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Beyond the urban-rural dichotomy: Towards a more nuanced analysis of changes in built-up land

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ABSTRACT

Urban land and rural land are typically represented as homogenous and mutually exclusive classes in land change analyses. As a result, differences in urban land use intensity, as well as mosaic landscapes combining urban and rural land uses are not represented. In this study we explore the distribution of urban land and urban land use intensity in Europe and the changes therein. Specifically, we analyze the distribution of built-up land within pixels of 1 km^2. At that resolution we find that most built-up land is distributed over predominantly non-built-up pixels. Consistently, we find that most urban land use changes between 2000 and 2014 come in small incremental changes, rather than sudden large-scale conversions from rural to urban land. Using urban population densities, we find that urban land use intensity varies strongly across 1 km^2 pixels in Europe, as illustrated by a coefficient of variation of 85%. We found a similarly high variation between urban population densities for most individual countries and within areas with the same share of built-up land. Population changes have led to different combinations of urban land expansion and urban intensity changes in different study periods (1975–1990, 1990–2000, and 2000–2015) and countries. These findings suggest that land use change models could be improved by more nuanced representations of urban land, including mosaic classes and different urban land use intensities.

1. Introduction

The majority of the land surface of the Earth has been modified for use by humans, leading to a reduction and fragmentation of natural habitat, alteration of nutrient and water cycles, and changes in the supply of ecosystem services (Ellis et al., 2013; Schroter, 2005). Throughout human history, land use was primarily related to the production of food. Yet, due to population growth, economic developments, and migration, urban land occupies a rapidly increasing share of the land (Angel, Parent, Civco, Blei, & Potere, 2011; Seto, Guneralp, & Hutyra, 2012). This rapid increase is expected to continue in the near future, and the projected demand for urban land is of the same order of magnitude as the demand for cropland, pastures, and biofuel production (Lambin & Meyfroidt, 2011). Urban land expansion has large impacts on the environment, for example through land take and the reduction of food production (van Vliet, Eitelberg, & Verburg, 2017), soil sealing and alteration of biogeochemical and hydrological cycles (Scalenghe & Marsan, 2009), and habitat degradation affecting biodiversity (Seto et al., 2012). Therefore, it is increasingly important to include urban land in large-scale land change assessments.

Maps that underlie analyses of urban land use change and form the starting point of land use change scenarios typically include a strict urban-rural dichotomy: a location is either urban land, or it is one of several non-urban classes. This is for example the case in land use change assessments at the European scale (Lotze-Campen et al., 2018; Schulp, Van Teeffelen, Tucker, & Verburg, 2016; van Delden, van Vliet, Rutledge, & Kirkby, 2011), as well as in large-scale assessments in other world regions (Jiang, Deng, & Seto, 2013; Pijanowski et al., 2014; Sohl et al., 2012). This dichotomy originates from remote sensing image classification, as pixels typically have the land use associated with the predominant land cover in a location, such as cropland and forests (Verburg, van Asselen, van der Zanden, & Stehfest, 2013). Urban land use is typically associated with locations that are predominantly built-up, while mosaics of urban and non-urban land use, such as peri-urban land and village landscapes, are largely classified as non-urban land cover. In addition, homogenous classes cannot distinguish urban intensity. Hence, urban centers and suburban areas are essentially represented as one and the same, even though these classes differ widely.

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This simplified representation of urban land limits the analysis of urban land use change processes, as it restricts changes to a conversion of non-urban to urban land, and thus hampers the assessment of future land use change scenarios and policy impacts.

The aim of this paper is to analyze (1) the spatial variation in the distribution of urban land in Europe and recent changes therein, as well as (2) the spatial variation in urban intensity in Europe and recent changes therein. For the first analysis we expect that land is distributed along a gradient form completely rural to completely urban, with most urban land included in predominantly non-urban pixels. As a consequence, we hypothesize that the conventional interpretation of land uses as related to the predominant land cover in a pixel leads to an underestimation of the total amount of urban land. Consistently, we expect that urban land use change mostly consists of small incremental increases of the amount of urban land in a pixel, rather than sudden conversion from completely rural to completely urban pixels. For the second analysis we expect that there is a large variation in urban land use intensity, and also in changes in urban land use intensity. Overall we expect that the current representation of urban land as one homogenous class misses essential variation in urban land use and urban land use changes. We discuss our findings in the context of land use change models and their capacity to assess future urban land use changes, and suggest how findings in this study could improve current practice.

2. Materials and methods

This paper presents three separate analyses of urban land use and urban land use change. First, we analyze the distribution of urban land and urban land use changes in Europe; second, we analyze the effects of spatial aggregation on the representation of urban land; and third, we analyze the variation in urban land use intensity and urban land use intensity changes. Table 1 provides an overview of these analyses and their main characteristics. In the rest of this paper we refer to *urban* as a land use class, while we refer to *built-up* as the land cover type that we use as a proxy to identify urban land use, consistent with the interpretation in most land use maps. Urban land use therefore includes all areas that are predominantly built-up, regardless of their size, hence including the full range from small villages to large metropolises. We did not further differentiate between different urban land use types, such as residential, commercial, and industrial use, as data on built-up land often does not allow such differentiation. Urban land use intensity is assessed based on urban population density. We acknowledge that urban land use intensity can have other dimensions, but population density was the only indicator for urban land use intensity for which spatial data was available.

