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Research article

Assessment of ecosystem services for urban regions in the context of the Sustainable Development Goals exemplified by the Bonn/Rhein-Sieg region

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Abstract

The implementation of the Sustainable Development Goals (SDGs) and the conservation and protection of nature are among the greatest challenges facing urban regions. There are few approaches so far that link the SDGs to natural diversity and related ecosystem services at the local level and track them in terms of increasing sustainable development at the local level. We want to close this gap by developing a set of indicators that capture ecosystem services in the sense of the SDGs and which are based on data that are freely available throughout Germany and Europe. Based on 10 SDGs and 35 SDG indicators, we are developing an ecosystem service and biodiversity-related indicator set for the evaluation of sustainable development in urban areas. We further show that it is possible to close many of the data gaps between SDGs and locally collected data mentioned in the literature and to translate the universal SDGs to the local level. Our example develops this set of indicators for the Bonn/Rhein-Sieg metropolitan area in North Rhine-Westphalia, Germany, which comprises both rural and densely populated settlements. This set of indicators can also help improve communication and plan sustainable development by increasing transparency in local sustainability, implementing a visible sustainability monitoring system, and strengthening the collaboration between local stakeholders.

Key words: Sustainable Development Goals, biodiversity, ecosystem services, urban development, sustainability

Introduction

The expansion of urban areas around the world is associated with a loss of natural resources, ecosystems and biodiversity. Human settlements tend to be established in areas with high biodiversity and a high measure of ecosystem services. This places urban areas in direct competition with biodiverse habitats. Thus, urban growth seriously compromises existing ecosystems (e.g. Elmqvist et al. 2013). Existing biodiversity is reduced by the loss of habitats and biomass (see Seto, Güneralp, and Hutyra 2012) while invasive species are introduced (Elmqvist, Seto, and Parnell 2013). Combined with the increased biodiversity in urban green spaces, e.g. private home gardens, the biodiversity within cities often exceeds that of the surrounding area (McKinney 2008; Kowarik 2011). At the same time, the displacement of natural inner city areas reduces ecosystem services and biodiversity in city centres (McKinney 2008). It also has a negative impact on citizens' quality of life and health as well as on the resilience of urban spaces, especially against

(micro)-climatic changes. After all, there are strong connections between ecosystem services and human well-being (Millenium Ecosystem Assessment 2005; Naturkapital Deutschland—TEEB DE 2016). Hence, the sustainability and viability of urban spaces strongly depend on socio-ecological aspects.

The United Nations Sustainable Development Goals (SDGs) (United Nations 2015) have been promoting a global sustainability agenda since 2015. Their scope extends far beyond international agendas for the protection of biodiversity, such as the Aichi Targets (Secretariat of the Convention on Biological Diversity 2010), and they are regarded as the world's major action programme for sustainability. Since cities are the most important human settlement areas—more than half of the world's population already lives in cities today (United Nations 2018)—the success of SDGs in urban areas is crucial for their global success [cf. e.g. (United Cities and Local Governments 2016)]. Local decision-makers, therefore, have a decisive role to play in implementing and defining the SDGs (Fenton and Gustafsson 2017, cf. also Koch and Krellenberg 2018). There are many indicators to track the implementation of SDGs or sustainable development in general at the local level. Examples include the US Cities Sustainable Development Report (Lynch, LoPresti, and Fox 2019) or the SDG Portal (www.sdg-portal.de) for German municipalities.

Although the SDGs take into account the impact of biodiversity and related ecosystem services quite comprehensively, especially in urban areas (Secretariat of the Convention on Biological Diversity 2015), specific measurements and indicators remain elusive. Hence, sustainability assessments derived from the SDGs and their indicators neglect nature-related sustainability aspects, and related reports and sets of indicators insufficiently capture these aspects. We elaborate on this problem in the next section.

This article intends to address this problem and show the possibilities of a comprehensive, urban, biodiversity-related sustainability certificate. Based on the German urban region of Bonn/Rhein-Sieg, we derive a set of indicators for recording urban ecosystem services and biodiversity in the sense of the SDGs. We aim to show that every municipality and every institution under public law can carry out a very comprehensive analysis of its own sustainable development in terms of the SDGs without a great deal of research and use this for its own sustainability monitoring.

Applying SDGs to local conditions

The challenge of applying the global scope of the SDGs to the problems of urban spaces arises from the basic principle of the SDGs and the UN's proposed indicators for tracking this process [United Nations (2017) provide an overview of these indicators]. Yet, the SDG's idea of reaching and involving all people over the world leads to compromises of sustainable standards that often are below the sustainability standards that especially the highly developed countries have. At the same time, the quality of comparable data is deficient and there are too few institutions that track data for urban spaces (Klopp and Petretta 2017). Hence, many of the UN's proposed SDG indicators do not exist at the national level. For Germany, a list by the Federal Statistical Office (Statistisches Bundesamt 2018) shows that for the total number of 231 SDG indicators, only about 120 comparable source figures are available nationwide. For example, for the 18 SDG indicators for SDG 13 (*Take urgent action to combat climate change and its impacts*), the Federal Statistical Office only lists a single German indicator (Statistisches Bundesamt 2018). Yet, this does not mean that climate protection measures in Germany are insufficiently tracked. The question also arises whether the additional data required in the SDGs would lead to an escalation of data volume: 'The imperative to measure progress towards Sustainable Development Goals (SDGs) has resulted in a proliferation of targets and indicators fed by an ever-expanding set of observations' (Bowen et al. 2017). Indicators for local situations and issues must be developed that are readily available, precise and comparable to make it possible to easily track and communicate the contents of the SDGs (cf. Hák et al. 2018; Janousková, Hák, and Moldan 2018).

Hence our development of indicators aims to use existing data from the Bonn/Rhein-Sieg region and combine it in such a way that we capture the content of the SDGs without having to collect new data.

Furthermore, the SDGs for evaluating biodiversity in urban areas often provide targets that fall below German standards or German/European legislation. Examples include the demands for a *Red List Index* (indicator 15.5.1) and the *Proportion of the population using safely managed drinking water services* (indicators 6.1.1 and 6.1.2). However, the availability of a Red List for plants and animals is not the final step in achieving sustainable development. Instead, a highly developed urban region should develop and pursue these goals and indicators on the way to achieving more sustainability. It therefore often makes sense to include SDGs and their sub-goals (*targets*) and indicators as a basis for extended local sustainability monitoring. Examples include the demand for capturing the *Proportion of land that is degraded over the total land area* (indicator 15.3.1) or the *Forest area as a proportion of total land area* (indicator 15.1.1). These indicators are only suggestive of the quality of life, biodiversity or ecosystem services in a region if put in context and viewed on a regional and location-specific level.

The same applies to the demands in the SDGs for (inter)national treaties. One example is indicator 15.8.1, which captures the *Proportion of countries adopting relevant national legislation and adequately resourcing the prevention or control of invasive alien species*. However, such legislation cannot be more than a precondition, which is not brought to fruition until actual implementation or improvement at the local level can be verified.

Waterbodies play a decisive role in biodiversity and ecosystem services in urban regions. However, the two water-related SDGs (goal 6 *Clean water and sanitation* and goal 14 *Life below water*) often apply only indirectly to river systems, streams or lakes and reservoirs, since the focus is on drinking water quality and maritime flora and fauna, respectively.

To separate the problem of drinking water from the function of local waterbodies as habitats, recreation or fishing areas, it therefore makes sense to also adapt the indicators for goal 14—which focus on these same aspects, but particularly in marine areas—to describe the quality of urban waterbodies. Example indicators that can be adapted in this way are (1) *Index of coastal eutrophication*, and (2) *plastic debris density* in waterbodies (indicator 14.1.1) or *Proportion of fish stocks within biologically sustainable levels* (indicator 14.4.1).

This procedure aligns with the methods other sets of indicators based on the SDGs use, which often rely on existing indicators and data, even if they are not part of the SDG indicator set, but are similar or identical in substance. This is also the approach used for the *SDG Index and Dashboard Report* (Sachs et al. 2017). For our set of indicators, we rely on the SDGs and targets listed in Table 1.

