Green growth? On the relation between population density, land use and vegetation cover fractions in a city using a 30-years Landsat time series.

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Abstract

Both compact and dispersed green cities are considered sustainable urban forms, yet some developments accompanied with these planning paradigms seem problematic in times of urban growth. A compact city might lose urban green spaces due to infill and a dispersed-green city might lose green in its outskirts through suburbanisation. To study these storylines, we introduce an operationalised concept of contrasting changes in population density (*shrinkage* or *growth)* with vegetation density (*sealing* or *greening*) over time. These trends are ascribed to different land use classes and single urban development projects, to quantify threads and pathways for urban green in a densifying city**.** We mapped the development in vegetation density over 30 years as subpixel fractions based on a Landsat time series (for 2015: MAE 0.12). The case study city Berlin, Germany, developed into a city that is both gaining in vegetation—greening—and population—growing—in recent years but featured highly diverse trends for both compact and green city districts before that. Pathways to achieve a *greening-growing* scenario in a compact city include green roofs, brownfield and industrial revitalisation, and bioswales in predominantly green city districts. A threat for compact cities pose infill developments without greening measures. A threat for dispersed-green cities is microsealing in private residential gardens—gravel gardens—or car parking infrastructure. We conclude that neither a compact nor a dispersed-green city form concept logically leads to a development towards more environmental quality—here vegetation density—in times of densification but rather context specific urban planning.

1 Introduction

An increase in urban green cover and increases in population density are often considered to be antagonists (Haaland & van den Bosch, 2015). A number of studies find that growth in population density – whether compact inner-city growth or dispersed suburbanisation on the urban fringes - is inevitably connected to negative outcomes such as a reduction in vegetation cover (Elmqvist et al., 2018; Nuissl et al., 2009; Wolff & Haase, 2019). This notion of over-crowding in regard to population density increases can be found across the literature. However, none of these studies actually measures how vegetation cover has developed in its full spatial-temporal configuration for an entire city with population density developments. We therefore ask ourselves, whether both entities can grow at the same time and under different conditions in a city or parts of it and what the paths and threats for this development are?

From an urban ecological view, growth in population density should go hand in hand with an increase in vegetation density to prevent a degradation of viable ecosystem services that are critically important for human well-being such as regulating air temperature or local recreation (Pauleit et al., 2019). Therefore it is worrying that a wide range of authors have observed both a trend in the degradation of urban vegetation, and a worldwide increase in population density in cities, leading to a reduction in per capita ecosystem service provisioning (Elmqvist et al., 2018; Fuller & Gaston, 2009).

One prominent way of dealing with densification in urban planning and the green city is the implementation of greening strategies following the concept of green infrastructure according to Pauleit et al. (2019), as integrating vegetation into the city provides numerous beneficial flows of ecosystem services to its inhabitants (Andersson et al., 2019; Haase et al., 2014) as well as offering considerable potential for biodiversity conservation (Schwarz et al., 2017). Important tools for growing cities include small-scale elements of green infrastructure such as green roofs, roadside vegetation such as trees and hedgerows or bioswales and the formation of new green spaces such as parks. However, the processes on private grounds around buildings i.e. front and backyards or gardens are overlooked. Such areas can make up about 40 % of total vegetation cover in a city and are very important for comprehensive spatial scale assessments (Haase, Jänicke & Wellmann, 2019).

The current European planning paradigm largely draws on the compact cities approach to sustainability (De Roo & Miller, 2019). The compact city paradigm emphasizes the need to integrate different land uses in close proximity to enable short daily commutes to save energy and land (Echenique et al., 2012). The opposite of the compact city is the concept of the dispersed city (in Europe also referred to as the 'garden city'), which emerged in industrial England in the 19th century. Here, urban structure is shaped by open built-up space, low rise and low-density housing, where buildings, streets, green spaces and other urban amenities form a mosaic-like and more dispersed pattern (Holden and Norland, 2005, p.2148). In a dispersed city, we have less congestion but higher segregation. In terms of environmental quality, the dispersed city is also supposed to be a green city due to its higher share of open space and less air pollution (Westerink et al., 2012).

Most literature suggests that cities can generally be characterised as a compact or a dispersed city (Holden & Norland, 2005; Jenks & Burgess, 2000; Westerink et al., 2013). However, experiences from different cities across Europe over time tell us that we often observe both: growth in the form of densification and infill as well as dispersed growth at the periphery (Wolff & Haase, 2019). The processes however, of both population and built space densification in terms of the change in vegetation cover are often unequally distributed in a city, raising questions of equity and justice about access to green spaces (Kabisch & Haase, 2014). From this arises the need for a spatially and temporally explicit analysis of population- and vegetation density developments in an integrated manner to evaluate and design better policies. Important is thereby to enable active citizenship for instance with open data and result policies, working towards a kind of mosaic governance (Buijs et al., 2016).

To portray spatial-temporal trends in urban vegetation cover, Earth observation (EO) based time series analysis is very appropriate (Li et al., 2017). Landsat satellite imagery is particularly suitable to monitor land cover and land use change because of its long recording history and open data policy (Wulder & Coops, 2014). As the resolution of Landsat (30 metres) is still higher than the size of many urban objects, the problem of mixed pixels consisting of multiple land cover classes is a remaining challenge (van der Linden et al., 2018). In contrast to discrete land cover classification that tends to underrepresent smaller elements that occur comparatively frequently in an urban vegetation context (Zhu et al., 2015), spectral unmixing methods describe the quantitative composition of land cover within pixels and thus the continuous character of land cover throughout urban spaces (Small & Sousa, 2016). Spectral unmixing is a widely used concept in Earth observation and non-parametric machine learning regression approaches are becoming more frequently used in different urban and non-urban land cover composition mapping applications (Suess et al., 2018; van der Linden et al., 2018). However, contributions to urban ecological studies (Haase et al., 2019b) or for long time series analyses in cities (Michishita, Jiang, & Xu, 2012; Schug et al., 2018) are still rare.

Having the new time series based on Earth observation technologies at hand, we are able to assess more comprehensively whether green growth—or green shrinkage, respectively—is occurring or if this is merely envisioned and identify properties and characteristics that are typical for both types of city paradigms: the compact and the dispersed-green city, as outlined by various authors. Such information helps us to uncover what Neuman (2005) calls ‘the compact city fallacy’ that cities are a continuous co-evolutionary process rather than a form or a state. In doing so, in this study, we quantify vegetation and population density changes and co-relate both on different spatial scales for the city of Berlin, Germany to answer the following questions:

- How can Landsat time series data and spectral unmixing contribute to a better understanding and hypothesis testing for the spatial realisation of different urban planning concepts?
- What are long-term urban vegetation trends in different land use classes?
- Can densification of built space be detected in specific land use classes and recommendations for action be provided?
- What are the paths and threats for green-growth in compact or dispersed areas?

2 Study area

Berlin is a Central European city (52° N, 13° E) with an area of about 900 km^2 (Figure 1) featuring 3.6 million inhabitants (Statistical Office for Berlin-Brandenburg, 2018). The main constituents of green and blue infrastructure are forests with 18%, parks and allotment gardens with 12%, a river network with 7 % and agriculture with 4% of Berlins surface coverage (Senate administration Berlin, 2018). Settlement and transportation infrastructure, in turn, cover about 60% of the city's surface. Both residential density and urban form vary substantially between Berlins districts. The highest population density can be found in the central Wilhelminian-time perimeter block developments with a 20 meters eaves height stemming from the 1870s. In the Eastern—former socialist—part as well as in the south and north of the city there are mostly pre-fabricated large scale high rise complexes stemming from the 1960s to 1990s. In the outer districts, single family homes are widespread, consisting of detached-, semi-detached house and villas with gardens around them (Figure 1).

Multiple trends in urban development can be discerned in the city over the last 30 years. Following World War II, the city was divided into an eastern and a western part, with East-Berlin as the capital of the German Democratic Republic (GDR) and West-Berlin as a West-German enclave surrounded by GDR territory. After the reunification of both parts in 1990, two separately functioning, but not entirely different cities had evolved. Special characteristics in East-Berlin included vacant inner city perimeter blocks because GDR housing policies were focussed on promoting large scale pre-fabricated building blocks in the urban fringe. Besides those residential structures, large scale industrial grounds were located in central parts of the city (Nuissl & Rink, 2005). West-Berlin, in turn, had lower residential vacancy rates and a more continuously used built infrastructure in the central districts.