Our analyses are conducted for Europe, which comprises all EU-28 countries as well as the countries of the European Free Trade Association, i.e. Iceland, Norway, Switzerland, and Lichtenstein. Moreover, we zoom in on the Netherlands, Switzerland, and Romania for a more detailed discussion of urban land use patterns in different geographical and planning conditions, because we expect that these conditions affect the distribution of urban land and urban land use changes. The Netherlands has long been known for its relatively efficient planning, with the aim to reduce sprawl and concentrate urban functions (Halleux, Marcinczak, & van der Krabben, 2012). Therefore we expect the Netherlands to have a rather strict separation between urban and rural land. Switzerland has a variety of spatial planning regimes at the cantonal level, but land use is also influenced by a rugged topography in large parts of the country (Knoepfel & Nahrath, 2007), which we assume to lead to a more scattered urban land pattern as compared to the Netherlands. Romania is characterized by a still immature spatial planning system, developed in the post-socialist era (Munteanu & Servillo, 2014), which we expect to yield a rather dispersed urban land pattern.

Table 1
Overview of data used for the analyses in this study. Note that the data for built-up area in 2014 is used in combination with the population data for 2015, colloquially referred to as the data for the year 2015 in the analysis of urban land use intensity.

Analysis	Related hypothesis	Data sets used	Temporal extent of the analysis	Spatial extent of the analysis
(1)	Absence of urban-rural dichotomy at the scale of 1 km^2 pixels	GHS built-up grid (Pesaresi et al., 2015)	1975, 1990, 2000, and 2014	Europe, the Netherlands, Switzerland, and Romania
	Loss of urban land after majority aggregation	Globeland 30 (Chen et al., 2015)	2010	the Netherlands, Switzerland, and Romania
	Absence of sudden rural-to-urban land conversions at the scale of 1 km^2 pixels	GHS built-up grid (Pesaresi et al., 2015)	Change in the period 2000–2014	Europe, the Netherlands, Switzerland, and Romania
(2)	Large variation of urban intensity at the scale of 1 km^2 pixels	GHS built-up grid (Pesaresi et al., 2015), GHS population grid (Freire, MacManus, Pesaresi, Doxsey-Whitfield, & Mills, 2016)	2015	Europe, the Netherlands, Switzerland, and Romania
	Large variation in urbanization pathways (intensification / expansion)	GHS built-up grid (Pesaresi et al., 2015) GHS population grid (Freire et al., 2016)	Changes in the periods 1975–1990, 1990–2000, and 2000–2015	All countries in Europe

2.1. Analysis of the distribution of urban land use and urban land use change

The distribution of urban land use is assessed based on the percentage of built-up area per 1 km^2 pixel, using the Global Human Settlements (GHS) built-up grid. The GHS database is a multi-temporal data set, which presents the percentage of built-up land within pixels of 1 km^2, as derived from 30 m resolution Landsat imagery (Pesaresi et al., 2015). We reclassified the GHS data in bins with increasing amount of built-up land, in order to draw a histogram and analyze their distribution. Each bin has a width of 5%, hence these bins represent the pixels that have between 0% and 5% of built-up land, between 5% and 10% of built-up land, etc. We sum the total amount of built-up land within each bin in order to assess the distribution. When most pixels can be characterized as either predominantly rural or predominantly urban, the histogram of this distribution will be skewed towards the higher percentages, i.e. a relatively high amount of built-up land in pixels that have a high percentage of built-up, and a relatively low amount of built-up land in pixels that have a low percentage of built-up land. We hypothesize that such distribution does not exist, and we accept this hypothesis if less than half of the total built-up area is found in pixels with > 50% built-up.

We assess the distribution of urban land use changes using the change in built-up area per pixel, between 2000 and 2014, as derived from the same GHS data. For each 1 km^2 pixel we calculate the difference in the percentage of built-up land between both years, and reclassify these differences in 5% bins. If pixels can be characterized as either predominantly rural or predominantly urban, changes in built-up land should typically be large, representing a conversion from predominantly rural to predominantly urban land. Instead, according to our hypothesis, we expect that most urban land-use changes will be rather small. We accept this hypothesis when more than half of the new built-up area comes in fractions of < 50% of a 1 km^2 pixel.

To further analyze the effect of representing urban land use only in pixels that are predominantly built-up, we analyze the change in built-up land as a result of a majority aggregation from fine-resolution data. We conduct this analysis by aggregating land cover data at a 30 m resolution to pixels of 1 km^2, as well as to multiple other resolutions in between. Such aggregation resembles the interpretation in land use models, as pixels showing land use based on the predominant land cover, and a 1 km^2 resolution is rather common in national to continental land use change models (Schulp et al., 2016; Sohl et al., 2012; van Delden et al., 2010). As fine resolution data we use the Globeland30 dataset, instead of the Global Human Settlements data, because Globeland30 has multiple non-urban land cover classes, which allow for a more realistic assessments of the consequences of a majority aggregation. Globeland30 is a global land cover data set based on Landsat imagery (Chen et al., 2015). A majority aggregation will favor classes that come in larger patches, at the cost of land covers that occur in smaller patches. If our hypothesis about the distribution or urban land over 1 km^2 pixels holds true, this will yield a net loss of urban land after aggregation, and this loss will be larger for aggregation to coarser resolutions and for areas with more scattered urban land (e.g. we hypothesize a larger effect in Romania and a smaller effect in the Netherlands).