Table 1: List of SDG targets evaluated in this article

SDG	Goal	Evaluated targets
SDG 1	End poverty and all its forms everywhere	1.5
SDG 2	End hunger, achieve food security and improved nutrition, and promote sustainable agriculture	2.3, 2.4
SDG 3	Ensure healthy lives and promote well-being for all at all ages	3.4, 3.9
SDG 6	Ensure availability and sustainable management of water and sanitation for all	6.1, 6.2, 6.3, 6.4, 6.5, 6.6, 6.b
SDG 9	Build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation	9.4
SDG 11	Make cities and human settlements inclusive, safe, resilient, and sustainable	11.3, 11.4, 11.6, 11.7, 11a, 11 b
SDG 12	Ensure sustainable consumption and production patterns	12.4, 12.8
SDG 13	Take urgent action to combat climate change and its impacts by regulating emissions and promoting developments in renewable energy	13.1, 13.2
SDG 14	Conserve and sustainably use the oceans, seas and marine resources for sustainable development	14.1, 14.4, 14.7
SDG 15	Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss	15.1, 15.2, 15.3, 15.5, 15.8, 15.a

The nature in the Bonn/Rhein-Sieg region

The city of Bonn (141.1 km^2) and the surrounding Rhein-Sieg District (1153.2 km^2) with a total population of almost a million inhabitants are characterized by a metropolitan area in its north-central part along the Rhine and Sieg rivers (Fig. 1). About 330 000 people reside in the city of Bonn (2365/km^2), another c. 210 000 people (1352/km^2) in the cities and municipalities directly adjacent north-east of Bonn including Siegburg, the district's capital. Thus, this north-central part of the region (23% of the area) is home to 58% of the population and is characterized by 47% coverage of artificial areas. Another 163 000 inhabitants live in the other municipalities directly adjacent to the city of Bonn in the West and the South-East—however, these include large agricultural areas and forest areas as well, resulting on average in lower population densities between 500 and 1000 inhabitants per km^2. In contrast, the municipalities further west and especially all the municipalities that cover the eastern 40% of the region have much lower population densities (between 170 and 470 inhabitants/km^2) and only 4.5–16% artificial areas. Thus, there are strong gradients of population density and land use, allowing for potential comparisons between the central, western and eastern parts of the study area. The western municipalities have intensive agricultural landscapes on 65% of the area due to agriculturally highly productive loess soils. In contrast, the eastern part is characterized by low mountain ranges with somewhat poorer soils. As a result, this region is characterized by a mosaic of grassland (meadows), a smaller fraction of arable land and some fragmented forested areas (Mutke et al. 2019 based on official statistics and European Corine land cover data).

Nature conservation areas make up a considerable proportion of the land surface in the area (15.8%, compare Fig. 2), especially due to a few large reserves (Wahner Heide, Kottenforst, Siebengebirge), much exceeding the national average (4% excluding marine areas). In the City of Bonn, nature reserves take up 23% of the surface area especially due to the large forest area of the Kottenforst.

This large forest area within the city limits of Bonn provides important ecosystem services, such as positive climatic effects, carbon fixation and as an important recreational area for the inhabitants of Bonn. However, in addition to these forests outside the main city area, urban green spaces within the settlement area, such as parks or playgrounds, are of particular importance for the quality of life of the urban population. Even though most of these areas are comparably small and fragmented, the city administration takes care of about 80 000 trees in public green spaces that make up 10% of the city area in total (Fig. 3). Particularly low plant cover is typical of the city centre, but also some commercial and industrial areas (Beuel-Ost, Weststadt). The densely built-up areas have considerably higher night-time temperatures during summer that are modelled to be some 6–8 C above those of the surrounding areas of forests and agricultural land (GEO-NET Umweltconsulting 2020). In contrast, in some districts outside the city centre such as Friesdorf or Limperich, private gardens contribute considerably to overall green spaces. These districts go back to farming communities which were only swallowed by the city during urban encroachment in the 20th century. Overall, the percentage of artificial areas in Bonn has doubled since the 1950s (Hachtel et al. 2008).

Regarding blue spaces, the Rhine River was highly polluted in the 1970s. Today it has much reduced loads of pollutants such as Cadmium, Phosphate and Ammonium (ICPR 2019). The river structure of the Rhine is still highly modified, e.g. with boulder banks (Fig. 4).

As demonstrated in this section, there is a large amount of freely available data provided by public agencies to characterise, e.g. land cover, infrastructure, local climate or environmental pollution. These data allow us to assess many aspects of the regional ecosystems and their related ecosystem services. This is only partly true for more detailed analyses of biodiversity, even though there is already a good amount of data available for our study area. However, even this small region is home to more than 2000 species of plants and several thousand species of animals and fungi, for most of which documentation is fragmentary at best. These numbers are comparable to other German cities of similar size (Mutke et al. 2019). In a comparison of the floras of 85 European cities, Bonn is in the midfield (La Sorte et al. 2014); 11% of the region's native plant species have become locally extinct in the last 150 years. During the last 30 years, local species numbers for mammals documented per 33 km^2 mapping units decreased by more than 50% on average in our study area (Mutke et al. 2019).

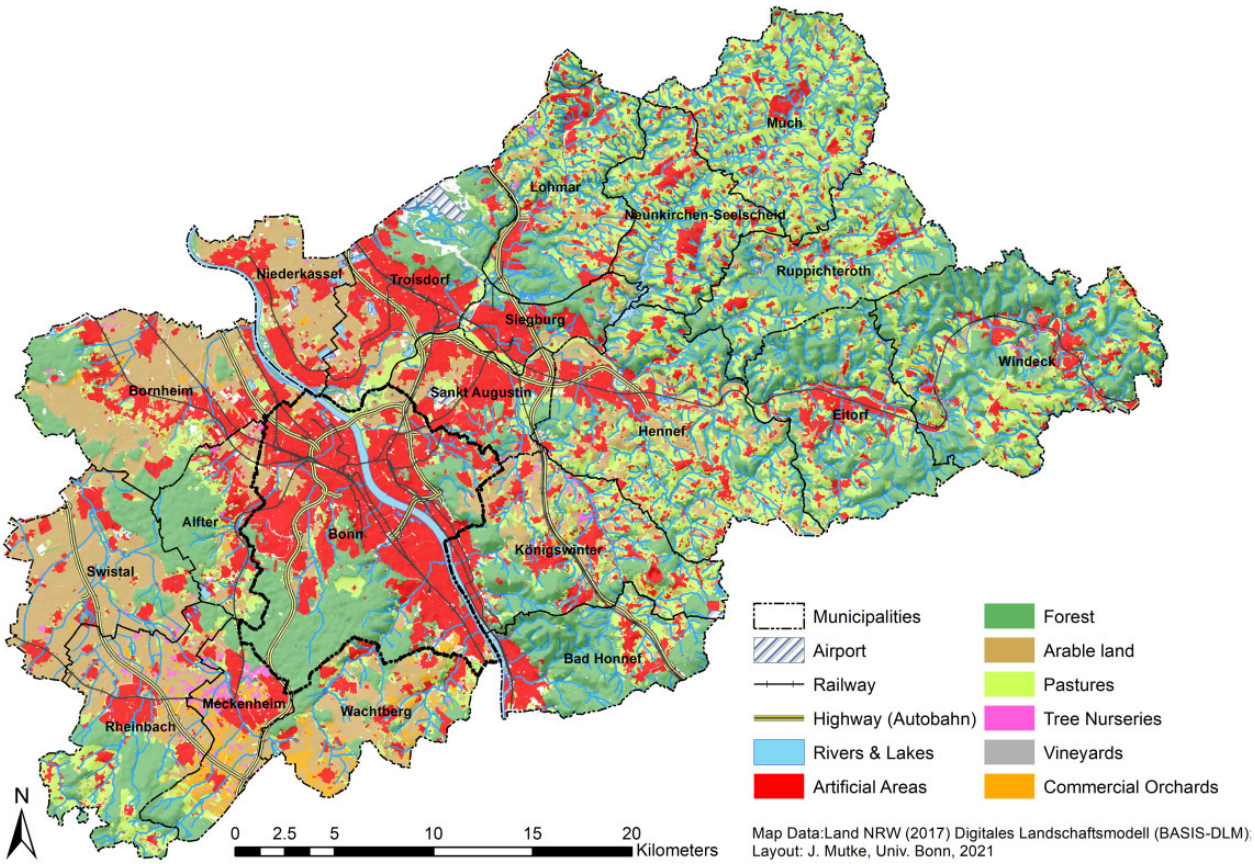

Figure 1: Current land cover in the region of Bonn and the surrounding Rhein-Sieg District. Adapted from Mutke et al. (2019) based on official data in the German Digital Landscape Modell (BASIS-DLM; Land NRW 2017)

Materials and methods

Inclusion of ecosystem services

The SDGs and their *targets* do not produce any direct measures for local-level implementation. Meanwhile, the exact relationships and interactions between the anthropocentric SDGs and biodiversity remain unexplained.

The concept of ecosystem services (Wood et al. 2018) is suited to explain the interactions between nature and (urban) planning and the implementation of the SDGs (Elmqvist et al. 2013; Geneletti et al. 2020: 1–5). Ecosystem services are an approach to capturing the importance and value of nature in anthropocentric terms. Nature is seen as a direct or indirect provider of provisioning, regulating and cultural services (Millenium Ecosystem Assessment 2005), which in turn produce direct or indirect economic, material, health-related or mental benefits to humans (Naturkapital Deutschland—TEEB DE 2012). On the European level, the classification of the *Millennium Ecosystem Assessment* was enhanced by the European Environment Agency, resulting in a standardized approach to ecosystem services under the *Common International Classification of Ecosystem Services (CICES)* (Haines-Young and Potschin 2018). Table 2 provides an overview of this classification.

