# Geospatial Model for Hyperlocal Mapping of Urban Tree Canopy Cover

## Geospatial model for hyper-lokal kortlægning af urbant trækronedække

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Climate change causes challenges and increased risks in cities, necessitating urgent adaptation without leading to path-dependency. Therefore, nature-based approaches are gaining attention where urban trees hold great potential by providing climate-regulating ecosystem services. However, available hyperlocal geodata and maps on urban tree canopy (UTC) cover are currently insufficient, and promising AI-based mapping approaches are often complex and require special skills. Together, that pose challenges specifically for small cities that often hold limited resources. For the small Danish city, Randers, this study demonstrates how UTC cover effectively can be mapped from Danish geodata using geospatial techniques as an alternative to AI-based models. The developed model shows promising performance with high spatial accuracy, thus providing valuable spatial information and local UTC baselines communicated visually through maps.

Klimaforandringer skaber udfordringer og øgede risici i byer, hvilket nødvendiggør hurtig tilpasning uden at føre til stiafhængighed. Derfor rettes mere opmærksomhed mod naturbaserede tilgange, hvor bytræer har stort potentiale ved at levere klimaregulerende økosystemtjenester. Imidlertid er tilgængeligt hyper-lokalt geodata og kort over urbant trækronedække (UTC) i øjeblikket utilstrækkelige, og lovende AI-baserede kortlægningsmetoder er ofte komplekse og kræver særlige kompetencer. Tilsammen udfordrer det særligt små byer, som ofte har begrænsede ressourcer. Dette studie demonstrerer for den mindre danske by, Randers, hvordan UTC-dække effektivt kan kortlægges ud fra danske geodata ved hjælp af geospatiale teknikker som et alternativ til AI-baserede modeller. Den udviklede model præsterer lovende med høj rumlig nøjagtighed, og giver dermed værdifuld rumlig information og lokale UTC-baselines kommunikeret visuelt via kort.

**Keywords:** Urban tree canopy; Geospatial modelling; Remote sensing; Ecosystem services; Climate change adaptation; Small cities

### 1. Introduction

Rooted in the acceleration of human-induced global climate change, the risk of hazards to people and assets related to climate change has increased for all cities and urban areas (Dodman et al., 2022). To mitigate the consequences of climate change, cities and municipalities are developing and, to a more limited extent, implementing adaptation plans (Buzási et al., 2024; Dodman et al., 2022; Eisenack & Roggero, 2022; Reckien et al., 2018). However, developing and implementing

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climate adaptation plans as well as realising, monitoring, and evaluating concrete actions requires expertise, staff, and finances. These are integral parts of an adaptive capacity (Adger et al., 2007; Brooks & Adger, 2005; Major & Juhola, 2021) that in many ways is linked to "size", resulting in smaller towns, cities, or municipalities (1,000 - 100,000 inhabitants (Fitton et al., 2020)) having limited resources, compared to larger ones, and thus less capacity for adapting to climate change (Fila et al., 2024; Fitton et al., 2021; Häußler & Haupt, 2021; Lehmann et al., 2021b; Major & Juhola, 2021; Otto et al., 2021). Nevertheless, small cities are already today, and even more in the future, affected by climate change and therefore also in need of adaptation and resilient development (Dodman et al., 2022; Häußler & Haupt, 2021).

For cities to adapt to the changing climate and more extreme weather events, especially nature-based approaches, including nature-based solutions and ecosystem-based adaptation, hold great potential (Goodwin et al., 2024; Hobbie & Grimm, 2020; Johnson et al., 2022). Nature-based approaches are widely recognised as low-regret, flexible, and multifunctional adaptation and mitigation measures that provide a variety of provisioning, regulating, and cultural ecosystem services which can underpin the development of "the urban futures we want" (Dodman et al., 2022; Frantzeskaki et al., 2019; Hobbie & Grimm, 2020; McPhearson et al., 2023).

