to this is accessibility to green spaces in urban or peri-urban spaces (e.g., Žlender & Thompson, 2017; Comber, Brunsdon & Green, 2008). Nowadays with all these new challenges, the old topics of UGS planning and research, combined with growing densities in cities, the demand for multifunctional UGSs is tremendous, which leads us to the concept of ecosystem services in the following chapter (Derkzen, 2017).

Baycan-Levent, Vreeker and Nijkamp (2009) conducted a study to compare the perceived performance of UGSs in 24 European cities. The study showed that the appreciation of UGS in city planning and management has increased in the last decades. During this process, ecological and environmental economics had to come up with new methods to capture the value of environmental assets, since the classic economic approaches were dependent on monetary units. Some environmental benefits, provided by UGSs, cannot be expressed through monetary values. Therefore, they developed multi-criteria methods to capture the diversity of the multifaceted functions and services of an (urban) ecosystem. Baycan-Levent, Vreeker and Nijkamp (2009) used a multi-criteria analysis (MCA) called 'Regime Analysis'. Thereby, they looked at UGS from different perspectives, including UGS planning, availability, changes, and financing of UGS, and evaluated those directly (e.g., the monetary value of house prices next to a park) and indirectly (e.g., erosion risk reduction through UGS). Baycan-Levent, Vreeker and Nijkamp (2009) found that a high availability of UGS results in a higher score of their indicator. A weakness of their indicator is the dependence on expert perspectives, which constitute only subjective viewpoints of decision makers, but does not include the majority of the UGS users (Baycan-Levent, Vreeker & Nijkamp, 2009).

2.2. Measuring Nature and its Benefits for People

In the course of this thesis, I will focus on different landscape functions, as defined in the introduction. Nevertheless, in this section I want to show where the used framework has its origin and in which ways it is embedded or connected to other concepts, and how the state of the art developed in recent years.

In every city worldwide, there are UGSs present (Derkzen, Teeffelen & Verburg, 2015): parks, ponds, single trees, or patches of green surfaces. This suggests that UGSs are valuable, with advantages outnumbering disadvantages of these spaces. If that was not the case, the valuable space of UGS in cities would most likely be used differently. Humans are dependent on goods and services they obtain from a co-production with nature. In many cases, these goods and services are not fully replaceable by other products (e.g., one third of the world population relies on wood fuel as their often only energy source) (IPBES, 2019). Some examples such as oxygen are even irreplaceable. Those advantages are often referred to as ecosystem services (Derkzen, 2017; Baycan-Levent, Vreeker & Nijkamp, 2009; Díaz et al., 2015). One of the most obvious and rather well-known examples of ES would be the absorption of carbon dioxide (CO_2) from the air while producing oxygen (O_2) as a by-product during the process called photosynthesis (Canadell, 2014). There are also ecosystem disservices (Pinto, Ferreira & Pereira, 2021), such as the risk a tree poses during a storm. Lyytimäki and Sippilä (2009) criticize that most researchers in the field of ecosystem services only consider the advantages (services) and neglect the negative sides (disservices). The authors state that even small disservices, compared in the area affected to the whole city, can have a huge impact on the people affected by it (e.g., a bad smell by de composing biomass) (Lyytimäki & Sippilä, 2009).

The term ecosystem service was first introduced in the 1960s (MA, 2005). The Millennium Ecosystem Assessment (MA) (2005: 54) defines ES as "*the benefits people obtain from ecosystems.*" An ecosystem is defined as a unit of all living species (including humans) and the non-biological environment they live in and has enormous diversity of complex relationships (Bolund & Hunhammar, 1999; MA, 2005). Ecosystem services have been categorized in different ways and looked at from different perspectives (MA, 2005). Also, in the context of UGS, there are different groupings. Kabisch et al. (2016: 586) follow a functional categorization as they order ecosystem services into the following groups: *(1) play a role in recreation and health, supporting everyday life; (2) contribute to conservation of biodiversity; (3) contribute to the cultural identity of the city; (4) offer places for nature experiences; (5) help maintain and improve the environmental quality of the city; (6) bring natural solutions to technical problems in cities.* Baycan-Levent, Vreeker and Nijkamp (2009) completed a valuation of the different ecosystem services and categorizes those value into: *(1) ecological values; (2) economic values; (3) social values; (4) planning values; (5) multidimensional* *values.* Costanza et al. (1997) came up with a finer subdivision and created 17 major categories of ecosystem services (Baycan-Levent, Vreeker & Nijkamp, 2009: 201): *(1) gas regulation; (2) climate regulation; (3) disturbance regulation; (4) water regulation; (5) water supply; (6) erosion control and sediment retention; (7) soil formation; (8) nutrient cycling; (9) waste treatment; (10) pollination; (11) biological control; (12) refugia; (13) food production; (14) raw materials; (15) genetic resources; (16) recreation; (17) culture.* The MA (2005: 57) categorizes ES in 4 groups: "*provisioning services, regulating services, cultural services and supporting services*". The first category, the provisioning services, include all the products that are provided by nature. Obviously, this includes food and water to drink, but also all kind of materials humans use in their lives, such as wood, biofuel or natural medicine. Regulating services mean, as the word says, all regulating functions nature provides, such as temperature regulation, pollination or water purification. The services that belong into this category are usually invisible and therefore not always as present in our perception, even though all people benefit from them, in some cases even dependent on them (Andersson et al., 2015). All kind of non-material benefits we gain from nature related to religious, inspirational, or cultural meanings, but also benefits for recreation or education, go into the cultural services. Those can be appreciated by everyone and usually are visible (e.g., a beautiful scenery in a park) (Andersson et al., 2015). Since they cannot be replaced when degraded (La Rosa, Spyra & Inostroza, 2016), are locally experienced and perceived individually, they have a relatively high impact on the urban population's well-being (Gugulica & Burghardt, 2023). The supporting services consist of services to produce the other three categories, such as the nutrient cycle (MA, 2005).

The complex and multidimensional structure of ecosystems and UGSs in general result in a diverse classification of ES (Baycan-Levent, Vreeker & Nijkamp, 2009). This impedes a standardized approach to evaluate these ES on a global level. What remains, however, is that quality of life in an urban environment is to a certain connected to ES. Some services cannot be imported and must be produced locally (e.g., fresh air) (Andersson et al., 2015). Also, cultural services are often bound to specific locations, gain their value through human perception and cannot be outsourced (Andersson et al., 2015).

Bolund and Hunhammar (1999: 294ff) identified seven different natural urban ecosystems in the city of Stockholm and determined which of these ecosystems produce which services. By developing this assignment, the authors endeavored to campaign for locally produced ecosystem services in cities. Bolund and Hunhammar (1999) state that even though not all the resources used by the inefficient cities can be produced in the boundaries of the urban area, it is important for efficiency, educational or ethical reasons to produce some ecosystem services locally. Some of them cannot be produced from a distance, such as noise reduction. They also hope that with increasing awareness of the ecosystem and their importance, city designs can be planned more sustainably and efficiently, especially in the face of fast-growing cities (Bolund & Hunhammar, 1999).

Burkhard et al. (2012) looked at CORINE land cover (CLC)[8] data and made an index, where the author determined a value for every land cover class, expressing the support of ecological integrity and the supply of ecosystem services for the corresponding class. This resulted in a budget of ecosystem services supply and demand for each land cover. The authors then mapped their results for a greater area surrounding the German cities Leipzig and Halle for the years 1990 and 2006. Both maps showed a strongly negative supply/demand budget for the urban land cover classes, which shows the urgency of UGS-friendly urban policies and environmentally efficient city planning (Burkhard et al., 2012). According to Christie et al. (2019), 'The Economics of Ecosystems and Biodiversity' (TEEB, 2010) tried to introduce an economic evaluation of ecosystem services by assigning them a monetary value. The scientific community responded with criticism for adopting a narrow perspective and that overlooks various other viewpoints and evaluation processes crucial for capturing the complete picture (Christie et al., 2019). However, qualitative valuations are difficult to feed into economic assessment methods (Leeuwen, Nijkamp & Noronha, 2009).

The Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES), an international science-policy platform (Christie et al., 2019), published a conceptual framework, which is meant to serve as an analytical tool on different themes related to biodiversity and ecosystem services to ensure lasting sustainable development (Díaz et al., 2015). This tool allows to assessing, reporting, and communicating the relations between (the state of) nature and humanity on a supra national scale (Hill et al., 2021). As part of their framework, the IPBES came up with six different components creating a link between humans and the natural environment (Díaz et al., 2015). The six components include (Hill et al., 2021: 910): (1) *nature (e.g., biodiversity); (2) anthropogenic assets (e.g., education); (3) institutions, governance, and other indirect drivers of change (e.g., cultural factors); (4) direct drivers of change in nature (e.g., extreme events); (5) nature's contribution to people (NCP); (6) good quality of life.* According to Hill et al. (2021: 910) the term NCP includes "*all the benefits and detriments that people get from their relationships with the rest of the living world.*" With its creation in 2015 the concept of NCP was referred to as '*Nature's benefits to people*' and later renamed to '*Nature's Contribution to People*' (Díaz et al., 2015; Kadykalo et al., 2019). In a dialogue between different academic disciplines, cultures, government, organizations and local communities (including indigenous people), the term was created as a conglomerate from different expressions and languages (Hill et al., 2021). This shows not only the transdisciplinary environment in which the concept was created, but also its inclusive nature. The inclusiveness lies in the integration of different viewpoints as well as different socio-ecological systems.

[8] Subsequently referred to as CLC

Furthermore, the concept of the NCP detects trends, responds with a link to the involved governments, thereby creating new policies (Hill et al., 2021). The main difference from ES lays in the term's inclusive nature. Since the concept of ES are clearly come from a western perspective (Christie et al., 2019; Hill et al., 2021; Kadykalo et al., 2019) it would be ignorant to apply it on a global scale, which is the goal of IPBES though. Therefore, the authors include different cultural valuation approaches in the NCPs (Díaz et al., 2015). This allows the concept to include the western idea of ecosystem services with a separation between human and nature, as well as conceptions from other cultures where the transitions between humans and their natural environment are fluent (Hill et al., 2021). The integrative system of the concept allows an identification of the status of nature and the influence on humans by using a standardized reporting system and, additionally to this generalized view on natures benefits, also a subjective perspective based on the context and background of an individual on the same scene. This creates a context-specific but still standardized perspective on nature and its contribution to people. This is what is meant, when the concept is characterized as pluralistic: it is an open-minded approach, which includes different knowledge systems. The concept recognizes both nature and human assets. This allows people with different cultural and educational backgrounds to come together and work on one overarching concept or objective (Hill et al., 2021).

For example, in an agricultural system, there are natural components, which are not or only partly influenced by humans, such as the weather or a nutritious soil. Furthermore, there are anthropogenic assets, which go into food production, such as knowledge about farming, soil cultivation or livestock breeding. These can be looked at from a generalized viewpoint. Depending on the location and individuals involved in the system, there is also a subjective perspective of the farmer towards food production, that often are of a religious or spiritual nature. Food can then be seen as a gift from nature and part of a natural cycle (Hill et al., 2021).

IPBES (2019) made a classification of 18 different NCPs, that have evolved from the concept of ES and sometimes they overlap. The classifications are divided into three groups. Material NCPs are physical elements that humans need to live and survive, such as food. Non-material NCPs are natural phenomena that people benefit from in psychological or subjective means. This could be for spiritual or aesthetic reasons. Lastly, there are the regulating NCPs, which are defined as processes that regulate the state of nature and the material and non-material NCPs and are perceived by humans (e.g., the water cycle). NCP only includes positive impacts on human quality of life (Hill et al. 2021; Kadykalo et al., 2019), which is part of the overall concept of IPBES (Díaz et al., 2015). Other than in ES the people and nature are

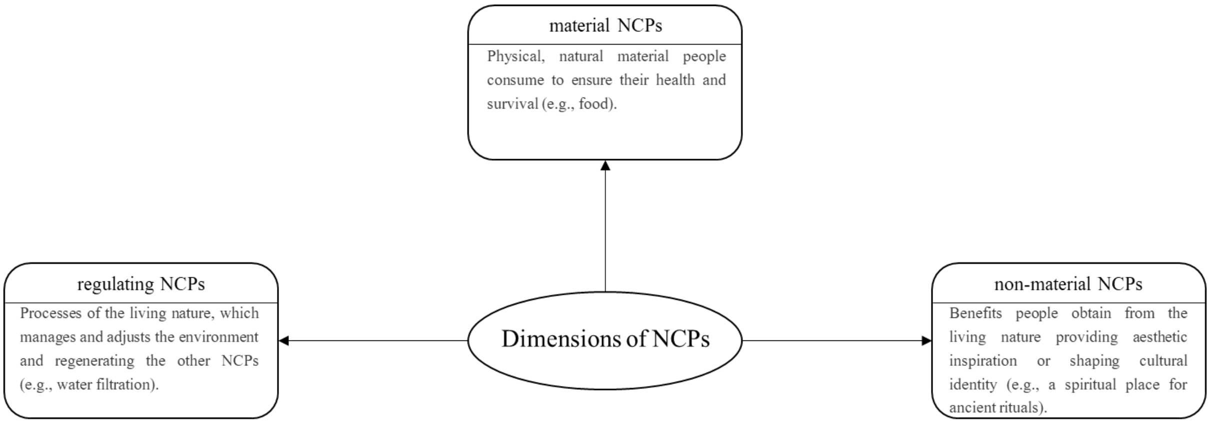

fig. 1: Three dimensions of NCPs as described by Hill et al. (2021).

inseparable and there is no cultural NCP, since the cultural aspect is embodied in the whole concept as the subjective perspective (Hill et al., 2021; Kadykalo et al., 2019).

Christie et al. (2019) wrote a paper, where they critically appraised the values of the concept of NCP within the large-scale assessment of the conceptual model in Europe and Central Asia. The main objective is to show a potential added value in comparison to previous assessments of ecosystem services (e.g., MA, 2005; TEEB, 2010). The authors conclude that the NCP concept is a more holistic approach and that there is added value through more knowledge from indigenous and local communities influencing the conceptual framework of IPBES positively. Furthermore, it serves as a voice of more diverse communities, which has a great reach due to the concept's international character (Christie et al., 2019).

I will mainly follow the ideas of the framework of NCP, due to its open-minded and inclusive approach (Díaz et al., 2018), and define different landscape functions that occur in European cities. The concept from IPBES constitutes an open-minded, globally applicable, transdisciplinary, and inclusive approach and holds an enormous potential for a new way towards a more sustainable and inclusive future.

2.3. Environmental Indicators

Ecosystems are valuable due to the functions they provide to people. However, there is no standardized measurement system to express those values appropriately (Boyd & Banzhaf, 2007; Charoenkit & Piyathamrongchai, 2019; Hölting et al., 2019). Boyd and Banzhaf (2007) measured final LF and proposed an accounting system on how to express their value from ecological, social and economic perspectives. The authors argue that such a system could work similarly to the gross domestic product (GDP), which works with market prices and units sold. The main problem is that there are no globally consistent units in green accounting. A weighting system is needed to express relative values of the related services, an equivalent to monetary values in a market-based system. Boyd and Banzhaf (2007) argue that a green GDP make sense with purpose to evaluate ecosystem services in a standardized method, but an economic approach like this leaves out a few important factors, which impact LF and the corresponding human well-being (Boyd & Banzhaf, 2007).