Regarding the socio-ecological sustainability of urban areas, provisioning and regulating services are of particular importance for successfully implementing the SDGs (such as access to clean water). To capture the quality of biodiversity and its ecosystem services in urban spaces as specified in the SDGs, we further refer to the following concrete ecosystem services (Table 3).

Data used and methods

In the following list of a set of indicators based on the SDGs and ecosystem services, we refer to data sets that are generally available throughout Germany or Europe. This is to ensure comparability with other regions. Important sources for us are therefore the Federal Statistical Office (www.destatis.de), the Federal Environment Agency (www.umweltbundesamt.de), the Statistical Office of the State of North Rhine-Westphalia (www.it.nrw) and data collected locally by municipalities as part of their sustainability activities. For each indicator, a reference is made below to the associated dataset. The basis of our investigations is a data analysis and its assignment to SDG indicators. Here, we include the difficulties described in Section 'Applying SDGs to local conditions'. As far as there are no data directly corresponding to the SDG indicators, we refer to data that correspond to the content of the assigned SDG targets, e.g. data on urban green spaces. Or, conversely, we transfer SDG targets so that they can be described by available data. As, for example, in the case of SDG 14, which actually refers to ocean sustainability and which we use here to capture the quality of urban waters.

Results

Our development of indicators aims to use existing data from the Bonn/Rhein-Sieg region and combine it in such a way that

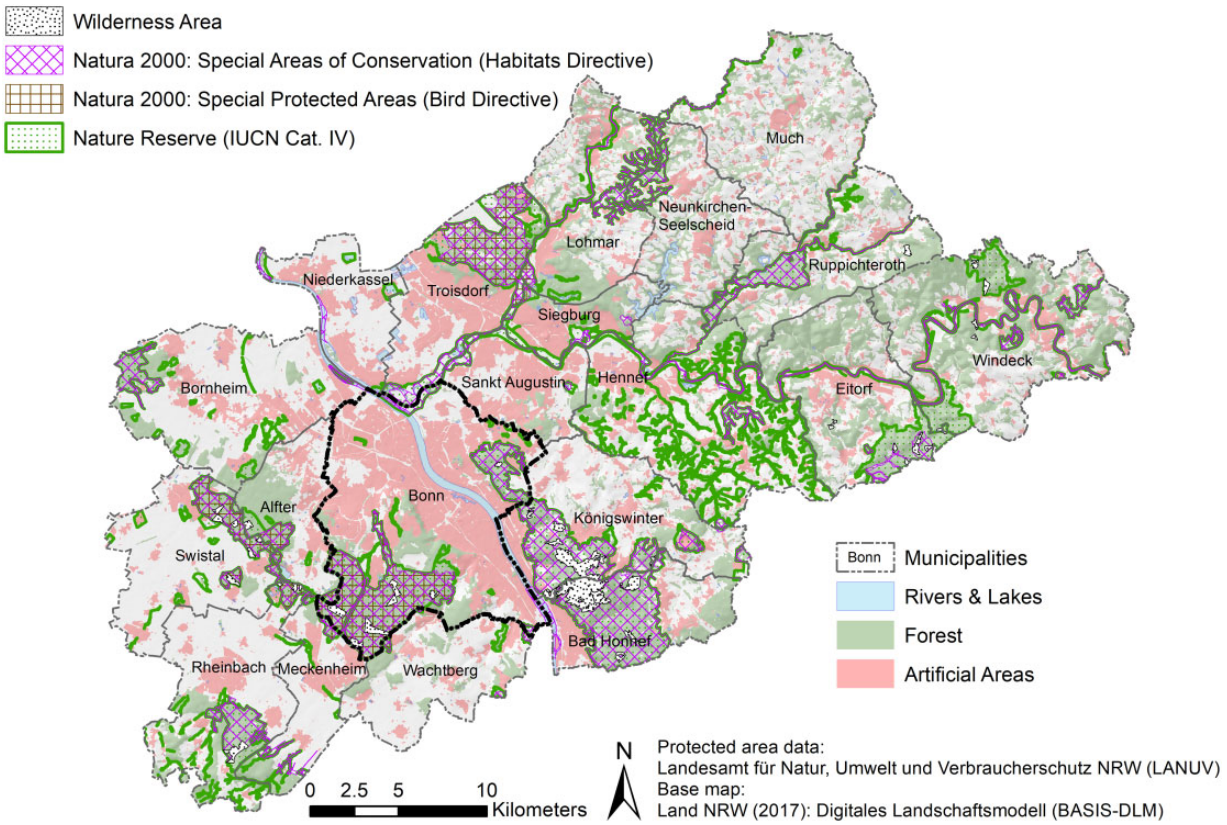

Figure 2: Protected area coverage in the region of Bonn and the surrounding Rhein-Sieg District. Adapted from Mutke et al. (2019) based on protected area data by LANUV NRW (2017) and base map data in the German Digital Landscape Modell (BASIS-DLM; Land NRW 2017)

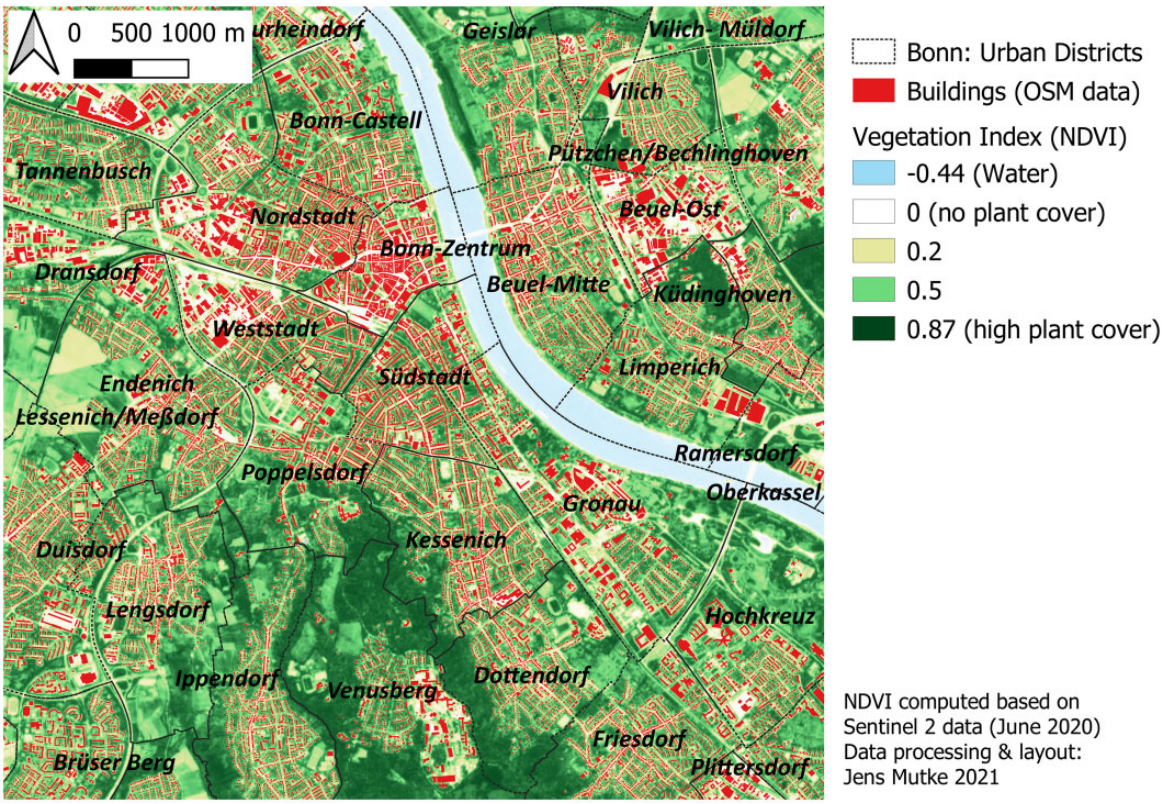

Figure 3: Plant cover in the central part of Bonn based on Sentinel 2 satellite data for June 2020, downloaded from the EU COPERNICUS programme. The photosynthetic active biomass (living plants) is indicated by the Normalized Difference vegetation index (NDVI). Negative values typically represent water. Values between 0 and 0.2 indicate areas without plant cover. Base map data was taken from OpenStreetMap (www.openstreetmap.org)