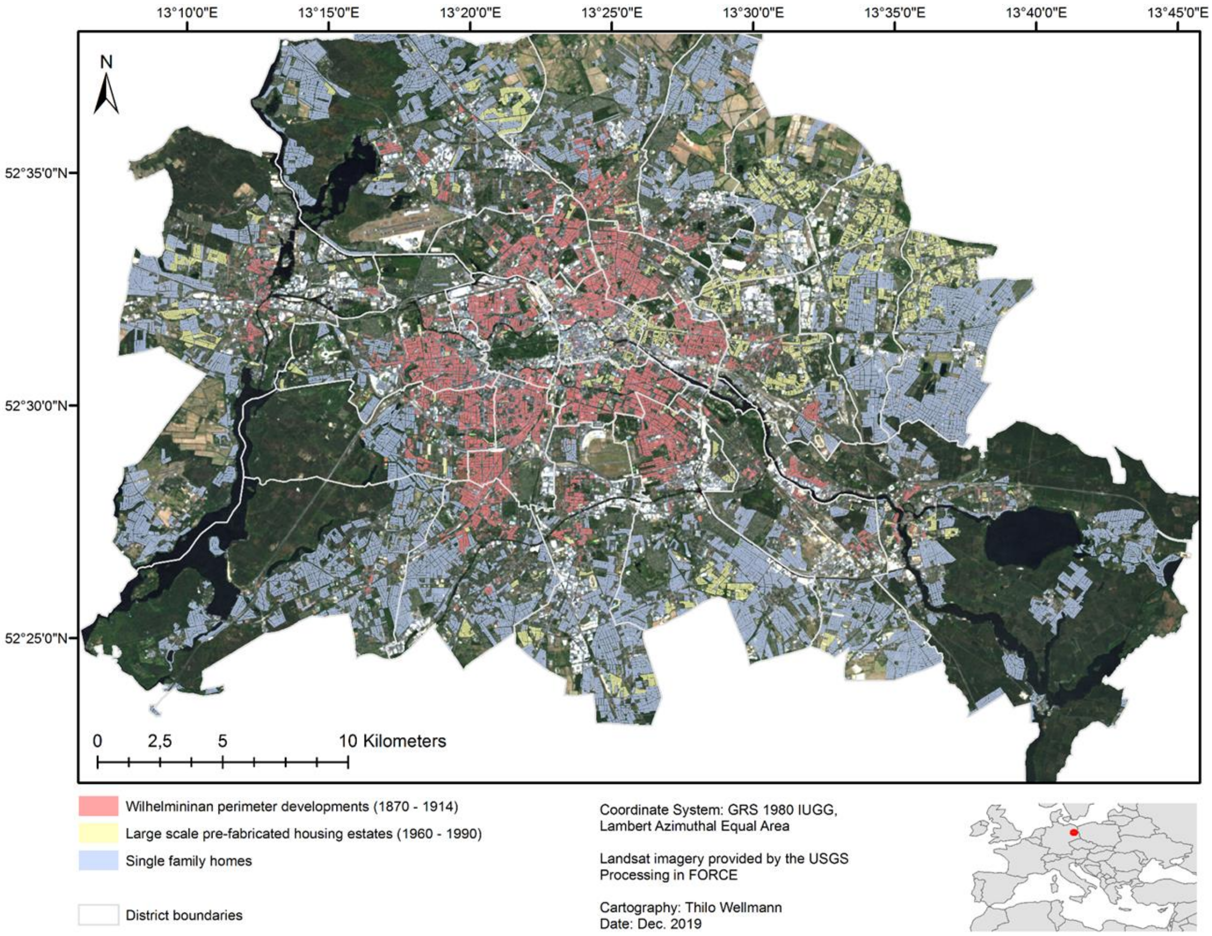


Figure 1. True colour Landsat 8 OLI (Operational Land imager) representation of the study area covering 96% of the city of Berlin with the three dominant building types and the district borders

Overall, the population density in East-Berlin (3,175 pop/km²) was much lower compared to West-Berlin (4,509 pop/km²) in 1991. While this tendency remained until today, the eastern part densified more intensively (increase of 425 pop/km²) in contrast to the western part (increase of 191 pop/km²) since 2011. Large shares of this trend can be attributed to sub-urbanisation processes and the revival of the previously fallow inner city quarters (Nuissl & Rink, 2005), meaning that both compact and dispersed city growth occurs.

The growth in population, however, was not a linear process (Figure 2). In 1950, a cumulative population of 3.3 million and in 1970 3.2 million lived in East and West Berlin. After a mild rise in population number directly after the German reunification (3.4 million), there was a period of shrinkage between the years 1993 and 2000, in which Berlin faced a loss of 130,000 inhabitants. This period of shrinkage was followed by a decade of stability. Since 2010, the trend in population development turned around and Berlin grew by 370,000 inhabitants, thus surpassing its former population maximum.

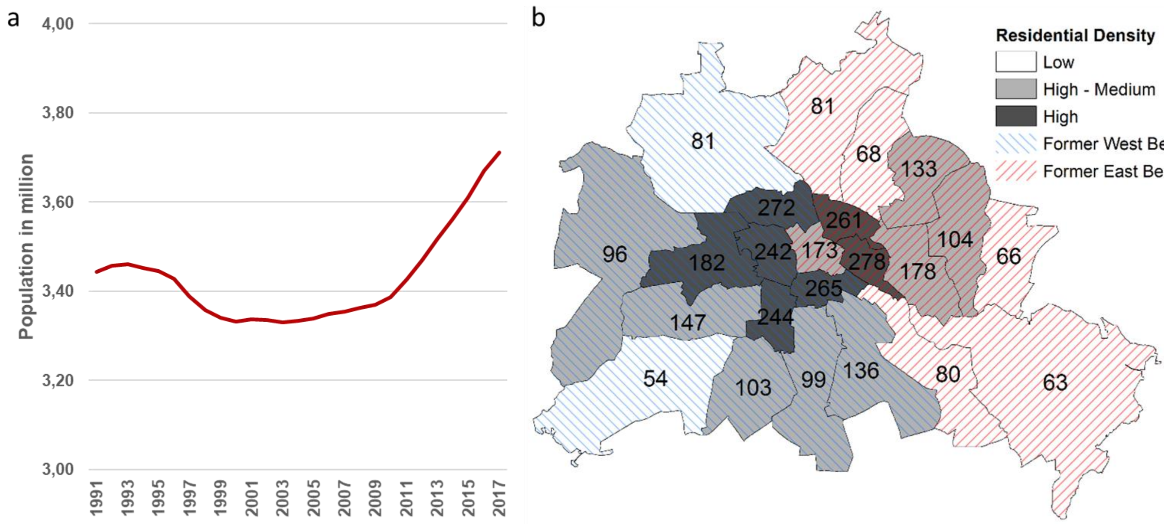


Figure 2. a) Population development in Berlin (*Berlin Brandenburg Statistical Office*) from 1991 to 2017 and b) residential density of Berlin, separated in its former western and eastern districts for the year 2017.

3 Data & Methods

We acquired Landsat satellite imagery for seven years between 1988 and 2018 (Figure 3). Imagery was pre-processed and a regression-based unmixing approach was performed in order to generate fraction maps of vegetated and non-vegetated surfaces. Results were validated for the year 2015. Two indicators were derived from the resulting historic and recent fraction maps: Firstly, a time-series contrasting vegetation and population densities portraying the dynamics of both entities in an integrated way and secondly, a spatial-temporal evaluation of the urban vegetation cover per land use class on a city wide scale. Based on this, greening and soil sealing tendencies for land use or land management change in different density types are highlighted at a local level.