2.2. Analysis of the variation in urban land use intensity and changes in urban land use intensity

We analyze the variation in urban land use intensity based on the variation of urban population density in the year 2015. Urban population density is calculated as the population density in a 1 km^2 pixel divided by the percentage of built-up land the same pixel, which were taken from Global Human Settlements Layer population density grid for 2014 (Freire et al., 2016) and built-up grid for 2015 (Pesaresi et al., 2015), respectively. This calculation implicitly assumes that all people live in built-up areas, while some people might also live in areas that are not indicated as urban land. For that reason we restrict this analysis to pixels with at least 10% built-up land, as the effect of our assumption could be large in pixels with < 10% built-up land. Variation in urban land use intensity is expressed in terms of the coefficient of variation (CV), i.e. the standard deviation of the urban population density divided by the mean of all pixels. Moreover, we also assess whether urban land use intensity is related to the percentage of built-up land in a pixel, by calculating the mean and CV for each bin of 10% built-up land separately. We accept our hypothesis of a 'large variation' in urban land use intensity when the CV is higher than 50%.

Subsequently, we analyze how changes in population relate to urban land use intensification and urban expansion at a pixel level in the different countries in Europe. For this analysis we calculate for each 1 km^2 pixel the change in population density and the change in built-up land, for the periods 1975–1990, 1990–2000, and 2000–2015. For each period, the contribution of population change to urban land use intensification ($Urban_{Intensification}$) and urban expansion ($Urban_{Expansion}$), respectively, was calculated as:

$$Urban_{intensification} = \sum_i \Delta D_i * A_{end_i}$$

$$Urban_{expansion} = \sum_i \Delta A_i * D_{start_i}$$

where ΔD_i represents change in population density in pixel i in a given time period and A_{end_i} represents the built-up area in pixel i at the end of that time period. Conversely, ΔA_i represents change in built-up area in pixel i in a given time period and D_{start_i} represents the population density in pixel i at the start of that time period. Subsequently, we sum over all pixels within a country, and compare results per country to assess the different urbanization trajectories in the respective countries.

The population density grid used in this analysis presents results at a 1 km^2 resolution, but these population densities are the result of a downscaling exercise from large spatial units (Freire et al., 2016). The average size of administrative units from which population density data is derived is 17 km^2 for Europe (Doxsey-Whitfield et al., 2015). The heterogeneity within these administrative units is not represented, which means that actual variation in urban population density at a pixel level might be higher than reported in this study. Moreover, the maps of population density for individual years are not entirely independent, as in some cases estimates from different years are based on the same fine scale data but adjusted for population growth over time at a coarser scale (Doxsey-Whitfield et al., 2015). While this dependency hampers analysis on the pixel level, it does not constrain analysis on the country level, as the spatial units within which population growth is calculated is much smaller than the size of a country. Therefore, analyses of changes in urban population density are all presented at the national level without considering heterogeneity at the pixel level.

3. Results

3.1. Distribution of urban land use and urban land-use change in Europe

The distribution of built-up land over pixels of 1 km^2 shows that the majority of all built-up land in Europe is found in pixels that are < 50% built-up (Fig. 1, top-left). In other words, the majority of all urban land use is found in locations that are predominantly rural. This observation also holds for The Netherlands, Switzerland, and Romania (Fig. 1, top-row), yet large differences exist between these countries. In the Netherlands, a relatively large share of built-up land is actually found in predominantly urban pixels (almost half of all built-up land is found in pixels with > 50% built-up land). The opposite is true for Romania, where most built-up land is found in small fraction of otherwise rural areas, while Switzerland is somewhere in between The Netherlands and Romania. A similar analysis of earlier time periods shows a very similar

