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Simulation and Evaluation of Urban Growth for Germany Including Climate Change Mitigation and Adaptation Measures

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Abstract: Decision-makers in the fields of urban and regional planning in Germany face new challenges. High rates of urban sprawl need to be reduced by increased inner-urban development while settlements have to adapt to climate change and contribute to the reduction of greenhouse gas emissions at the same time. In this study, we analyze conflicts in the management of urban areas and develop integrated sustainable land use strategies for Germany. The spatial explicit land use change model Land Use Scanner is used to simulate alternative scenarios of land use change for Germany for 2030. A multi-criteria analysis is set up based on these scenarios and based on a set of indicators. They are used to measure whether the mitigation and adaptation objectives can be achieved and to uncover conflicts between these aims. The results show that the built-up and transport area development can be influenced both in terms of magnitude and spatial distribution to contribute to climate change mitigation and adaptation. Strengthening the inner-urban development is particularly effective in terms of reducing built-up and transport area development. It is possible to reduce built-up and transport area development to approximately 30 ha per day in 2030, which matches the sustainability objective of the German Federal Government for the year 2020. In the case of adaptation to climate change, the inclusion of extreme flood events in the context of spatial planning requirements may contribute to a reduction of the damage potential.

Keywords: urban growth; Germany; scenario; mitigation; adaptation; Land Use Scanner

1. Introduction

Since more than half of the world's population lives in cities the impacts of climate change on urbanized areas are a key challenge for most countries [1].

Urbanization has progressed in recent decades and is projected to continue. It is therefore not surprising that 60 to 70% of the world's CO_2 emissions are related to urban areas and it goes along with serious changes of the available land resources [2]. Aside from these processes, there are also regions that face a period of urban restructuring due to demographic and industrial decline and where the settlement structure reaches carrying capacity problems [1,3]. These regions reveal the chance for an active restructuring in terms of climate change adaptation needs.

Possible impacts of the anthropogenic climate change are well known. Although the occurrence probability and intensity of certain extreme weather events is highly uncertain, they appear with serious damage potential or health risks [4]. Beyond others increased surface runoff due to surface sealing in urban areas leads to massive inundation and damage [5]. Urbanized areas have historically often developed close to rivers and are thus located in flood prone areas and affected by floods. Together with inefficient spatial planning, protection of these settlements is inadequate [6–8]. Another implication induced by climate change is the development of urban heat islands, which influences human health by heat-related illness or mortality [9,10]. Furthermore, urbanization reduces the availability of natural open space due to built-up and transport development, leading to a discussion about the optimal provision of urban green areas in settlements [11]. Against this background the question arises, how can land and, in particular urban land, be managed in a sustainable way?

The Federal Government in Germany adopted the sustainability strategy and the strategy for adaptation to climate change as roadmaps for a sustainable land management [12,13]. In both documents, advice is given how adaptation to climate change can be achieved. One finding is, that settlement structures need to be adapted to the possible impacts of climate change. By which measures this could be achieved is the central research question of this study.

The above-mentioned strategies result in new challenges for regional planning [14]. Especially climate change mitigation is becoming increasingly important, because 7.5% of the greenhouse gas emissions in Germany directly result from land use and land use changes (activities in forestry, agriculture and built-up and transport areas) [15]. Moreover, biomass is a sink for carbon dioxide and thus mitigates climate change. Simultaneously, built-up and transport areas consume 69 ha (2011 to 2014) of the land resources in Germany every day [16]. This land is therefore no longer available for other land uses and thus also not available for the purpose of climate mitigation. Bart (2010) found evidence for the necessity to reduce built-up and transport area development to reduce CO_2 emissions in Europe [17].

The aim of this study is to examine what measures have an effect on the achievement of climate change mitigation objectives and what measures are appropriate to adopt the land use and settlement patterns to climate change adaptation. Such measures may lead to changes in planning practice and usually affect multiple ecosystem services in different ways [18]. The adopted measures can result in synergies or conflicts on achievements of climate change mitigation and adaptation. They have been discussed in detail in a national and a regional participation process with decision-makers within the project in which this study is carried out.

In this article, land use scenarios for 2030 in Germany are presented that implement policy measures for the development of built-up and transport areas to contribute to climate change mitigation and adaption. The scenarios are simulated with the GIS-based land use change model Land Use Scanner. A number of alternative policy scenarios are compared with a reference scenario to evaluate the impact of different measures on the achievement of climate change mitigation and adaptation objectives. For evaluation purposes, a set of indicators is developed that enable to visualize the qualitative and partially quantitative differences to the reference scenario.

2. Methods and Data

2.1. Modelling Land Use Change

A diverse suite of modeling approaches has evolved during the last decade, some of these deal explicitly with processes leading to urban growth, others consider urban growth as one type of land-use change amongst others. Recent surveys of operational land-use change models offer insights into elementary model concepts and characteristics, including aspects of urban growth [19–21]. Many land-use change models are based on a multi-model approach. This means that global trends for specific land-use types or the general economic and demographic development of the study area are analyzed in external models, which are loosely coupled to the land-use change model by transferring their results as regional demand within administrative units. The land-use change model allocates these land-use based on the local suitability for a land-use category. Examples for these kinds of models are the Land Use Scanner [22], DynaClue [23], EU-ClueScanner [24] or Environment Explorer [25]. The local suitability for land use is often assessed in a previous analysis, where the effect of different location characteristics is evaluated statistically, e.g., in a binomial or multiple logistic regression analysis [6].

Criteria of model selection for our study have been:

- the ability to simulate urban and non-urban land use types;
- to integrate regional demands for land use for sub-regions of a study area; and
- to simulate a large country like Germany with high spatial resolution.

Upon these requirements, we have chosen the Land Use Scanner, which is in its current development similar to the EU-CLUE scanner and incorporates the knowledge of other models, such as CLUE or the "Environment Explorer".

2.2. The Land Use Scanner Model

The Land Use Scanner is an operational, spatially explicit simulation model that uses an optimization algorithm to allocate the demand for land to appropriate grid cells (see Figure 1) [22,26].

The basic characteristics of the Land Use Scanner for Germany are [27]:

- A spatial resolution of 100 m.
- 13 land-use classes (6 urban land-use classes). In general, any number of land-use classes can be implemented in Land Use Scanner.
- A discrete modeling algorithm, where a raster cell represents only one land-use class (see [22]).
- By using the same parameters, the model results are reproducible.
- Planning regulations are included in the simulation.
- The model gives results in subsequent time steps (five year steps).

"The discrete allocation model allocates equal units of land (cells) to those types of land use that have the highest suitability, taking into account regional land use demand. This discrete allocation problem is solved through a form linear programming, the solution of which is considered optimal when the sum of all suitability values corresponding to the allocated land use is maximal. The allocation is subject to the following constraints:

- the amount of land allocated to a cell cannot be negative;
- in total, only 1 ha can be allocated to a cell; and
- the total amount of land allocated to a specific land-use type in a region should be between the minimum and maximum claim for that region.

Mathematically the allocation problem can be formulated as:

$$\max_{x} \sum_{cj} S_{cj} X_{cj} \quad (1)$$

subject to:

$X_{cj} \geqslant 0$ for each c and j;

$\sum_{j} X_{cj} = 1$ for each c;

$L_{jr} \leqslant \sum_{c} X_{cj} \leqslant H_{jr}$ for each j and r for which claims are specified;

in which:

X_{cj} is the amount of land allocated to cell c to be used for land-use type j;

S_{cj} is the suitability of cell c for land-use type j;

L_{jr} is the minimum claim for land-use type j in region r; and

H_{jr} is the maximum claim for land-use type j in region r." [22]

The demand is determined in external models for regions such as counties. Suitable grid cells are identified by using suitability maps, where location factors such as current land use, physical conditions, planning regulations or the accessibility of infrastructures are combined. The individual types of land use thereby compete with each other. A detailed description of the model, the data sets applied as well as the development of regional demand numbers for the land use types and suitability maps considered can be found in Goetzke and Hoymann (in press) [27].