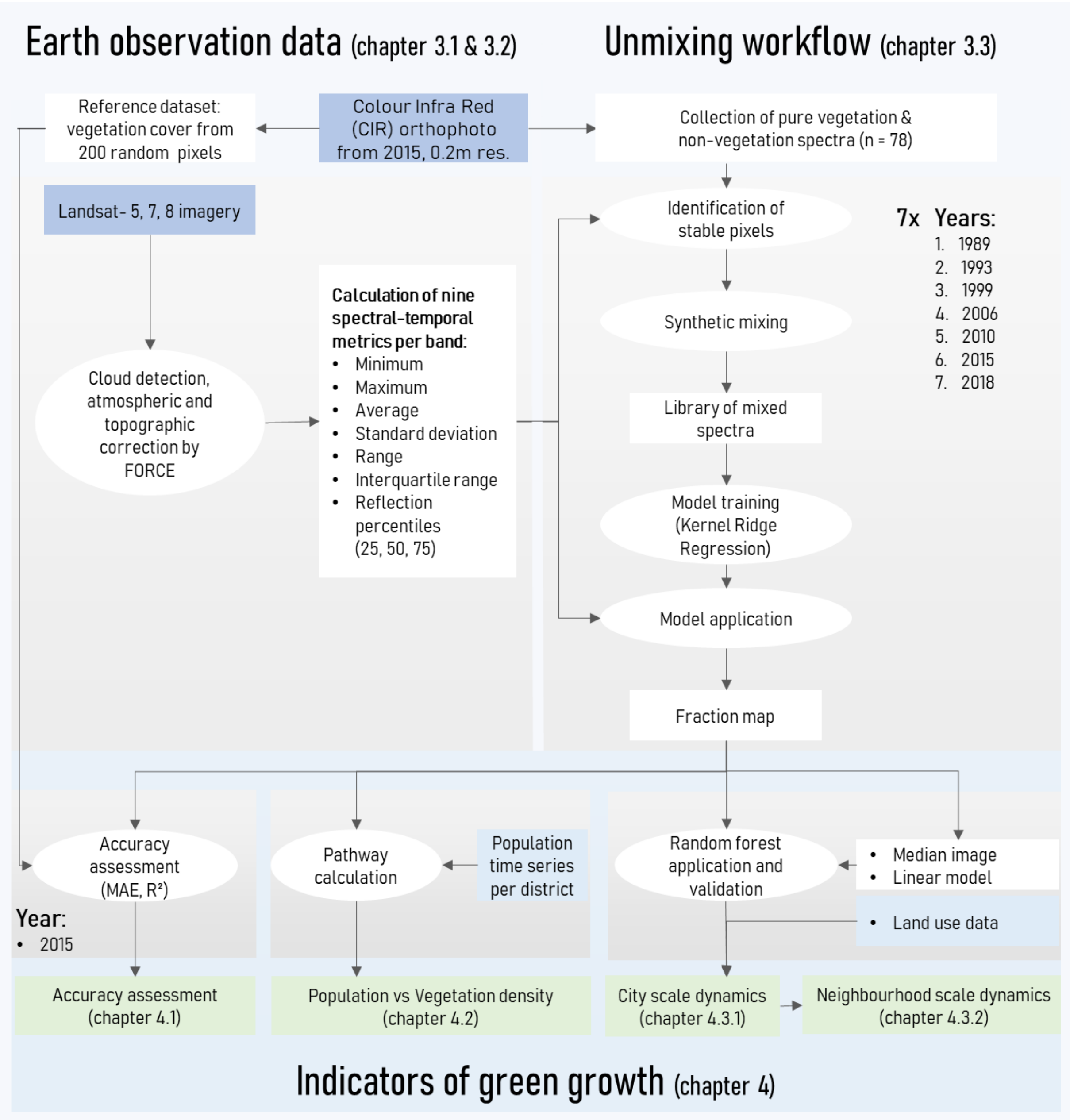


Figure 3. Flowchart of the proposed methodology of using a Landsat time series for spectral unmixing to derive spatially explicit products relating the three entities population density, vegetation density and land use in a city over time.

3.1 Landsat data and model input features

We acquired Landsat-5 TM (Thematic Mapper), Landsat-7 ETM+ (Enhanced Thematic Mapper) and Landsat-8 OLI (Operational Land Imager) imagery for seven points in time. This choice was made based on the availability of a cloud-free observation in July the most vegetation active month. For the purpose of feature space harmonisation and information extraction, spectral-temporal metrics were generated for each three-year period using the six spectral bands of all available pixels with clear-sky observations (Frantz, 2019). These metrics included median, mean, maximum and minimum reflectance, 25^{th} and 75^{th} percentile of reflectance and standard deviation, range and inter-quartile range of reflectance (Figure 3 & Table 1). As an example, all data from 1988 to 1990 was downloaded for the target year 1989. The data was acquired as level 1 product and then pre-processed to level 2A using the FORCE framework, which is a cloud detection and radiometric correction chain for optical EO data providing analysis-ready data for remote sensing applications (Frantz, 2019).

Table 1. Landsat images used in this study with indication of sensor, acquisition dates and data availability.

	Years	**Date of July scene**	**Sensor of July scene**	**Average number of acquisitions per pixel**
1	1988 - 1990	07.07.89	Landsat 5 TM	3.8
2	1992 - 1994	02.07.93	Landsat 5 TM	2.4
3	1998 - 2000	11.07.99	Landsat 7 ETM+	10.7
4	2005 - 2007	06.07.06	Landsat 5 TM	7.9
5	2009 - 2011	09.07.10	Landsat 7 ETM+	8.2
6	2014 - 2016	07.07.15	Landsat 7 ETM+	9.4
7	2017 - 2018	20.05.18	Landsat 8 OLI	13.5

3.2 Additional Earth observation and vector data

For additional reference in the process of deriving training and validation data, we acquired a very high-resolution (0.2 metres) colour infrared (CIR) orthophoto from 03.07.2015. From this dataset we derived the actual vegetation extent for the comparison with the modelled results. The *Statistical Office Berlin-Brandenburg* provided the population data on an annual basis for every borough between 1991 and 2017 while the Urban Structure (In German: Stadtstruktur) database provided detailed land use and building type information and whether these structures are owned privately (e.g. residential housing), publicly (e.g. forest) or semi publicly (allotments) (Stadt Berlin, 2018). Using the latter two datasets we calculate population density as residential density incorporating only land use classes with residential usage into the density analysis. For discerning dense and dispersed urban form we use the threshold of 90 m^2/capita or city quarters as in Wolff & Haase (2019). Since Berlin features very high density quarters on a European scale, we added a third class representing even denser and more compactly build quarters by splitting the "compact" class around its median value (Figure 2).

3.3 Spectral unmixing

We performed pixel-wise spectral unmixing using a kernel ridge regression (KRR) to map fractions of vegetated and non-vegetated surfaces within the 30 m pixels of the Landsat data. KRR is a machine learning regression method that uses non-linear kernels to perform a linear regression on high dimensional data (Vovk, 2013)(Figure 3). We used KRR for mapping the land cover fractions based on a labelled spectral library that contains pure image spectra and synthetic mixtures between them together with labels showing the weights during mixing (please, see Okujeni et al. (2017, 2013) for a more detailed description).

For library composition, we firstly evaluated whether an image pixel qualified as a pure library pixel, i.e. complete homogenous coverage of the same land cover type, in 2015 with the CIR orthophoto. Secondly, we assured that those pure pixels were stable across the investigation period by evaluating whether the observed spectra in 2015 remained stable throughout the entire investigation period. We collected a total of 78 spectra of pure vegetation and non-vegetation surfaces.

Data for regression training was generated by synthetically mixing pure endmember reference spectra as in Okujeni et al. (2013) and extended by an ensemble approach (Okujeni et al., 2017). In this study, we randomly create 1,000 synthetic mixtures between classes. Mixing complexity likelihoods were set to 50 % for a 2-endmember case and 50 % for a 3-endmember case, meaning that a spectrum could be mixed against a spectrum from the same or the other class. Based on this training data the KRR implementation of *scikit-learn* was used from within the *EnMAP-Box* (Sebastian van der Linden et al., 2015) for unmixing with an ensemble size of 10.