Such measurement methods are a subgroup of environmental indicators. The European Environment Agency (EEA, 2017) defines an environmental indicator as a "*parameter or a value derived from parameters that describe the state of the environment and its impact on human beings, ecosystems and materials […]*". The most widely used indicator in the field of this thesis is area of UGS per resident, since it is easily practicable, and it is comparable globally (De la Barrera, Reyes-Paecke & Banzhaf, 2016). However, this indicator says nothing about distribution within the city's perimeter (De la Barrera, Reyes-Paecke & Banzhaf, 2016). Vegetation cover is used as a simple measurement of UGS quality, since plants and trees are responsible for most of the provided functions (De la Barrera, Reyes-Paecke & Banzhaf, 2016).

Usually, environmental indicators are measured by aggregating all the involved values into one significant index, which allows scientists, policymakers, or stakeholders to compare different areas (Hölting et al., 2019). This is called a 'multifunctionality indicator' and will be applied in this thesis to measure UGS MF in Europe (Stürck & Verburg, 2017). The UGS MF indicator should represent an exceptionally complex structure with ecological and socio-economic aspects. However, the indicator should be easy to understand and transferrable to other applications to ensure comparability (Hölting et al., 2019). Additionally, Hölting et al. (2019) indicate that a thorough discussion on strengths and weaknesses of the indicator is sensible.

Gugulica and Burghardt (2023) introduced a new model to quantify cultural ecosystem services by analyzing social media posts with a trained text model. The authors found that, in comparison to other methods, this could be a cost-efficient variant to analyze interaction between people and their surrounding nature, which has a correlation to the individual perception of non-material NCPs. Furthermore, the authors found that those functions are localized in hotspots and that the spatial distribution is anything but random (Gugulica & Burghardt, 2023).

According to a review conducted by Boulton, Dedekorkut-Howes and Byrne (2018) two of the most applied indicators related to UGS are directed at their availability and the accessibility. There is no direct correlation between provision and accessibility of green spaces, so it makes sense to measure these two indicators to get an impression of the overall status of an area. Provision is usually measured as UGS per area and then normalized with the number of inhabitants (e.g., Kabisch & Haase, 2014; De la Barrera, Reyes-Paecke & Banzhaf, 2016). Accessibility, however, is much more complex to calculate and depends on many different impact factors (De la Barrera et al., 2023).

In their research conducted in the socio-economically diverse municipality of Santiago de Chile, De la Barrera, Reyes-Paecke and Banzhaf (2016) examined the disparities in quality, quantity and accessibility of UGS. Their findings revealed a positive correlation between socio-economic status of residents and the availability and accessibility of UGS, which aligns with similar studies conducted in different cities (e.g., Landry & Chakraborty, 2009; Pham et al., 2012) (De la Barrera, Reyes-Paecke & Banzhaf, 2016).

2.4. Multifunctionality

Various studies found that a high MF has a direct relation to an increased human well-being, but could also lead to a conflict of interest between different user groups (De la Barrera, Reyes-Paecke & Banzhaf, 2016; Hölting et al., 2020; Lafrenz, 2022). The size of an UGS correlates to a high degree with the multifunctionality of the same area, which applies for all categories of LF (De la Barrera, Reyes-Paecke & Banzhaf, 2016). MF is regarded as a sustainable solution to the urban lack of space, which renders it appealing to stakeholders (Charoenkit & Piyathamrongchai, 2019). While politicians and decision-makers aim at higher MF levels, the implementation is challenging (Hölting et al., 2019). There is evidence, that suggested the more powerful and influential stakeholders enforce functions according to their visions and needs, while mostly non-profitable LF are ignored and fall short (Turkelboom et al., 2018). Manning et al. (2018) did research on MF, where they assigned weights on functions to make an individual, stakeholder-group-based indicator, which differs between differing groups (Hölting et al., 2020). An approach where different user groups are involved in the planning phase to restructure or improve UGS make sense, since the satisfaction of needs related to NCP of all urban dwellers have a huge impact on human well-being, as showed before.

Different authors differentiated between perspectives of how to approach multifunctionality, where the biophysical and socio-ecological approaches were the most common ones (e.g., Brandt & Vejre, 2004; Manning et al., 2018). In the context of this thesis, a socio-ecological view on MF is most appropriate, since the concept of NCP is also looked at from a similar perspective, namely the co-production of human and nature.

Green infrastructure[9] (GI) became a relevant concept in city planning the past few years (Ahern, 2007; Mazza et al., 2011). It is defined as a network of natural and semi-natural elements creating and enhancing LF (Hansen & Pauleit, 2014). Similar to the terms of LF and NCP, the definition of GI remains blurry, even though key elements, such as connectivity or multifunctionality, are consistently involved in this concept. Additionally, GI is often applied to urban spaces due to the concept's interaction between social and ecological components, and it can be combined with other sustainable planning approaches (Hansen & Pauleit, 2014). In an urban context the assessment of MF is relatively high due to the high demand of LF (Charoenkit & Piyathamrongchai, 2019). Harnessing the synergistic effects of multifunctionality within an urban context has the potential to enhance the effectiveness of GI and transform it into a practical tool for city planning. Additionally, possible tradeoffs and user group conflicts should be kept in view to achieve the full potential of the framework (Hansen & Pauleit, 2014).

MF means that multiple services are provided by the same land, whether the services are market goods (e.g., crop) that have a monetary value, or they are non-market goods (e.g.,

[9] Subsequently referred to as GI

carbon sequestration) that serve the well-being of everyone and cannot be valued in a monetary unit. A multifunctional approach makes land use increasingly more productive and effective. In the United Kingdom this is applied for landscape analysis and decision-making, but this can also be applied on urban areas only (The Royal Society, 2023).

2.5. Surrounding Factors

The change in UGS purposes also change the beneficiaries of the UGS. Nowadays with a global population growth and urban densification, we observe a trend towards the request of multifunctional UGSs by urban residents (Roberts, Glenk & McVittie, 2022). It is remarkable, that there is social injustice related to this development. Since poorer neighborhoods lack multifunctional parks and other green areas, areas with a higher social status more often benefit from multifunctional UGSs. People with low incomes usually depend more on the use of public places of nature, since they do not have access to private green spaces (e.g., gardens) (Lin, Meyers & Barnett, 2015). The increased proportion of private UGS promotes the inequity further. Those inequalities should be considered thoroughly, when planning to restructure neighborhoods and the corresponding UGS (Derkzen, 2017). De la Barrera, Reyes-Paecke and Banzhaf (2016) excluded private green spaces in their study, as they are only accessible to a minority user group, despite the existence of the ecosystem services they provide for the public.

Derkzen (2017) mentions that the decrease of top-down policies and more community engagement in the development of multifunctional UGSs could constitute an opportunity to create socially equal access to UGSs. Nevertheless, in some cases, there are also government agencies, who provide for a more equal availability of UGSs. In Berlin, every inhabitant should have access to 5000 m^2 green space in their neighborhood within 500 m of their residency (Kabisch et al., 2016). Such concrete numbers make it easier for city planners and decision makers to aim at more equally distributed UGSs.

Because of the above-mentioned benefits and challenges of UGS, the availability and accessibility of UGSs for different groups have experienced a great share of attention in recent years (Guan et al., 2023; Kabisch et al., 2016; Pinto, Ferreira & Pereira, 2021). One of the decisive factors for accessibility is the distance from home to the next UGS, and for people to use city greeneries for activities that positively impact human health (Kabisch et al., 2016). Kabisch et al. (2016) conducted a study about the availability of UGSs in European cities. Using land cover data, they identified areas which they defined as green space and applied a minimum size of the areas they want to include in the frame of the respective city's borders. After that, they applied a buffer (300 m and 500 m) to find all areas of certain maximum distance to the found UGSs. After applying a grid net over their maps, they could calculate cells with UGSs per capita. This resulted in an indicator, which can be used to make statements about the general availability of UGSs in different city districts (Kabisch et al., 2016).

3. Methodology

The main goal of this thesis was to develop an indicator that expresses the value of MF in European UGSs. The spatial patterns of this UGS MF indicator were then compared to patterns of socio-economic surrounding factors, to examine a possible relation between the two samples. To achieve that, I divided my approach in three parts: area of interest[10] (AOI), UGS MF indicator and surrounding factors (see fig. 2). In a first step, the AOI was defined. In this thesis, I only considered UGS. This means that the urbanity as well as green space needed to be defined. As soon as the AOI was set and available as spatial data, I developed a MF indicator. Different LF and weighting from the literature helped me to come up with a transparent and replicable process of the indicator development. This indicator was then applied to the AOI, resulting in a UGS MF map. This map can be used on different spatial scales to explore and recognize differences between contrasting areas. As a last step, I developed maps of surrounding factors in the areas of the considered UGS. The comparison allows the reader to draw conclusions on the spatial disparities and what socio-economic factors might have an influence on these differences.

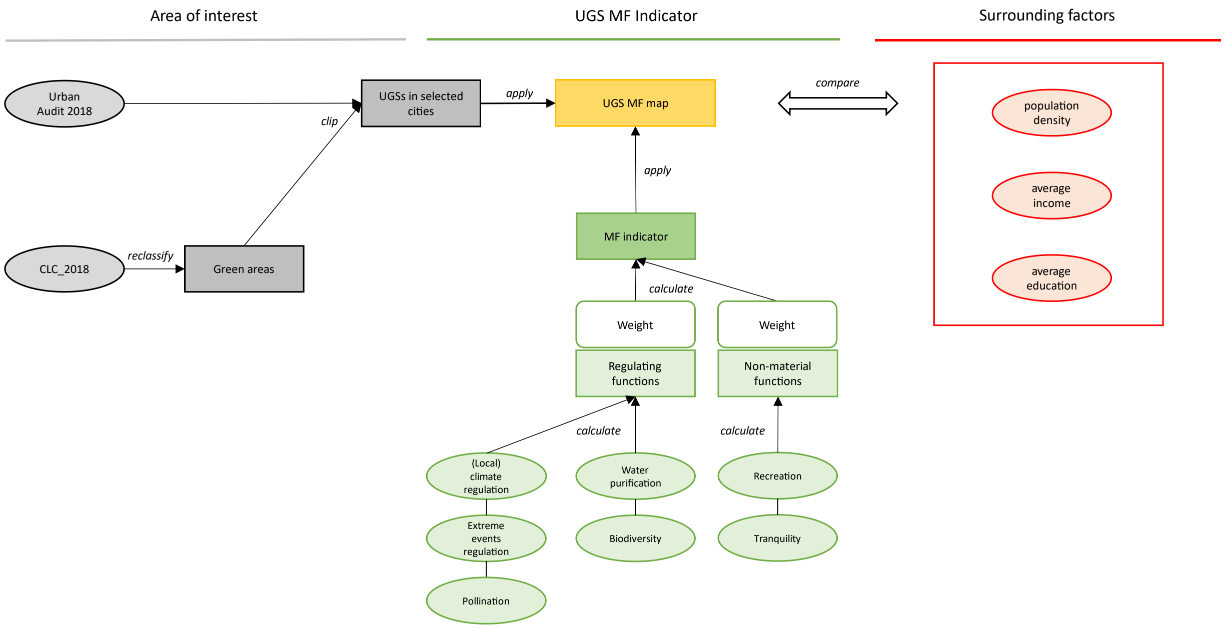

fig. 2: Data model for this thesis, divided into three sections: Area of Interest (grey), MF indicator (green), surrounding factors (red). This thesis resulted in a UGS MF indicator map (yellow), which was compared to the surrounding factors.

[10] subsequently referred to as AOI

3.1. Data Analysis

3.1.1. Design of the Area of Interest

After defining which urban areas are considered (Urban Audit 2018, core cities), the UGSs were filtered out (Eurostat, 2023). From the list of the 44 land cover classes of the CLC data, I chose only those that could serve as urban green space. I came up with the following selection, named according to the 'CLC Product User Manual' (EEA, 2021):

1.4.1. Green urban areas	2.3.1. Pastures	2.4.4. Agro-forestry areas	3.2.1. Natural grassland
2.2.1. Vineyards	2.4.1. Annual crops associated with permanent crops	3.1.1. Broad-leaved forest	3.2.4. Transitional woodland-scrub
2.2.2. Fruit trees and berry	2.4.2. Complex cultivation patterns	3.1.2. Coniferous forest	5.1.1. Water courses
2.2.3. Olive groves	2.4.3. Land principally occupied by agriculture, with significant areas of natural vegetation	3.1.3. Mixed forest	5.1.2. Water bodies

tab. 1: Selection of land cover classes that served as UGS.

I made the selection of the land classes from CLC according to other authors that do research on UGS (Bolund & Hunhammar, 1999; Charoenkit & Piyathamrongchai, 2019; Guan et al., 2023; Kabisch et al., 2016; Pinto, Ferreira & Pereira, 2021). Furthermore, I chose only land uses which were capable of serving multiple LF and thereby actively contribute to UGS MF. There is a category named 'Green urban areas'. Nevertheless, the definition of this class is not congruent with what I defined as UGS. Therefore, I had to combine more classes to come up with the UGSs I wanted to examine in this thesis. I did not include 'sport and leisure facilities' due to the fact that various of those spaces do not correspond with my definition of UGS. Sport and leisure facilities include, for example, tennis courts, racecourses, playgrounds on concrete or other facilities, which are not considered green spaces. The dataset with potential UGSs was transformed from raster data to polygons due to compatibility reasons. The city borders, from the 'Urban Audit' dataset, were then intersected with the potential UGS polygons. The polygon layer with the respective city borders was then filtered and only member states of the EU-27_2007[11] were considered, since the data matches with the AOI in this case. The result was transformed into a raster format and resulted in a new layer with all the UGS in considered city areas (see fig. 3), which I later applied the MF indicator on.

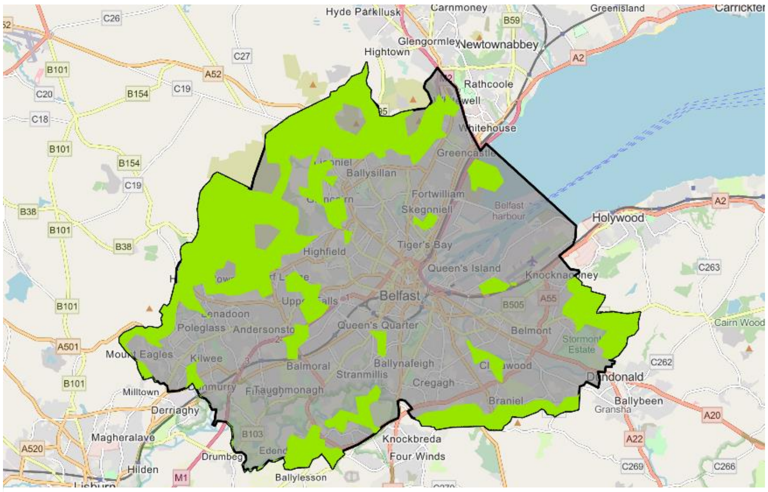

fig. 3: The city of Belfast (UK), after the transformation into a raster layer with all the considered UGS (green) and the city area (grey) for better visualization (Screenshot ArcGIS Pro)

[11] For a complete list of the EU-27_2007 member states see Appendix 1.