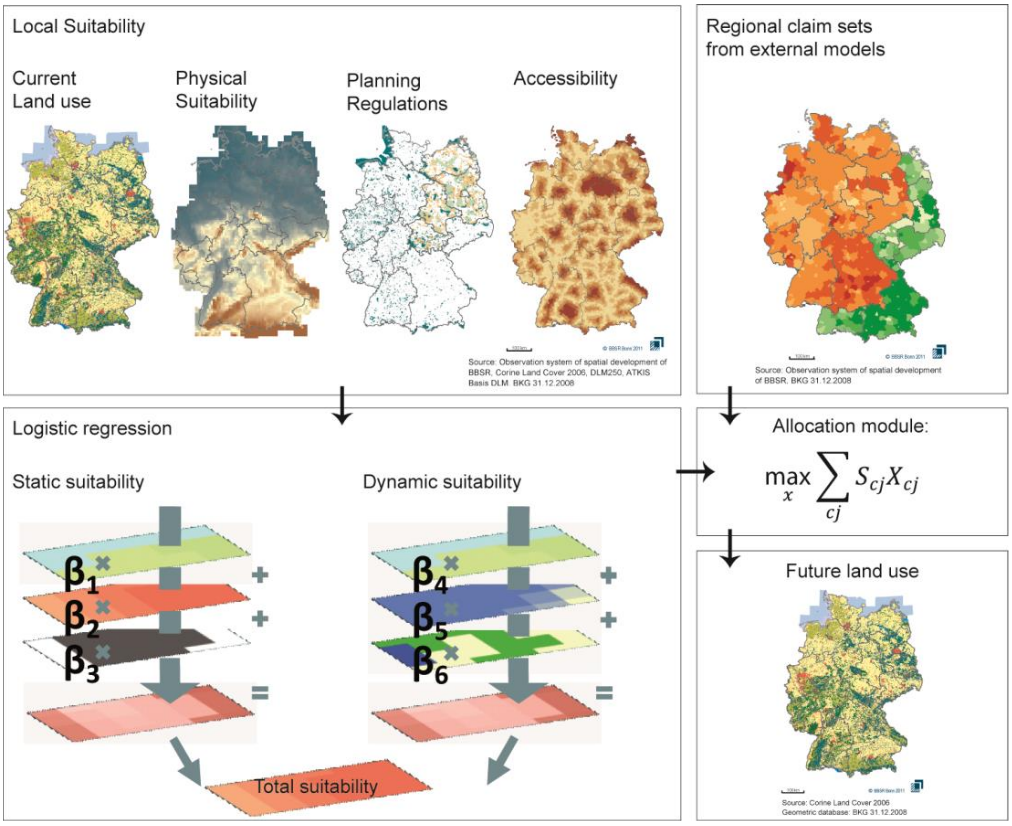

Figure 1. Overview of the German Land Use Scanner model application.

2.3. Land Use Change Scenarios

First of all, a reference scenario has been simulated. In this scenario, we assumed that the observed demographic and economic development will continue in the next two decades and that the effect of these developments on the change of built-up and transport area will be similar, too. Based on this reference scenario, alternative scenarios are implemented into the model to analyze their contribution to and effect on climate change mitigation and adaptation as well as environmental protection and conservation. These measures either control the demand for a certain land use type (quantity control) or their spatial distribution patterns (locational effect). They have been discussed in an intensive consultation process with planners at the regional level and with stakeholders at the national level. Through appropriate modeling, the effect of the different measures can be quantified and compared to the reference scenario.

The modeled measures are listed in Table 1. It should be noted that measures without an impact to land use changes have not been considered, even if they make a quite significant contribution to climate change mitigation and adaptation. Such measures, for example, are the adaptation of the sewage system to heavy rain events or the use of communal roof areas for solar energy. In this article, three measures will be presented exemplary in more detail.

The objective of climate change mitigation in this study is to reduce the growth of built-up and transport area as much as possible in order to reduce land loss, to preserve carbon sinks, and to form compact and efficient settlement structures. Different measures can contribute to this objective. It is not the aim of the study to quantify the saving of CO_2 emissions but to quantify their effect on land use change. Climate change adaptation in contrast aims at the reduction of potential climate change induced risks for built-up and transport area as well as residents. Finally, nature conservation tries to preserve as much natural areas as possible and promotes the retreat of built-up and transport area in regions with low or without demand for built-up areas.

Table 1. Measures that control the settlement development, their assignments to a land use strategy, and to indicators that are used to measure their effect (*Measures and indicators presented in this publication are marked in italics*).

		Land Use Strategies			Indicators									
		Climate Change Mitigation	**Climate Change Adaptation**	**Nature Protection**	***Increasing Built-Up and Transport Areas***	**Access to New Built-Up Areas**	**Locational Integration of New Built-Up Areas**	**Changing Carbon Storage in Land Use and Soils**	***Increasing Built-Up and Transport in Flood-Prone Areas***	***Increasing Built-Up and Transport in Areas with Thermal Heat Load***	**Greening Settlement Areas**	**Soil Sealing**	**Increasing Built-Up and Transport in Areas Designated for Nature and Landscape Protection**	**Increasing Built-Up and Transport in Unfragmented Space**
Measures	*Preserving and developing urban green areas*	x	xx	x	x	*x*		xx		*xx*	xx	x		
	Strengthening inner-urban development	xx		x	x	*x*	xx	x	*x*	*x*	x	x		
	Realizing higher densities in new built-up areas	xx		x	x	x		x		x	x	x		
	Strengthening public transport	xx		x		xx	xx			x	x			
	Reducing land take by transport infrastructure	xx	x	x	x			x		x		x		
	Settlement retreat, recentralization	xx	xx	xx	x	x	x	x	x	x	x	x	x	x
	Designating more priority and preserved areas in regional planning	xx	xx	xx				xx	x	x	x			
	Enhanced flood protection		xx						*xx*					
	Restrictive open space and nature protection	x		xx			x						xx	xx
	Energy production on non-agricultural areas unsuitable for settlement purposes	xx						x						

Table 1. *Cont.*

		Land Use Strategies			Indicators									
		Climate Change Mitigation	**Climate Change Adaptation**	**Nature Protection**	***Increasing Built-Up and Transport Areas***	**Access to New Built-Up Areas**	**Locational Integration of New Built-Up Areas**	**Changing Carbon Storage in Land Use and Soils**	***Increasing Built-Up and Transport in Flood-Prone Areas***	***Increasing Built-Up and Transport in Areas with Thermal Heat Load***	**Greening Settlement Areas**	**Soil Sealing**	**Increasing Built-Up and Transport in Areas Designated for Nature and Landscape Protection**	**Increasing Built-Up and Transport in Unfragmented Space**
Land use strategies	Climate protection				x	x	x	x						
	Climate change adaptation								x	x	x	x		
	Nature protection												x	x

Some of the above-mentioned measures may affect the regional land claims of built-up and transport areas and thus the demand for land, which is currently assigned to another (mostly agricultural) land use. Other measures do not affect the built-up and transport area demand, but the spatial distribution of built-up and transport area development. Therefore, the definition of suitability maps must be adjusted. Finally, some measures also include a change in the "conversion cost" of a land use to another. In the model, the "conversion costs" are implemented as a conversion matrix which describes the possible land use type-specific changes.