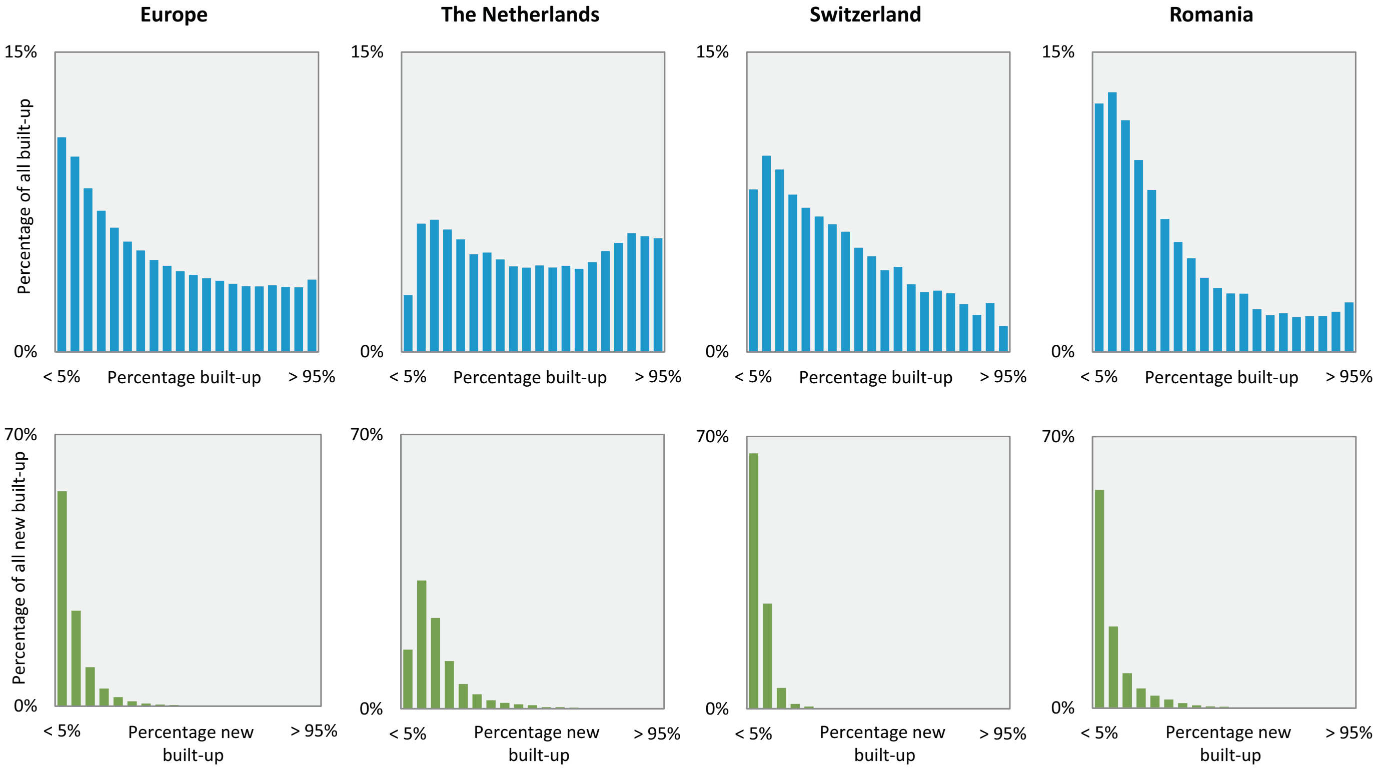

Fig. 1. Distribution of built-up land in 2014 as a function of the percentage of built-up land within a pixel and changes in built-up land between 2000 and 2014 as a function of the percentage increase of built-up land within a pixels in Europe and selected countries. All graphs have the same scale on the y-axis to allow for cross-country comparisons.

figure, but with slightly higher shares of the built-up area in pixels with a lower percentage of built-up land (See Supplementary material). The increase in built-up land in Europe between 2000 and 2014 was mainly the consequence of small increases in built-up land in many pixels, while hardly any conversions from completely rural to completely urban were observed (Fig. 1, bottom-left). For The Netherlands, Switzerland and Romania new built-up all came in small fractions of a pixel, although these fractions were smallest in Switzerland and largest in the Netherlands (Fig. 1, bottom row).

Aggregation of Globeland30 data leads to a net loss of built-up land for all aggregated resolutions except for the highest resolution, and for all countries (Table 2). The net loss in built-up area increases with decreasing resolution after aggregation for all countries, leading to a loss in built-up area of 17%, 24%, and 40% in the Netherlands, Switzerland and Romania, respectively, for aggregation into pixels of 1 km^2. These numbers reflect the different distributions of built-up land in these countries, consistent with the results shown in Fig. 1. The Netherlands shows the smallest underrepresentation of built-up land, which is due to the relatively large and compact built-up areas. The smaller but compact villages of central Switzerland are sometimes maintained, but several settlements are lost in the aggregation process. The small and linear villages in the Carpathian Mountains of Romania are almost completely lost in a majority aggregation, leading to large underrepresentation of built-up land on the national level. Fig. 2 provides a representative snapshot of each country, illustrating underrepresentation in built-up land due to majority aggregation in distinct urban structures.

3.2. Distribution of urban land-use intensity and urban land-use intensity change in Europe

At the European level we find a mean urban population density of 3011 people per km^2 of built-up land in 2015, with a standard deviation of 2571 people per km^2 built-up land, yielding a coefficient of variation (CV) of 85%. Urban population density, however, differs markedly between countries, ranging from 1837 inhab./km^2 of built-up land in Norway to 9755 inhab./km^2 of built-up land in Lichtenstein (See Supplementary material for results of all individual countries). Similar to the variation in urban population density, the CV in urban population density differs between countries, ranging from 25% in Luxembourg to 137% in Norway. The values for case study countries, the Netherlands, Switzerland, and Romania, are 2339 ± 61%, 2823 ± 62% and 3188 ± 81%, respectively. When we analyze the variation within pixels with a similar fraction of built-up land, we find that the mean urban population density increases with higher fractions of built-up land (Table 3). Yet, at the European level, the CV is higher

Table 2
Changes in built-up area for the 2010 land cover map after majority aggregation to different resolutions.

Country	Built-up area at original 30 m resolution	Change in built-up area after majority aggregation			
		100 m	250 m	500 m	1000 m
The Netherlands	5134 km^2	−0.2%	−2.5%	−9.1%	−17.0%
Switzerland	2042 km^2	0.0%	−1.3%	−6.7%	−22.2%
Romania	13,738 km^2	0.2%	−1.4%	−12.6%	−40.0%