3.1.2. Indicator Development

3.1.2.1. Landscape Function Analysis

Based on a review of MF indicators by Hölting et al. (2019) most of the examined scientific approaches produced a single metric to express MF levels in the respective study area. This is the approach that guided the calculation of the hereinafter developed indicator on UGS MF. Nevertheless, it is important for policymakers and other users of the indicator to comprehend the single elements and dynamics which contributed to the value of the UGS MF indicator. Therefore, I intended to develop every LF separately, applied a weighting, grouped them in the NCP categories described before, added weightings to the categories and then calculated a single value UGS MF indicator. This makes the whole process transparent and ensures reproducibility for further research.

A literature review of different frameworks, expressing the value of LF to people, and studies addressing the evaluation of LF and MF served as the basis of the development of the UGS MF indicator (see tab. 3). The mentioned frameworks defined by the MA (2005), TEEB (2010; 2011) and IPBES (2019) were explained in the previous chapters. Furthermore, the 'Common International Classification of Ecosystem Services'[12] (CICES) is added as an additional framework (Haines-Young, & Potschin, 2018). The CICES classification system categorizes LF in three categories: regulating, cultural and provisioning functions (Charoenkit & Piyathamrongchai, 2019). It helps to have an additional concept to develop the indicator. During my review, I found only two studies considering ecosystem disservices or negative LF (Lyytimäki & Sipilä, 2009; Shapiro & Báldi, 2014). This led to the decision that the UGS MF indicator developed in this thesis does not include the disadvantages of UGSs, but rather focus on the strengths and advantages.

After the literature review, I wanted to consider the most mentioned LF in the UGS MF indicator. Some LF could be grouped, since they matched thematically, even though different terms were used for the same function. The case of 'climate regulation' was challenging, since different papers/frameworks defined it incongruously. Therefore, I used the LF '(local) climate regulation', which I defined as 'carbon sequestration' and covers the biochemical function. For the global climate, vegetation possesses an important function. By sequestration and storing of greenhouse gases, UGS actively counteracts the global climate change (MA, 2005; TEEB, 2011). Vegetation under and above ground has the ability to sequester and store carbon (Charoenkit & Piyathamrongchai, 2019). This is immensely important for urban areas, since space covered with vegetation is spatially limited, while CO_2 rates are higher than in rural areas. I did not include oxygen production, since it can be seen as part of the sequestration process. UGS also plays a role in the regulation of local climate, influencing temperature and

[12] Subsequently referred to as CICES

precipitation (MA, 2005). But large-scaled temperature measurements are of a low spatial resolution and cannot be applied to small scale UGS to show local differences over a large study area.

Category	LF	Frameworks	Studies
Regulating	**(Local) climate regulation** (incl. carbon sequestration)	Haines-Young, & Potschin, 2018 [CICES]; IPBES, 2019; MA, 2005; TEEB, 2011	Bolund & Hunhammar, 1999; Burkhard et al., 2012; Charoenkit & Piyathamrongchai, 2019; Hill et al., 2021; Hölting et al., 2020; McPhearson, Kremer & Hamstead, 2013;; Stürck & Verburg, 2017 The Royal Society, 2023
	Oxygen production	MA, 2005	
	Extreme events regulation (incl. flood regulation/erosion prevention)	Haines-Young, & Potschin, 2018 [CICES]; MA, 2005; TEEB, 2011	Burkhard et al., 2012; Charoenkit & Piyathamrongchai, 2019; Hölting et al., 2020; Stürck & Verburg, 2017; The Royal Society, 2023
	Rainwater drainage		Bolund & Hunhammar, 1999
	Water purification	Haines-Young, & Potschin, 2018 [CICES]; IPBES, 2019; MA, 2005; TEEB, 2011	Bolund & Hunhammar, 1999; Burkhard et al., 2012; Charoenkit & Piyathamrongchai, 2019; Hill et al., 2021; The Royal Society, 2023
	Water regulation	Haines-Young, & Potschin, 2018 [CICES]; IPBES, 2019; MA, 2005; TEEB, 2011	Bolund & Hunhammar, 1999; Burkhard et al., 2012; Charoenkit & Piyathamrongchai, 2019; Hill et al., 2021; McPhearson, Kremer & Hamstead, 2013; The Royal Society, 2023
	Biodiversity (incl. habitat quality/habitat availability/species diversity)	Haines-Young, & Potschin, 2018 [CICES]; IPBES, 2019; MA, 2005; TEEB, 2011	Boyd & Banzhaf, 2007; Burkhard et al., 2012; Charoenkit & Piyathamrongchai, 2019; Hill et al., 2021; Hölting et al., 2020; Leeuwen, Nijkamp & Noronha, 2009; McPhearson, Kremer & Hamstead, 2013; Stürck & Verburg, 2017; The Royal Society, 2023
	Pollination	Haines-Young, & Potschin, 2018 [CICES]; IPBES, 2019; MA, 2005; TEEB, 2011	Boyd & Banzhaf, 2007; Burkhard et al., 2012; Charoenkit & Piyathamrongchai, 2019; Hill et al., 2021; Hölting et al., 2020; Stürck & Verburg, 2017
	Disease control	Haines-Young, & Potschin, 2018 [CICES]; MA, 2005; TEEB, 2011	Boyd & Banzhaf, 2007; The Royal Society, 2023
	Soil quality regulation	Haines-Young, & Potschin, 2018 [CICES]; IPBES, 2019; MA, 2005	Boyd & Banzhaf, 2007; Burkhard et al., 2012 Hill et al., 2021;
	Nutrient cycle	MA, 2005	Burkhard et al., 2012
Non-material	**Recreation**	Haines-Young, & Potschin, 2018 [CICES]; MA, 2005; TEEB, 2011	Bolund & Hunhammar, 1999; Boyd & Banzhaf, 2007; Burkhard et al., 2012; Charoenkit & Piyathamrongchai, 2019; Hölting et al., 2020; La Rosa, Spyra & Inostroza, 2016; Leeuwen, Nijkamp & Noronha, 2009; McPhearson, Kremer & Hamstead, 2013; Stürck & Verburg, 2017
	Aesthetic values	Haines-Young, & Potschin, 2018 [CICES]; IPBES, 2019; MA, 2005; TEEB, 2011	Burkhard et al., 2012; Charoenkit & Piyathamrongchai, 2019; Hill et al., 2021; Hölting et al., 2020; La Rosa, Spyra & Inostroza, 2016; Leeuwen, Nijkamp & Noronha, 2009
	Cultural/historical values (incl. cultural heritage values/educational values/religious values)	Haines-Young, & Potschin, 2018 [CICES]; IPBES, 2019; MA, 2005; TEEB, 2011	Bolund & Hunhammar, 1999; Charoenkit & Piyathamrongchai, 2019; Hill et al., 2021; La Rosa, Spyra & Inostroza, 2016; Stürck & Verburg, 2017
	Health benefits		Leeuwen, Nijkamp & Noronha, 2009; Stürck & Verburg, 2017
Material	Food production (incl. crop/dairy/fruit/meat production etc.)	Haines-Young, & Potschin, 2018 [CICES]; IPBES, 2019; MA, 2005; TEEB, 2011	Boyd & Banzhaf, 2007; Burkhard et al., 2012; Charoenkit & Piyathamrongchai, 2019; Hölting et al., 2020; Hill et al., 2021; Stürck & Verburg, 2017; The Royal Society, 2023
	Resources and raw material production	Haines-Young, & Potschin, 2018 [CICES]; IPBES, 2019; MA, 2005; TEEB, 2011	Burkhard et al., 2012; Charoenkit & Piyathamrongchai, 2019; Hill et al., 2021; Hölting et al., 2020; Stürck & Verburg, 2017; The Royal Society, 2023
	Biochemicals and natural medicine production	Haines-Young, & Potschin, 2018 [CICES]; IPBES, 2019; MA, 2005; TEEB, 2011	Burkhard et al., 2012; Charoenkit & Piyathamrongchai, 2019; Hill et al., 2021;
	Water supply	Haines-Young, & Potschin, 2018 [CICES]; MA, 2005; TEEB, 2011	Burkhard et al., 2012; Charoenkit & Piyathamrongchai, 2019; Hölting et al., 2020

tab. 2: Analysis of a literature review to identify potential LF for the development of the UGS MF indicator. Bold LF were fed into the indicator.

I created a LF called 'extreme events regulation' and included the two most mentioned risks, 'erosion prevention' and 'flood regulation'. Vegetated soil stabilizes soil and therefore prevents erosion to a high degree (MA, 2005). Erosion prevention is usually measured in the erosion rate or soil loss (Charoenkit & Piyathamrongchai, 2019). The characteristics of land cover has a great impact on water regulation. In the case of soil sealing, water runoff can turn into floods or interrupt the water cycle (MA, 2005). There were different LF considering water, from which the LF 'water purification' was fed into the UGS MF indicator. 'Water purification' means the process of removal of pollutants by microorganisms and plants, as well as filtration of certain pollutants through soil and sequestration (La Notte et al., 2021). La Notte et al. (2021) state in their report that in large scale approaches nitrogen retention usually serves as a proxy for the purification of water and shows the respective ability of the ecosystem. Since 'water regulation' is already included in the present LF 'flood regulation', it was not included as a function of its own. 'Biodiversity' and 'pollination' did not need restructuring and were adopted. Habitats are the basis for the life of a certain animal or plant species and provide them with everything they need to survive (TEEB, 2011). Provisioning of habitat can be assessed through the species presence or landscape characteristics, while the species diversity is measured through species (animals or plants) that appear in a certain area (Charoenkit & Piyathamrongchai, 2019). Insects (and also birds and bats) pollinate plants and therefore ensure the lifecycle of these species (TEEB, 2011). Changes in ecosystems can disturb pollination immensely (MA, 2005). Most studies measure pollination with bee habitat quality (Charoenkit & Piyathamrongchai, 2019). The LF 'Disease control', 'soil quality regulation' and 'nutrient cycle' had not as many mentions in the reviewed papers, and it seemed that they are either not important in an urban, European setting or that they were also represented in the other LF. Microorganisms in the ground serve the elimination of waste and therefore reduce the amount of water pollution (TEEB, 2011).

For the non-material LF the mentioned functions were grouped into three overarching topics, which were considered consistently from the different authors: 'recreation', 'aesthetic values' as well as 'cultural/historical values'. It was shown that people often choose places for recreation purposes based on the natural landscapes. For urban dwellers, UGS constitute important places to spend their leisure time (MA, 2005). Recreation has an impact on mental and physical health of people (TEEB, 2011). Komossa et al. (2018) mapped the outdoor recreation potential, distinguishing five recreational user group types, based on the valuation of certain characteristics of their recreational needs for each type. The authors used existing typologies and translated the respective demands into coherent landscape attributes. The five mentioned recreational types were referred to as: *(1) convenience recreationalist, (2) day tripper, (3) education recreationalist, (4) nature trekker), (5) spiritual recreationalist* (Komossa et al., 2018: 108). The 'convenience recreationalist' tries to relieve tension from everyday life with a close trip to nearby nature. This fits perfectly into the scheme of an urban resident. The landscape preferences of this group were created by using data to water proximity, elevation, vegetation variety and air quality. The 'spiritual recreationalist' wants to connect with nature on a deeper level, which defines a way of life. This also suits the definition of non-material NCPs (Díaz et al., 2018) since the framework emphasizes spiritual values and a certain sense of place. The typology of this user group is based on their preferences using data for protected areas with a specific spiritual flora and the availability of cultural/historical heritage sites (Komossa et al., 2018). The other user groups did not match an urban environment and were therefore not included in the UGS MF indicator. By using these two outdoor recreation types, all aspects that I wanted to include in the non-material NCPs were included: recreation, aesthetics (by the preferences of each group) and cultural/historical values. Additionally, the

'Quietness Suitability Index' complements the recreation factors, since the absence of noise has a positive effect on the perceived quality of an UGS (Gozalo et al., 2018).

After a thorough study of the papers that address LF in urban settings (e.g., Bolund & Hunhammar, 1999; Charoenkit & Piyathamrongchai, 2019; McPhearson, Kremer & Hamstead, 2013) it becomes clear that material NCPs are of a relatively low importance for urban dwellers. Charoenkit & Piyathamrongchai (2019) include them in their work, but also show that they are the least important of all functions as measured by the percentage of studies that address material NCPs. McPhearson, Kremer and Hamstead (2013) included food provisioning in their indicator, but only calculate the value on the basis of community gardens. Since I did not consider private spaces for the UGS MF indicator, they would not be included anyway. The other studies about UGS MF I consulted do not include material NCPs either. Especially in a European context, urban food production, even though it has a great potential for climate change mitigation, nowadays it only contributes a fraction of the urban consumption (Filippini, Mazzocchi & Corsi, 2019). This also applies for other material NCPs. Based on these insights, I decided to not include material LF in the UGS MF indicator.

3.1.2.2. Data Normalization

To make the UGS MF indicator more feasible, all the data, which was later used to calculate individual LF values, had to be normalized. Therefore, I used a simple method, called 'Multiple Ecosystem Services Landscape Index' (MESLI), following the approach from Stürck and Verburg (2017) developed by Rodríguez-Loinaz, Alday & Onaindia (2015):

$$MESLI = \sum_{i=0}^{n} \frac{LF_{ij} - LF_{imin}}{LF_{imax} - LF_{imin}}$$

LF_{ij} here means a certain value 'i' at a certain spatial location 'j' from the dataset of the respective LF. LF_{imin} respectively LF_{imax} are the lowest respectively the highest values of the corresponding LF data. This index results in a normalization between 0 and 1, making it more comparable to other values without losing the distribution of the values. This is also the most applied normalization approach in the evaluation of urban LF (Charoenkit & Piyathamrongchai, 2019). In one case, the normalization had to be altered. The LF 'carbon sequestration' included negative values in the dataset. This meant that the range had to be adjusted from -1 to 1. Additionally, all the LF layers were transformed into a consistent coordinate system. The coordinate system World Geodetic System (WGS) 72 (Albers) was used in this thesis, due to the realistic representation of the considered area as well as the fact that most data was already plotted with this respective representation.

3.1.2.3. Weighting

Paracchini et al. (2011) presented three different way on how to calculate weight on an indicator, including economic, social and environmental factors. The first method rates each factor with the same importance as the others. The sub-factors used to calculate the factors in the three described categories are then weighted according to their number. So, for instance, if the environmental factor 'habitat provisioning' has three sub-factors included, the weighting of each of those sub-factors is equal to $^1/_3$ of the weighting of 'habitat provisioning'. In the second approach the authors present, the weight is applied according to the impact of the factors on the indicator, with respect to sustainability in this case. The third method considers the regional aspect when applying an indicator in different environments, and the weighting is adjusted according to where it is applied (Paracchini et al., 2011).

In urban LF studies, if a weighting is applied, usually the weighting process are based on opinions of experts in the respective field or public stakeholders. Therefore, the weighting process of four papers related to MF indicators, including expert opinions as well as those from public stakeholders, were analyzed (Alam, Dupras & Messier, 2015; Fernandez-Campo et al., 2017; Meerow & Newell, 2017; Salvati & Zitti, 2009). Due to different rating approaches and scales, the values were simplified to a scale from 0 to 1 to make them comparable to each other. After translating the summarized rankings to the LF used in the hereinafter developed UGS MF indicator, a ranking order and according weights were determined (see tab. 4). This was then divided for each category by the number of ranking points, before for each LF the weighting was calculated by using the result of the division multiplied by the individual ranking points. This also means I decided for an indicator value range from -0.1042 (due to possible negative values mentioned above) to 1 to measure MF, while 1 indicates the highest possible MF level.