The land-use data used in this model is based on the LBM-DE, a digital landscape model for Germany that has been created for governmental purposes. The LBM-DE has the geometry and spatial resolution of ATKIS ("Authorative Topographic-Cartographic Information System"), which is the official topographic and cartographic information system for Germany. In LBM-DE the spatial information is combined with the Corine Land Cover classification scheme [28]. LBM-DE was created for the first time in 2009. Thus, there was no time series available for this dataset. Therefore, the conversion matrix was developed from a change detection analysis of the Corine Land Cover datasets of the years 1990 and 2006. The analysis revealed the probability of change from one land use type to another. Due to the different spatial scales of LBM-DE and Corine Land Cover small inaccuracies are possible, but the general trend of land use change can be analyzed adequately with Corine Land Cover.

In this publication it is described in what way three exemplary scenarios differ from the reference scenario and how the assumptions are operationalized and implemented in the Land Use Scanner. Results are also compared for three exemplary indicators (see Section 2.4).

2.3.1. Preserving and Developing Urban Green Areas

Settlement areas are particularly affected by climate change-induced changes in temperature due to the development of urban heat islands. Especially long-lasting heat waves may mean a burden on the health of residents, especially older and sick people as well as infants. The thermo-mechanical load of buildings and infrastructures rises with an increasing number of hot days [9,29]. Higher building densities and an expansion of the settlement area amplify this problem. In addition, soil sealing increases the direct runoff of rainfall because the water retention in soil and vegetation is impeded [30].

The measure "Preserving and developing urban green areas" aims at the thermal stress relief of cities with an expected increase in hot days by strengthening the recreation areas in cities as well as increasing the natural water retention and groundwater recharge rate. This is primarily done by improving the supply and accessibility of green and open space within the settlement area and between settlements. Thus, this measure primarily addresses climate adaptation aspects. In addition, positive effects for climate change mitigation may result from a higher carbon sequestration potential due to extensive green volume in urban areas.

The measure is implemented into the land use model by a bundle of individual assumed developments, which include the following:

- securing existing inner-urban green and recreational areas as well as appropriate open space and green space planning in new built-up areas;
- developing new urban green areas;
- preserving regionally important open space functions as well as green and blue structures; and
- demolishing and concentrating urban structures as well as renaturation.

In the model, existing urban green areas are protected by an increase in the "conversion costs" (changes in the conversion matrix) of urban green areas into built-up land. In addition, inner-urban development is reduced, leading to an increase in new built-up land at the urban boundary. Furthermore, these new built-up areas need to be combined with a systematic development of blue and green structures. The lowered inner-urban development rate is calculated as the ratio of the housing development between 2009 and 2012 and the development of built-up areas in the same time span. For regions with an above-average ratio, their value is decreased to the average, which corresponds to a compact but not a highly densified architecture. This leads to a slight increase in demand for built-up areas.

New urban green areas are developed on brownfields and vacant lots. This is implemented in the model by reducing the "conversion costs" of the conversion matrix for a change from brownfields to urban green areas. Also, the demand for urban green areas is increased. In a study on behalf of the German Federal Agency for Nature Conservation (BfN) 55.75 m^2 of urban green per inhabitant are recommended [31]. In the scenario, the amount of urban green space is increased to this value in those regions that currently have lower amounts. The accessibility of urban green areas is also considered. The mentioned study by BfN recommends a distance of not more than 500 m for green space near to residential areas [31]. Therefore, the suitability for urban green areas is increased in residential areas with a distance of more than 500 m to existing urban green areas.

Important regional open space functions and regional green belts, defined in regional spatial plans, are preserved in the model by defining spatial planning preservation areas as priority areas. While in preservation areas interests of different land uses have to be weighted by the spatial planning authorities, in priority areas other land uses than the designated land use is prohibited.

In shrinking regions and cities with a high vacancy rate, part of the existing buildings will be demolished in order to create more opportunities for urban green space. The 2011 German Census was used as a database to estimate the vacancy. Taking a fluctuation reserve of 3% of the housing stock into account, there are more than 660,000 empty homes in Germany. However, this stock cannot be fully demolished, as the clearing of whole buildings cannot always be carried out consistently. This is why the measure distinguishes between growing and shrinking regions. In the latter, the potential for dismantling is greatest. Between 2001 and 2010, about 284,700 homes were demolished in East Germany [32]. According to rough estimates from a study by BBSR, at least 115,000 buildings from the current building stock could be demolished by 2030 [33]. In addition to the dismantling of the currently existing vacancies, the measure also considers a deconstruction of forecasted vacancies. Results of the study "Current and future development of housing vacancy rates in the sub-regions of Germany" form the basis for their calculation [33]. In this study, the development of unoccupied dwellings is projected by 2030 in various scenarios. The results show that another 170,000 buildings could be demolished. For the implementation into the land use model it is assumed that only as many buildings are demolished and space is renatured as is necessary to satisfy the demand for urban green areas.

2.3.2. Strengthening Inner-Urban Development

A higher urban density has a positive climate impact, since it entails less greenhouse gas emissions caused by transport, heating and energy supply compared to lower urban densities [34]. However, there is potential for conflict regarding the reinforced need to adapt the inner-urban development to climate change, because higher building densities may increase the heat island effect. Accordingly, urban structures and climatic conditions must be considered, so that the inner-urban development satisfies the need for protecting the climate, reducing land consumption as well as for adapting to climate change.

The measure aims to reduce land consumption at the edge of urban areas. The revitalization of brownfields, the closure of gaps between buildings, the use of vacancies as well as the densification of built-up areas are used as ways to reduce land consumption while satisfying the demand for building land. They lead to a compact and efficient settlement structure and infrastructure follow-up costs are reduced. Thus, climate change targets are in the focus of this measure, but also the nature conservation strategy benefits from an improved inner-urban development. Inner-urban development potentials (IUD) have not been surveyed nationwide before. Therefore, several data sources are used to implement this policy into the land use model.

The above-mentioned database on vacancies in Germany (2011 Census) also reveals the potential reuse. From the vacancy rates and the projected built-up development the reuse potential can be determined to calculate the land use demand. In addition to the reuse of the currently existing vacancies, the reuse of forecasted vacancies is also calculated based on current estimates [33]. Using similar estimation methods as described in the previous section, there are more than 1.25 million additional dwellings that could be reused, theoretically. Based on the assumptions of the current and projected vacancy reuse, a new development of more than 25,000 buildings does not take place in this scenario compared to the reference. This value takes into account that large amounts of vacant dwellings cannot be reused in shrinking regions because of the missing demand. In growing regions the vacancies can be nearly completely reused and the demand for space could be largely satisfied by the consistent use of vacancies. In counties or cities without permanent vacancy (e.g., Munich), this measure is without effect.

Brownfield redevelopment and the development of vacant lots are the most important elements of inner-urban development. To represent this process in the land use model, several approaches are combined. First, the conversion costs of brownfield sites in residential and commercial areas have been reduced and brownfields will be completely redeveloped by 2030. Furthermore, the need for built-up and transport areas is reduced due to the use of brownfields. The magnitude of this potential has been estimated in the project "Implementation of measures to reduce land consumption—Internal development potential" [35]. According to these results, the IUD potential in Germany is from 15 to 20 m^2 per inhabitant, which corresponds to approximately 120,000 to 165,000 ha nationwide. The amount of IUD was extrapolated based on the values for counties listed in Table 2. In this way, the proportion of projected built-up and transport area demand, which can be realized as inner-urban development, is calculated. However, only 70% of the potentials are classified as "can be activated" [35]. Therefore, the available potential is reduced by 30% for each county.

Table 2. Inner-urban development potential per inhabitant classified by population development.