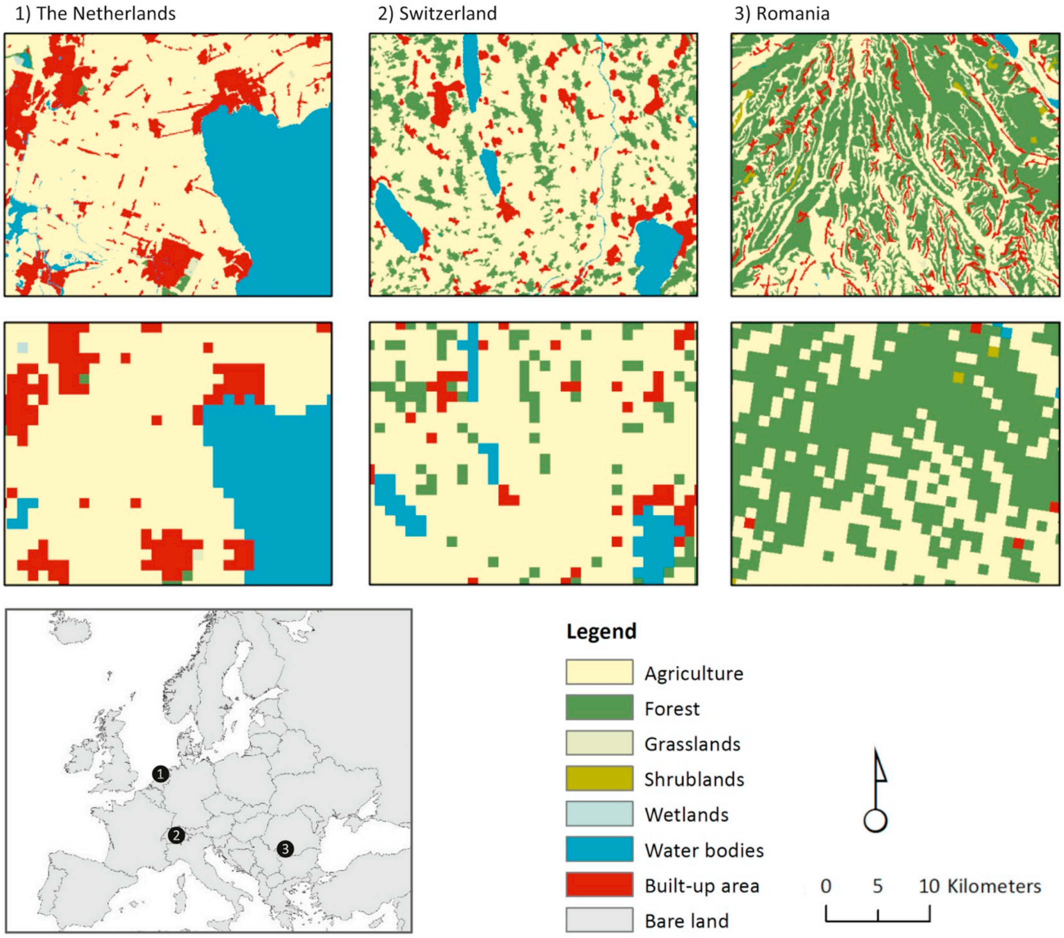

Fig. 2. Illustration of the consequences of majority aggregation within 1 km2 pixels on built-up land.

50% for all categories, indicating that there is a high variation within each class as well as across these classes. Within the case study countries we find several built-up density classes with a CV below 50%, especially in the Netherlands and Switzerland. These values reflect a more homogenous distribution of urban intensity, which could reflect the settlement structure in both countries as these have relatively few extremes such as extensive low-density urban sprawl and intensive high-rise apartment blocks.

Changes in population can lead to changes in built-up land, changes in population density, or both. We analyzed the relation between population change and changes in built-up area for all countries in Europe for the time periods 1975–1990, 1990–2000, and 2000–2015. Between 1975 and 1990, population increased throughout Europe, and most of this population increase was accompanied with a large increase in built-up land and a small decrease in urban population density. This is shown in Fig. 3 in the relatively large and positive red bars and small negative blue bars for this time period. After the 1990s, urban change patterns diverged (see Fig. 3 for case study countries and Supplementary material for all countries in Europe). In several post-socialist countries, including Romania, the total population decreased or remained stable while the built-up land area increased and the urban population density decreased, representing urban disintensification. In several western European countries, such as Switzerland, population continued to increase in parallel with only a moderate amount of urban expansion. Instead, urban population density increased in these countries, thus representing urban intensification. A third group of countries, including the Netherlands, continued their historic trend of built-up land increase in parallel with population growth and only a small increase in

Table 3
Mean urban population density and coefficient of variation in Europe, in bins of different shares of built-up area for the year 2015.

Percentage built-up area	Europe		The Netherlands		Switzerland		Romania	
	Mean	CV	Mean	CV	Mean	CV	Mean	CV
Between 10% and 20%	2599	106%	1706	70%	2349	63%	2841	74%
Between 20% and 30%	2737	79%	1961	61%	2625	54%	2775	75%
Between 30% and 40%	2945	69%	2239	54%	2882	54%	2986	78%
Between 40% and 50%	3203	64%	2616	46%	3147	49%	3436	83%
Between 50% and 60%	3481	61%	2847	42%	3699	51%	4151	74%
Between 60% and 70%	3752	57%	3049	41%	3974	58%	4699	76%
Between 70% and 80%	4121	56%	3345	37%	4100	43%	6025	61%
Between 80% and 90%	4591	56%	3761	35%	5001	52%	7782	54%
Between 90% and 100%	5704	65%	4072	39%	6220	38%	8717	42%
All pixels > 10%	3011	85%	2339	61%	2823	62%	3188	81%