To provide these ecosystem services in cities, the management of urban trees is essential given that trees are a key component of urban ecosystems (Dobbs et al., 2017; Östberg et al., 2018). Urban trees are, however, part of the often overlooked and undervalued *trees outside forests* which, nevertheless, constitute a significant part of tree resources and can be important means to address sustainability issues (Liu et al., 2023; Peros et al., 2022; Schnell et al., 2015). Within cities, urban trees contribute to important micro-climate regulation which, among other ecosystem services, increase human well-being and the liveability of cities (Liang & Huang, 2023; Livesley et al., 2016).

Yet, to manage the provision of ecosystem services for climate change adaptation in cities, information and measurements are necessary and should be available to support decision-making of plans, policies, and strategies (King & Locke, 2013; Klobucar et al., 2021). An effective way to review and estimate the ecosystem services provided by urban trees is to map the urban tree canopy (UTC) cover, as it can be mapped relatively efficiently using remote sensing. Additionally, UTC is highly linked to and to a great extent representative of the ecosystem services provided by urban trees (Guo et al., 2023; Klobucar et al., 2021; Liang & Huang, 2023; Schwarz et al., 2015). E.g. urban trees provide (micro-)climate regulating services for which the canopy provides shade, evapotranspiration, and intercepts rainfall. As a result, tree canopies can help mitigate the urban heat island effect, decrease local temperature during heatwaves, and mitigate pluvial flooding from rain events by delaying peak flows and reducing stormwater runoff volumes (Hobbie & Grimm, 2020).

Furthermore, research has found various human health aspects to be linked to specifically the extent of canopy cover (Ulmer et al., 2016), where a threshold of 30% canopy cover, as a minimum, has been identified as significantly related to overall improved human health (Astell-Burt & Feng, 2019). Several studies on the effects of UTC have consequently led to evidence-based recommendations for urban forestry, i.e. the *3-30-300 rule* in which the requirement of at least 30% canopy cover constitutes one of the three components to ensure that the benefits of urban greenery are provided to citizens (Browning et al., 2024; Konijnendijk, 2023; Nieuwenhuijsen et al., 2022). However, to be able to comply with a requirement of 30% canopy cover and thus benefit from the appertaining ecosystem services, measurements of the canopy cover are, as earlier stated, needed.

Previous studies have often mapped canopy cover from already available satellite data and land cover maps. However, the relatively low spatial resolution associated with, for instance, the European CORINE and Urban Atlas results in aggregations that ignore small green areas and elements. Thereby, street trees are excluded from the maps which make them unsuitable as a source of information for UTC, especially at the hyperlocal scale (Cardinali et al., 2023; Guo et al., 2023; Labib et al., 2020).Furthermore, Urban Atlas only covers 788 functional urban areas across Europe – areas of more than 50,000 inhabitants – and is an additional example of data disadvantage that smaller places experience.

### *1.1 Geodata Availability in a Danish Context*

In Denmark, a third of the population lives in the four Danish cities larger than 100,000 inhabitants (Aalborg, Odense, Aarhus, and Copenhagen). In comparison, almost half of the Danish population lives in towns and small cities, which counts more than 500 urban areas (Statistics Denmark, 2024b). Hence, a significant share of the Danish population is potentially disadvantaged regarding resources and data available for needed climate change adaptation, including developing, implementing and monitoring adaptation plans.

Climate change in Denmark is projected to result in more days with warm- and heatwaves, more precipitation during the winter, summer precipitation being concentrated in more extreme rain events with 24-65% more cloudbursts, and storm surges being more severe and frequent along with a sea level rise of 30-61 cm by the end of the century (DMI, 2024a). From a national perspective, the Danish Emergency Management Agency has identified 14 national risks currently of greatest importance to address in Denmark; four of these risks are directly related to climate change and events, and the acceleration of climate change is stated as one of four highly relevant and underlying reasons for concerns in general (Danish Emergency Management Agency, 2022).

Considering the availability of Danish geodata, which for instance could support climate change adaptation, open geodata of a high spatial resolution has been a priority at a national level. In 2012, the Basic Data Programme was established by the Danish Government to ensure the availability of free basic public geodata that includes selected parameters of the Danish geography and demography, managed by the Danish Agency for Climate Data. The purpose of the initiative was to provide updated, reliable, and standardised geodata to support public administration and affairs by improving the basis for decisions and efficiency. Additionally, the geodata was to be freely available for research, business, and development. Despite the cost of releasing and continuously acquiring high-quality geodata, the evaluation of the entire programme in 2020 concluded that the socio-economic value of the programme amounted to approximately one billion Euros, emphasising the value of open geodata (Danish Agency for Climate Data, 2021; Gregersen et al., 2020).