For validating the vegetation cover fractions in the year 2015, 200 pixels of the Landsat image were randomly selected and their vegetation content evaluated by digitising the extent found in the CIR orthophoto. The statistical analysis was based on the model coefficients, the mean absolute error (MAE) and the R^2 between digitised observed values and modelled values.

3.4 Conceptualising the co-relation between vegetation and population density

This chapter develops a methodology that integrates both trends in population density from census data and vegetation cover from fraction mapping in long-term urban analysis. In order to systematise the co-relation of both proxies, we use a matrix that spans between the increases or decreases in both entities and is applicable for whole cities as well as subdivisions of various forms (Table 2).

Table 2. Conceptual matrix of an integrated population density and vegetation cover analysis classifying the urban dynamics depending on change of both entities.

Trends	Vegetation cover increase	Vegetation cover decrease
Population density increase	Greening & Growing City (GG)	Sealing & Growing City (SG)
Population density decrease	Greening & Shrinking City (GS)	Sealing & Shrinking City (SS)

Greening-growing (GG) dynamics imply a concurrent increase in both vegetation cover and population density in the respective time period. *Greening-shrinking* (GS) dynamics in turn represent a city gaining in vegetation cover as population density diminishes which had been observed in shrinking cities after wholesale demolitions. In contrast to this, a *sealing-growing* (SG) and a *sealing-shrinking* (SS) city would represent two dynamics which stand for a rather unsustainable urban development as more vegetated land is converted to built-up land. In the SG case this is accompanied with an increase in population density and in the SS case a loss in population density. According to this matrix, either parts of cities or entire cities can be systematically analysed and compared over longer periods of time.

To avoid over-determination, we omitted the introduction of static classes. The derivation of adequate thresholds would be highly case study specific and is thus not core of the overall methodology. In general, the concept is open to an introduction of such classes.

3.5 Urban vegetation change by land use classes

For the analysis of the long-term vegetation cover trends per pixel, we carried out a random forest classification, parametrised with 500 trees using vegetation fraction maps from all years as input. The random forest algorithm is a supervised learning method consisting of an ensemble of decision trees (Breiman, 2001). Classes were defined based on two additional layers and clear thresholds (Table 3). First, we calculated the median vegetation cover over the whole study period to describe the median vegetation content of each pixel throughout the years. Second, we calculated a linear regression model over each pixel's development in vegetation from which we took the regression coefficient, to determine the overall trend in the respective pixel. Training data was collected based on the class definitions in Table 3. To validate the resulting classification, we randomly drew 270 locations (each representing one Landsat pixel) and checked if the given locations matched our previously stated class definitions based on the linear regression coefficient and the median image (see the right hand columns of Table 3).

Drawing from the city wide analysis carried out above, we analyse trends in vegetation density per land use class and on a neighbourhood scale for single planning developments bringing about land-use or land management changes. We thereby add a stronger thematic focus to discern specific processes and drivers. In this chapter (4.3) we combine the vegetation density time series, high resolution orthophotos and the classifications of the population- and vegetation density dynamics (Table 2) to highlight opportunities and threats for the urban vegetation cover for existing and newly developed structures. Land use and ownership structure (private (e.g. residential housing), public (e.g. forest) or semi-public (allotments)) is drawn from the Urban Structure database (Stadt Berlin, 2018). Of the land use classes we selected four typical and widespread types of green infrastructure for further analysis, namely parks, forests, graveyards, and allotments in accordance with Pauleit et al. (2019).

Table 3. Classification of long-term vegetation trends based on indicators and their thresholds

Process	**Description**	**Example**	**Class definitions**	
			1. Linear regression coefficient	***2. Median image***
Greening	Vegetation cover increase	Unsealing of land, for instance in the case of new parks being build	Positive (>0.05)	
Sealing	Vegetation cover decrease	Construction of new buildings without integrating vegetation	Negative (<-0.05)	
Continuous vegetation	Continuous dense vegetation cover	Forest	Neutral (> -0.05 & < 0.05)	High (>75%)
Continuous mixed	Stable medium	Street with roadside vegetation	Neutral (> -0.05 & < 0.05)	Medium (75% - 25%)
Continuous sealed	Stable low	Large industrial or commercial estates	Neutral (> -0.05 & < 0.05)	Low (<25%)
Regrowth/ Replanting	1. Dense vegetation cover 2. Vegetation loss 3. Recovery	Replanting of lost vegetation, natural succession on previously after cutting		Medium (75% - 25%)

4 Results

4.1 Spectral unmixing: Accuracy assessment

Figure 4 illustrates the accuracy of the binary unmixing product for the year 2015 (see Figure A1 in the Appendix), featuring an overall MAE of 0.12. Based on a linear model fitted to the estimate and reference data, the model overestimates vegetation in areas with lower to medium vegetation shares but shows a generally good fit in areas with higher vegetation shares with an intercept of 0.15 and a slope of 0.81. Regarding the long-term vegetation trends, we found that 73% of the profiles match with the first indicator (model coefficient) and 94 % match with the second indicator (median image).

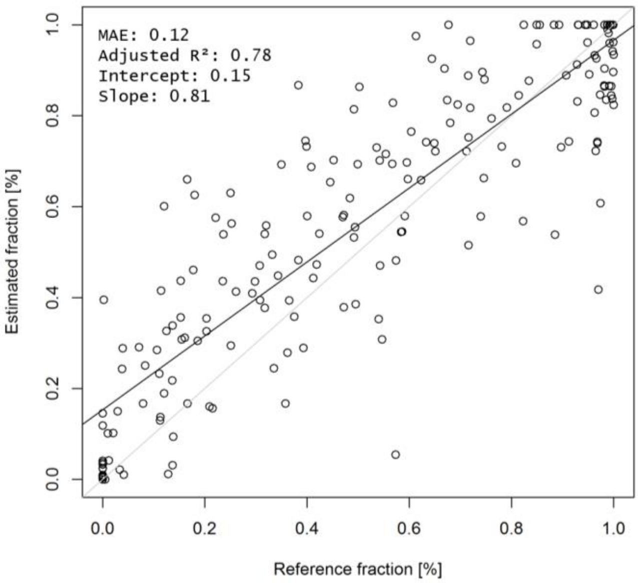


Figure 4. Accuracy metrics for the year 2015; a scatterplot with the modelled relationship between reference and estimations with the model parameters in black, an ideal 1:1 model fit in grey, the mean absolute error (MAE) and the adjusted R^2.

4.2 Green Growth? The relation of population density and vegetation cover in compact and dispersed parts of the city

Over the past 30 years, we can observe diverse changes in the spatial patterns of vegetation and population density (Figure 5). Between 1993 and 2006 *sealing-shrinking* was the predominant trend, as vegetation was lost and population density decreased. Since then, this trend changed for *green-growth* almost citywide, where both entities, vegetation and population density, are growing simultaneously. In fact, the most common land cover dynamic is to date *greening-growing*.

Figure 5 shows that periods of growth and shrinkage are not equally distributed across space and time, while greening was more widespread in the eastern—former socialist—part, trends for soil sealing had been more frequent in the West. West Berlin's development in the 1990s is characterised by population shrinkage along with soil sealing. From 2010 onwards, population re-growth let West Berlin joining the ballad of the fast growing capital and investor-driven construction. In the East, this process of population growth was more pronounced, with some districts continuously increasing in population density across the study period. Both compact (inner urban) districts as well as more dispersed suburban districts offer examples for *greening-growing* profiles. For both types, however, we also find the opposite, meaning *sealing* and or *sealing-shrinking* dynamics.