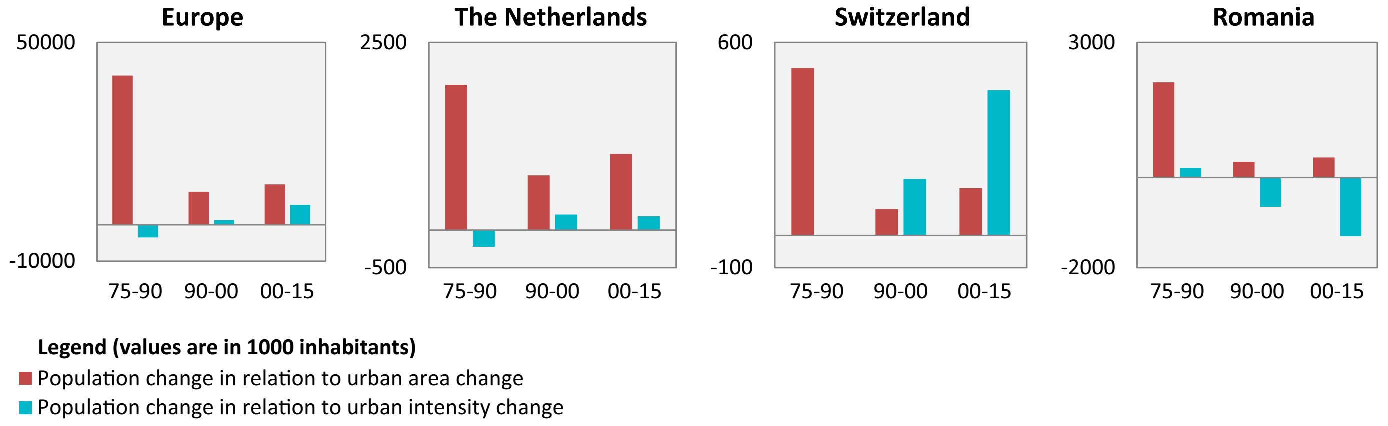

Fig. 3. Population changes related to changes in built-up land and changes in population density in Europe and three case study countries in the periods 1975–1990, 1990–2000, and 2000–2015. Positive values indicate urban expansion and urban intensification, while negative values indicate urban contraction and disintensification (i.e. decrease in population density).

population density, representing a trajectory of urban expansion.

4. Discussion

4.1. Urban land-use and urban land-use change in Europe

The distribution of built-up land over pixels confirms our hypothesis that no urban-rural dichotomy exists, as the majority of the built-up land is distributed in small fractions of otherwise non built-up areas. The distribution of built-up land differs between the Netherlands, Switzerland and Romania, but the absence of an urban-rural dichotomy was found in each country. Most built-up land expansion occurred as small incremental increases, rather than conversions of mostly rural pixels to mostly urban pixels. These findings confirm our hypothesis that urban change is mostly a gradual process rather than a sudden conversion of non-urban land to urban land. These findings also suggest that the focus of many studies on large metropolises (e.g. Bagan & Yamagata, 2012; Nkeki, 2016; see also Seto, Fragkias, Güneralp, & Reilly, 2011) might miss important urban change processes in smaller cities and peri-urban areas.

Consistently, a majority aggregation of high resolution land cover data leads to a underestimation of built-up land, which confirms our hypothesis that reflecting the predominant land cover in a pixel only leads to an underestimation of urban land use. While it is trivial that a majority aggregation yields a loss in information, it is not trivial a priori how this affects the amount of built-up land relative to other classes. As a result, the impacts of aggregation on the underestimation of the amount of built-up land depends on each countries' settlement pattern: clustered patterns (e.g. compact cities and large urban areas) lead to a small underestimation only, while more scattered development (e.g. villages, smaller cities and peri-urban areas) yield larger underestimations of the total amount of built-up land (Klotz, Kemper, Geiß, Esch, & Taubenböck, 2016; Liu, He, Zhou, & Wu, 2014). Such underestimations can have important implications for land use assessments as the combined effect of many small patches can have large impacts on the outcomes of, for example, analyses of the hydrological cycle and urban land take (Schueler, Fraley-McNeal, & Cappiella, 2009; van Vliet et al., 2017).

The differences in the distribution of built-up land as well as changes therein were qualitatively similar in all countries, but quantitatively different. These differences could reflect the differences in biophysical characteristics, but most likely also planning and policy aspects affecting urban growth (Hersperger et al., 2018). The Netherlands, for example, has been known for its relative extensive planning system, that has led to relatively large-scale yet compact urban expansion, as opposed to the more distributed and sometimes sprawling development in many other countries (Halleux et al., 2012). Consistently, the few open areas in the Netherlands have been preserved actively in the past (Koomen, Dekkers, & van Dijk, 2008). At the same time, the absence of such planning system, as well as the legacy of the socialist regime, has led to a much more dispersed settlement structure in Romania (Munteanu & Servillo, 2014).

The variation in urban population density, as expressed by CV values higher than 50% in Europe, as well as in almost all countries, generally confirms our hypothesis that there is a large variation in urban land-use intensity in Europe. Yet, there is a large difference between countries, and some have a much higher variation than others. This finding complements reported differences in population density between multiple large cities around the world (Angel et al., 2011; Schneider & Woodcock, 2008) and suggests that such differences extent to the entire spectrum from predominantly rural to mostly urban land, and within as well as across countries.

Urban change trajectories show a wide variety over time as well as across countries. In Europe, the period 1975–1990 was predominantly characterized by a urban expansion in combination with a small population decline in existing urban areas. After 1990, urbanization patterns started to change in several countries and as a result the intensity of existing urban areas increased in many countries in Europe. For example, in countries such as Switzerland and Austria, population growth was accompanied by a combination of urban expansion and an increase in population density in existing urban areas. At the same time, other countries, including Romania and Bulgaria, saw a decrease of population density in existing urban areas, in combination with urban expansion elsewhere. It should be noted, however, that built-up land can represent other uses than residential uses only, which can affect the analysis of urban land use intensity locally. Yet, because our analysis was conducted at a 1 km^2 resolution, and aggregated to the country level, we expect that such effects do not significantly affect our outcomes.