Population Development	Population Development 1/1/2009 to 31/12/2011	IUD/Inhabitant (m^2)
Strongly growing	at least 1.5% p.a.	approx. 8 m^2
Growing	0.25% up to below 1.5% p.a.	approx. 12 m^2
Stagnating	−0.25% up to below 0.25% p.a.	approx. 13 m^2
Shrinking	−1.5% up to below −0.25% p.a.	approx. 17 m^2
Strongly shrinking	more than −1.5% p.a.	approx. 38 m^2

The term densification is often put on the same level as inner-urban development. Here, however, densification is understood as an intensified use of far less used areas within the existing building environment. Densification thus happens "on land which has already been built but which has more open space potentials" [35], resulting in a structural compaction. Such potentials for example include row buildings or buildings in the backyard. A simple procedure for estimating densification potentials was applied. It was based on the amount of impervious surface for residential and commercial areas. Therefore, the Copernicus Fast Track Service Soil Sealing Layer delivered by the European Environment Agency (EEA) was used. The overbuilding degree (between 0 and 1) is compared with the designations set by the German Land Utilization Ordinance (Baunutzungsverordnung BauNVO). It takes into account that not all lots can be equally densified according to these limits. Depending on the measured degree of sealing, it is lifted to the next limit. This takes the claim into account that settlements should be qualitatively densified and their original village or urban character should be preserved. Since in reality the possibility of densification is limited—e.g., by a lack of access to open spaces, structural constraints and so forth—it is assumed that roughly only 10% of the available potential can be used.

2.3.3. Enhanced Flood Protection

The objective of the measure is to strengthen regional planning instruments for flood protection. It includes plans to precautionary exclude areas from settlement development that show an increased risk of flooding. In the current planning practice flood plains with a probability of being flooded with a 100 year return period (HQ_{100}) are designated as priority or preservation areas.

The modeled measure goes beyond these areas and defines all HQ_{100} as well as $HQ_{extreme}$ areas as priority areas. $HQ_{extreme}$ is an extreme flood event with a low probability. Such events do not have a defined return period but show the flooded areas for the case that flood protection structures (e.g., dikes) fail. In this scenario, built-up areas are allocated to other grid cells than in the reference scenario leading to an alternative settlement pattern. In this way, large areas with increased frequency of extreme floods remain free from new buildings, which significantly reduce the potential for damage. The assumptions do not affect the building stock, which cannot simply be withdrawn.

2.4. Impact Assessment of Measures with Indicators

In addition to projecting land use changes in alternative scenarios, the impact analysis of modeled measures is of importance. In order to evaluate the very different measures objectively, an assessment system is required, which allows comparing the impact of the measures qualitatively or quantitatively in relation to the reference scenario. Van den Bergh et al. (1999) analyzed the applicability of the ecological footprint and discussed a number of criteria an indicator or system of indicators should fulfill [36]. These criteria were principally approved by Giljum et al. (2011) [37]. Here, the sustainable urban development as well as the contribution to climate change mitigation and adaptation is evaluated. For this reason, indicators are required that can map these climate-related aspects. The impact of climate change and therefore the need for adaptation measures were analyzed by Lung et al. (2013) at the European level on the basis of indicators concerning heat stress, flood risk and forest/bush fire risk [38]. Siedentop et al. (2011) concluded in a study on integrated scenarios of spatial development in Germany that built-up areas with above-average heat load are a field of action for spatial development policy [39]. In that way we are able to analyze different scenarios in a comparative way and to identify possible trade offs in the achievement of the climate change mitigation and adaptation aims of the applied measures. Therefore, a multi-criteria evaluation approach was developed, which is based on a system of indicators and fulfills most of the above-mentioned criteria. They have been implemented in the Land Use Scanner model. The application of the indicators for the different alternative scenarios is presented in Table 1.

The applied indicators are calculated as index values. Therefore, individual index values for every county in Germany based on the national average value at a reference time are calculated [40]. The national average of all counties as of 2009 is used as a reference value. In general, the indicators presented capture the simulated changes in built-up and transport areas between 2009 and 2030.

The reference value, that means the national average in 2009, receives a value of 100. The individual values of the counties differ positively at values of >100 and negatively for values <100 from the reference value. The range of index values is limited to a scale of 0 to 200 in order to reduce the effect of outliers. Index values <0 therefore receive the value 0 and index values >200 receive the value 200. The measurement values are first multiplied by 100 and then divided by the reference value [40].

Since there is rarely a simple cause-and-effect relationship in the calculated measures, different perspectives are taken into account when measuring the effect. The indicators used shall describe the effect of a measure as holistically as possible. This allows decision-makers to capture the effectiveness of a measure at a glance. Therefore, an indicator consists of multiple sub-indicators that describe individual elements of a measure as simple and comprehensive as possible. In the overall indicator calculation, all sub-indicators are equally weighted. A content-related weighting might be appropriate in individual cases but it cannot be quantified.

To evaluate the 10 measures (Table 1), 10 indicators are used. Four indicators target the evaluation of the achievement of climate change objectives, another four target aspects of adaptation to climate change and two nature conservation aspects. The table matrix shows the many to many relationships between measures and indicators. Three indicators are introduced in this study.

2.4.1. Increasing Built-Up and Transport Areas

The increase in built-up and transport area is measured in two ways. First, the land consumption per day in hectare for Germany is used. This measuring unit is applied because it corresponds to the sustainability objective of the German Federal Government to reduce daily land consumption to 30 ha per day until 2020.

$$LC_{r,01} = \frac{1}{n_{years}} \times \frac{1}{365\ days} \times \sum_{rcu} X_{cu} \tag{2}$$

The second way of analyzing the increasing built-up and transport area is to aggregate the changes observed in the land use grid to regions and show the percentage change between 2009 and 2030.

$$LC_{r,02} = \frac{\sum_{cu} X_{cu}}{\sum_{c} X_{u}} \times 100\,[\%] \tag{3}$$

with:

X_{cu} is the amount of land allocated to cell c to be used for urban land-use type u;

$LC_{r,01}$ is the daily land consumption within a period of n years for all regions r; and

$LC_{r,02}$ is the share of new built-up and transport area of region r.

2.4.2. Increasing Built-Up and Transport Area in Flood Prone Areas

The indicator consists of two sub-indicators. To examine if built-up and transport area development takes place outside of $HQ_{extreme}$ areas, the application of the sub-indicator "Land consumption by built-up and transport areas in flood-prone areas" ($IND\_FL_{r,02}$) is sufficient. In order to demonstrate at the same time which areas already have a high ratio of built-up and transport areas in flood-prone areas at the same time, a link to an overall indicator is set by the sub-indicator "Current built-up and transport areas in flood-prone areas" ($IND\_FL_{r,01}$). Thus, the indicator consists of two subindicators in order to consider the future land consumption as well as the current setting with built-up and transport area. The sub-indicators and the combined indicator are calculated as follows:

$$IND\_FL_{r,\,01} = \frac{\frac{\sum_{cu} X_{cu} in\_HQ_{extreme}}{\sum_{cu} X_{cu}}}{\frac{1}{n_r} \times \sum_{r} \frac{\sum_{cu} X_{cu} in\_HQ_{extreme}}{\sum_{cu} X_{cu}}} \times 100 \tag{4}$$

$$IND\_FL_{r,02} = \frac{\frac{\sum_{cu} newX_{cu} in\_HQextreme}{\sum_{cu} newX_{cu}}}{\frac{1}{n_r} \times \sum_{r} \frac{\sum_{cu} newX_{cu}}{\sum_{cu} newX_{cu}}} \times 100 \tag{5}$$

$$IND\_FL_{r} = 0,5 \times IND\_FL_{r,01} + 05 \times IND\_FL_{r,02} \tag{6}$$

with

$X_{cu}\_in\_HQextreme$ is the current amount of land allocated to cell c to be used for urban land-use type u in areas prone to extreme flood events;

X_{cu} is the amount of land allocated to cell c to be used for urban land-use type u;

$IND\_FL_{r,01}$ is the indicator of the share of the current built-up and transport area in areas prone to extreme flood events in comparison to the built-up and transport area of the region r;

$newX_{cu}\_in\_HQextreme$ is the amount of land allocated due to simulation to cell c to be used for urban land-use type u in areas prone to extreme flood events;

X_{cu} is the amount of land allocated due to simulation to cell c to be used for urban land-use type u;

$IND\_FL_{r,02}$ is the indicator the share of the new built-up and transport area in areas prone to extreme flood events in comparison to new built-up and transport area of the region r; and

IND_FL_{r} = the total indicator "Increasing built-up and transport in flood prone areas"

The results are finally categorized for a map representation. The classification rules are presented in Table 3. The average value is 100.