Landscape function for the UGS MF indicator	Importance (1-5)	Weight
Local climate regulation	5	0.2
Water purification	3	0.12
Extreme events regulation	4	0.16
Biodiversity	4	0.16
Pollination	3	0.12
Recreational potential	5	0.2
Quietness suitability index	1	0.04
Sum		1

tab. 3: Weights for the included LF according to their importance based on reviewed literature (Alam, Dupras & Messier, 2015; Fernandez-Campo et al., 2017; Meerow & Newell, 2017; Salvati & Zitti, 2009).

3.1.2.4. Technical implementation of the UGS MF indicator

First, a buffer of 2 m was implemented around each UGS. Since parks or other green spaces do not have sharp borders, due to plants or trees having overhanging branches and also the roots cross the park's borders, it is logical to expand the reach of the LF functions by some distance. In the case of certain LF, such as 'local climate regulation' the area of influence could reach much further, but this was not implemented due to simplification reasons. After that, all the raster data was resampled to a raster of 10m x 10m. The down scaling process helps to make a spatially more precise distinction when allocating the LF to each specific UGS. Most of the original data was scaled on a 1 km grid before, which does not allow a precise analysis and mapping of MF (see fig. 4).

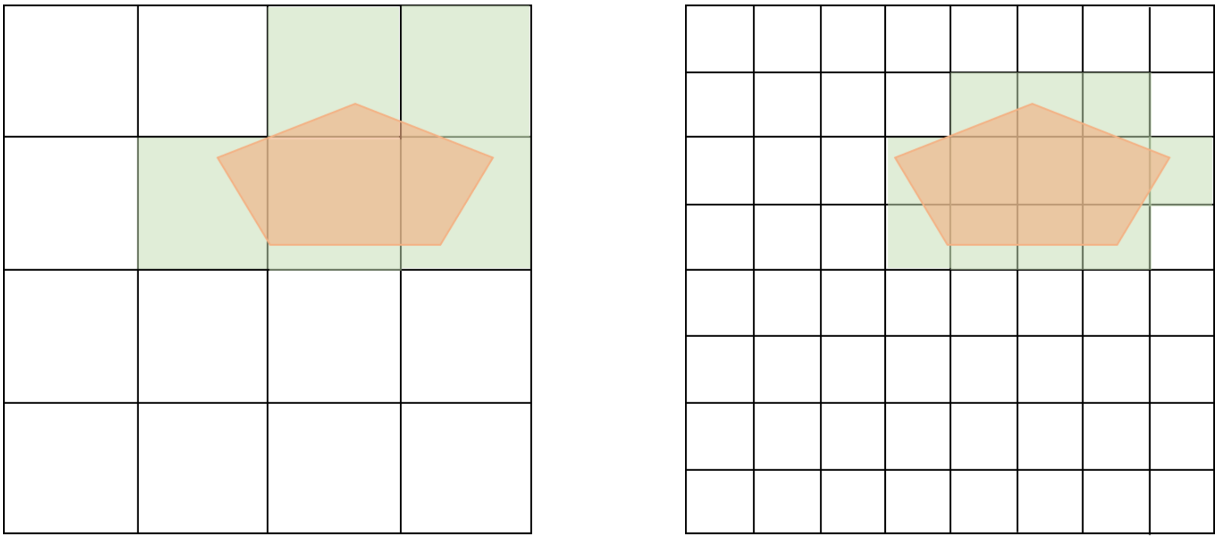

fig. 4: The idea of resampling. With a larger grid size on the left the raster data affected (green raster) by extracting it by a polygon shape (orange polygons) is spatially less precise than with half of the grid size on the right.

After all the raster data was in the right spatial scale, before adding the LF layers and respective normalized values together, the layers were visually tested for covariance. Thereby, it was tested if multiple layers show the same spatial distribution. This would be the case if two or more LF are based on the same primary data and would lead to an overvaluation of a certain trend in the data.

Finally, the indicator could be calculated (see fig. 5). For a start the layers connected to the same LF were united into one layer. Thereby, all the included layers were assigned the same weight using the 'Weighted Sum' tool. Subsequently, the same tool was used to calculate the MF indicator, while assigning the weights discussed in the weighting section (see tab. 3). The resulting weighted MF layer was then extracted with the UGS mask (AOI). This process resulted in the final UGS MF map. For a better comparability, I chose to present the MF values for all case studies in the same rounded equal interval, which I used in the MF indicator map.

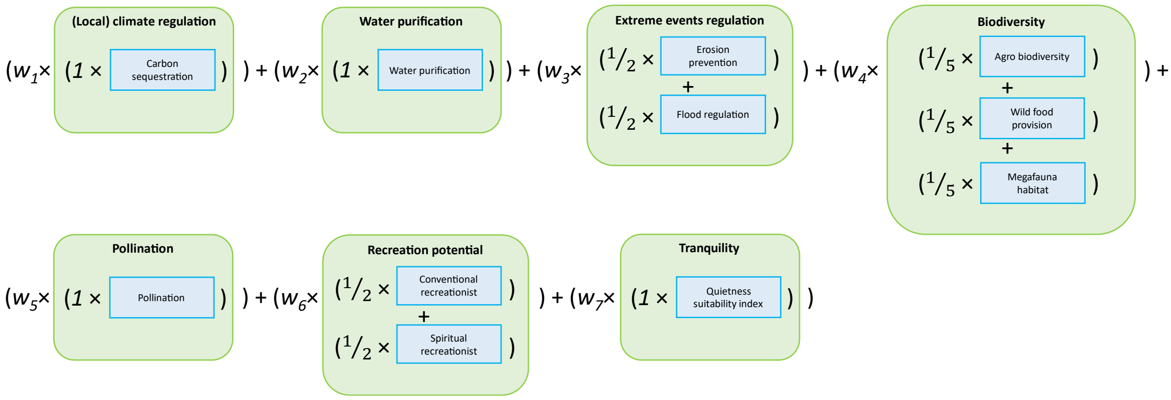

fig. 5: Calculations for the MF indicator consisting of seven LF (green) and their respective layers (blue) and weightings (w_x).

3.1.3. Case Studies

After developing a map for almost 1000 cities or city parts, I had to choose different case studies to interpret, discuss and understand the developed indicator. For this purpose, I decided to apply the following characteristics to be met by the chosen cities:

- 5 cities across the EU-27 area
- Population between 200'000 and 500'000 inhabitants
- Different socio-economic characteristics
- Widely dispersed geographic locations
- Different recognizable patterns in the MF indicator of the UGS

fig. 6: The chosen case studies in an overview, marked with red triangles: Palma de Mallorca in the South-west of the map, Aberdeen in the North-west, Nuremberg in the center of Europe and the map, Bialystok in the East and Tampere in the North-east (Screenshot from ArcGIS Pro).

This confinement led me to the case studies (see fig. 5): Aberdeen (Scotland, UK), Bialystok (Poland), Nuremberg (Germany), Palma de Mallorca (Spain), Tampere (Finland). By the choice of these cities all four compass directions and, therefore, main geographic locations in the EU were included in the case studies. One study site is located on an island (Palma), one further site is located by the sea (Aberdeen). Three locations (Bialystok, Tampere, Nuremberg) are located in the inland of the respective countries. Subsequently, I will explain further characteristics, which led me to the choosing of the respective cities and will present findings related to the MF indicator.

Aberdeen, located in the North-east of Scotland, was always relying on fishing and farming industry due to its location by the coast and surrounding farmland. In recent years the economy grew to be more diverse and improved possibilities in the labor market, which led to a considerable growth of the city (Laing et al., 2006). Aberdeen now counts almost 230'000 inhabitants, with an increasing tendency. Consequently, there is an increasing pressure on UGSs in the center of Aberdeen due to the local densification.

Bialystok is located in eastern Poland close to the border to Belarus. While analyzing public UGS in the city, Krzywnicka and Jankowska (2021) found that the green areas available per residents are high compared to other polish cities. On the outskirts of Bialystok there is a high density of woods, while in the inner-city districts parks and green squares dominate.

Nuremberg lays in the state of Bavaria in southern Germany. German cities have a long tradition in the creation of public parks and other recreational facilities for its residents. Nevertheless, Nuremberg is rather known for its historic old town, while green sites are rare compared to other German cities with similar resident numbers (Mulzer, 2006).

Palma de Mallorca is the capital city of the island Mallorca, which belongs to Spain, situated in the Mediterranean Sea east of the Iberian Peninsula. Palma is a special case among the five selected cities due to different aspects. First of all, it is the only city located on an island. This might have an influence on green spaces. Situated most southern and closest to the equator from the chosen selection, Palma lays in a (temperate) subtropical climate zone, with very hot and arid summers. Additionally, it is well known as a tourist destination, which could have an influence on the utilization of UGSs. Palma de Mallorca plans to expand inner-city green spaces to improve air quality conditions in the next few years (Majorca Daily Bulletin, 2022). The planned ecological corridors would also improve other factors of the MF of UGS on the Spanish island.

Tampere, the third biggest city of Finland, has an at least three times larger area than all other chosen cities. This is the consequence of the zonal planning by the Finish authorities, which apparently functions in larger scales. Finland has a low density of residents, which also creates less pressure on urban areas and supports the conservation of the excessive nature around the inhabited areas (Lähde & Di Marino, 2019). This is also the case in Tampere, having a density of 354 residents per km^2.

3.2. Data Gathering

3.2.1. Area of Interest

Category	Name	Year	Resolution (km^2)	Source
CORINE Land Cover	CLC2018	2018	0.025	**EEA** (2023) CORINE Land Cover. Copernicus Land Monitoring Services. European Environment Agency, European Union. <https://land.copernicus.eu/pan-european/corine-land-cover>
City borders	Urban Audit 2018	2018	0.025	**Eurostat** (2023) URBAN AUDIT. <https://ec.europa.eu/eurostat/web/gisco/geodata/reference-data/administrative-units-statistical-units/urban-audit>

tab. 4: Data used to define the Area of Interest (AOI) with the according specifications.

To design the AOI, two essential factors were needed. Since the study area considers UGS, I needed data that defines the urban aspect and data that covers the green spaces in this environment. Therefore, I used CORINE land cover[13] (CLC) data available from the Copernicus Land Monitoring Service by the EEA (2023). Since the year 2000 the CLC inventory has been collecting European land cover data in 44 classes in a regular cycle of 6 years (EEA, 2023). They achieved over 85% thematic accuracy. The data is accessible for everyone without restrictions and the data has a minimum mapping unit of 25 ha (0.025 km^2) for raster data, which is probably, why their data is used in wide range of applications (EEA, 2023). I used the CLC data from 2018, which constitutes the newest release of Copernicus. From the CLC data, land covers, which serve as a UGS, were retrieved by a simple selection.

The dataset 'Urban Audit 2018' of Eurostat (2023) contains point and polygon data to the boundaries of European cities. I used the data from 2018, to make it compatible with the CLC data that derive from the same year. The data comes at three different levels: the core city, greater city and a functional urban area. Due to the nature of my research, the core city is the most relevant in this thesis. The dataset covers the EU-28 states, according to the European Commission (2019), plus Iceland, Norway, and Switzerland (Eurostat, 2023).

[13] Subsequently referred to as CLC

3.2.2. Urban Green Space Multifunctionality Indicator

Category	LF	Dataset	Resolution (km^2)	Source
Regulating	(Local) climate regulation	**'Carbon sequestration'**	1	Schulp, C., Nabuurs, G.J., Verburg, P. (2008) Future carbon sequestration in Europe-Effect of land use change. *Agriculture, Ecosystems & Environment* 127, 251–264.
	Water purification	**'Total N retention'**	0.01	Vallecillo Rodriguez, S., La Notte, A., Zulian, G., Polce, C., Kakoulaki, G. and Maes, J. (2019) Mapping and Assessment of Ecosystems and their Services, European Commission, JRC117795.
	Extreme events regulation	**'Erosion prevention'**	1	Pérez-Soba, M., Verburg, P., Koomen, E. (2010) Land use modeling-implementation. Preserving and enhancing the environmental benefits of "land-use services". Report to the European Commission DG Environment under contract No.07.0307/2008/511790/SER/G1. Wageningen, The Netherlands.
		'Flood regulation'	1	Stürck, J., Poortinga, A., Verburg, P. (2014) Mapping ecosystem services: The supply and demand of flood regulation services in Europe. *Ecological Indicators* 38, 198–211.
	Biodiversity	**'Agro biodiversity'**	1	Overmars, K., Schulp, C., Alkemade, R. et al. (2014) Developing a methodology for a species-based and spatially explicit indicator for biodiversity on agricultural land in the EU. *Ecological Indicators* 37, 186–198.
		'Wild food provisioning'	0.25	Schulp, C., Thuiller, W, Verburg, P. (2014) Wild food in Europe: a synthesis of knowledge and data of terrestrial wild food as an ecosystem service. *Ecological economics* 105, 292–305.
		'Megafauna habitat'	1	Van der Zanden, E., Verburg, P., Schulp, C., Verkerk, P. (2017) Trade-offs of European agricultural abandonment. *Land Use Policy* 62, 290–301.
	Pollination	**'Pollination visitation probability'**	1	Schulp, C., Lautenbach, S., Verburg, P. (2014) Quantifying and mapping ecosystem services: Demand and supply of pollination in the European Union. *Ecological Indicators* 36, 131–141.
Non-material	Recreation potential	**'Recreational potential for convenience recreationalist and spiritual recreationalist'**	1	Komossa, F., van der Zanden, E.H., Schulp, C.J., Verburg, P.H. (2018) Mapping landscape potential for outdoor recreation using different archetypical recreation user groups in the European Union. Ecological Indicators 85, 105-116.
	Tranquility	**'Quietness suitability index'**	1	EEA (2020) Quiet areas in Europe. European Environment Agency, European Union. <https://www.eea.europa.eu/data-and-maps/data/quiet-areas-in-europe-2>

tab. 5: The LF used in the UGS MF Indicator with the corresponding datasets, resolutions and sources ordered into non-material and regulating NCPs.

When developing an environmental indicator, data selection should be considered thoroughly. Especially, if the indicator covers a big scale study area, as in this case, the data should be consistent over the whole AOI. Therefore, it is of advantage, if either big scale data of a supranational organization (e.g., EU) or scientific research with a similar extent is found. This helps the study to be consistent and reproducible. Komossa et al. (2017) wrote a report during the EU Horizon 2020 project 'PROVIDE'. As part of their report, the authors collected and mapped the availability of different LF at a high spatial resolution of 1 km^2 (except one subset, which has a higher spatial resolution) (Komossa et al., 2017). The authors chose the considered LF according to a literature review and the EU-27 as their research area, which means it includes the same countries as the created AOI map except the non-member states Iceland, Norway and Switzerland as well as Croatia. The datasets Komossa et al. (2017) used in their report included 10 different LF s-datasets, which mostly were composed of secondary data they retrieved from different sources (e.g., land use data, catchment areas, point data of special attractions).