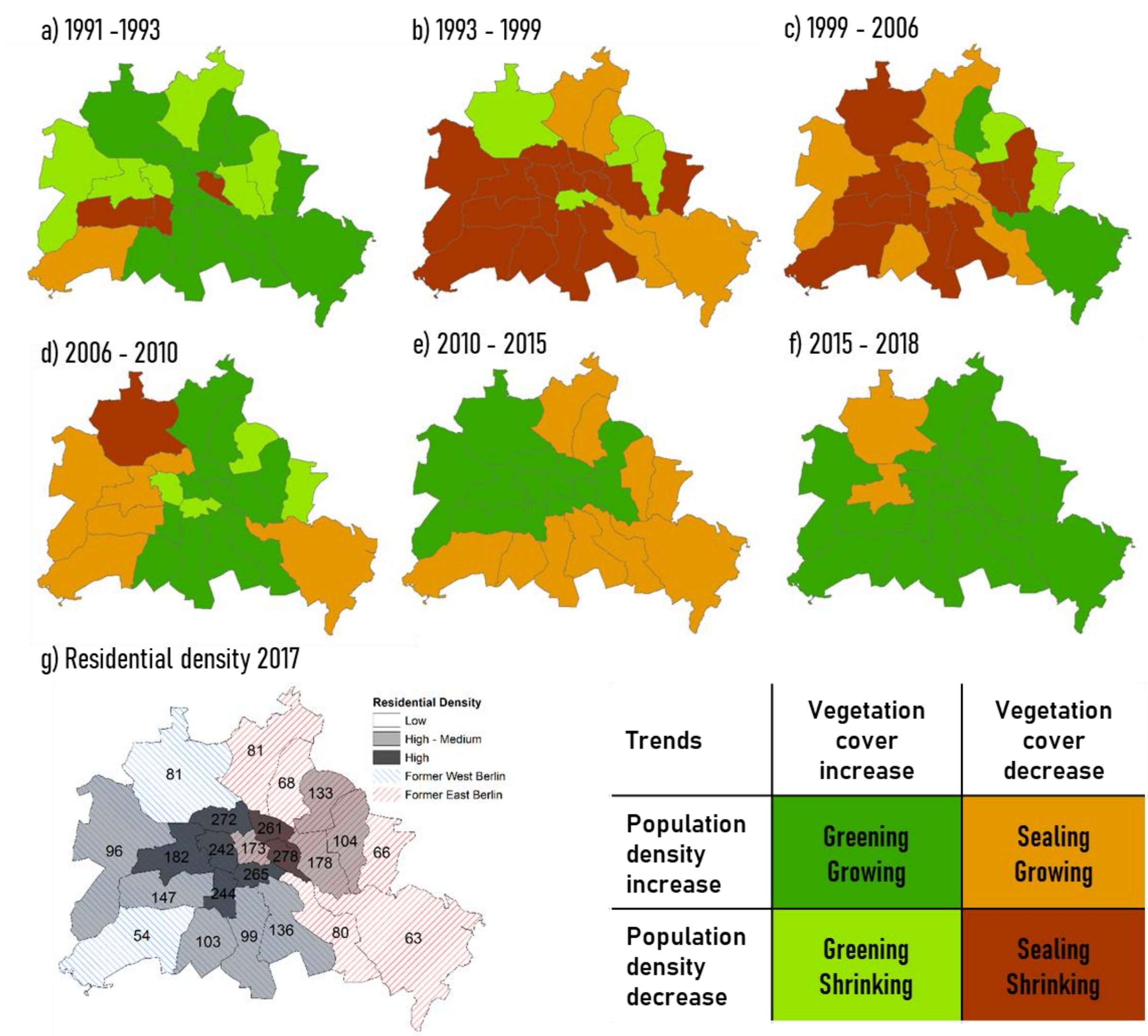


Figure 5. Annual change in vegetation cover in regard to population density between 1991 and 2018 (a – f) and (g) the residential density in the year 2017 (in population/km²) discriminating dense and dispersed areas of Berlin.

4.3 Vegetation density development in green infrastructure and built-up structures

4.3.1 City scale

In the city of Berlin, we find diverse spatial pattern in vegetation development (Figure 6) and different trends in various land use classes (Table 4). From a spatial point of view, one can observe that surface and soil sealing can be found in central and peripheral areas of the city. Contrary to that, we find large areas of greening rather in the Eastern—former socialist—parts. Examples for these processes are (see Figure 6): creation of new parks on former railway grounds such as `Gleisdreieck Park` (6a), infill in district Friedrichshain's perimeter development areas (6b) and greening of pre-fabricated housing estates in the district of Marzahn-Hellersdorf (6c). Also widespread are patterns of vegetation regrowth representing both spontaneous natural vegetation and purposely replanted vegetation.

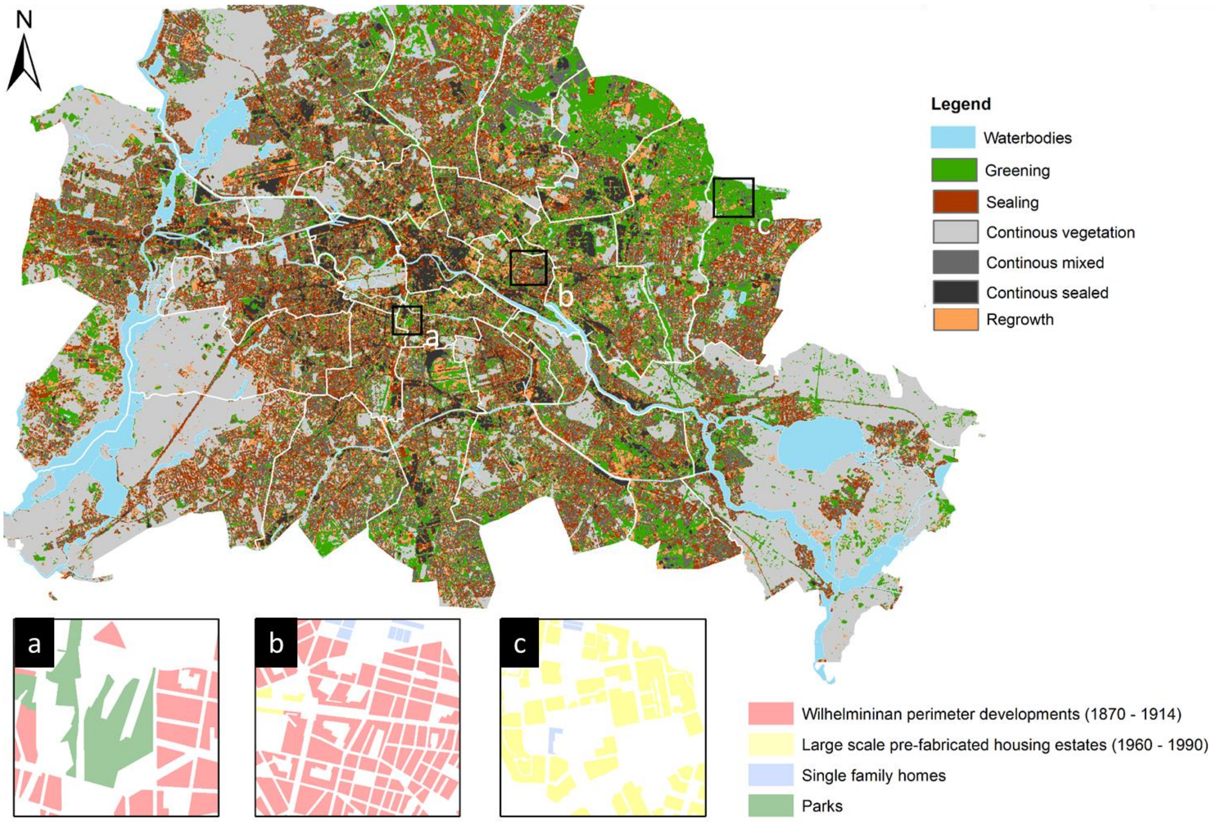


Figure 6. Map of different spatial trends in vegetation cover process changes and stability, respectively with three highlights representing a) Gleisdreieck Park b) Friedrichshain and c) Marzahn-Hellersdorf.

From a land use perspective, forests and graveyards feature the highest share in continuous vegetation in the city. In all classes of public green infrastructure, greening is more dominant than sealing resulting in a net increase in vegetation over the past 30 years since 1990 (Table 4). This statement is also true for public parks, where high greening values especially stem from parks created after 1990 at revitalized railway brownfields such as the 'Gleisdreieck' or 'Südgelände'. In contrast to the public green infrastructure, semi-public allotment gardens show a much larger trend to change for sealing. In the allotment garden class, only 30% can be attributed to a stable (continuous) vegetation from 1991 to 2017. In the class of streets and squares, we found only 8% of the total area were continuously sealed on a 30m resolution but 17% of the pixels show a vegetation regrowth trend, the latter describing regrowth after an initial loss.