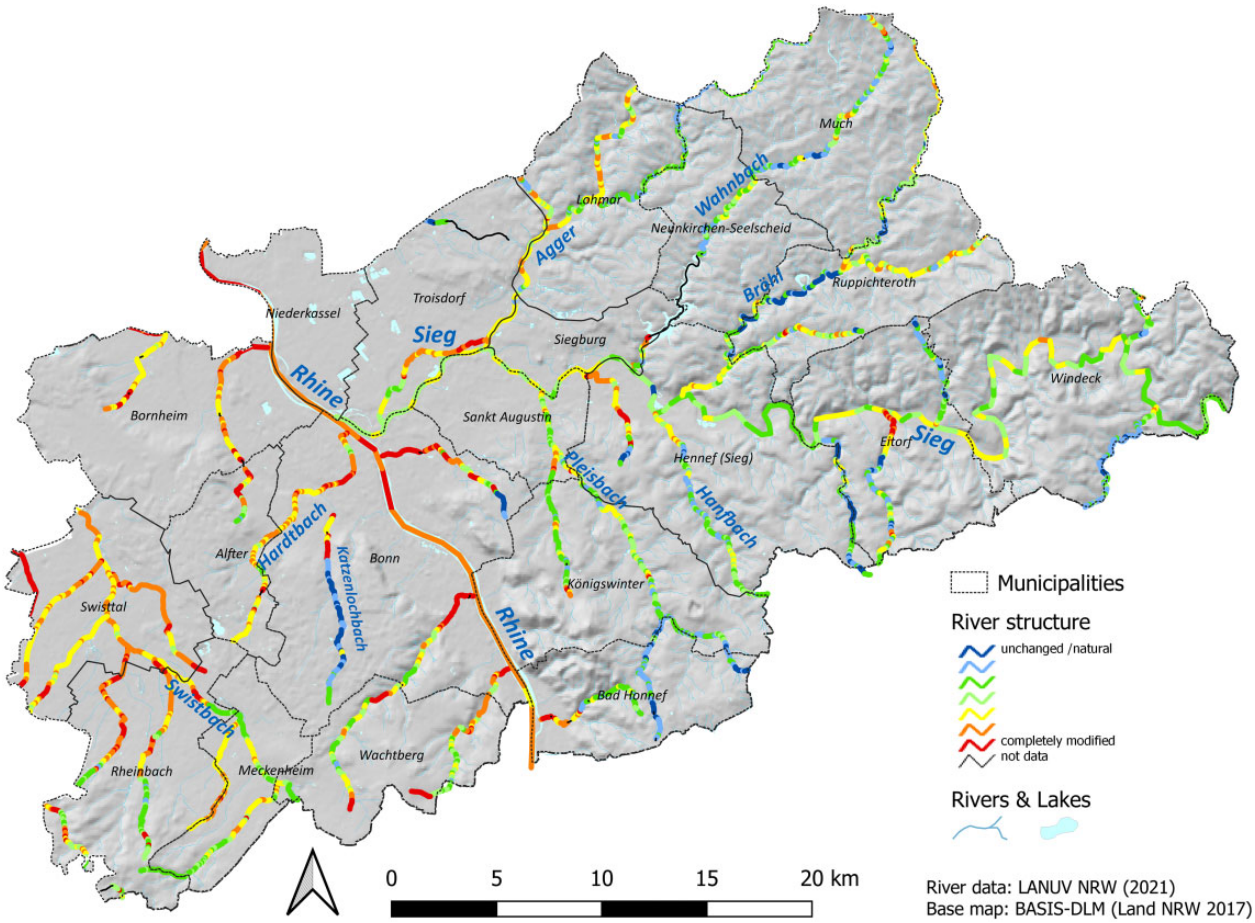

Figure 4: River structure of the Bonn/Rhein-Sieg region. Modified after Mutke et al. (2019) based on data by LANUV NRW (2021) and base map data in the German Digital Landscape Modell (BASIS-DLM; Land NRW 2017)

Table 2: Classification of ecosystem services under CICES v5.1 (Haines-Young and Potschin 2018)

Section	Division
Provisioning (Biotic)	Biomass
	Genetic material from all biota (including seed, spore or gamete production)
	Other types of provisioning services from biotic sources
Regulation and maintenance (Biotic)	Transformation of biochemical or physical inputs to ecosystems
	Regulation of physical, chemical and biological conditions
	Other types of regulation and maintenance service by living processes
Cultural (Biotic)	Direct, *in-situ* and outdoor interactions with living systems that depend on the presence in the environmental setting
	Other characteristics of living systems that have cultural significance
Provisioning (Abiotic)	Water
	Non-aqueous natural abiotic ecosystem outputs
Regulation and maintenance (Abiotic)	Transformation of biochemical or physical inputs to ecosystems
	Regulation of physical, chemical and biological conditions
	Other type of regulation and maintenance service by abiotic processes
Cultural (Abiotic)	Direct, *in-situ* and outdoor interactions with natural physical systems that depend on the presence in the environmental setting
	Other abiotic characteristics of nature that have cultural significance

we capture the content of the SDGs without having to collect new data. The result of our comparison between the SDGs and locally available data is listed in the following table. We have assigned the corresponding ecosystem service according to Table 3 and the result and/or data for the studied region. Cultural ecosystem services are abbreviated as (CS), regulating services as (RS), and provisioning services as (PS).

The first part of our indicator sets comprises the SDG *targets* which correspond directly to locally collected data from the Bonn/Rhein-Sieg region (Table 4). Section 'Public measures,

Table 3: Key ecosystem services in urban areas, their indicators and related SDG indicators

Ecosystem service	Available local indicators for the studied region	Related SDG indicators
Provisioning services		
Forests		
Wood production	• Forest area • Timber harvest	15.1.1, 15.2.1
Availability of food (mushrooms, herbs, game)	• Hunting range • Forest area	15.1.1
Particulate matter filtering, water purification	• Designated water protection zones in forests	15.1.2 11.6.2 indirectly
Waterbodies		
Water as drinking water	• Indicators of drinking water supply	3.9.1 indirectly 6.1.1, 6.2.1.a), 6.3.2, 6.4.2, 6.5.1, 6.5.2, 6.b.1 14.1.1 by analogy
Water as process water	Indicators on • Service water supply • Process water	6.2.1, 6.3.1, 6.4.1, 6.5.1, 6.5.2, 6.b.1
Fisheries	• Fish harvest	6.3.2 14.1.1, 14.4.1, 14.7.1 by analogy
Regulating services		
Urban green spaces (Plant covered inner urban private and public spaces)		
Microclimate: urban green spaces, especially parks, reduce ambient temperature	• Size and distribution of green spaces • Small-scale temperature data • Size of unsealed areas • Size of inner-city forest areas	11.7, 13.2.1, 15.1.1
Shade from avenue and park trees reduces the heat burden	• Number and distribution of urban trees • Small-scale temperature data • Size of unsealed areas • Size of inner-city forest areas	11.7, 13.2.1, 15.1.1
Urban nature promotes climate protection by binding CO_2	• Size of green spaces • Size of unsealed areas • Size of inner-city forest areas • Number and distribution of urban trees • Estimated biomass of urban trees • CO_2 retention potential of green spaces and trees	11.7, 15.1.1
Urban vegetation improves air quality	• Distribution of vegetation • Air quality data	11.6, 15.1.1 If necessary 3.9.1
Urban nature can reduce noise	• Distribution of vegetation • Noise maps	15.1.1
Forests		
Nature and landscape conservation	• Certified forests • Area of protected areas • Area under contractual nature conservation	11.4, 15.1.1, 15.2.1, 15.3.1, 15.5.1, 15.a.1
Microclimate—Shade and evaporation for cooler air	• Urban forest area • Small-scale temperature data	13.2.1, 15.1.1
Forests can reduce noise	• Urban forest area • Noise maps	15.1.1
Storage of CO_2	• Average wood supply per hectare or tree species • Potential retention of CO_2/m^3	15.1.1 9.4.1 indirectly
O_2 production	• Oxygen production in m^3 O_2/ha of forest	15.1.1
Waterbodies		
Microclimate (evaporation leads to cooling in summer)	• Proportion of waterbodies of the total area • Small-scale temperature data	13.2.1, 6.6.1

(continued)

Table 3: (continued)

Ecosystem service	Available local indicators for the studied region	Related SDG indicators
Nutrient retention	• Areas of organic farms • Phosphate and nitrate reduction in floodplains • Factory sewage discharge	2.4.1 14.1.1.a by analogy
Flood and erosion protection	• Floodplains • Sealed area in the city • Dike protection zones	1.5, 13.2.1, 11.b.2
Near-natural waterbodies serve to conserve biological diversity	• Waterbody • Water quality, water structure quality • Chemical condition • Biodiversity data and monitoring	6.6.1, 15.8.1
Cultural services		
Urban green spaces (Plant covered inner urban private and public spaces)		
Positive psychological effects from urban green spaces can reduce health risks	• Share of green spaces in the settlement area • Accessibility of green spaces within a 300 m radius of residence	11.7, 15.1.1
Experience of nature: Urban nature provides habitat for animals and plants	• Size and distribution of green spaces • Biodiversity in green spaces, comprehensive monitoring • Accessibility of green spaces within a 300 m radius of residence	11.7, 15.1.1
Leisure and recreation	• Accessibility of green spaces within a 300 m radius of residence • Satisfaction	11.7, 15.1.1
Forests		
Rest and recreation areas	• Visitor numbers • Accessibility of forests	15.1.1
Waterbodies		
Important resources for experiencing nature	• Visitor numbers • Accessibility of waterbodies	15.1.2
Leisure and recreation	• Visitor numbers • Accessibility of waterbodies	6.6.1

plans and legal framework' lists the following separately: Table 5: Public measures, plans and legal framework, Table 6: Economic data, Table 7: Adaptation of general SDG indicators to the local level, Table 8: Urban indicators on the quality of inland waterbodies in the urban region based on SDG 14, as well as Table 9: Ecosystem services for resilience, health, temperature and extreme weather.