The 'Climate regulation' subset was used as a measurement for the eponymous LF. The original data used land cover data emission and sequestration rates and carbon stock measurements. The data shows carbon sequestration as well as emission and is measured in Mg C / km^2 (Komossa et al., 2017). Due to the wide coverage, a justification for this subset to be used as a proxy for climate regulation was seen as fulfilled. Vallecillo Rodriguez et al. (2019) examined different LF and mapped them. In the case of water purification, they used the value 'total nitrogen retention' as a proxy for the according LF, which I used in the UGS MF indicator as well. The next LF, which is embedded in the UGS MF indicator, is called 'extreme events regulation'. For this LF, I used the datasets 'Erosion prevention' and 'Flood regulation' from Pérez-Soba, Verburg and Koomen (2010) respectively Stürck, Poortinga and Verburg (2014). The first dataset was built from land cover data as well as erosion risk factors (e.g., slope), while the second is composed of environmental variables related to flood regulation, a hydrological model and potential damage values. Natural vegetation supports erosion prevention, where the risks are high. The data is based on ton/ha erosion prevention measurements. The flood regulation data is measured with a normalized index between 0–100 (Komossa et al., 2017). For the LF biodiversity of the UGS MF indicator three different datasets were used: 'Agro biodiversity', 'Wild food provisioning' and 'Megafauna habitat'. The 'Agro biodiversity' subset was composed of CLC data, different spatial distributions of plants and animals, as well as soil nutrient measurements. The original data used percentage of relative species richness (Overmars et al., 2014). The data of 'Wild food provisioning' consists of vascular plants and is measured in number of existent species out of the 81 most common vascular plant species in the EU. The original data was retrieved from land cover data, local case studies as well as different inventories/databases (Schulp, Thuiller & Verburg, 2014). The subset 'Megafauna habitat' was developed on the basis of a habitat framework. The data shows the number of species present in each cell (Van der Zanden et al., 2017). The LF 'pollination' had an equivalent in the dataset provided by Komossa et al. (2017). Here, the 'Pollinator visitation probability' was used as a proxy of pollination. The data used CLC data to assign bee habitats based on expert knowledge as well as certain landscape elements supporting the pollination process. The LF was measured based on visitation probability (%) of pollinators (Komossa et al., 2017).

In the category of non-material NCPs, the developed UGS MF indicator consists of three different LF. Since the data used by Komossa et al. (2018) covers all three LF in the non-material section, as described in the previous chapters, I used a subset of this dataset ('convenience recreationalist' and 'spiritual recreationalist'). The data has a high spatial resolution of 1 km^2 and distinguishes between 5 classes, which reach from low (1) to high (5) (Komossa et al., 2018). Additionally, data from the EEA (2020) that consists of a 'Quietness suitability index', was used to integrate a proxy for calmness. The data is normalized between 0 and 100 and is calculated on a 1 km raster as well.

3.2.3. Surrounding Factors

Category	Name	File	Source
District Boundaries	**Community Council 2018**	Vector layer	**Aberdeen City Council Open Spatial Data Portal** (2018) Community Councils 2018. ArcGis Online feature layer. <https://spatialdata-accabdn.opendata.arcgis.com/datasets/accabdn::community-councils-2018-1/explore>
	Geometrie_NUE_Bezirke	Vector layer	**Wiki OpenStreetMap** (2017) Nürnberg/Stadtteile. Quellen: Stadtbezirke als Shapefiles. <https://wiki.openstreetmap.org/wiki/N%C3%BCrnberg/Stadtteile#Quellen>
	Statistical areas in Tampere	Vector layer	**Tampereen kaupungin dataportaali** (2012) Statistical areas in Tampere. >https://data.tampere.fi/data/en_GB/dataset/tampereen-tilastoalueet>

tab. 6: Surrounding factors datasets with the corresponding category, resolution and source.

For the surrounding factors I used socio-economic data on neighborhood level of each case study city, since the scale of the same data on EU level does not meet the standards required for this thesis. The smallest EU data scale available is 1 km^2, whereas my MF indicator is constructed on a $100m^2$ grid. The socio-economic conditions were tried to be displayed with three main factors: population density, unemployment rates and average professional qualifications. The decision for those factors was made based on the availability of this data as well as Krishnan's (2010) framework on socio-economic data analysis.

In case of Aberdeen, I used the census data from 2011, since this is the latest publication with the relevant information (Aberdeen City Council, 2012). Apart from population data, which can be easily transformed into density by dividing it with the total area of the neighborhood, I used Aberdeen's statistics of unemployment rate. For the latter, I summed the numbers for long-time unemployed adults, adults that never worked and full-time adult students and divided it by people over 18 years of age to get the unemployment rate. Furthermore, I calculated an average qualification level from the categories no qualification (0) to qualification level 4. For the neighborhood boundaries I used the Community council structure of 2018 (Aberdeen City Council Open Data Spatial Portal, 2018).

For Nuremberg, the city provides different data on district level (Amt für Stadtforschung und Statistik für Nürnberg und Fürth, 2023). I used data from the year 2020, since it was the closest available compared to the UGS MF data. Unfortunately, due to privacy restrictions, the city does not provide educational or professional qualifications on the district scale, but only total numbers for the whole city. Therefore, I used only population figures per district to calculate densities in the respective areas as well as unemployment rates. The map with the different city districts were provided from the city and made available by Wiki OpenStreetMap (2017). To make the data compatible with the city map I had to dissolve city parts that were integrated into one district for statistical reasons.

The city of Tampere (Tampereen kaupungin dataportaali, 2012) provided a map with the different city districts. The names of the district had to be adjusted manually. After that, they could be joined with the population data, retrieved from the statistical yearbook 2018-2020 of the Tampere region (Tampereen kaupungin, 2020). Unfortunately, the population data was the only available data on district scale and everything was published in Finnish. So, this was the only socio-economic factor I could examine for the Finnish city.

For Palma de Mallorca and Bialystok, there was no open spatial data for city districts available. Also, no census or socio-economic data on district level were found despite an intense research effort. Therefore, I decided to do the regression of the surrounding factors with the available data of the cities Aberdeen, Nuremberg and Tampere.

3.2.4. Spatial Statistics of Surrounding Factors and Multifunctionality Indicator

To compare the UGS MF indicator with the surrounding factors, the socio-economic data regarding population density, unemployment rates as well as professional level, I did a spatial regression of the two datasets. First of all, I had to adjust the data type of the MF indicator data to integrate them in one layer with the socio-economic data. For this purpose, the MF indicator layers had to be transformed from raster data into polygon features. In a first step, I multiplied the MF level (0 – 1) with the factor 100, and later transformed it with the following code using the raster calculator into integers:

$$Int(\text{raster\_layer} + 0.5)$$

This code transforms float types into integers by just cutting off the decimals. To avoid distortion of the values, I added 0.5 to ensure the correct rounding of the values. Finally, the raster layers were transformed into vector layers. In a next step, the two vector layers of each city, containing MF indicator values and surrounding factors, were spatially joined. Every UGS containing MF indicator value was basically expanded by the socio-economic values of the same area. To allocate the polygons, I used the center as defining point for the UGS polygons. Before going into the regression process, the null values, a remnant of the transformation from raster data to vector data, had to be deleted. Finally, the spatial regression of the UGS MF indicator values and the surrounding factors was calculated. Thereby, I used the ordinary least square[14] (OLS) method. OLS, or methods based on OLS, are usually used for spatial regression analysis (Esri, 2023). The regression analysis shows the relation between a dependent variable, in this case the MF indicator values, and a set of independent variables, in this case the surrounding factors population density, average professional level and unemployment rate. I unified the independent variables average professional qualification and unemployment rate to a range of 0 – 100 for a more convenient interpretation of the OLS results, namely the coefficient.

[14] Subsequently referred to as OLS

4. Results

4.1. Multifunctionality indicator

I developed an indicator that enables a comparison between different cities in the EU. Therefore, I applied the MF indicator on a large scale AOI, which cannot be discussed thoroughly in this thesis. Nevertheless, before concentrating on the case studies, I want to present some findings about the entire AOI here. This helps the reader to get an overview over the state of European UGSs in regard to their MF and allows to evaluate the subsequent number of the case studies in a bigger frame.

From the examined urban area almost 40% were assigned as UGS (see tab. 7). The range of the MF values reached from 0.077 to 0.617, where 0 was the lowest and 1 the highest possible score. This results in a range of 0.54. The mean value over all UGSs was 0.315, with a standard deviation of 0.06. Subsequently, tab. 7 shows all the important figures of the MF indicator for each case study as well as the overview of all cities included during the research.

City	Population[15]	Area [km^2]	Density [residents/km^2]	UGS proportion [%]	Mean MF-Value	Max. MF-Value	Min. MF-Value	Range MF-Value	Std. Deviation
Aberdeen	227'430	187	1216	35.06	0.309	0.493	0.185	0.308	0.041
Bialystok	294'242	102	**2885**	34.93	0.257	0.392	0.165	0.227	0.04
Nuremberg	**510'000**	188	2713	26.86	0.311	0.42	**0.233**	0.187	**0.026**
Palma de Mallorca	422'587	208	2032	32.29	0.301	0.446	0.165	0.281	0.058
Tampere	244'223	**689**	354	**60.80**	**0.341**	**0.494**	0.128	**0.366**	0.046
Total AOI	-	157'094	-	39.71	0.315	0.617	0.077	0.54	0.06

tab. 7: Indices for the five case studies and the total AOI. Highlighted in bold numbers are the highest resp. lowest vales of each classification. The numbers, apart from population data, are collected from ArcGIS calculations.

4.1.1. Aberdeen

Aberdeen has the second-lowest population density of the five case studies, which constitutes only half the density of Nuremburg. The proportion of UGS in regard to the total area amounts to over 35%, which is considerably high compared to the other cities. However, Aberdeen has most of its UGS located towards the city borders (see fig. 7). In the northern part of the city center there are a few smaller greenspaces, but most UGS are to find in the West of the city perimeter. Additionally, you will find some smaller UGSs in the South of the city. The city

[15] Derived from City Population (2023) for the years 2020 or 2021.

center, where the majority of the residents live and work, as well as the coastline, are completely lacking UGSs in the considered size.

The MF values of Aberdeen are characterized by a mean of 0.309 with a standard deviation of 0.041. These values classify in the middle range of the case studies. This applies also for the range of the MF values (0.308) and the minimum value (0.185). The maximum value of 0.493 is close to the highest values of the case studies. It is remarkable, how the MF values are distributed in the city of Aberdeen. The UGSs closest to the coast and the city center scored the lowest in the indicator. The further west and north an UGS is located, the values increase almost linearly, it seems.

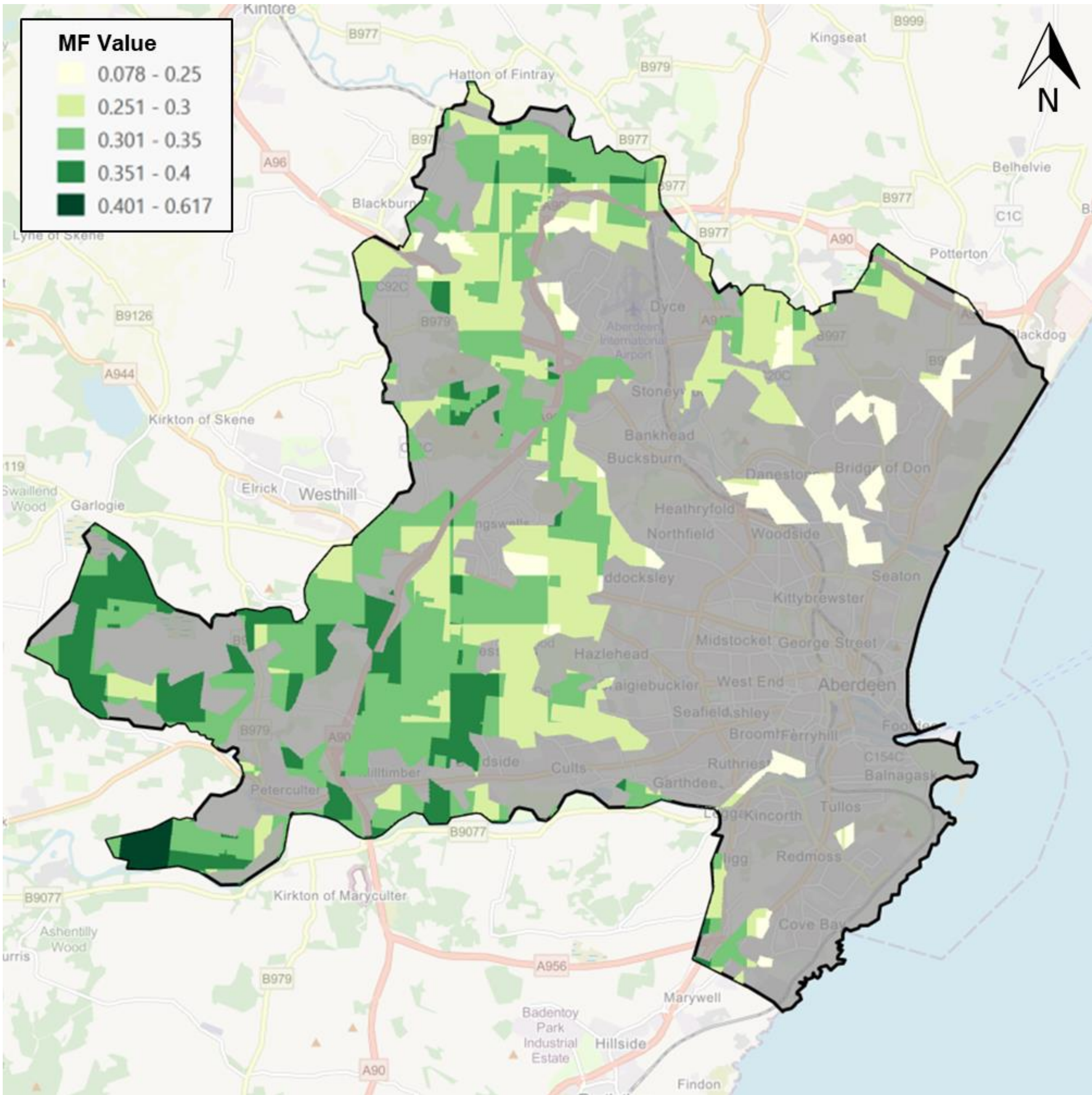

fig. 7: The extents of the city of Aberdeen (grey with black outlines) and all UGSs (different shades of green) inside the city's borders. The higher the saturation the higher is the MF-value in the respective area (screenshot from ArcGIS pro).