Private residential areas show a trend towards sealing over the last 30 years with the exception of larger building blocks that underwent more greening measures. This is true for both low-density structures like detached houses and villas, but also for the dense inner city closed perimeter blocks. Together they feature the highest sealing and lowest greening values of all built-up structures.

Table 4. Percentage of long-term vegetation trends (1989 to 2018) per urban land use class, with an indication of the dominating process per class. Colour coding is in accord with the upper legend of Figure 6 highlighting the largest values for each of the regarded temporal trajectories.

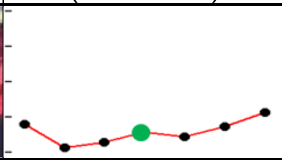
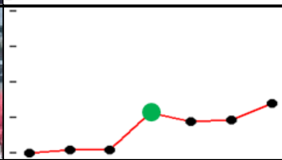
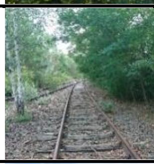
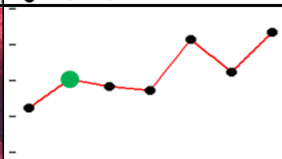
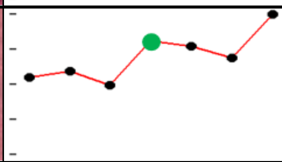
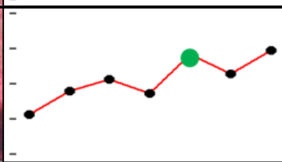
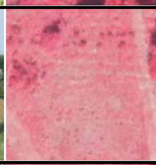
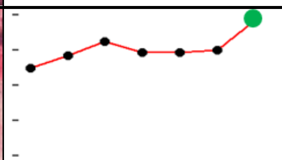
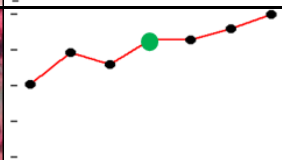
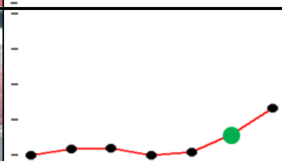
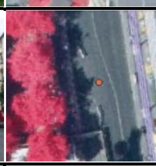
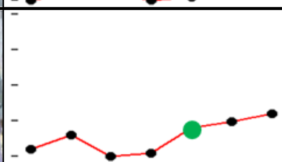
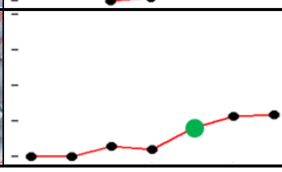
	Public grey infrastructure	**Public green infrastructure**			**Semi-public green infrastructure**	**Private Residential areas**					**Private production facilities**
Temporal trajectories	Streets and squares	Forests	Parks	Graveyards	Allotment gardens	Closed perimeter blocks	Large scale housing estate	Detached houses	Semi-detached houses	Villas	Industry and commerce
Greening	18	5	30	7	16	11	41	10	17	7	18
Sealing	18	1	5	4	17	32	9	30	22	32	16
Continuous vegetation	21	91	44	77	30	0	5	14	13	22	2
Continuous mixed	19	1	7	5	26	23	17	32	32	25	6
Continuous sealed	8	0	1	0	0	11	2	0	0	0	35
Regrowth	17	2	13	7	10	24	26	14	15	14	22

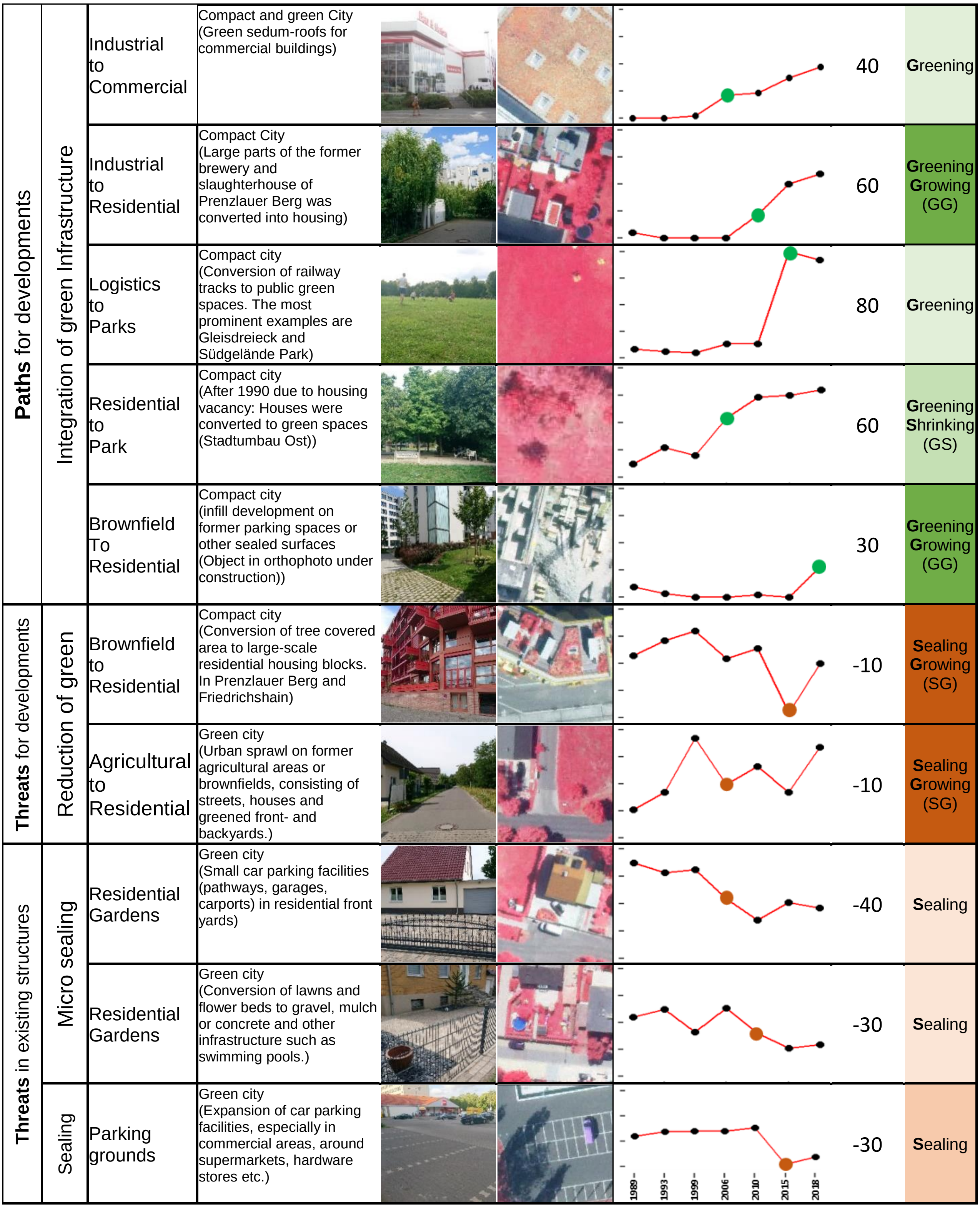
4.3.2 Neighbourhood scale: management and use changes

In this section, trends found at the city scale are brought together with the site specific process regime. Setting a focal point on the local level (here we consider 30 by 30 metres as local) we can explain pattern found at the city level and analyse underlying drivers and processes. Table 5 shows the effects of changes in land use or land management on the vegetation cover. Positive changes are classified as greening or even *greening-growing* dynamics while changes reducing the coverage are classified as *sealing* or *sealing-growing* dynamics depending on the expected change in population. We further discern between paths and threats in new and existing infrastructure and whether or not these dynamics are especially relevant for compact or green/dispersed city types.