Figure 4 shows the structural quality of the larger waterbodies in the Bonn/Rhein-Sieg region. Here it is shown in addition to indicator 6.3.2 *Proportion of bodies of water with good ambient water quality* and gives information about the proximity to the natural state of the waterbodies and their wetlands, regardless of water quality. Waterbodies coloured in blue are in their natural state, and those coloured in red are altered completely. These are especially the Rhine and its tributaries within the urban area, as well as the waterbodies in the western part of the Bonn/Rhein-Sieg region.

Public measures, plans and legal framework

The first enhancement option arises from comparing the public measures for environmental protection, disaster management and human interference with the environment (Table 5). This table covers a total of six SDG indicators relating to the legal implementation of measures. While most of these measures are governed by the European Union or German federal legislation affecting the local level, their implementation and observance remain (supra)national, so they are only relevant in international comparison.

Among the few exceptions is subgoal 11.3, which demands direct citizen participation in local urban development. On one hand, there are legal requirements within the region, such as open consulting hours for citizens or Q&A sessions before council meetings. On the other, a growing number of municipalities offer online participation mechanisms. The City of Bonn, for example, offers the online portal www.bonn-macht-mit.de to involve citizens in local decisions.

Economic data

Economic data are usually more accessible than data on natural areas. While it allows no direct conclusions about biodiversity or the quality of urban nature, it does allow indirect ones (Table 6). In particular, the value of nature in society and the quality of natural areas and their provisioning of economically verifiable ecosystem services can be captured or derived. One of

Table 4: Urban biodiversity and ecosystem services

SDG	SDG indicator according to Statistisches Bundesamt (2018)	Related ecosystem services according to Table 3	Result for the studied region
6.1	6.1.1: Proportion of population using safely managed drinking water services	• Water as drinking water (PS)	100% (Statistisches Bundesamt 2018).
6.2	6.2.1.a Proportion of population using safely managed sanitation services	• Water as process water (PS)	100% (Statistisches Bundesamt 2018)
6.3	6.3.1: Proportion of wastewater safely treated	• Water as process water (PS)	Water purification capacity Bonn: Water consumption: 21 million m^3, water purification capacity: 32 million m^3 (Wahnbachtalsperrenverband 2017).
6.3	6.3.2: Proportion of bodies of water with good ambient water quality	• Near-natural waterbodies serve to conserve biological diversity (RS) • Fisheries (PS)	The rivers in the study region generally have water quality Grade II (moderate pollution). Individual sections of the Sülz and Sieg rivers have a slightly higher water quality (I–II, low pollution), or slightly lower, like the Sieg near Troisdorf (II–III critical pollution) (Umwelt.NRW 2020)
6.4	6.4.1: Water use efficiency GDP (€) per litre of freshwater consumed in 2015	• Water as process water (PS)	Bonn: €21.725 million/20 million m^3 = €1.08 per litre of water Rhein-Sieg district: €16.497 million/35 million m^3 =← €0.47 per litre of water (Wahnbachtalsperrenverband 2017)
6.4	6.4.2 Level of water stress: freshwater withdrawal as a proportion of available freshwater resources	• Water as process water (PS) • Water as drinking water (PS)	Water use of Bonn/Rhein-Sieg: Wahnbachtalsperrenverband: 42 million m^3 (2016) Approx. 55 million m^3 total (2016) Of which Bonn: 21 million m^3 (Wahnbachtalsperrenverband 2017)
11.3	11.3.1 Ratio of land consumption rate to population growth rate		Bonn: 1.02:1.02 Rhein-Sieg district: 1.08:1.00 (IT.NRW 2017a, 2017b)
11.6	11.6.1 Proportion of urban solid waste regularly collected		Bonn 2015: 166,562 t (520 kg per capita) (Rhein-Sieg Abfallentsorgungsgesellschaft 2017)
11.6	11.6.2: Annual mean levels of particulate matter in cities	• Urban vegetation improves air quality (RS)	Annual mean levels of PM10 for Bonn: 15 μg per cubic meter (2019) 26 μg per cubic meter (2009) (Umweltbundesamt 2019)
11.7	11.7.1: Average share of the built-up area of cities that is open space for public use for all	• Positive psychological effects from urban green spaces can reduce health risks (CS) • Leisure and recreation (CS)	141 km^2 (11%) (2015) (IT.NRW 2017a, 2017b)
11.b	11.b.2: Local governments with implemented disaster control strategies	• Flood and erosion protection (RS)	All municipalities in the region. For example Bonn Network Civil Protection and Disaster Risk Reduction: https://www.bonn.de/microsite/en/international-profile/international-location/bonn-network-for-disaster-risk-reduction-and-management.php
15.1	15.1.1: Forest area	• Timber production (PS) • Food production (PS) • Microclimate (RS) • Noise-reducing effects (RS) • Storage of CO_2 (RS) • O_2 production (RS) • Rest and recreation areas (CS)	Bonn/Rhein-Sieg: 391 km^2 (2015) (31% of total area) (IT.NRW 2017a, 2017b)
15.1	15.1.2: Proportion of important sites for terrestrial and freshwater biodiversity that are covered by protected areas	• Particulate matter filtering, water purification (PS) • Nature and landscape conservation (RS)	Bonn: 77 km^2 (54% of total area) (Hachtel et al. 2008)
15.2	15.2.1: Progress towards sustainable forest management	• Nature and landscape conservation (RS)	State forest: FSC-certified. Bonn municipal forest: Naturland-certified
15.5	15.5.1: Red List Index	• Near-natural waterbodies serve to conserve biological diversity (RS) • Nature and landscape conservation (RS)	There is a Red List for mushrooms, plants and animals, published by LANUV NRW (2011)

Table 5: Public measures, plans and legal framework

SDG	SDG indicator according to Statistisches Bundesamt (2018)	Related ecosystem services according to Table 3	Result for the studied region
1.5	1.5.4 Proportion of local governments that adopt and implement local disaster risk reduction strategies in line with national disaster risk reduction strategies	• Flood and erosion protection (RS)	Bonn especially has numerous and far-reaching measures for flood protection along the Rhine and against flash flooding of streams in the south of Bonn. The Rhein-Sieg district also has prevention plans and communication measures, such as a siren warning system. In addition, the is a federal Emergency Information and News App ('NINA').
6.b	6.b.1: Proportion of local administrative units with established and operational policies and procedures for participation of local communities in water and sanitation management	• Water as process water (PS) • Water as drinking water (PS)	Water supply and sanitation are managed by local water boards and public utilities, as is waste disposal.
6.5	6.5.1: Degree of integrated water resources management	• Water as process water (PS) • Water as drinking water (PS)	Water supply and sanitation are managed by local water boards and public utilities.
11.3	Proportion of cities with a direct participation structure of civil society in urban planning and management that operate regularly and democratically		All municipalities in the Bonn/Rhein-Sieg region have different options for involving citizens in the planning and realization of projects. One example is the online citizen participation portal of the city of Bonn: www.bonn-macht-mit.de.
11.a	11.a.1: Number of countries that have national urban policies or regional development plans		The City of Bonn and the Rhein-Sieg district implement many joint regional cooperation projects and development plans. Those relating to the environment include measures on climate protection, flood protection and contractual nature conservation. One major joint project is the landscape park Grünes C (www.bonn.de/microsite/gruenes-c), which has a surface of 37 km^2 and connects the towns of Alfter, Bonn, Bornheim, Niederkassel, Sankt Augustin and Troisdorf.
12.8	12.8.1: Extent to which (i) Global citizenship education and (ii) Education for sustainable development are mainstreamed		The Bonn Map of Sustainability (bonnsustainabilityportal.de) lists 260 sustainable development initiatives in the study region.

the major ecosystem services for humanity is the provision of food and fertile land for farming (SDG 2.3).

Adaptation and specification of SDG indicators

Due to the often very general formulation of the SDGs, necessitated by their universal approach, individual targets and indicators are formulated very imprecisely and abstractly or even too strictly at the local level and in certain areas.