In contrast to all other indicators, only those urban land use types area included in the calculation that considerably contribute to soil sealing and thus surface runoff. That means, that recreational areas are not considered due to the assumption that a flooding of urban green areas do not lead to substantial economic damage.

Table 3. Classification scheme for index values.

Classification	Index Values
Well below average	0–50
Below average	50–100
Above average	100–150
Well above average	150–200

2.4.3. Increasing Built-Up and Transport Area in Areas with Thermal Heat Load

In many areas, there are already more than 7 hot days per year (maximum temperature >30 °C). The most affected areas are the Upper and Middle Rhine, the Rhine-Main area and Brandenburg. By 2100, the number of hot days will further increase significantly in many regions of Germany. The applied indicator is called "Increasing built-up and transport area in areas with thermal heat load". This indicator consists of two sub-indicators, which are included with equal weighting in the overall indicator:

1. Proportion of land consumption for built-up areas in areas with thermal heat load.
2. Share of built-up areas on municipal areas in 2030 (residential development) within a distance of 500 m to green and blue structures (urban green and recreational areas, forests, wetlands, water).

3. Results

The results section presents a selection of results to show the manifold possibilities of analysis. The section is structured by the different indicators. It contrasts the indicator values for the reference scenario as well as the three alternative scenarios.

3.1. Indicator Increasing Built-Up and Transport Area

Figure 2 shows the past development as well as the expected land consumption per day for the reference scenario until 2030 ($LC_{r,01}$). The daily consumption of new land for built-up and transport will decrease from 69 ha in 2014 to about 45 ha per day in 2030. The goal of the Federal Government's sustainability strategy to reduce the daily consumption of new land for built-up and transport area to 30 ha in 2020 will not be achieved although a significantly decreasing trend can be observed. However, only 19.5 ha of them are claimed by built-up land. For recreation and green areas, daily land consumption is just under 9 ha and, for traffic areas, it is 15.5 ha. The daily land consumption for operational areas (without mining) then reaches 1 ha. Without the recreation and green space, land consumption will be almost under 36 ha per day in 2030. The regional differences in land use development, which have been observed in the past, continue.

The following Table 4 shows the results for the alternative scenarios in the time period 2026 to 2030.

Table 4. Daily land consumption of built-up and transport area in Germany during the time period 2026 until 2030 in ha.

	Built-Up and Transport Area				
	Buildings and Open Space	**Transport Areas**	**Recreational Areas Incl. Cemeteries**	**Operational Areas Excl. Mining**	**Total Land Consumption**
Reference scenario	19.5	15.5	9	1	45
Preserving and developing urban green areas	17.7	15.3	13	1	47
Strengthening inner-urban development	6.6	13.9	8.5	1	30
Enhanced flood protection	19.5	15.5	9	1	45

The daily consumption of land taking place between 2026 and 2030 by implementing the measure "Preserving and developing urban green areas" is 47 ha/day and only slightly above the reference scenario (Table 4). This is primarily a result of a higher demand for urban green and recreational areas (13 ha/day). The reason for the differences between this scenario and the reference scenario is that housing is relocated to the urban boundary as open space within settlements is converted into more green areas than according to the reference scenario. In addition, a lower housing density is required resulting in long access roads.

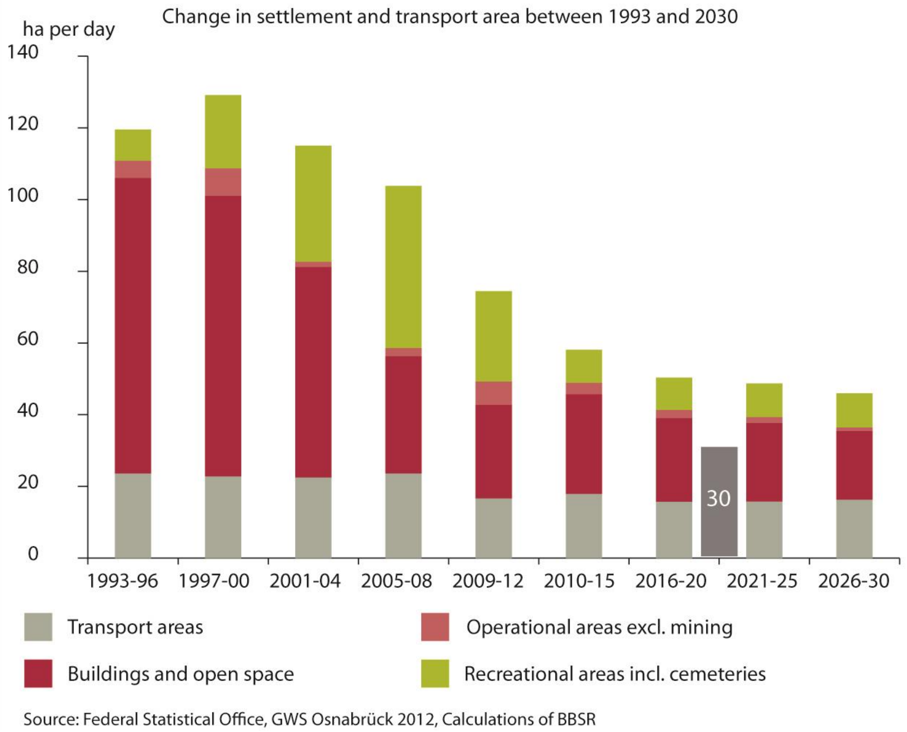

Figure 2. Daily land consumption for built-up and transport area between 1992 and 2030 for the reference scenario.

By using brownfields and vacant lots within settlements, land consumption could be reduced by 120,000–165,000 hectares according to a recent study [35]. This is more than one third of the estimated 2030 demand. A substantial part thereof cannot, or only with difficulty, be activated, and supply and demand do not always meet. The effectiveness of the measure "Strengthening inner-urban development" is well below the above-mentioned potential. In addition to the priority use of these areas, the measure also includes the use of building vacancy rates and the use of redensification potentials. Among those assumptions adopted in the model, this leads to a decrease in daily land consumption in 2030 from 45 ha/day in the reference scenario to 30 ha/day (Table 4). In 2020, the daily land consumption by built-up and transport is a little over 32 hectares. By consistently implementing this measure, the 30-hectare objective of the Federal Government's sustainability strategy might be approached.

The daily land consumption of the measure "Enhanced flood protection" equals the results of the reference scenario. For this scenario, only the suitability map in the land use model was adapted, not the demand figures.

Figure 3a shows the development of built-up and transport area between 2009 and 2030 for German municipalities in percent ($LC_{r,02}$). The map is a result of the simulations with the Land Use Scanner model. Although the model simulates land use changes on grid-level they are hardly visible in a map for the whole of Germany. Therefore, the simulation results have been aggregated for municipalities. In this way regions with considerable changes in built-up and transport area can be highlighted. These are especially the densely populated cities in West Germany and around Berlin.