We find that a wide range of land use classes can in fact contribute to a greening city and some even to *greening-growing* city. The biggest increases in green can here be found in the cases where new housing or parks are created on formerly industrial land. Moreover brownfields and roads offer big potentials for various greening measures. There are however also contrary examples, where vegetation is lost. In a *sealing-growing* scenario these would be the construction of residential buildings on formerly vegetated land without green roofs, or green roofs that cannot compensate for the loss of green at the specific site. A *sealing* scenario is often linked to the extension of car-parking infrastructure or the conversion of private vegetated gardens to rock gardens or sealed land around houses.

Table 5. Paths and threats for existing structures and new urban developments illustrated with aerial images (vegetation appears in red) representing one Landsat pixel and coinciding with the displayed temporal profiles (*first point in time after the modification is highlighted) and lastly the changes in green cover and the thereof derived classification (some street images are taken on different spots if an area was not accessible).

Process typology		**Examples from the City of Berlin**			**Associated Vegetation Cover trend**		
Type	Land use class(es)	Urban form and description	Street image (2019)	Aerial image (2017)	Green cover trend * (1989 – 2018)	Green changes in %	Indic.
Paths for existing structures – Management changes	Residential	Compact and green city (Greening of front- and backyards in residential structures.)				10	Greening
	Industry	Primarily compact city (Revitalisation of former industrial estates, e.g. Breweries to commercially used office spaces mixed with residential usage)				30	Greening Growing (GG)
	Transport infrastructure	Compact and green city (Spontaneous greening in form of natural succession along the rails of the regional trains across entire Berlin)				40	Greening
	Brown-fields	Green city (Nature Protection in form of fencing for e.g. the breeding period of the Eurasian Skylark On former Tempelhof airfield)				20	Greening
		Compact & Green City (Community gardens were established as an interim usage on brownfields with some persisting over large time spans)				30	Greening
		Green City (Grazing on peri-urban grasslands with sheep, goats, or Heck- and Highland cattle)				20	Greening
	Riverbed	Compact & Green City (River restoration projects together with tree planting campaigns, e.g. in the Wuhle valley)				20	Greening
	Streets	Compact & Green City (Conversion of a street to a biking and pedestrian path equipped with green adjacent to it)				30	Greening
Green Street infrastructure		Compact & Green City (Tree planting campaigns in Berlin since 2004; e.g. 415 new trees in Neu-Kölln or >1,000 in Friedrichshain)				30	Greening
		Green City (Street-wise bio swales with trees, shrubs and grassy vegetation were established since 2010 in Berlin Adlershof commercial area)				20	Greening



5 Discussion

Contrary to European (Pauleit et al., 2019) and international studies (McDonald et al., 2019), in the study undertaken here for Berlin, green growth can be found in both compact and dispersed areas of the city along a comparably long temporal trajectory from 1989-2018. This highlights that the urban form is not necessarily the only decisive factor or essential in the analysis of a city's environmental characteristics and green land cover, as other authors have also suggested (Echenique et al., 2012; Neuman, 2005). Furthermore, a city does not necessarily follow a single planning and development paradigm like the compact or the dispersed city as both are rather ideal paths. It becomes clear that a combination of contrasting spatial development visions and respective planning efforts are needed followed by either densifying or de-densifying land cover changes to create ecologically healthy and socially fair environmental conditions and to address the host of processes that shape and produce the distinct urban land forms; or as Tratalos et al. (2007) put it: "at any given density, there is substantial scope for maximising ecological performance".

Therefore, quantifications of such different spatial (de)densifying processes (here vegetation density developments) are the key to disentangle urban developments and produce future sustainable urban form(s).Thus, the question to ask is not: Is the city compact or spread, but rather is it compact and spread in 'the right places' and 'at the right time' and, most importantly, are the processes leading to a degree of compactness or dispersion (including the respective type and amount of vegetation) appropriate for the given urban form and for the number of inhabitants. Therefore, construction processes need to be reviewed (Tratalos et al., 2007), different types of green infrastructure need to be considered (Pauleit et al., 2019), and then related to environmental properties (e.g. green space types but also blue and grey open spaces) and put into a larger urban context. We, therefore, analysed the city across temporal and spatial scales (from city- to land-use to neighbourhood scale) to continuously detect the multitude of urban dynamics. Set against such backgrounds, Berlin and its multi-path urban development is the perfect study site for the given context, in particular due to the different starting points in the East and West in 1990 after the German reunification.

Overall, our case study city of Berlin is becoming a greener city as the remote sensing data time series used in this paper shows. The greening trend in Berlin can primarily be attributed to high values in continuous ground-based tree, shrub and lawn vegetation, the embankment vegetation of rivers and lakes as well as remnant forests and positive greening to sealing ratios in public green spaces, which is an indicator of good maintenance and management. In spite of the fact that Berlin's population increased over recent decades, the city has a *greening-growing* dynamic. For questions of environmental justice i.e. the availability and accessibility of green spaces for the resident population, this is a major advantage, because in almost all districts (with high or low incomes) vegetation is increasing, even in those districts with the highest population increase (Biernacka & Kronenberg, 2018; Kabisch & Haase, 2014).

Densification, infill developments and suburbanisation processes do not necessarily lead to a deterioration in environmental quality. Rather the opposite seems to be the case in Berlin: with an increase in population density, we frequently observe an increase in vegetation density and vice-versa. We explain this finding by the fact that the increasing population pressure exerts pressure on urban planning processes to speed up the implementation of green infrastructure for recreation. It shows that a population density increase is not necessarily accompanied by a loss in vegetation and, in addition, if there is a reduction in population (density) due to a number of reasons, it is not a logical consequence that there will be an increase in vegetation following shrinkage. Instead, in times of urban shrinkage, more focused efforts towards establishing sustainable vegetation must be made and laissez-faire is not an option (Haase et al., 2019a).

Based on the Berlin time series, we observe a decrease in green in low density private residential areas (such as villas and detached housing). Hence, gradual soil sealing and a subsequent reduction in vegetation is a major environmental problem in the city of Berlin, as it is the predominant source and process of vegetation loss but not visible at first glance. Most small-scale sealing occurs on private residential ground i.e.—backyards, street corners, infill houses or pedestrian zones, as was found in a recent study on a neighbouring city (Strohbach et al., 2019). Another land use class where sealing is the predominant vegetation trend are the central closed perimeter blocks, suggesting that Berlin simultaneously features infill and suburbanisation tendencies.

These findings highlights that in densifying cities, efficient technical and transparent legal solutions are needed to maintain and improve the amount and quality of vegetation (Wolch et al., 2014). Urban planners, lawmakers and landowners need to be incorporated and most importantly need to work together (Wu, 2008) as a kind of mosaic governance, after Buijs et al. (2016), involving a heterogeneous array of people, institutions and practices associated with active and informed citizenship. This paper demonstrates how a long Landsat sensor-based unmixing time series could contribute to this issue as a precise tool for environmental assessments, potentially covering large areas and long time periods and thus publicly informing all of the aforementioned groups of people using clear quantitative and spatially allocated arguments. Here, one of the main arguments is to have remote sensing literate public officials that are able to handle big-data earth observation data (Ilieva & McPhearson, 2018). Hence, in the long run, the methodology could contribute to improving the smartness of sustainability 'design' in urban densification by proactively steering the involved governance processes.

The full spatial-temporal scope of vegetation developments become even more important in a context of urban densification, because "as cities grow, interactions between people and nature depend increasingly on landscape quality outside formal green space networks, such as street plantings, or the size, composition and management of backyards and gardens” (Fuller & Gaston, 2009). Therefore, it is not sufficient to merely study the amount of formal public/open greenspaces as provided in e.g. the Urban Atlas data set for Europe. In this light it is very promising that we find high numbers of vegetation regrowth along roads, which is subject to multiple stressors but also filter and retention space for pollutants and fast runoff water. Another such promising green provider where many people live, are the green areas around large scale prefabricated housing complexes that underwent wide greening measures (mostly tree based) in the last years.