An example of too strict a wording is the number of deaths from air pollution, which at the same time highlights the problem of inaccurate or unavailable data. It is true that in Germany (Statistisches Bundesamt 2017) and in the Bonn/Rhein-Sieg region (IT.NRW 2019), respiratory diseases are one of the most frequent causes of death. The extent to which air pollution is the cause is not clear. We, therefore, refer to medical projections. Due to the improvements in general environmental quality in many European countries, it also makes sense to possibly record cases of illness instead of deaths. Other SDG indicators refer specifically to relationships between countries. Here it makes sense to refer to cooperation between individual municipalities instead of countries.

Figure 5 gives an overview of the CO_2 emissions from motor vehicles in the Bonn/Rhein-Sieg region per km^2 in 2013. Emissions are particularly high in the conurbation of Bonn, Sankt Augustin, Siegburg and Troisdorf and along the A3 and A59 autobahns in the centre of the region and the A61 in the west. In the sparsely populated eastern part of the region, car traffic and emissions are also much lower.

Quality of urban waterbodies

Urban waterbodies, especially rivers and lakes, are crucial for ecosystem services, as they provide cultural, regulatory and provisioning services. They are also crucial to many aspects of the quality of life in urban areas, especially in relation to physical and mental health. The protection and quality of these ecosystems are of particular importance for urban areas. However, the SDGs, in particular goal 15 (*Terrestrial ecosystems*), do not fully meet this need, although this SDG comprises freshwater ecosystems. Our proposal is to derive additional indicators based on SDG 14 (*Conserve and sustainably use the oceans, seas and marine resources for sustainable development*) (Table 8). The

Table 6: Economic data

SDG	SDG indicator according to Statistisches Bundesamt (2018)	Related ecosystem services according to Table 3	Result for the studied region
1.5	1.5.2: Direct economic loss attributed to disasters	• Flood and erosion protection (RS)	Is not centrally recorded in the studied area. In connection with the flood in the summer of 2021, however, flood damage amounting to a high three-digit million sum is to be assumed.
2.3	2.3.1: Volume of production per labour unit by classes of farming/pastoral/forestry enterprise size	• Food availability (RS)	Bonn: €5 million (2015) Rhein-Sieg district: €81 million (2015) (IT.NRW 2017c)
2.4	Proportion of agricultural area under productive and sustainable agriculture	• Nutrient retention (RS)	Total agricultural area: Bonn: 22.84 km^2 (2015) Rhein-Sieg district: 492.29 km^2 (2015) (IT.NRW 2017a, 2017b) In the Bonn/Rhine-Sieg region, 87 of the total 896 farms work organically on more than 12% of the agricultural area.
11.4	11.4.1: Total expenditure per capita spent on the preservation, protection, and conservation of all cultural and natural heritage	• Nature and landscape conservation (RS)	Funding comes from EU, national, district-level, and municipal sources. This includes funds from the European Agricultural Fund for Rural Development (EAFRD), the Nature Conservation Funding Directive of the State of North Rhine-Westphalia (Föna), or the Funding Guidelines for Biological Stations in North Rhine-Westphalia (FÖBS).
15.a	15.a.1: Official development assistance on conservation and sustainable use of biodiversity	• Nature and landscape conservation (RS)	Conservation of biodiversity and sustainable use of ecosystems is funded by EU, national, district-level and communal means, in addition to research, private initiatives, associations and foundations. These include the NRW Foundation, the State Office for the Environment and Nature Conservation (LANUV) or the Environment and Development Foundation of the State of North Rhine-Westphalia.

indicators of this SDG are useful for inland waterbodies. These ecosystems are first related and second used in a similar way.

One example is indicator 14.1.1: *Plastic debris density*. Plastic debris threatens not just marine flora and fauna but also inland waterbodies. In addition, a large share of plastic debris in river systems eventually ends up in the ocean. Lebreton et al. (2017) estimate a total of 1.15 and 2.41 million tonnes (MT) annually. This is a significant share of the total annual increase of 4.8–12.7 MT of plastic debris (Jambeck et al. 2015). Hence, marine protection does not start on the coast, but inland. This applies to plastic particles smaller than 5 mm, so-called microplastic. For the studied region, for example, Mani et al. (2015) measured a concentration of 588 825 microplastic particles in the Rhine per km^2 of water surface.

We suggest a total of four additional indicators covering water quality, aquatic life and protection of waterbodies.

Ecosystem services for resilience, health, temperature and extreme weather

In addition to the listed enhancements, the SDGs have two additional decisive gaps when it comes to urban biodiversity and ecosystem services. This is especially true for

SDG 3: *Ensure healthy lives and promote well-being for all at all ages*
SDG 13: *Take urgent action to combat climate change and its impacts*

Biodiversity and ecosystem services in cities or settlements are generally attributed to a high value for psychical health and mental well-being. Probably the most popular example are the debates surrounding driving bans in German inner cities due to harmful particulate emissions [cf. emissions from motor vehicles in the region (Fig. 5)]. In addition, green spaces, urban forests and waterbodies influence the quality of life in a city in multiple ways. They increase resilience to climate change and extreme weather and can serve as sinks for CO_2 emissions (David, Crane, and Stevens 2006; Strohbach and Haase 2012), thus contributing significant economic value (cf. Escobedo et al. 2008) (Table 9).

The settlement and transportation area in the study region has grown significantly in the past. What is more, it is growing disproportionately to the number of inhabitants (Table 4), increasing the number of so-called heat islands. At the same time, the observed climatic changes increase the temperature in the region. In its sustainability report, the City of Bonn (2015: 58) states: 'In the 2012–2015 reporting period, the average annual temperature rose by 6% over the 2002–2011 period. This period also includes the warmest year (2014) and the mildest winter (2015) since weather records began.' Despite this

Table 7: Adaptation of general SDG indicators to the local level

SDG	SDG indicator according to Statistisches Bundesamt (2018)	Related ecosystem services according to Table 3	Result for the studied region
1.5 & 13.1	1.5.1 Number of deaths, missing persons and directly affected persons attributed to disasters per 100,000 population	• Flood and erosion protection (RS)	2021: 9 dead persons (Rhein-Sieg Rundschau 2021)
3.9	3.9.1: Mortality rate due to domestic and ambient air pollution	• Urban vegetation improves air quality (RS)	Deaths that could be avoided if the lowest levels of air pollution for PM2.5 and NO2 were met: Bonn: 164 (PM2.5), 132 (NO2). Sankt Augustin: 105 (PM2.5), 120 (NO2) (ISGlobal 2021)
3.9	3.9.2: Mortality rate attributed to unsafe water, unsafe sanitation and lack of hygiene [exposure to unsafe Water, Sanitation and Hygiene for All (WASH) services]	• Water as drinking water (PS)	No known cases for the studied region.
6.6	6.6.1: Proportion of population using safely managed drinking water services	• Leisure and recreation (CS) • Microclimate (evaporation leads to cooling in summer) (RS)	Bonn: Running waters: 543 ha (2015), 555 ha (2005) Standing waters: 14 ha (2005), 14 ha (2015) Not specified: 4 ha (2005) Total: 556 ha (2005), 575 ha (2005) Rhein-Sieg district: Running waters: 1,434 ha (2015), 1,237 ha (2005) Standing waters: 680 ha (2015), 557 ha (2005) Not specified: 4 ha (2005) Total: 2,389 ha (2015), 2,250 ha (2005) (IT.NRW 2017a, 2017b)
6.5	6.5.2: Proportion of transboundary basin area with an operational arrangement for water cooperation	• Water as drinking water (PS) • Water as process water (PS)	For drinking water supply: Wahnbachtalsperrenverband (Bonn/Rhein-Sieg district). Rhein-Sieg district: Aggerverband, Wasserversorgungsverband Euskirchen-Swistal, Stadtwerke Troisdorf, Stadtwerke Niederkassel, Bad Honnef AG (Wahnbachtalsperrenverband 2017)
9.4	9.4.1: CO2 emissions	• Storage of CO2 (RS), indirect	Emission maps. CO2 emissions from motor vehicles are shown in Fig. 5
12.4	12.4.2.b: Proportion of hazardous waste treated		Treated hazardous waste from households: Bonn: 308 t (2015) Rhein-Sieg district: 519 t (2015) (Rhein-Sieg Abfallentsorgungsgesellschaft 2017)
13.2	13.2.1: Number of countries with NDCs, long-term strategies, national adaptation plans, strategies as reported in adaptation communications and national communications	• Microclimate: urban green spaces, especially parks, reduce ambient temperature (RS) • Shade from avenue and park trees reduces heat burden (RS) • Microclimate: Shade and evaporation for cooler air (RS) • Microclimate (evaporation leads to cooling in summer) (RS) • Flood and erosion protection (RS)	The region has a wide range of strategies to address the impacts and mitigate climate change and climate extremes.
15.8	15.8.1: Proportion of countries adopting relevant national legislation and adequately resourcing the prevention or control of invasive alien species	• Near-natural waterbodies serve to conserve biological diversity (RS)	According to the local authorities involved in these measures, there are sufficient funds to carry out such projects.