4.1.2. Bialystok

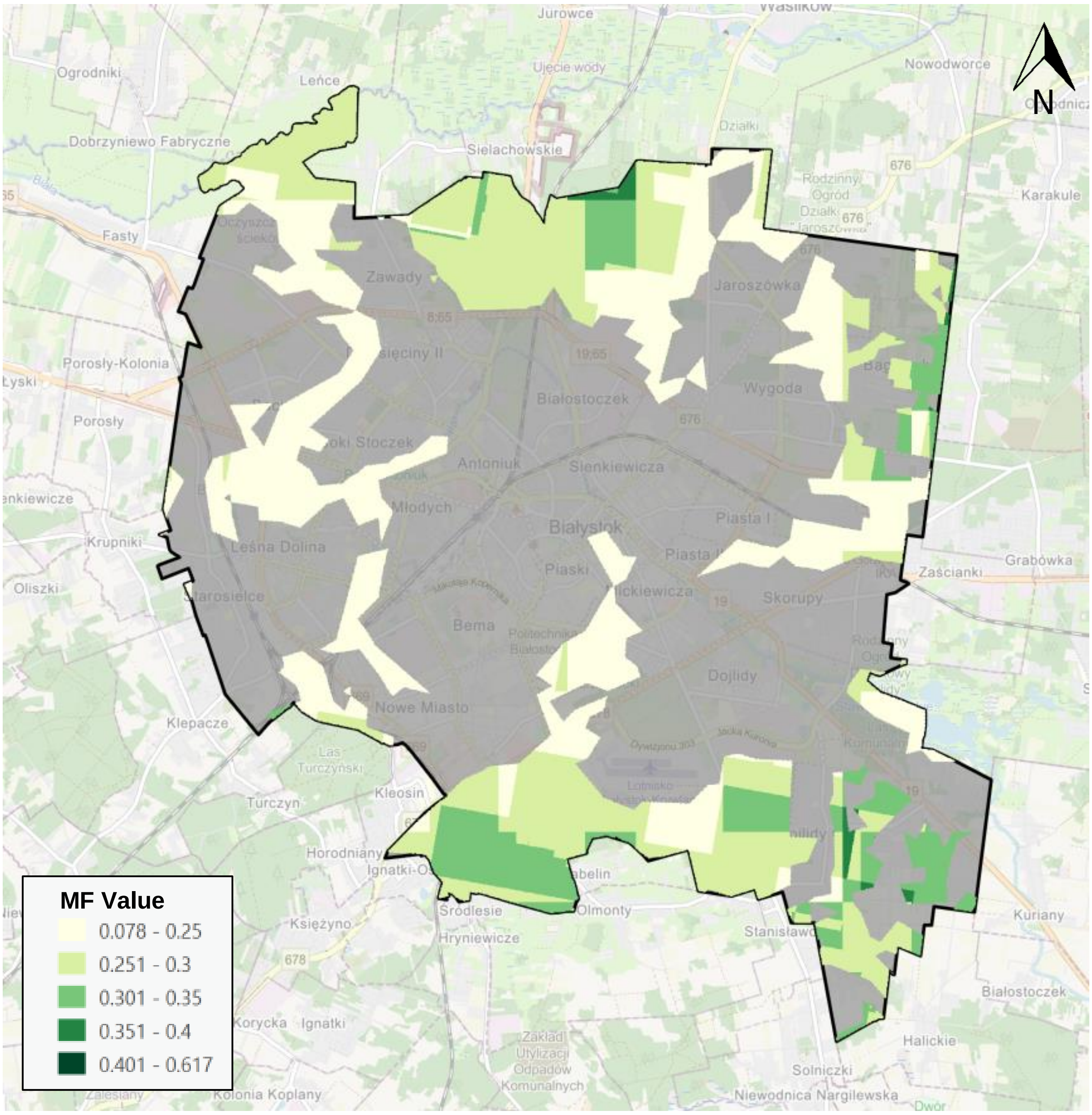

fig. 8: The extents of the city of Bialystok (grey with black outlines) and all UGSs (different shades of green) inside the city's borders. The higher the saturation the higher is the MF-value in the respective area (screenshot from ArcGIS pro).

As seen on fig. 8, many of the inner-city parks are not included in the case study of this thesis, since they did not meet the requirements of size or purpose to be acknowledged as UGS per definition used in this thesis. The spacious woodlands on the outskirts are clearly apparent. Bialystok scored the lowest mean MF values (0.257) and maximum MF value (0.392) of all the case studies. The other values are situated in the middle range of the examined cities.

4.1.3. Nuremberg

Nuremberg is surrounded by wooded areas to all sides (see fig. 9). Inside the city perimeter there are a few large UGS in the South and in the enclave in the East. Smaller UGSs in the north-eastern part of Nuremberg complete the picture, since the inner-city lacks UGSs completely. This is also represented in the UGS proportion (26.86%), which is the lowest score in that field. However, Nuremberg scored the highest values in the minimum MF value (0.233) and has the lowest standard deviation (0.026). This means that the quality of Nuremberg's UGSs are evenly distributed. The mean of the MF values in Nuremberg is the second highest value of all cities exmamined.

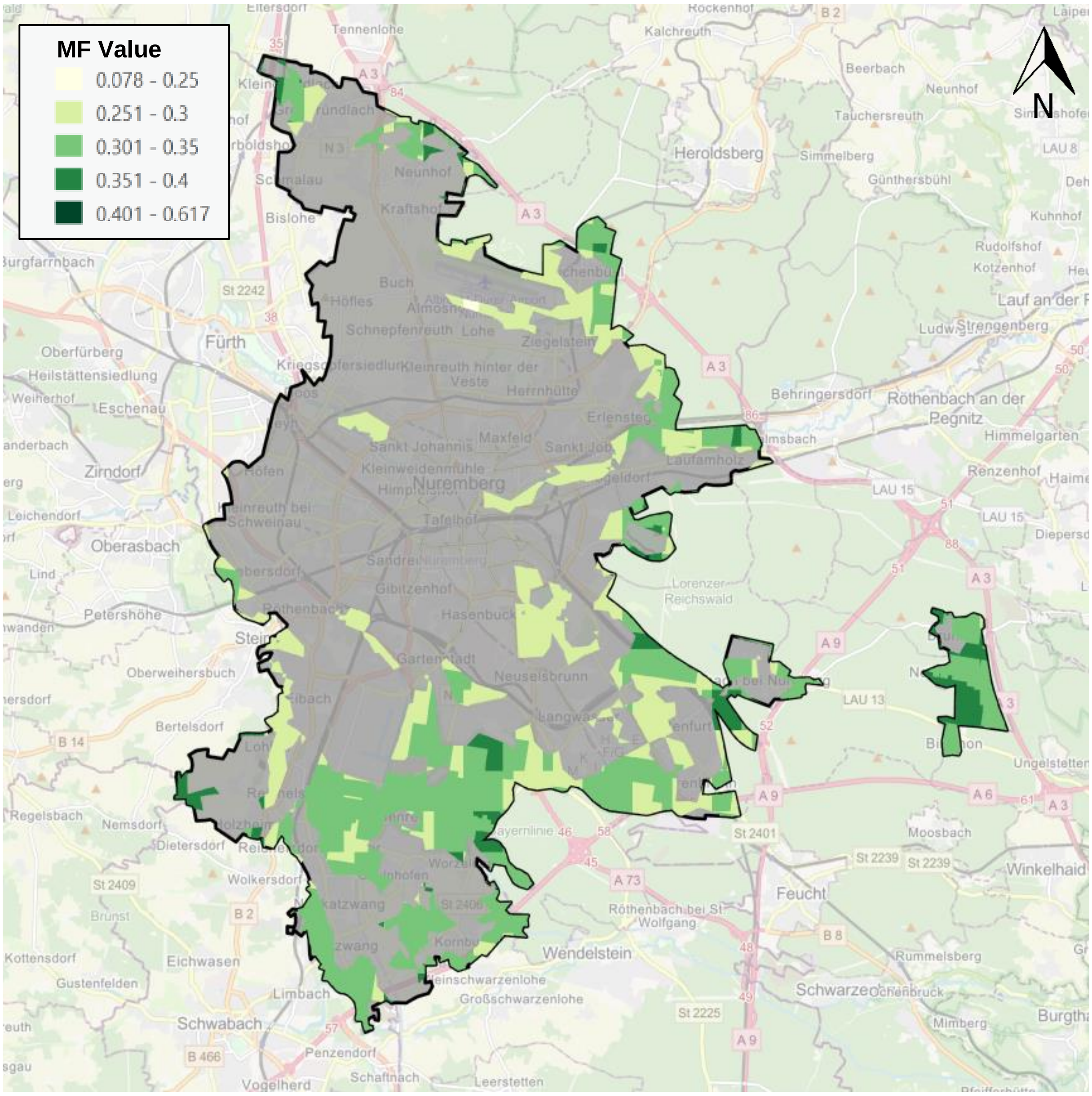

fig. 9: The extents of the city of Nuremberg (grey with black outlines) and all UGSs (different shades of green) inside the city's borders. The higher the saturation the higher is the MF-value in the respective area (screenshot from ArcGIS pro).

4.1.4. Palma de Mallorca

At this point in time, Palma de Mallorca mostly lacks UGSs around the center and harbor. In the northern part of Palma there are extensive green areas and in the South-east, many fragmented UGS patches also assure access to UGS for the residents. Nevertheless, apart from the missing green areas in the center, the UGS MF indicator scores are well distributed over space.

The distribution looks similar to Aberdeen with higher MF values towards the inland, but less fragmentated. The indicator values of Palma are all average, scoring in middle range of the five case studies, apart from the standard deviation (0.058), which is the highest in Palma.

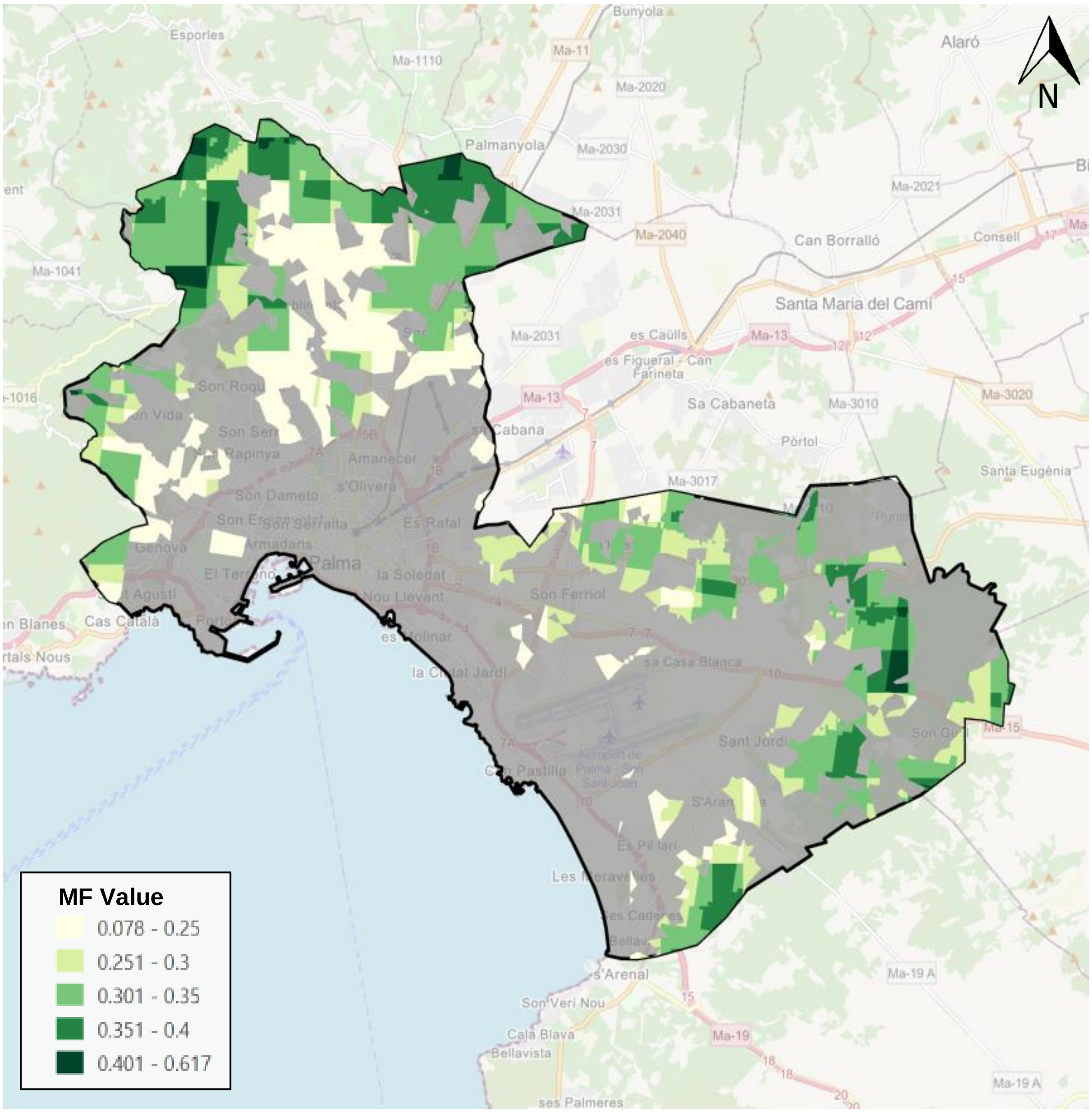

fig. 10: The extents of Palma de Mallorca (grey with black outlines) and all UGSs (different shades of green) inside the city's borders. The higher the saturation the higher is the MF-value in the respective area (screenshot from ArcGIS pro).

4.1.5. Tampere

While the city center in the South has a high density of UGSs compared to the total area, the northern part consists almost exclusively of UGS areas. Therefore, it is not surprising that Tampere scored the highest values in multiple categories regarding the MF indicator. The mean MF value of Tampere's UGSs (0.341) is obviously higher than the values of the other case study and the mean of the entire European AOI. Furthermore, the highest maximum value (0.494) among the case studies was calculated in the Finnish city. The standard deviation (0.046) is comparatively high, which has its origin in the segregation between the city center in the South and the northern woodland.

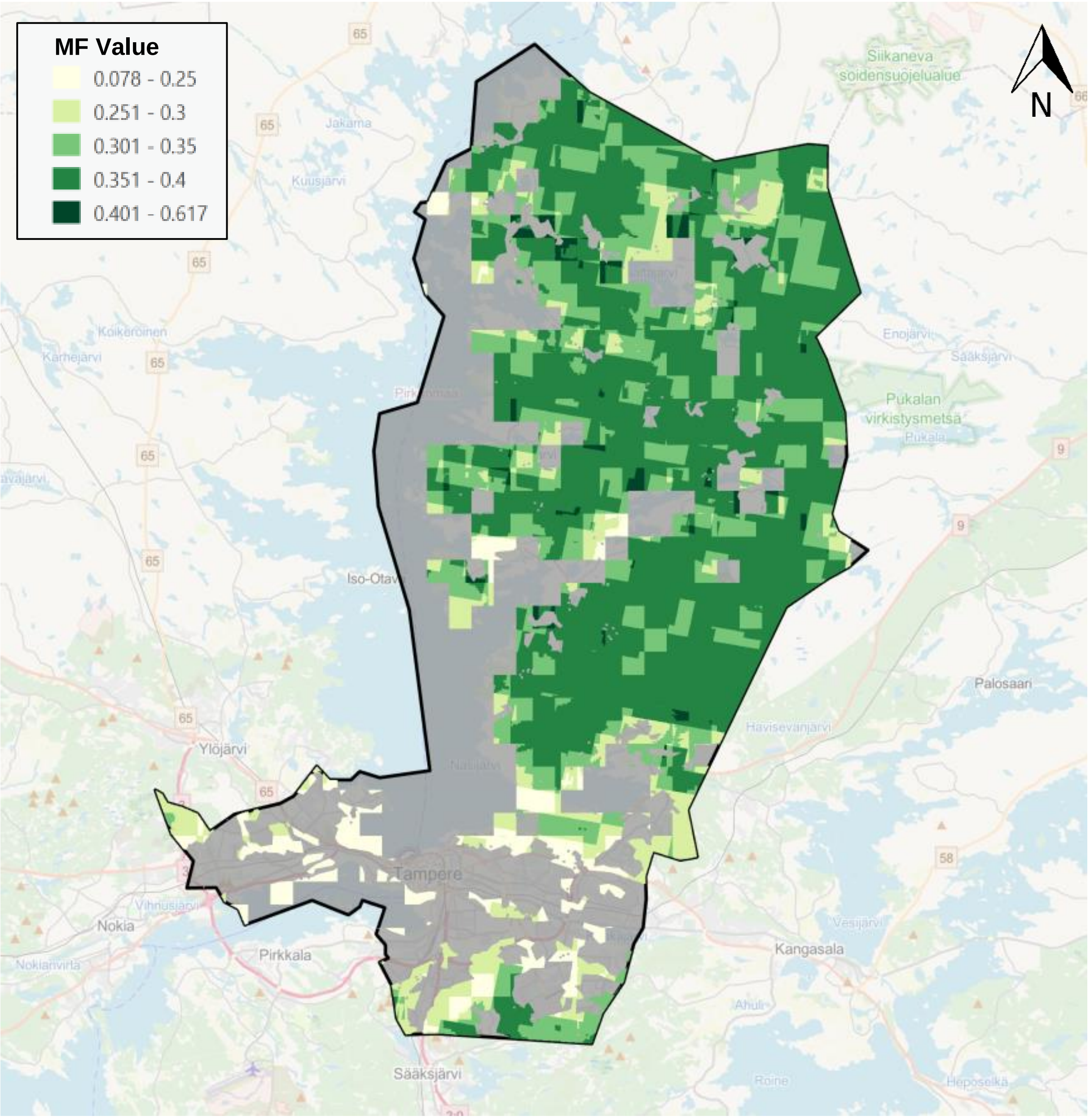

fig. 11: The extents of the city of Tampere (grey with black outlines) and all UGSs (different shades of green) inside the city's borders. The higher the saturation the higher is the MF-value in the respective area (screenshot from ArcGIS pro).