Observed urban intensity changes complement recent observations indicating that urban growth is associated with both intensification and disintensification (Wolff, Haase, & Haase, 2018). The differences between urbanization trajectories could be a result of biophysical, social and institutional differences. The decline in family sizes, due to decreased fertility in combination with increased life expectancy that is found in many European countries, is likely one of the drivers underlying these changes. This process leads to a larger number of households without necessarily increasing the population itself (Goldstein, Lutz, & Testa, 2003; Testa & Grilli, 2006). In addition, observed increases in urban population intensity also suggest that some planning measures have been successful, as compact development has been a characteristic of urban planning in several countries in Europe in recent decades (Halleux et al., 2012; Rudolf, Kienast, & Hersperger, 2018).

The results as presented in this paper are critically dependent on the resolution of the spatial data. We selected 1 km^2 because this resolution is frequently used in models that are underlying land use change scenarios at national scales or larger (e.g. Schulp et al., 2016; Sohl et al., 2012; van Delden et al., 2010). Using a higher resolution might yield a distribution of built-up land that is closer to a urban-rural dichotomy, i.e. including more pixels that are predominantly built-up. Such higher resolution will likely yield a somewhat larger number of changes that reflect a conversion from rural to urban land. Consistently, the underestimation of built-up land after aggregation will be smaller when the data is aggregated to a higher resolution than the 1 km^2 used in this study. Hence, this would reduce the size of our results, but it will not reverse them. Moreover, while higher resolutions provide more accurate delineation of built-up land strictly, lower resolutions also provide useful information on landscape structure and composition, which is relevant for land use change analysis as well as planning and policy support (Malek & Verburg, 2017; Verburg et al., 2013)

4.2. *Implications for land-use modelling for planning and policy assessments*

Land use models are an important tool for the analysis of land use changes as well as for the assessment of potential outcomes of plans and policies (Jantz, Goetz, & Shelley, 2004; Jiang et al., 2013; Lawler et al., 2014; Sterk, van Ittersum, & Leeuwis, 2011). Most models include one single class of urban land use, while this study shows that landscapes are characterized by a gradient from predominantly rural to predominantly urban, and that there is a wide variety in urban land-use intensity. While the analysis was conducted in Europe, we expect that results hold true for other regions as well, and especially in regions where landscapes are characterized by mosaics of urban and non-urban uses. This is for example the case in large parts of China that are characterized as village landscapes (Ellis et al., 2009), as well as in large parts of Africa that are still characterized by a low urbanization rate (Linard, Gilbert, Snow, Noor, & Tatem, 2012) and suggests that existing land use models could be improved by including a more nuanced representation of urban land.

A straightforward way to partly solve this issue is to increase the spatial resolution, which is increasingly possible as a result of recent advances in remote sensing (e.g. Chen et al., 2015). Yet, increasing the spatial resolution of a model would lead to much higher computational costs, and would require a higher resolution for data on explanatory factors used in the allocation of land use changes, both of which are currently still a constraint (Verburg et al., 2013). More importantly, a higher spatial resolution does not necessarily increase the accuracy of the data, nor does it necessarily increase the accuracy of the model, due to the intrinsic uncertainty in local land use change processes (Brown, Page, Riolo, Zellner, & Rand, 2005; Manson, 2007). On top of that, pixel-based analyses on a higher spatial resolution do not describe properties like landscape structure and composition, which are for example characteristic for peri-urban and village landscapes, as the classification is still based on the urban-rural dichotomy. Finally, differences in land use intensity cannot be represented this way. Therefore, we expect that the cell sizes of 1 km^2 or larger will remain relevant for large-scale land-change assessments in the near future, as is currently the case (Schulp et al., 2016; van Delden et al., 2011; van Vliet et al., 2016).

Several global products have presented built-up land as a percentage of a larger pixel, typically 1 km^2. These percentages are often the result of a spatial aggregation of fine-scale, dichotomous, land cover data, and occasionally derived from continuous data such as night-light intensity (Pesaresi et al., 2015; Potere, Schneider, Angel, & Civco, 2009). However, to our knowledge, such more nuanced representations, as well as representations of different urban land use intensities, have not been used in large-scale land use change models yet. A few applications have already made improvements to the representation of urbanization in land use models. For example, Mustafa et al. (2018) present a model that differentiates between low, medium, and high density urban areas, although densities are defined by the share of built-up land strictly, hence reflecting urban land cover composition and not urban land use intensity. Others have applied continuous field approaches, where urban activity such as population and jobs are distributed first, while land uses are only assigned afterwards based on the distribution of urban activities (van Vliet, Hurkens, White, & van Delden, 2012; White, Uljee, & Engelen, 2012). These so-called activity-based models simulate urban land use intensities and intensity changes, but they do not yet represent mosaic landscapes. Recent developments in the mapping agricultural landscapes could potentially be used to improve the characterization of urban land as well. These methods go beyond land use related to the predominant land cover, and include land cover composition and land use intensity in their classification (e.g. Ellis & Ramankutty, 2008; van Asselen, Verburg, Vermaat, & Janse, 2013; van der Zanden, Levers, Verburg, & Kuemmerle, 2016). Consistent with agricultural land use, urban land use change can manifest itself as intensification and expansion, and both processes affect other land uses differently. Therefore, these approaches offer a way forward to the representation and modelling of urban land use changes.