Table 8: Urban indicators for the quality of inland waterbodies in urban areas based on SDG 14

SDG	SDG indicator according to Statistisches Bundesamt (2018)	Related ecosystem services according to Table 3	Result for the studied region
14.1	14.1.1.b: Plastic debris density in waterbodies	• Water as drinking water (PS) • Water as process water (PS) • Fish harvest (PS)	Rhine: 588 825 particles/km^2 of water surface at normal flow rate (Mani et al. 2015)
14.1	14.1.1.a: Acidification of waterbodies	• Near-natural waterbodies serve to conserve biological diversity (RS)	Average pH value 2018 Sieg: 8 Rhine: 8.2 (Bundesanstalt für Gewässerkunde 2018)
14.4	14.4.1: Proportion of fish stocks within biologically sustainable levels	• Fisheries (PS) • Near-natural waterbodies serve to conserve biological diversity (RS)	Data for fish stocks in the Bonn/Rhine-Sieg region are recorded by the Sieg Fishing Cooperative (*Fischereigenossenschaft Sieg*) in Hennef for the purposes of species protection and biodiversity (http://www.sfghennef.de).
14.7	14.7.1: Sustainable fisheries	• Fisheries (PS) • Near-natural waterbodies serve to conserve biological diversity (RS)	Quotas are determined and enforced by Sieg Fishing Cooperative.

development, Bonn plans to seal new areas, as added in the sustainability report: 'A further increase [in the settlement and traffic area] due to the development and realization of further settlement areas is expected,' (Stadt Bonn 2015: 51). Hence, as temperatures rise, the free land area and the related, temperature-regulating ecosystem services are further reduced. Further negative effects of soil sealing include significantly reduced water runoff and the ability of areas to regulate the effects of increased rainfall and flooding.

The settlement area of the studied region which is in designated flood plains is about 4%. Figure 6 gives more information about the exact distribution of these areas (coloured pink). A large part of these areas are dike protection zones, urban green spaces, such as parks and natural areas, such as the nature reserve at the Sieg estuary in the north of the map; 3.4% of Bonn's population live in flood plains, also along the streams originating from the eastern or western hills, which flow into the Rhine in Bonn.

Discussion

Our set of indicators derived from the SDGs shows that it is possible to comprehensively present the socio-ecological status of a German urban region based on the SDGs. As with similar indicator sets, we can achieve this by using comparable, existing data sets to represent SDGs 6, 11 and 15. A large share of this data is tracked by state-level statistical offices, permits nationwide and often Europe-wide comparisons and is, therefore, a useful addition to offers such as the SDG portal for municipalities (www.sdg-portal.de). In addition, we have included the indicators of SDGs 2, 3, 9, 12, 13 and 14. Although in the SDGs they are not used for tracking the ecological quality of urban spaces, they can be used for this purpose.

Contribution of this indicator set to sustainable development in urban regions

These indicators focus on promoting the socio-environmental aspects of sustainable urban development. Our approach contributes on several levels by:

- Mapping the socio-environmental sustainability situation in an urban region
- Offering a long-term model of sustainable development in line with the SDGs
- To some extent tracking urban biodiversity and the quality of urban ecosystem services
- Testing the effectiveness of measures and plans for urban infrastructure
- Defining and assessing problems and issues flexibly and in context

Limitations arise from the anthropocentrism of the SDGs since their focus on sustainability in satisfying human needs applies to biodiversity and its mechanisms only to a very limited extent. Furthermore, by defining concrete goals, sub-goals and indicators, the SDGs suggest a rigid concept of sustainability and are not applicable without restriction: sustainable development depends on local conditions and must be implemented in context. In addition, sustainable development is a constant transformation process, a continuous journey with (small and large) steps towards improvement. Hence, our indicator set as a monitoring system to accompany the SDGs must be constantly and flexibly adjusted. At the same time, the generally defined SDG indicators apply within the context of German or European concepts of sustainability in urban areas. They always need to be adapted to local conditions and require a reference framework to be assessed.

Transferability of our approach and recommended actions

Our indicator set can be used in context for all cities around the world to map biodiversity-related ecosystem services, track sustainable development in line with the SDGs, and provide an optional framework and standards to engage in exchange with other regions. The goal for urban regions must be to raise awareness among citizens, administrators, businesses and organisations for their own and their shared sustainability deficits, responsibilities and possible measures to enable them to act for sustainability.

For Germany, our indicators are based almost entirely on data collected based on laws and regulations. Hence, in theory, all indicators could be tracked in all German municipalities.

Table 9: Ecosystem services for resilience, health, temperature and extreme weather

SDG	Indicator	Ecosystem service	Result for the studied region
3.4	Accessibility of green spaces. Percentage of inhabitants in a 300 m radius.	• Positive psychological effects from urban green spaces can reduce health risks (CS) • Experience of nature: Urban nature provides habitat for animals and plants (CS) • Leisure and recreation (CS)	Bonn: 75% Troisdorf: 69% Sankt Augustin: 84% Data from: 2013 (Leibniz-Institut für ökologische Raumentwicklung 2019)
3.4	Satisfaction with green spaces	• Leisure and recreation (CS)	Bonn: 67% of citizens rate the condition of Bonn's green spaces as good or very good, data from 2010.
15.5	Share of nature and species reserves of the total area	• Nature and landscape conservation (RS) • Important resources for experiencing nature (CS) • Near-natural waterbodies serve to conserve biological diversity (RS)	Bonn: 23% Rhein-Sieg district: 15% Data from: 2013 (Leibniz-Institut für ökologische Raumentwicklung 2019)
13.1	The proportion of settlement area in flood plains.	• Flood and erosion protection (RS)	Bonn: 4.3% Rhein-Sieg district: 3.6% Data from: 2012 (Leibniz-Institut für ökologische Raumentwicklung 2019).
13.1	Loss of open space per inhabitant in square metres.	• Positive psychological effects from urban green spaces can reduce health risks (CS), reversed • Leisure and recreation (CS), reversed • Rest and recreation areas (CS), reversed	Bonn: 0.4 sqm per inhabitant Rhein-Sieg district: 1.1 sqm per inhabitant Data from: 2016 (Leibniz-Institut für ökologische Raumentwicklung 2019)
3.4	Annual average temperature in C.		Bonn: 2018: 11.9 C 2016: 11.3 C GEO-NET Umweltconsulting (2020)
3.4	Deviation of the mean temperature from the long-term mean (1971–2000) in C.		Bonn: 2018: +1.7 C 2017: +1.1 C GEO-NET Umweltconsulting (2020)
13.1	Annual precipitation in millimetres.		Bonn: 2018: 515 mm 2017: 685 mm GEO-NET Umweltconsulting (2020)
13.1	Deviation of the mean precipitation from the long-term mean (1971–2000) in millimetres.		Bonn: 2018: –170 mm 2017: 0 mm GEO-NET Umweltconsulting (2020)

Exceptions include the concentration of plastic in water bodies or regulations that might be obsolete due to the particularities of individual municipalities. In addition, to permit comparisons between cities, the problem statement must usually follow the available data and methods. Furthermore, the lack of evaluation standards limits the applicability of qualitative statements (such as 'better' or 'worse').

Our model results in the following recommendations for decision-makers in urban regions:

- Implement local and publicly visible sustainability monitoring, e.g. by offering an online platform based on the SDGs.
- Transparently represent sustainability and its development in the region to improve political decision-making, raise awareness among citizens, organisations and businesses, and find solutions to motivate them for the journey towards sustainability in the region.
- Increase cooperation between scientific disciplines, urban administrators and researchers, and citizens/volunteers/businesses in the region.

Strengths and weaknesses of the Bonn/Rhein-Sieg region

With its strongly urban core and rural hinterland, the region can be seen as a model for many other regions, especially in Europe. The region also must contend with typical problems.