Figure 3b–d shows the deviation in built-up and transport area development of the particular alternative scenario to the reference scenario. Thus, the maps represent quantitative changes between alternative scenarios and the reference scenario. Furthermore, they represent different allocations of changes due to the implemented measures in the alternative scenarios. Blue and green colors therefore mean that the increase in built-up and transport area is much lower in the alternative scenario than in the reference scenario. Yellow color shows an equal development and red colored regions have a higher increase in built-up and transport area development in the alternative scenario than in the reference scenario.

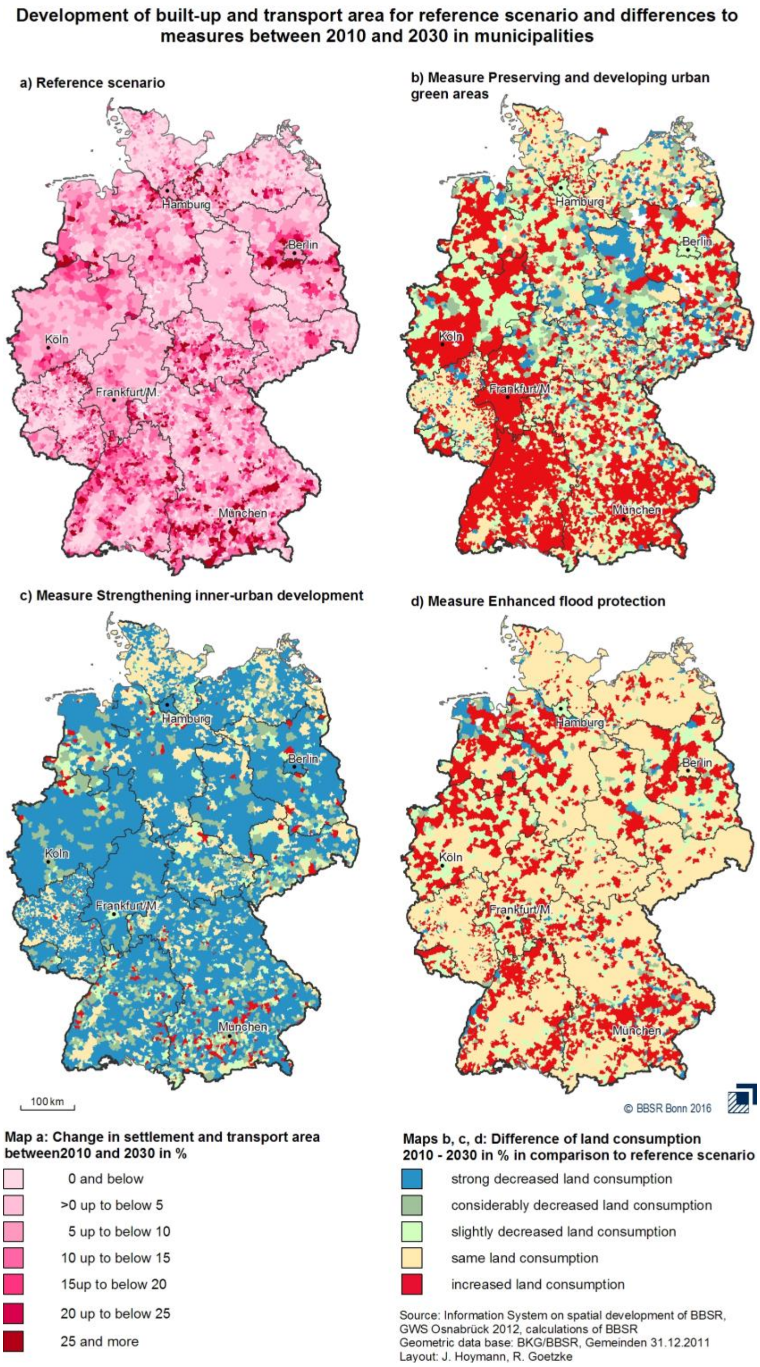

Figure 3. Developing built-up and transport areas for the reference scenario (**a**); and differences in measures in municipalities between 2010 and 2030 ((**b**) preserving and developing urban green areas; (**c**) strengthening inner-urban development; and (**d**) enhanced flood protection).

Figure 3b shows that built-up and transport area will strongly increase for large parts of western and southern Germany. In these areas a number of large prosperous and highly densified cities are located, where a development of urban green within the existing built-up area is difficult. Therefore, more land is consumed at the urban boundary for lower density housing and urban green areas. In the eastern part of the country land consumption is considerably lower than in the reference scenario. This is due to the use of vacancies and the demolition of buildings to satisfy the demand for recreational areas.

In this spatial context, the measure "Strengthening inner-urban development" has very different effects (Figure 3c). In some regions more than half of the built-up area demand could be met by stronger internal development. Examples include Berlin and its surrounding region, parts of the Ruhr area or several regions in Lower Saxony. In other regions characterized by strong urban sprawl, however, the inner-urban development can only cover a part of the demand for space. Due to the high demand, the potential is already largely exhausted (e.g., Munich and surroundings). Another reason is that in economically prosperous regions with a rural settlement structure only a few vacancies or brownfields exist (e.g., Emsland, Upper Bavaria, and Swabia). Even regions that have a very high inner-urban development potential, such as the Altmark, can reduce their built-up and transport development only to a limited extent. The reason is that the demand for built-up areas has already come largely to a standstill and that the existing potentials cannot be used. Recreational areas and national traffic infrastructure projects (e.g., A14 motorway) contribute to further land consumption. This development will not be affected by the measure.

The fact that the decline is not even higher depends first and foremost on the regional mismatch of demand for housing and the availability of vacant buildings or brownfields. A breakdown of the "Increasing built-up and transport areas" indicator into the various land use types (Table 4) reveals that the decline in land consumption is primarily driven by the buildings and open space category. The small decline in traffic area development is closely linked to the building and open space development, as fewer access roads are required due to the lower expansion of built-up areas.

Figure 3d shows solely the different allocation of built-up and transport area demand in comparison to the reference scenario, because the demand figures are the same in both scenarios. It can clearly be seen, that single municipalities that are located directly at a river have a lower increase in built-up and transport area development while municipalities located within some distance to the river system have an increase. This illustrates the different allocation of land uses due to the changes in the suitability maps. Therefore, less built-up and transport area development takes place in areas prone to extreme flood events.

3.2. Indicator Increasing Built-Up and Transport Area in Flood Prone Areas

The result of this calculation for all scenarios is shown in Figure 4. Figure 4a shows the indicator IND_FL for the reference scenario. Land consumption by built-up and transport is considerable in areas prone to extreme flood events ($HQ_{extreme}$). In Figure 4b–d, land consumption in flood-prone areas by 2030 ($IND\_FL_{r,02}$) is illustrated. Only in Figure 4d, $HQ_{extreme}$ areas are taken into account as priority areas. This figure illustrates two issues: First, the flood risk for built-up and transport areas can significantly be reduced by designating further priority areas for flood protection in the vast majority of the counties. Exceptions are the counties in which the built-up area demand is very high and in which, at the same time, the amount of available open space outside flood-prone areas is very small. Secondly, it appears that areas that have been affected by the flood in 2013 on the Elbe and its tributaries, seem to have a comparatively low flood risk. This is due to the small built-up area demand and a sufficient number of retention areas compared with the national average.

The indicator also shows a slight improvement for some regions in the scenario that aims at "Preserving and developing urban green areas" (Figure 4b). Affected areas are for example in Brandenburg, Saxony-Anhalt or Mecklenburg-Western Pomerania. As mentioned earlier, in these regions buildings can be demolished and the corresponding areas can be developed as urban green, thus the demand for built-up and transport area decreases.