It is not clear a priori what characteristics is best used to represent urban land use intensity. This study used population density as this was the only characteristic for which consistent datasets were available. Yet other metrics of urban land use intensity are possible, such as floor area and economic or social activity (e.g. Louail et al., 2015). Such metrics could also reflect current urban planning initiatives that promote intensification and mixed land uses (Koomen, Dekkers, & Broitman, 2018), and the viability of several metrics has already been shown in several small-scale studies that analyze urban patterns (Lemoy & Caruso, 2017; McIntosh, Trubka, Kenworthy, & Newman, 2014; Taubenböck, Standfuß, Wurm, Krehl, & Siedentop, 2017). Further advancing these and potentially other approaches to improve the representation of urban land could greatly improve the our capacity to model land-use changes.

A more nuanced representation of urban land use, as suggested above, is needed to improve our capacity for model-based assessments of land use plans and policies. Currently available models can include measures that promote or regulate the conversion to urban land, but existing spatial plans often include much wider range of policy measure achieve more holistic visions than only restricting urban sprawl (Grădinaru, Iojă, Pătru-Stupariu, & Hersperger, 2017; Rudolf et al., 2018). Fig. 4 shows an example of a vision at the scale of interest from the Swiss “Raumkonzept Schweiz”. This is a strategic document that identifies envisioned types of urban and rural development at a broader scale, without explicitly providing restrictions at the very local level (ARE, 2012). These strategies for settlements and landscapes address development in terms of landscape mosaics and in terms of urban densification. This example illustrates that an improved representation of urban land use in land-change modelling as suggested above would be coherent with information in land-use plans and policies, thus confirming the need for further model development in this direction (Hersperger et al., 2018).

5. Conclusion

This study analyses the distribution of urban land and urban land use intensity in Europe as well as for separate countries within Europe. We find that there is a gradient between completely rural and completely urban land, with more than half of all built-up area in pixels that are predominantly rural. Similarly, we find a high variation in urban land use intensity in Europe and in the change trajectories in different countries. While some countries accommodate population growth with urban expansion, others increase the population density within existing urban areas, especially in more recent time periods. This suggests that the dichotomous representation of urban land and rural land, which is

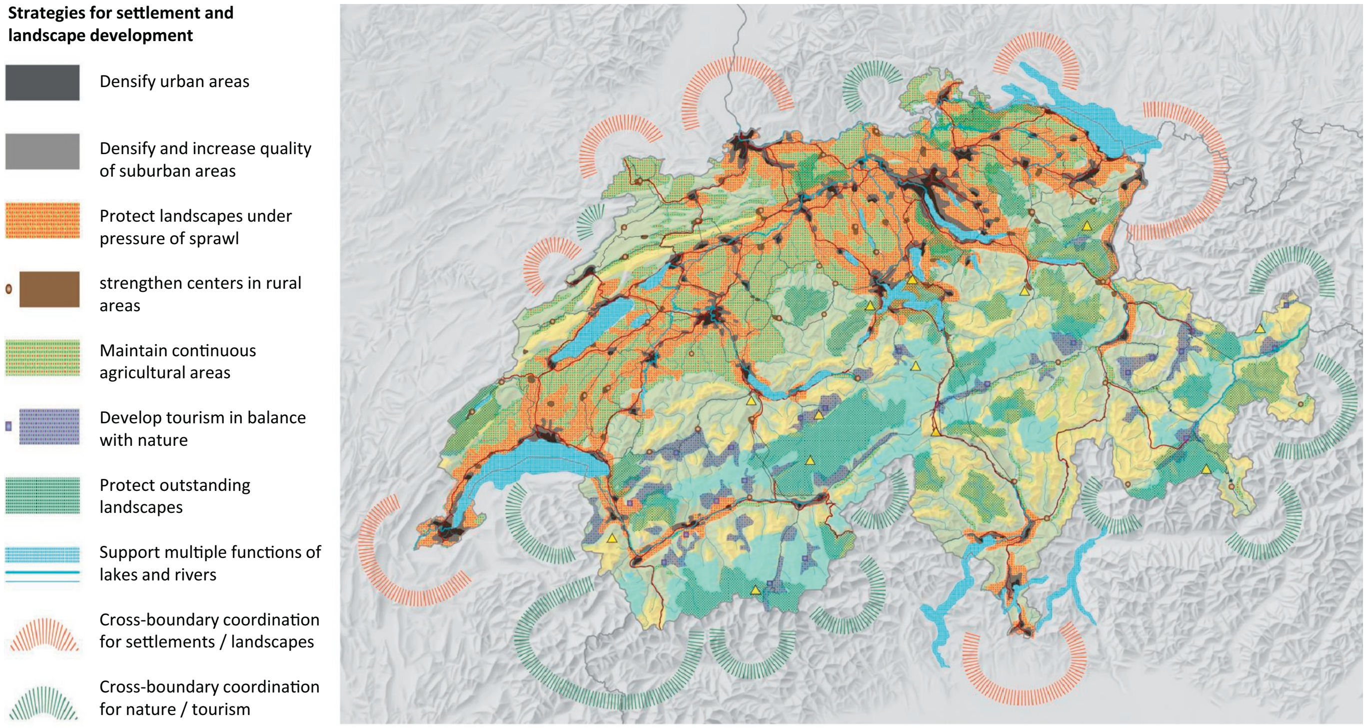

Fig. 4. Strategies for settlements and landscape developments in Switzerland: Each spatial planning concept identifies intended urban development trajectory on a landscape scale, in terms of densification, expansion, or restriction (adjusted from ARE, 2012). Assessing such strategies in a land use model would require a more nuanced representation of urban land use than provided by currently available tools. Only legend items related to spatial planning concepts are depicted in the figure legend.

underlying many land use change analyses and models, can be improved by including more nuance in the characterization of urban land and urban land use changes.

Competing interests

The authors declare no competing interests.

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