We find that a *greening-growing* city is not compatible with the widespread use of motorised private transport i.e. passenger cars. We recommend the transformation of roads—at least partly—into cycle and pedestrian space with more vegetation in and around it and the general reduction of parking area. Worrying is furthermore the trend of gardens being covered with, mulch, rocks, concrete, artificial turf, swimming pools and car parking infrastructure, taking their toll on the urban vegetation extent. Since such gardens cannot, or very limited, provide multiple ecosystem services, it is in the public interest to reduce such activities with appropriate policies (Strohbach et al., 2019). As green roofs are not visible from the street level and accessible maximally by local tenants, they can only contribute to regulating ecosystem services but cannot be perceived by people (Yu et al., 2016). We, therefore, recommend façade greening, especially if perceivable green is lost in the course of a development or the opening of green roofs to either the tenants, customers of a specific business (e.g. rooftop bar, sports ground) or the public. Why not having an entire park with trees, hedgerows and lawns built on top of a supermarket?

In this study, we methodically use spectral unmixing to derive a long time series of fractional vegetation cover for an urban region. Commonly, studies of urban vegetation dynamics use the Normalized Difference Vegetation Index (NDVI) as a proxy for vegetation extent (De Carvalho & Szlafsztein, 2019; Kabisch et al., 2019). With regression based unmixing, however, we calculate the actual spatial extent and density of vegetation, getting rid of the need for a proxy that does not provide for a direct spatial quantification. In doing so, we have the clear advantage of using all of the bands from the satellite image as opposed to only two as is the case with the NDVI (Okujeni et al., 2015). Moreover, spectral unmixing has shown promising results for further applications in planning-relevant urban ecology such as species distribution modelling (Wellmann et al., 2020).

Uncertainties and outlook

This study exclusively looks at the space within the administrative borders of the city of Berlin and not beyond. This means that the larger metropolitan area, featuring the city, peri-urban areas and adjacent villages partly exhibit their own dynamics and processes is excluded (Nuissl et al., 2009). The main reasons for this strict delineation are first, that planning regimes and responsibilities in the surrounding municipalities of large cities are different. And second, data is missing for small communities regardless of them being close to a city or not. Therefore, for this research, we decided to exclusively study the city of Berlin as a highly diverse city in itself, in terms of its history and urban form.

However, as recent studies for urban dynamics in Europe suggest: densification and growth within cities are more likely to increase the land use pressure in the peri-urban areas rather than reducing it, as former inner-urban land uses are spatially outsourced into the peri-urban surroundings. Empirical evidence for such processes and patterns are still sporadic rather than systematic. Therefore, there is substantial need for further research on the interactions along the urban to rural interface, in particular transgressive approaches (Hedblom et al., 2017).

We refrained from adding a static class for the classification of the vegetation and population density dynamics. This was done to omit arbitrary and not necessarily uniformly true threshold values, as growth pattern around the world differ severely in both their magnitude and shape. It does, however, add the uncertainty that small changes cannot be separated from major ones. We thus recommend adding thresholds for future studies based on the growth or shrinkage patterns adapted to the given setting and data. As this study is a first methodological paper and thus not based on large scale evidence we refrained from providing the values for Berlin.

As this study is based on a binary vegetation to non-vegetation unmixing product, qualitative information of the type and the quality of change is missing. Possibilities that should be considered to achieve this would be the addition of qualitative information from remote sensing (Wellmann et al., 2018) or the inclusion of vegetation configuration (such as patch size, core area, connectivity) as determinants of green infrastructure performance as important planning considerations (Pauleit et al., 2019). Finally, more in depth field work would add valuable information. Combining the unprecedented quantitative capabilities of Earth observation with these qualitative methods will show great potential for the fields of urban research and could provide solid, open access and easily applicable results for the applied and multi-actor planning of better cities.

6 Conclusions

Compact and dispersed city dynamics have long been understood as archetypical antagonists in urban planning. With this Earth observation data supported research, we want to contribute to a non-binary vision of urban (form) as we conclude that neither a compact urban form, nor a dispersed city leads to transparently deducible increases in environmental quality, measured here in terms of vegetation density. Rather, both areas have their unique configurations and processes that shape these configurations and thus they need to be addressed differently and evaluated with care.

To achieve sustainable urban growth, each type of urban form requires different management and planning interventions. Here, we propose a vegetation fraction time series for the long term, repeatable and cost effective analysis of urban developments. In doing so, the relation between population and vegetation densities, were evaluated across spatial-temporal scales, from city- to land use- to local neighbourhood perspective. Highlighting the promising fact that growth without the deterioration of environmental quality (here, measured in vegetation cover) is indeed possible but by far no logical consequence.

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8 Open data policy

The fractional vegetation cover time-series for Berlin is available for download here: https://doi.org/10.5281/zenodo.3870592.

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Appendix A

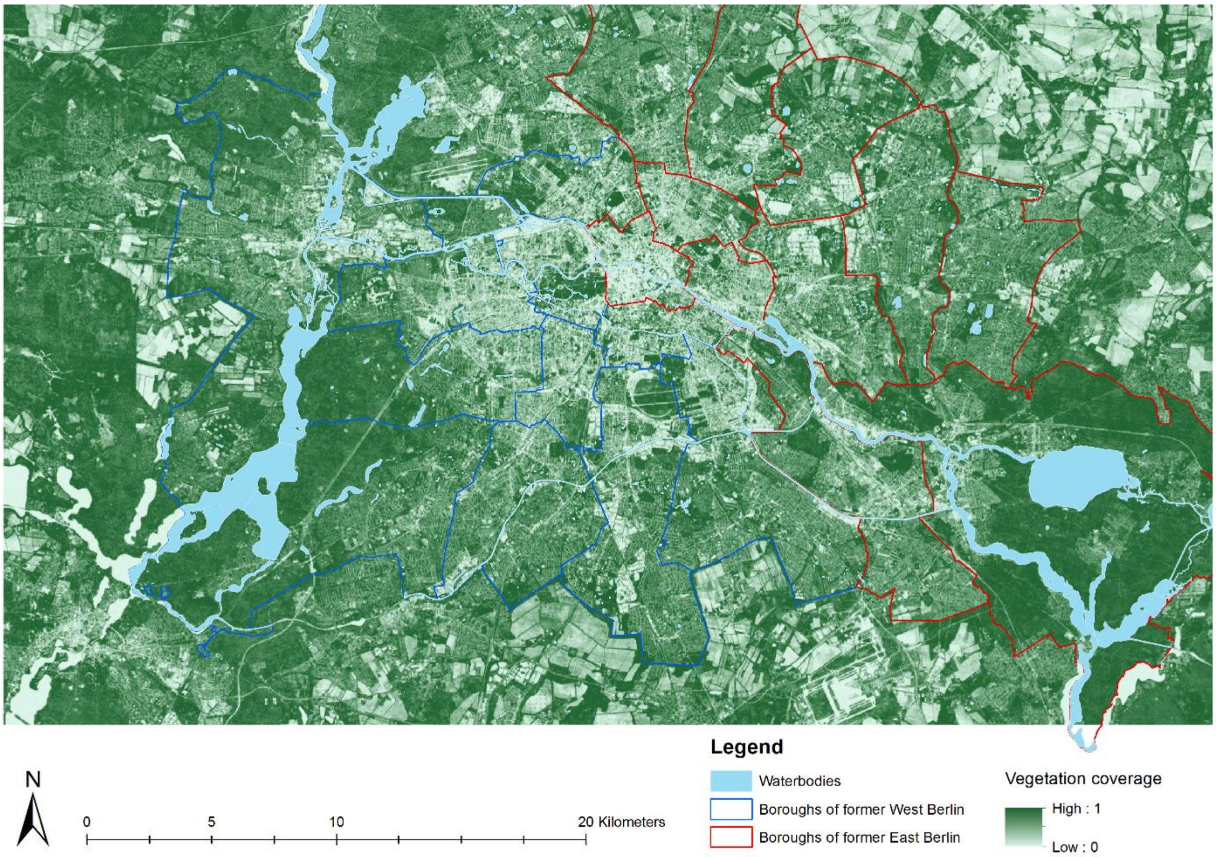

Figure A1. Vegetation coverage for the city of Berlin and its immediate surroundings for the year 2015.