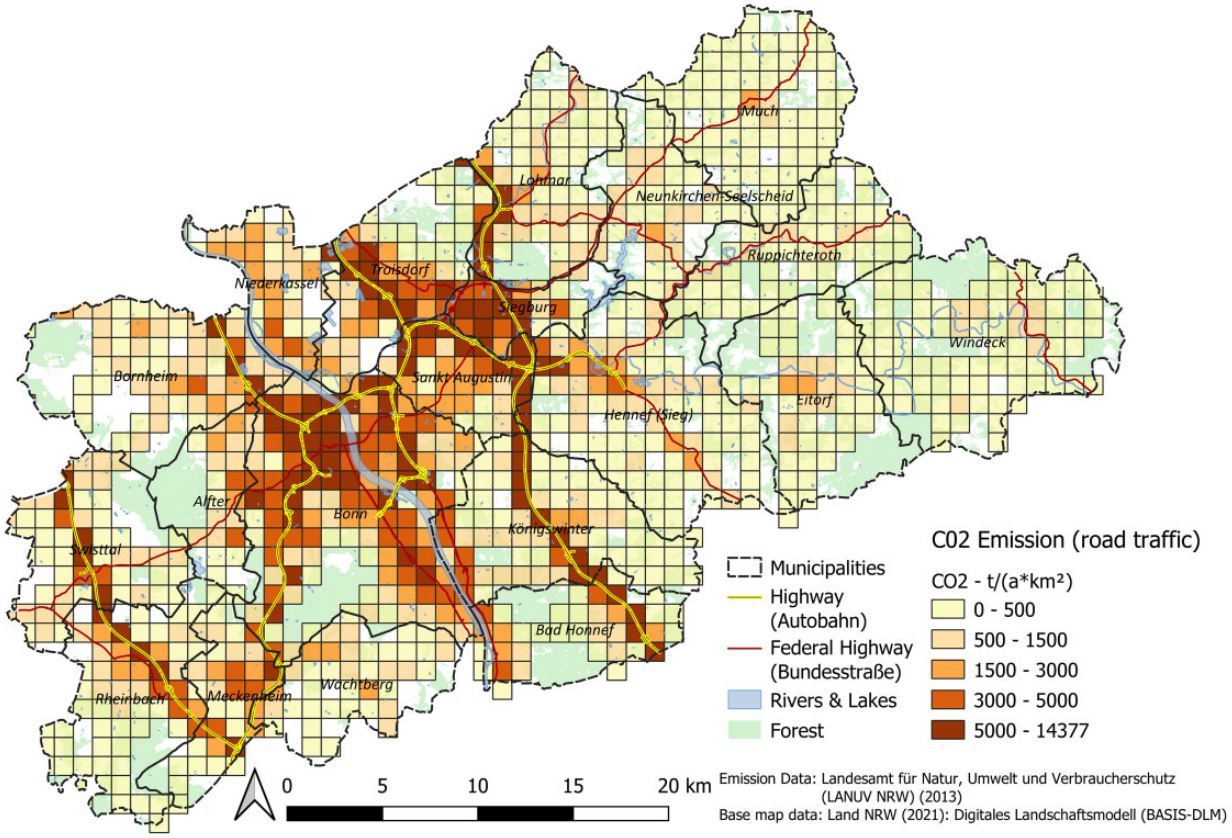

Figure 5: CO_2 emissions for road traffic in the Bonn/Rhein-Sieg region. Adapted from Mutke et al. (2019) based on emission data by LANUV NRW (2018) and base map data in the German Digital Landscape Modell (BASIS-DLM; Land NRW 2017)

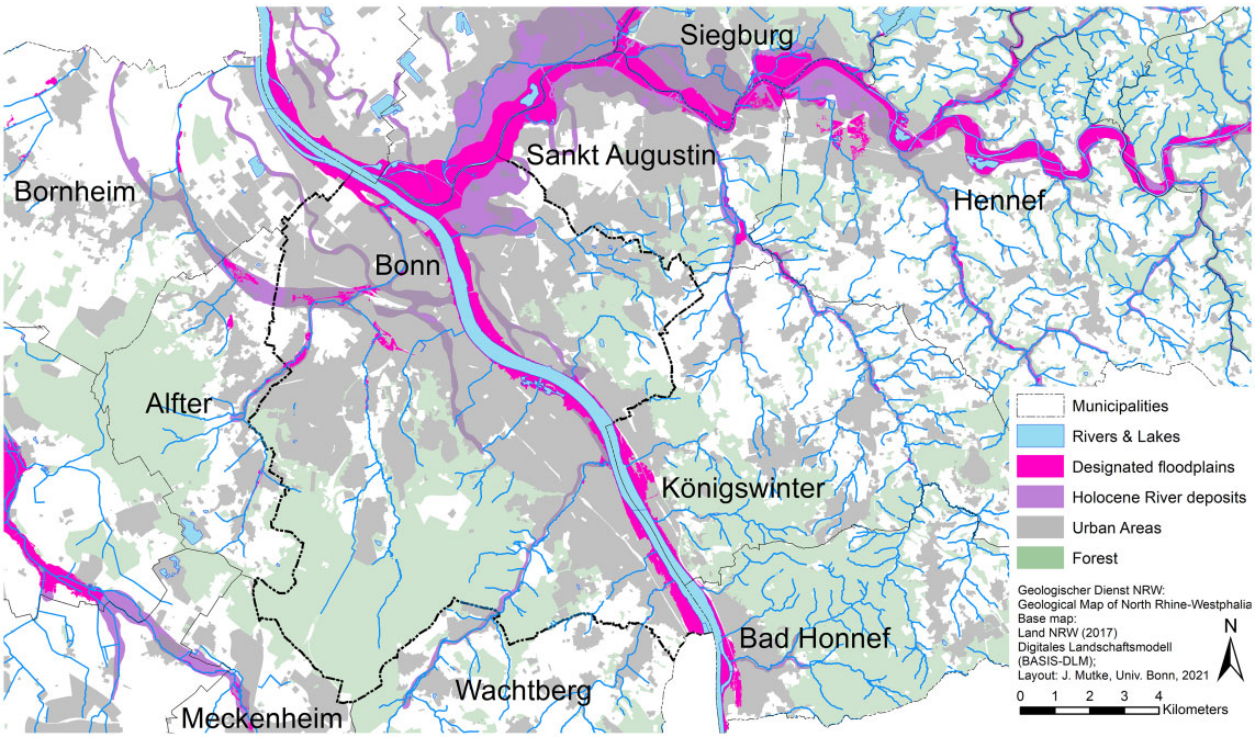

Figure 6: Water bodies and flood plains in the conurbation of Bonn, Sankt Augustin, Siegburg and Troisdorf. Adapted from Mutke et al. (2019) based on the German Digital Landscape Modell (BASIS-DLM; Land NRW 2017) and the Geological Map NRW (Geologischer Dienst Nordrhein-Westfalen (2017))

The city of Bonn, for example, is more in line with the German and European average in terms of the proportion of sealed surfaces, access to green spaces or air quality (ISGlobal 2021; Pereira Barboza et al. 2021). The region, on the other hand, looks somewhat better. For example, the second largest city, Sankt Augustin, offers its citizens access that is far above average in a European comparison, also due to its rather rural structure. But here, too, the quality of the air is at best average, and the region is above the values recommended by the World Health Organisation (ISGlobal 2021).

Average precipitation and especially temperatures have risen sharply in the region in recent times and are well above historical comparative values (GEO-NET Umweltconsulting 2020). In September 2018, for example, Sankt Augustin was the hottest place in Europe. The effects of heavy rainfall were particularly dramatic in July 2021, when nine inhabitants of the region died in floods.

With reference to our indicator sets derived from the SDGs, the region performs well in terms of urban biodiversity and ecosystem services (Table 4), public measures and plans (Table 5) and economic data (Table 6). This also applies to drinking water and water quality or the treatment of waste and wastewater. Here, the requirements of the SDGs are met at a high level and measures taken in the past to protect the environment show a clear effect. What is crucial, and this also applies to other municipalities outside our study region, is how they deal with the consequences of precipitation and high temperatures and the associated consequences for infrastructure and the lives of citizens. Although a large proportion of people live in urban regions, the SDGs unfortunately have little to say here.

Some of the indicators listed here are used in the sustainability reports of the City of Bonn (Stadt Bonn 2015, 2020), which are published every few years and presents the progress of local sustainable development in the context of the SDGs. Individual data sets, e.g. on drinking water quality or greenhouse gas balance, are also made available online at opendata.bonn.de.

In terms of data collection, Bonn/Rhein-Sieg has a major locational advantage. There are many institutions in the field of environmental monitoring, universities and federal or United Nations institutions. For our project report, on which this article is based, we evaluated over 100 different data sources on local ecosystem services and local biodiversity. A joint publication of such data, ideally online, would make it easier to track sustainable development and offer citizens more opportunities to get involved locally for the environment.

Conclusion

There have been few approaches to comprehensively address the SDGs regarding the quality of nature at the local level and the specific problems of urban regions. Our initial question thus was to what extent we can capture the sustainable development and quality of ecosystem services of urban regions based on the SDGs. We have demonstrated that publicly available data can be used without the need of generating additional data to create a set of indicators that relate to a total of 10 SDGs and 35 SDG targets. Thus, we can comprehensively capture environmental sustainability in the context of the SDGs. With our approach, we, therefore, provide a basis for comprehensive sustainability monitoring of urban regions. Based on extensive data research, we present this set of indicators using the Bonn/Rhein-Sieg region as an example and provide a comprehensive insight into the region's ecological quality.

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Data availability

The authors confirm that the data supporting the findings of this study are available within the article and/or available from public sources given in the references of this article. Extended background data on biodiversity of the Bonn/Rhein-Sieg Region is available online in our project report 'Die Natur der Region Bonn/Rhein-Sieg—Ein lokales Assessment der Biodiversität und Ökosystemleistungen im Rahmen der UN Sustainable Development Goals (SDGs)' (https://www.biodiversity.uni-bonn.de).

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