The open geodata that maps specifically the Danish landscape and cities is provided by GeoDanmark, a common public data collaboration between the Danish Agency for Climate Data and the Danish municipalities (Danish Agency for Climate Data, 2023). The GeoDanmark geodata covers natural elements, which, regarding urban trees, includes data sets on the location of trees, individual or in groups; the location of fences, which might consist of trees; and the extent of forests, based on the criteria of minimum 2,500 $m^2$ area of forest. For the case of small cities, the data sets related to trees outside forests are arguably the most relevant. However, these data sets by GeoDanmark are limited to, in most cases, point locations and thus do not include the areal extent of the tree canopies to represent UTC cover. Furthermore, only large trees with a trunk diameter above 20 cm are mapped, unless supported by laths, and no trees on private plots are mapped due to the costs and reliability of the mapping method used (GeoDanmark, 2021). Yet, private trees can constitute a significant share of trees in a city and thus the appertaining ecosystem services provided in a city (Klobucar et al., 2021). For these reasons, the available GeoDanmark geodata on trees might significantly underestimate the number of urban trees and equally the extent of UTC cover if used as a basis for estimating it.

However, if considering other Danish geodata from a multi-sensor data fusion approach, the combination of LiDAR and high-resolution multispectral imagery, both available for Denmark, is widely applied in the literature for mapping UTC as it arguably can be considered “the gold standard for urban land cover mapping” (Browning et al., 2024; Yan et al., 2015). In this approach, digital elevation models (DEM) can be generated from LiDAR data, some of which are already produced and part of the available Danish geodata, including a nationwide digital terrain model (DTM) and digital surface model (DSM). The DEMs can in the multi-sensor data fusion approach be used to determine the height and texture of the surface and ground features to identify tall and highly textured objects like tree canopies. From the multispectral imagery, the normalised difference vegetation index (NDVI) can be calculated to distinguish between vegetation and non-vegetation (O’Neil-Dunne et al., 2014). Even though this approach has been widely applied for UTC mapping it is still not an international standard practice, especially in smaller urban areas. Additionally, the approach is often limited by the availability of up-to-date and high-quality geodata (Klobucar et al., 2021; Yan et al., 2015). However, in the case of Denmark, the national geodata should be able to overcome these issues.

When applicable geodata is available for a case, or generated for the purpose, several studies both develop and apply various classification and segmentation algorithms for the image processing, with one objective being to replace the more labour-intensive manual image analysis and interpretation (Banzhaf et al., 2020; Erker et al., 2019; Knopp et al., 2023; O’Neil-Dunne et al., 2014). In recent years, machine learning and specifically deep learning has advanced the techniques for image analysis even further (Araújo et al., 2021; Ma et al., 2019; Zhu et al., 2017), and has demonstrated great potential for efficient and accurate mapping of urban trees and canopies (Guo et al., 2023; Martins et al., 2021; Velasquez-Camacho et al., 2023). For the case of Denmark, a few studies have applied existing Danish imagery and LiDAR data, e.g. to map canopy cover on grassland (Hellesen & Matikainen, 2013) and at regional scale (Alexander et al., 2014) in leaf-off season using classification algorithms and machine learning, respectively. More recently, Li et al. (2023) applied a deep learning framework to map trees at higher resolution at the national scale from LiDAR and with RGB and near-infrared (NIR) summer aerial imagery.

Even though these approaches demonstrate promising results for mapping UTC, they are often complex and require non-transparent processes that necessitate specific technical knowledge to apply. Such domain-specific skills might not necessarily be generally available among those in need of the information on UTC (Klobucar et al., 2021; Sang et al., 2020; Tekouabou et al., 2022). For UTC mapping to provide real value, not least in small cities, a more accessible approach is therefore needed.