4.2. Surrounding Factors

4.2.1. Aberdeen

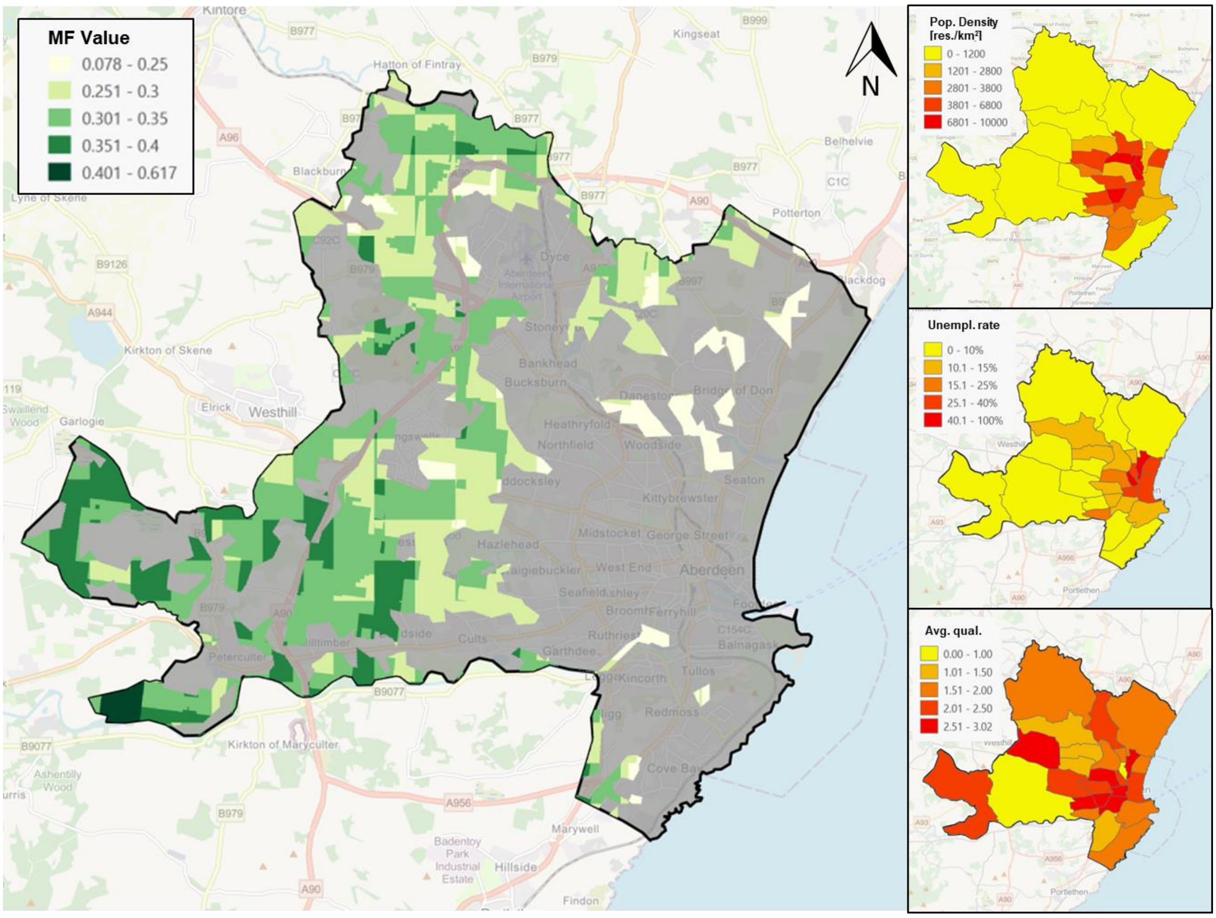

fig. 12: The distribution of the MF values (left), the population density (top right), the unemployment rate (middle right) and the average professional qualification (bottom right) for Aberdeen (screenshots from ArcGIS pro).

Summary of OLS Results - Model Variables

Variable	Coefficient [a]	StdError	t-Statistic	Probability [b]	Robust_SE	Robust_t	Robust_Pr [b]	VIF [c]
Intercept	31.448615	0.552525	56.918000	0.000000*	1.768592	17.781729	0.000000*	--------
P_DENS	-0.001425	0.000161	-8.876515	0.000000*	0.000236	-6.036537	0.000000*	1.174604
UNEMP_PER	0.208901	0.045998	4.541497	0.000008*	0.188389	1.108881	0.267729	1.222146
AVG_QUAL_PER	-0.030711	0.008829	-3.478259	0.000540*	0.013346	-2.301177	0.021561*	1.069843

fig. 13: Summary of the OLS results for the city of Aberdeen generated by ArcGIS pro from the OLS tool with all the statistics of the regression. The independent variables are population density (P_DENS), unemployment rate (UNEMP_PER) and average professional qualification (AVG_QUAL_PER). The dependent variable is the MF value.

For Aberdeen I researched and evaluated three surrounding factors to perform a regression with the MF values of the city’s UGSs. The population of Aberdeen is mostly concentrated in the city center close to the coast (see fig. 12, top right). In the South, the population density is rather high as well. Almost a similar picture shows the unemployment rate (see fig. 12, middle right). There are high values in the city center as well as in the South. Additionally, there are higher unemployment rates to be found west from the city center. The average qualification of Aberdeen's residents shows a more dispersed distribution (see fig. 12, bottom right). The city center and areas in the South, except of one district, face higher average qualification values than the northern parts of the city and the districts on the coastline.

Looking at the regression table (see fig. 13), all coefficients of the three independent variables, namely 'population density' (P_DENS), 'unemployment rate' (UNEMP_PER) and 'average qualification' (AVG_QUAL_PER), seem to be statistically significant with p-values below 0.05. There is a negative correlation between the dependent variable 'MF value' and the independent variable 'population density'. The results show that an increase by one person per square kilometer reduces the MF value by 0.0014%. Surprisingly, the unemployment rate has a positive correlation (coefficient of 0.209) with the MF values. This means that if the unemployment rate increases by 1% the MF value also increases by a bit over 0.2%. Between the independent variable 'average qualification level' and the dependent variable 'MF value' there is a negative correlation of -0.031, which means if the qualification level increases by 1% the MF value decreases by a bit over 0.03 %.

4.2.2. Nuremberg

Nuremberg's population distribution shows a similar picture as Aberdeen (see fig. 14, top right). There is a high population density in the city center and decreasing density values towards the outskirts of the city. The exception are three districts south of the city center and two districts in the heart of the center. In the case of the unemployment rate (see fig. 14, bottom right) the city center and districts to the South-east and North-west show the highest values. The northern and southern part has a low unemployment rate.

The OLS results for Nuremberg (see fig. 15) show statistically significant coefficients for the independent variables 'population density' respectively 'unemployment rates' and the dependent variable 'MF value'. The p-values are below 0.05. The variable 'population density' is negatively correlated (-0.001) with the MF value. This means for every additional resident per square kilometer the MF value decreases by 0.001%. Also, the correlation between the MF value and the unemployment rate is negative (-1.064). This means, that if the unemployment rate increases by 1% the MF value decreases by almost 1.1%.

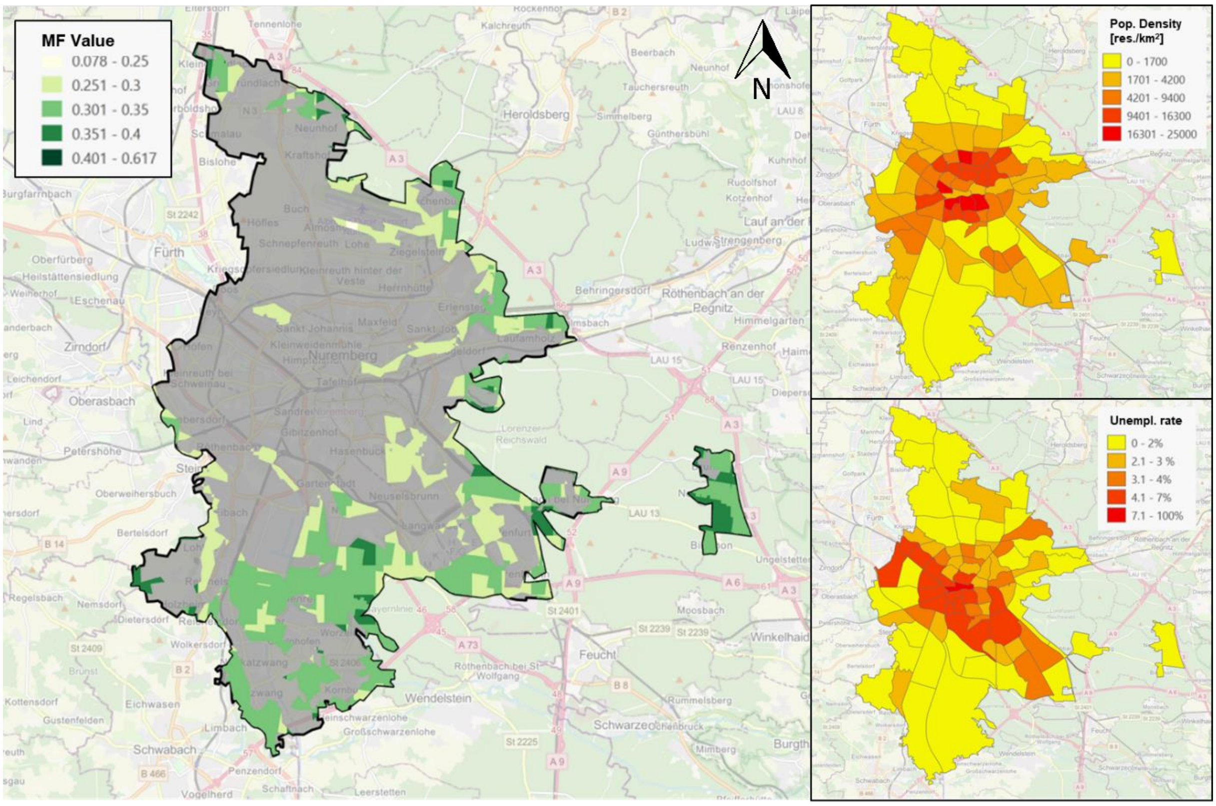

fig. 14: the distribution of the MF values (left), the unemployment rate (bottom right) and the population density (top right) for Nuremberg (screenshots from ArcGIS pro).

Summary of OLS Results - Model Variables

Variable	Coefficient [a]	StdError	t-Statistic	Probability [b]	Robust_SE	Robust_t	Robust_Pr [b]	VIF [c]
Intercept	34.072836	0.219949	154.912121	0.000000*	0.226017	150.753164	0.000000*	--------
POPDENSI	-0.000610	0.000091	-6.715779	0.000000*	0.000078	-7.818612	0.000000*	1.089914
UNEMP_PER	-1.064390	0.124816	-8.527667	0.000000*	0.111012	-9.588058	0.000000*	1.089914

fig. 15: Summary of the OLS results for the city of Nuremberg generated by ArcGIS pro from the OLS tool with all the statistics of the regression. The independent variables are population density (POPDENSI) and unemployment rate (UNEMP_PER). The dependent variable is the MF value.

4.2.3. Tampere

In Tampere I only found data on district level of the population density (see fig. 16, top right). The entire part in the North is only sparsely populated, while the southern part shows a relatively dispersed distribution. It seems like Tampere does not have a larger city center similar to the ones of Aberdeen or Nuremberg.

Looking at the OLS results of Tampere (see fig. 17), the coefficient of the independent variable 'population density' is highly significant. The coefficient of -0.001 means a negative correlation between the two variables 'population density' and 'MF value'. Same as in Nuremberg, it means that with every additional resident per square kilometer the MF value decreases by 0.001%.

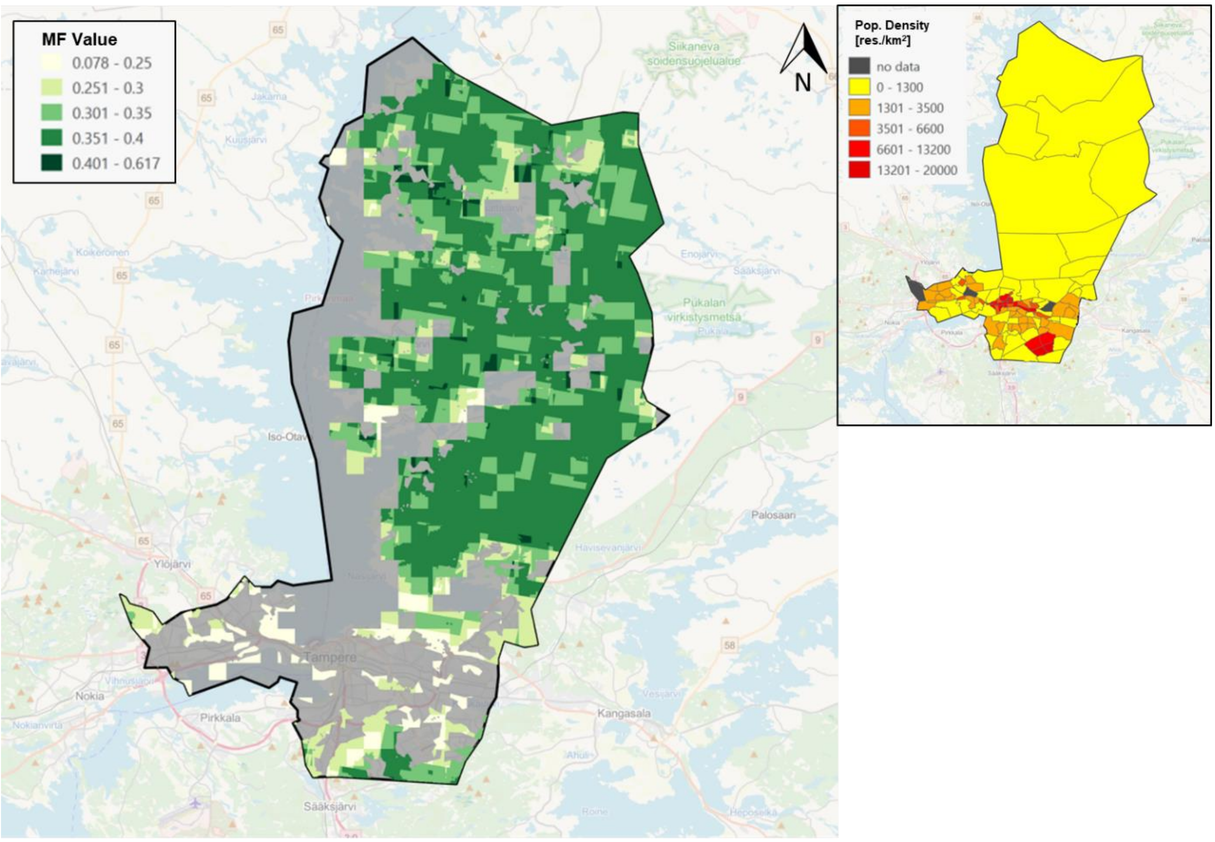

fig. 16: The distribution of the MF values (left) and the population density (top right) for Tampere (screenshots from ArcGIS pro).