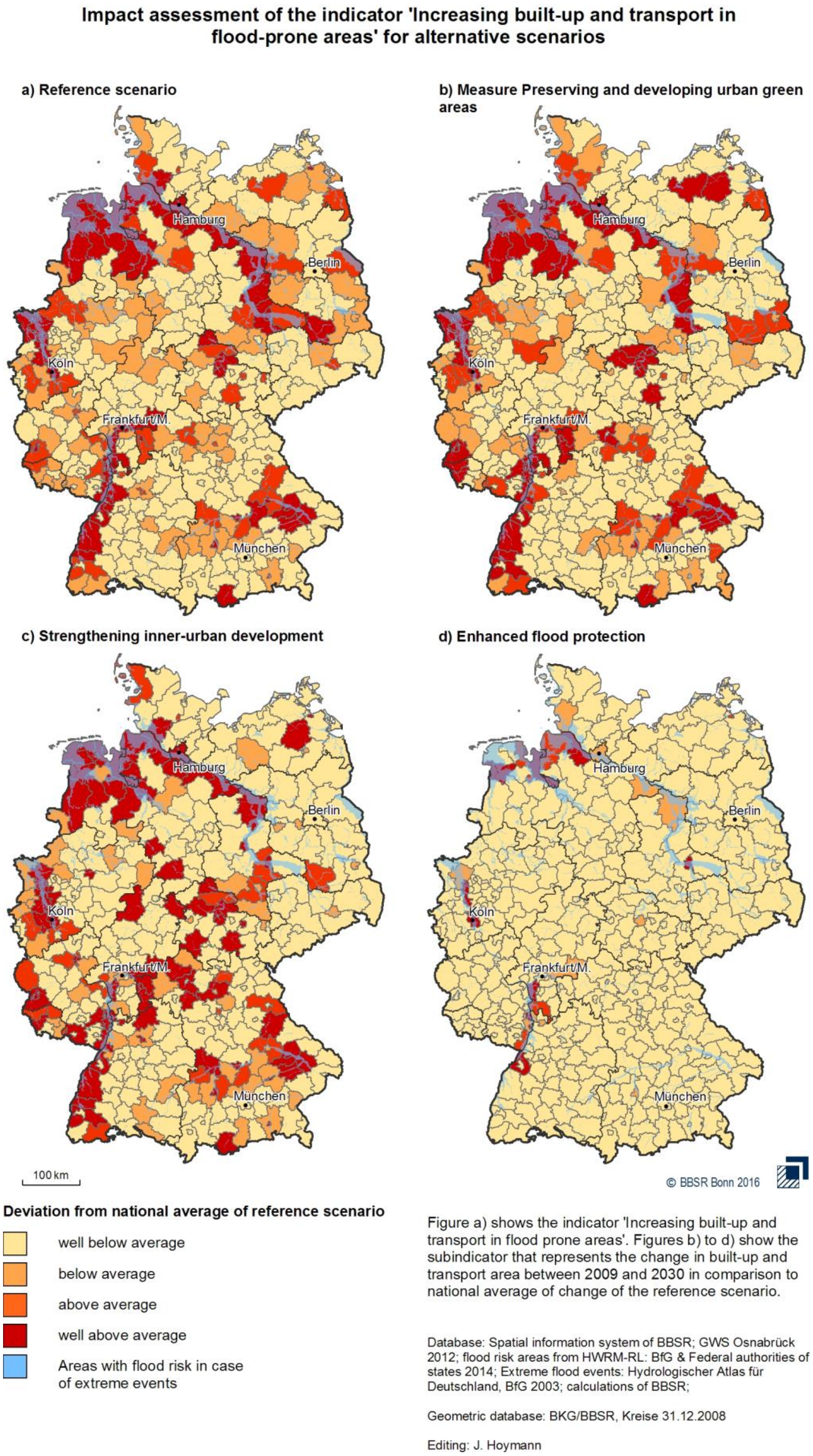

Figure 4. Increasing built-up and transport in flood prone areas. Comparing the (**a**) reference and alternative scenarios with: (**b**) "Preserving and developing urban green areas"; (**c**) "Strengthening inner-urban development"; and (**d**) "Enhanced flood protection".

Figure 4c shows that the measure leads to a considerable relief of areas prone to extreme flood events in regions that have only small demands for built-up and transport area. Those regions with high pressure on land due to considerable demand for built-up and transport area like Bavaria, the Hamburg region or the surrounding of Stuttgart also show an above average development of built-up and transport in areas prone to extreme flood events.

3.3. Indicator Increasing Built-Up and Transport Area in Areas with Thermal Heat Load

Figure 5a shows that large parts of the areas with thermal heat load are those with a considerable increase in built-up and transport area anyway. The measure is effective particularly in regions that have a high proportion of brownfields or vacant lots and with a low demand for built-up and transport areas (Figure 5b). In these regions, there are more developments of new green areas or demolition activities. This is particularly the case in parts of Saxony, in southern Brandenburg as well as in parts of Thuringia and Saxony-Anhalt. However, the total demand for new built-up and transport areas increases by the consistent application of the measure, because the possibilities of inner development are limited and a lower housing density is sought. For some regions, the consequence is that the "Increasing built-up and transport area in areas with thermal heat load" indicator slightly increases because of higher building and open space development compared to the reference scenario. As a result, there are only a few differences between the alternative scenario implementing the measure "Preserving and developing urban green areas" and the reference scenario because in many regions the positive effects resulting from a better accessibility of urban green and blue structures are offset by a higher land consumption of built-up and transport areas (including urban green areas) in thermally polluted areas.

It is striking that the measure "Strengthening inner-urban development" has a more distinctive effect than the measure "Preserving and developing urban green areas". Reasons might be the strong influence of the sub-indicator land consumption. As explained earlier, land consumption is considerably lower for the measure "Strengthening inner-urban development". As an improvement mainly occurs in the regions that have a low availability of free space per capita (south-west of Germany), but at the same time land consumption can be reduced, a weighting of the sub-indicators is considered in order to reach plausible results.

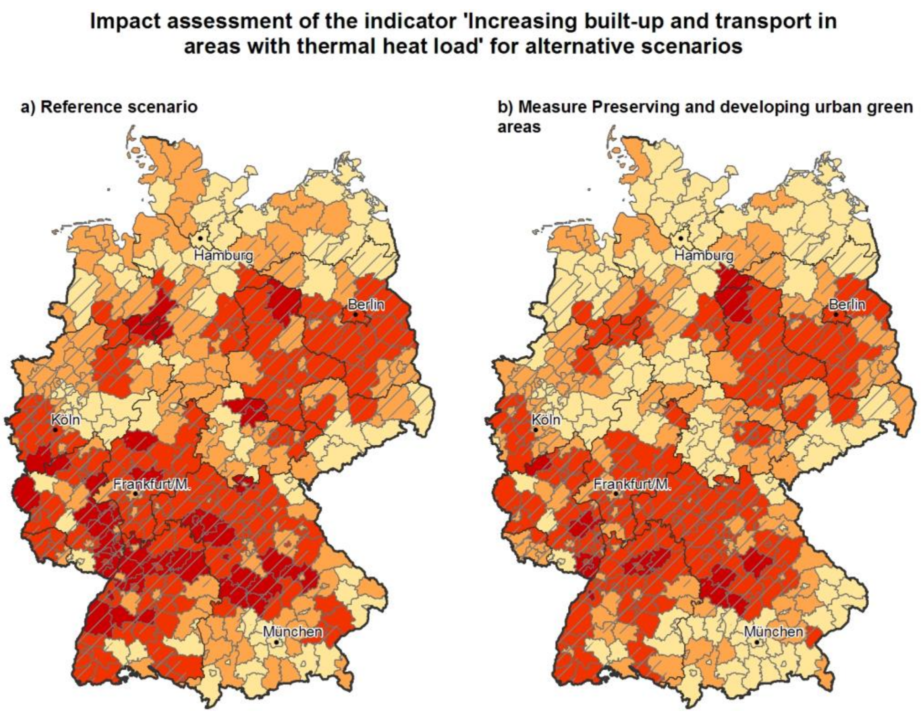

Figure 5. *Cont.*

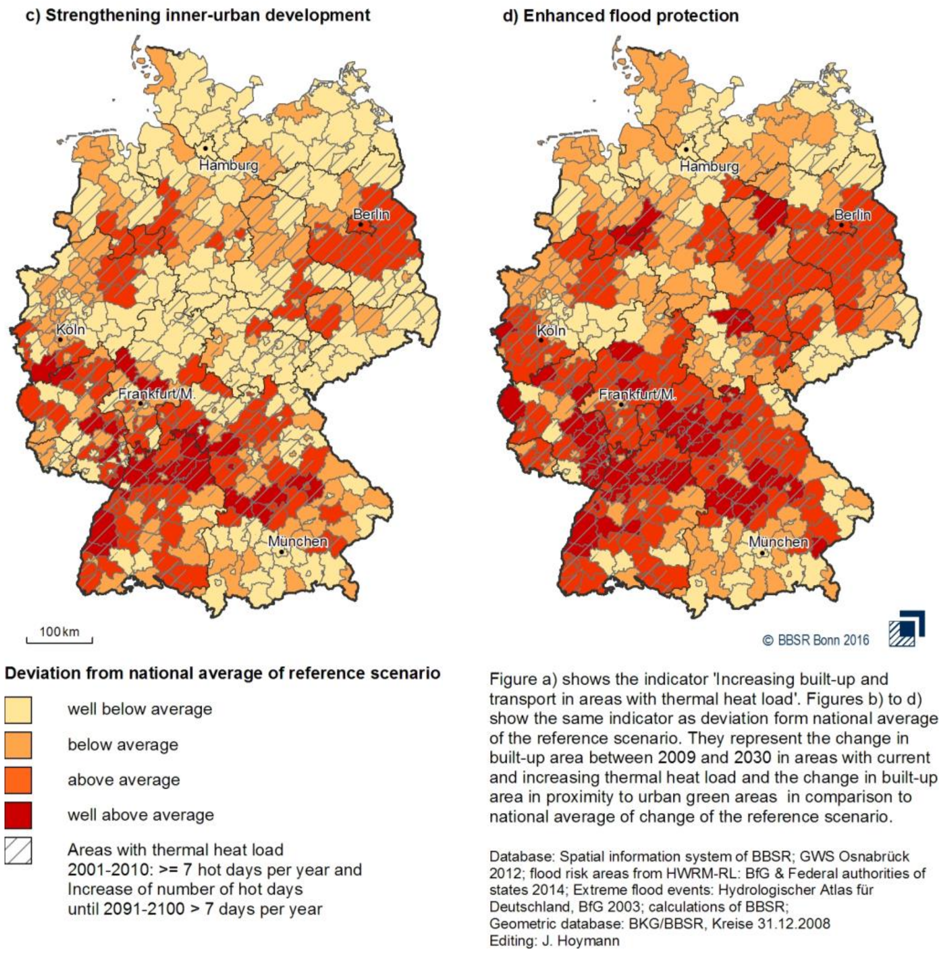

Figure 5. Land consumption in areas with heat stress. Comparing the (**a**) reference and alternative scenarios with: (**b**) "Preserving and developing urban green areas"; (**c**) "Strengthening inner-urban development"; and (**d**) "Enhanced flood protection".

4. Discussion

Even if the largest effect to reduce land consumption through inner-urban development can be seen in core cities and densely populated regions, the implementation of the measure is especially important in rural areas and in small- and medium-sized cities. The reason is that inner-urban development counteracts the emptying of city centers and the obliteration of neighborhoods and helps to maintain lively villages and towns. To develop political measures or incentives is beyond this study.

The contrasting juxtaposition of the scenarios shows that a reduction of built-up and transport area development has a considerable impact on the thermal relief than relocating the demand to the municipal border. A qualitatively development of built-up and transport area with adequate urban green space is therefore a prerequisite. Future research should analyze the optimal relationship between densification of settlement development and the appropriate supply of urban green spaces. Nevertheless, the weighting of sub-indicators needs to be analyzed in a next step.

Strengthening inner-urban development not only provides a contribution to thermal relief, but it also reduces the damage potential of extreme flood events in some areas. Thus, the measure does not only contribute to climate change mitigation but also contributes to several areas of climate change adaptation.

5. Conclusions

This article has shown how it is possible to evaluate the effect of policy measures to control the settlement development through the combination of methods of land use modeling with scenario techniques and an indicator-based measurement approach. Based on empirical data on current and past trends of settlement development, a reference scenario of land use has been calculated for 2030. Various measures that contribute to climate change mitigation, the adaptation to climate change or natural and environmental protection have been drawn based on the reference scenario. Indicators were developed that allow an assessment of the individual measures. Most indicators are composed of several sub-indicators, which are included with equal weighting in the calculation.

Based on the presented results it can be illustrated that different social objectives may cause different patterns of settlement development. Strengthening the inner-urban development leads to an economical use of soil resources and supports climate change mitigation. With respect to climate change and the expected increasing number of hot days, the objective is to ensure the sufficient accessibility and quality of urban green areas. To achieve this objective may lead to an increase in land consumption due to the increased demand for urban green areas. However, this demand does not cause an increase in sealed surfaces. Nevertheless, there is potential for conflict between the strengthened inner-urban development and the need to adapt to climate change, which is why it requires an in-depth examination of the various development and conservation objectives in urban land use management. It is clear that the relevant measures may not be mutually exclusive. Instead, we need strategies for sustainable urban development that combine aspects for climate change mitigation and adaptation to climate change [29].

One important aspect has to be considered when interpreting the model results. As documented in Goetzke and Hoymann (2016), a large amount of data from different sources were used to calculate the suitability maps [27]. The thematic accuracy of the datasets shall not be discussed here but inaccuracies due to different spatial resolutions, different base years or thematic resolution are probable. All spatial datasets have been resampled to a 100 m grid. Since some datasets have a lower resolution, the resampling pretends an accuracy that is not inherent to the data. However, it can be expected, that this inaccuracy in the input data is smaller than the inaccuracy in results when not using the datasets. A similar assumption can be made for the different base years. The ambition was to collect the most up-to-date datasets for the calculation of the suitability maps. Most of the datasets are updated frequently but for different points in time. Considering the applied land use classification, the ambition was to apply rather homogenous land use types. That is why the urban land use types have been differentiated into four types. By this, it was possible to simulate scenarios that focused on certain land uses and to get an insight into the development of settlement areas without using a specific urban growth model.

The decision to apply the Land Use Scanner model was helpful since in the scenarios not only urban growth was simulated but also shrinkage as well as relocation of parts of settlement areas. The applied model is very flexible to these kinds of developments.

In the next step of the work, the measures are combined with each other to obtain land use strategies. This leads to three more scenarios (climate change mitigation, adaptation to climate change and natural and environmental protection) that are evaluated in each case with several of the indicators presented.

Starting from an empirical database, a model such as the Land Use Scanner allows to develop scenarios of land use change and to derive indicators with policy-relevant statements. To assess specific individual projects with this approach is not possible, but it can help support decision-makers at the national or federal state level in assessing the impact of measures or instruments and initiate discussion processes.

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