Summary of OLS Results - Model Variables

Variable	Coefficient [a]	StdError	t-Statistic	Probability [b]	Robust_SE	Robust_t	Robust_Pr [b]
Intercept	33.071835	0.090983	363.494744	0.000000*	0.089418	369.855782	0.000000*
POP_DENS	-0.000894	0.000071	-12.624826	0.000000*	0.000142	-6.282705	0.000000*

fig. 17: Summary of the OLS results for the city of Tampere generated by ArcGIS pro from the OLS tool with all the statistics of the regression. The independent variable is population density (POP_DENS). The dependent variable is the MF value.

5. Discussion

The entire AOI, consisting of over 1000 cities and city districts over the EU-27_2007 territory, has a surprisingly high proportion of UGSs compared to the total urban area (39.17%). In all probability, this is due the zonal planning of European cities, which in most cases not only include the urban fabric around the center, but also contains the greener outskirts of the city. Furthermore, based on the literature review and scientific research I conducted in the course of this thesis writing process, I received the impression that European decision-makers and city planners understood the great importance of UGS in regard of environmental topic as well as the mental and physical health of their residents. Analyzing the case studies, I could confirm the patterns mentioned by Kabisch et al. (2016). They described that the availability of UGSs is generally higher in northern European cities, especially in Scandinavia, than it is in the southern part of Europe.

When comparing the values of the MF indicator between the five case studies (see tab. 7), the numbers differ quite obviously. The case study, which outstands the most, is Tampere. It has the highest UGS proportion, mean MF value and maximum MF value, while the city also covers the largest area. This seems very impressing. But on a second glance, it becomes clear that this has more to do with urban planning than with an actual disproportionate environmental effort of the Finnish city. The city borders of Tampere contain, apart from the urban fabric in the South, a large natural territory in the North, which overtops the area of the actual city by at least factor 2. This northern area is sparsely populated, contains large forest areas and lakes and, therefore, causes the high MF values for Tampere. Nevertheless, this example shows a major realization I made during this thesis. It is very hard to compare cities over such a large study area, due to different political and planning factors, regional circumstances and the focus on areas with hard borders. The latter can be described using the case of Tampere. I am convinced, the other case studies could have scored in the same value range as Tampere, if the city area would include some more natural areas outside the city borders. Therefore, Tampere is a special case, whose values should be treated with caution and the greater picture in mind.

The other four case studies are more comparable to each other. The biggest city, measured by the population, is Nuremberg. The high population density in the German city causes substantial pressure for the local UGSs. Nevertheless, Nuremberg convinces with the highest minimum MF value measured among the case studies as well as the smallest range of MF values. This means, in combination with a high mean MF value, that Nuremberg provides a high UGS quality in regard to MF over the entire city area. This matches the general perception of Germany's environmental policies. Assuming Nuremberg has the highest budget of the four case studies (excluding Tampere), this result does not surprise. Despite a high result, it should be mentioned, that Nuremberg has the lowest UGS proportion of all the case studies. This is, where the pressure due to the high population density shows.

In Bialystok, Poland, the population density is on a similar level as in Nuremberg. Nevertheless, Bialystok cannot match the MF indicator values of Nuremberg. On the contrary, Bialystok shows the lowest scores in the MF indicator mean value. It is interesting that the share of UGSs, in regard to the total area of Bialystok, is similar to Aberdeen with almost 35% and also the standard deviation (0.04) is comparable to the Scottish city. This indicates that the low scores are to explain due to continuously low quality of the respective green spaces, rather than a few outliers. I assume that this can be explained with two factors, apart from the population density. Firstly, Poland has the lowest GDP per capita of the five states, where the case study cities are located (The World Bank, 2023). This has a direct influence on the financial resources of the state. Since UGSs in most cases are funded and managed by governmental institutions, it does not surprise that Bialystok's UGSs scored low in the MF indicator. Additionally, looking at the map of the Polish city, it is striking that Bialystok is surrounded by nature including woods and agricultural land. With Bialystok having the lowest total area of the case studies, the distances to recreational areas outside the city are smaller than in the other cities. Therefore, the need for numerous, large-scale multifunctional UGSs might be lower than in larger cities. The other values are situated in the lower percentiles as well.

Palma de Mallorca scored low on the MF indicator as well, with the inner city having the lowest values and higher values being located at the outskirts of the city. It is striking that Palma has a high range and standard deviation of the MF values, meaning that the districts further away from the city center have a significantly higher quality of their UGSs, in regard of their MF, than the areas in the city center and around the coast line. I would assume, that in Palma the outskirts are dominated by private land owners, which positively influence the MF of the nearby UGSs, by either maintaining the green areas by themselves or with their influence on governmental institutions. It could also be the case that the natural conditions at the outskirts of Palma favor growth and biodiversity, which would have a great influence on the MF indicator. The temperature regime of the Balearic Islands could explain the low mean MF value of Palma. With high maximum temperatures and low precipitation throughout the year, UGSs are hard to maintain and to achieve a high biodiversity takes much more resources, especially water.

Aberdeen shows a great proportion of UGSs, but scored in the medium range of the case studies in regard of the MF indicator values. It has the biggest range of the five examined cities, while the high values concentrate mostly in the South-west of the city, scoring the second highest maximum MF value of the case studies. Looking at the map of Aberdeen, it seems like that this area is characterized by agricultural and wood lands.

Looking at the regression results between the MF values and the surrounding factors 'population density', 'unemployment rate', and 'average professional qualification' respectively, it can be concluded that they have an influence on the MF of UGSs. As expected, in case of the population density, there is a clearly negative correlation, meaning that areas with higher densities score lower in the UGS MF indicator. This tendency is visible in the three case studies, where the surrounding factors were analyzed. I think, the causal relations between these two variables are quite clear to understand: the higher the density, the less space or more valuable the available space. This means that UGSs in densely populated areas compete more with other land uses, than they do in sparsely populated places. From a economic view, the opportunity costs by constructing or maintaining huge green areas in a city part with a high demand for living space, are plausibly too high. Therefore, the UGSs are often situated in the less populated outskirts of the city.

The analysis of the unemployment rate was surprising. In the case of Nuremberg, they showed a negative correlation with the MF indicator values. The unemployment rates are higher in the city center, where also the population density is the highest. This tendency seems logic to me. Consequently, I expected a similar trend for the OLS results of Aberdeen. Nevertheless, the regression showed a positive correlation between the MF values and the unemployment rates. This means, if more people are unemployed in a district, the MF in the respective area's UGSs is higher. This result is questionable and there are indications that this correlation is not significant. Despite the p-value being below 0.05, the robust p-value is 0.27 and indicates possible insignificance in that case. Comparing the respective maps on fig. 12, in Aberdeen the areas with high unemployment rates are lacking UGSs. Therefore, the result of the OLS in Aberdeen could be distorted, due to a low data quantity in this area.

Unexpectedly, the result of the regression between the variables 'MF value' and 'average qualification' in Aberdeen shows a negative correlation. A positive correlation would be more comprehensible, since higher qualified people usually have a higher income and therefore more possibilities in the choice of their place of residence. Thereby, they usually strive for a greener environment with places for recreation nearby. I assume that the negative coefficient can be explained with the area in the South-west of Aberdeen, which has high MF values, while the average qualification is low. This is a scale problem. The district covers a rather large area. Therefore, the average qualification value distribution cannot be compared to the distribution of the MF values and it distorts the coefficient.

6. Conclusion

Generally speaking, the results of the case studies showed that UGSs in the EU are present with varying, but surprisingly high, proportions and different MF levels. In all cities, there is an overarching pattern of inner-city UGSs with low MF and increasing MF values towards the borders of the city. After analyzing the surrounding socio-economic factors, I would assume that this pattern is caused, first and foremost, by the population density, which could also be connected to other socio-economic variables. It would be interesting to also examine the correlation between the indicator and further socio-economic factors. Thereby, the availability of small-scale datasets is a great challenge and constitutes the major limitation of this thesis.

Additionally, I could show that the difference between cities from different countries are considerable. Complemented with more socio-economic data, the raised points of the difference between cities and countries could be examined more thoroughly. In this thesis I used the most recent data available to measure the multifunctionality. In further research, it could be interesting to produce time series of certain cities to see the development of UGS MF and predict future developments.

There is a lack of research in the area of UGS MF indicators and, therefore, I see great potential for more in-depth studies built upon the findings of this thesis. The indicator detects the potential for improvement in regard to MF in the biggest cities of the EU. Therefore, it could help city planners and decision-makers to enhance the MF of their city's green spaces. Especially in cities with challenging conditions, whether due to natural or financial nature, it might be worthwhile to explore the possibilities of sustainable concepts to upgrade UGSs. Nevertheless, it is important to take regional specifics and varying needs into account to serve the heterogenous population in an open-minded, integrative way. Different studies have shown that UGSs bring advantages to people and with increasing population densities, it is important to improve UGS MF as much as possible. An interesting concept for city planners to have in mind is GI. With the help of GI, some of the LF could be covered, additionally to those covered by multifunctional UGSs. European cities should follow the example of Nuremberg and improve the quality of their UGSs, since the quantity, despite being relatively high at this moment, will most likely decrease due to population density pressure. Only this way, population growth, environmental sustainability and human health can go together.

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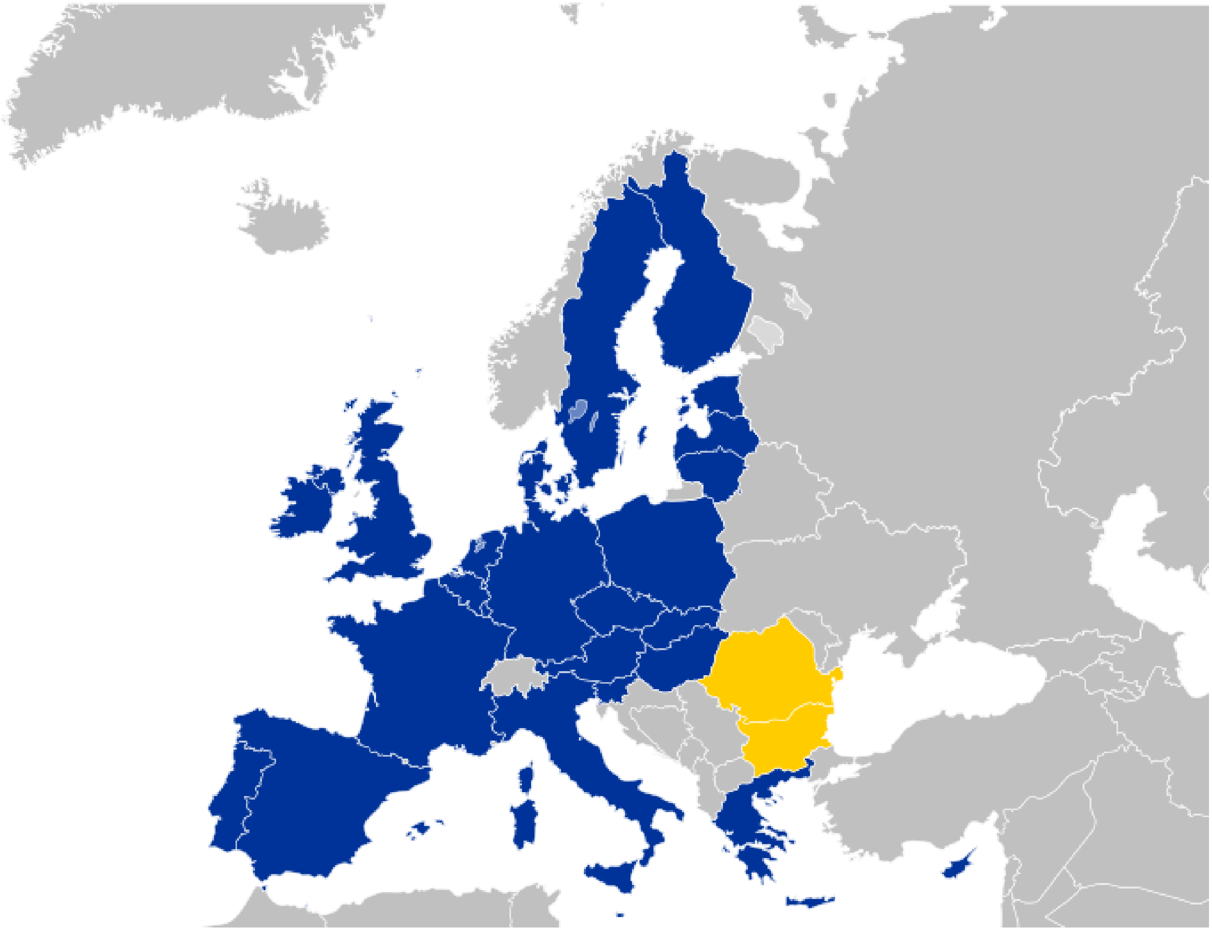
Appendix

Appendix 1: Member states of the EU-27_2007



Source: WIKIMEDIA COMMONS (2009) File:EU27-2007 European Union map.svg <https://commons.wikimedia.org/wiki/File:EU27-2007_European_Union_map.svg> (17.07.2023)

The EU-27_2007 had the following member states: Belgium, Bulgaria, Denmark, Germany, Estonia, Finland, France, Greece, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Austria, Poland, Portugal, Romania, Sweden, Slovakia, Slovenia, Spain, Czech Republic, Hungary, Cyprus, United Kingdom. The yellow marked states (Romania, Bulgaria) were accepted as the 26th respectively 27th member state.

Personal Declaration

I hereby declare that the submitted Thesis is the result of my own, independent work. All external sources are explicitly acknowledged in the Thesis.

Jan Sigrist

Zurich, 19th of July 2023