The Danish context, where basic geodata already exists in abundance but UTC maps are lacking, is an interesting test-case for a geospatial model for UTC mapping that can benefit local practitioners, e.g. from municipal technical and/or planning departments responsible for developing and implementing adaptation plans. It is then essential that the resulting UTC maps are adequately accurate for the purpose of application, including local public management of and planning for urban trees and the ecosystem services they provide, for instance, in relation to adapting to a changing climate.

A case-in-point is Danish municipalities' ability to address water-related hazards such as pluvial flooding or storm surges. In this context, with high-resolution and high-quality data available, almost all municipalities identified, reported on, and planned for such hazards (Lind & Hansen, 2024). In contrast, a study of the climate action plans of the 22 municipalities in Southern Denmark found that many did not adequately address hazards related to drought, warm spells, and heat waves, and referenced lack of accessible data of spatial relevance and sufficient quality as main reasons for this. However, the same municipalities were not having problems in respect to, e.g. flood-type hazards (Tollin et al., 2023, 2025).

To support a nature-based approach to climate change adaptation in small cities and inform this decision-making process, the present study intends to develop a geospatial model in GIS for identifying and mapping UTC cover at the hyperlocal scale based on existing Danish geodata. The model performance will afterwards be discussed along with the model's potential value and limitations as a tool and source of information in the context of small cities.

## 2. Methodology

A single-case approach is chosen for developing and evaluating the geospatial model for UTC cover mapping in order to focus on the iterative process of developing a functional model and optimising it. Serving as the geographical basis for this, a subpart of the Danish city Randers is chosen as the study area where UTC cover information is relevant to the city's ongoing efforts to adapt to climate change. The workflow for the developed model is described in detail in section 2.2. The geodata used as input for the model is downloaded from and freely available online at the Danish Agency for Climate Data's *Dataforsyningen* unless otherwise stated.

### *2.1 Study Area*

Randers is located in central Jutland in Denmark. It is the sixth largest city in Denmark and has a population of approximately 64,000 inhabitants (Statistics Denmark, 2024a). Based on the definition from Lehmann et al. (2021a), Randers is one of eight Danish small cities (population size between 50,000 and 99,999). The city centre of Randers is chosen as the specific study area and is in the present study defined by a combination of watersheds and urban fabric to constitute a relevant topographical demarcation in the local context. This study area thus represents an urban area of 0.5 $km^2$ to facilitate model development and evaluation for mapping of UTC cover at the hyperlocal scale.

The city, and the city centre, is situated at Randers Fjord, which since 2011 and with point of departure in the EU Floods Directive has been identified as one of the most at-risk areas in Denmark. In the new planning period (2022-2027), it has been reappointed together with 24 other areas in Denmark (Danish Coastal Authority, 2024). The 24 areas are located in 50 municipalities. Furthermore, several municipalities, including Randers, are home to more than one risk area.

Already today, the city is challenged by an overload of water in cases of rain events, storm surges, and highwater level in the fjord and when they occur concurrently. With climate change, Randers furthermore faces more heatwave days and an even greater risk of flooding due to the projected increase in winter precipitation and more intense and frequent cloudbursts (DMI, 2024b). Additionally, sea level rise will both reduce the buffer-capacity of the fjord and exacerbate the storm surges (Randers Municipality et al., 2020).

Randers is a relevant case for UTC cover information, as the city has a vision of combining climate change adaptation with city development to create synergies and integrate the adaptation into the urban landscape, where nature should be included as an essential component (Randers Municipality, 2019). Therefore, Randers, including the city centre, is an example of one of the small Danish cities in need of climate change adaptation and where information on local UTC cover could be valuable information for supporting a nature-based approach to the adaptation.

### *2.2 Workflow*

The model parameters applied to map UTC cover correspond to the features characterising trees and canopies in an urban context: non-buildings, tall, vegetation, and textured. The UTC cover is identified through thresholding with the four model parameters in spatially overlaying the appertaining geodata, as depicted in Figure 1. The approach shares similarities with partial semantic segmentation, but is centred on applying simple geospatial techniques within a GIS environment.

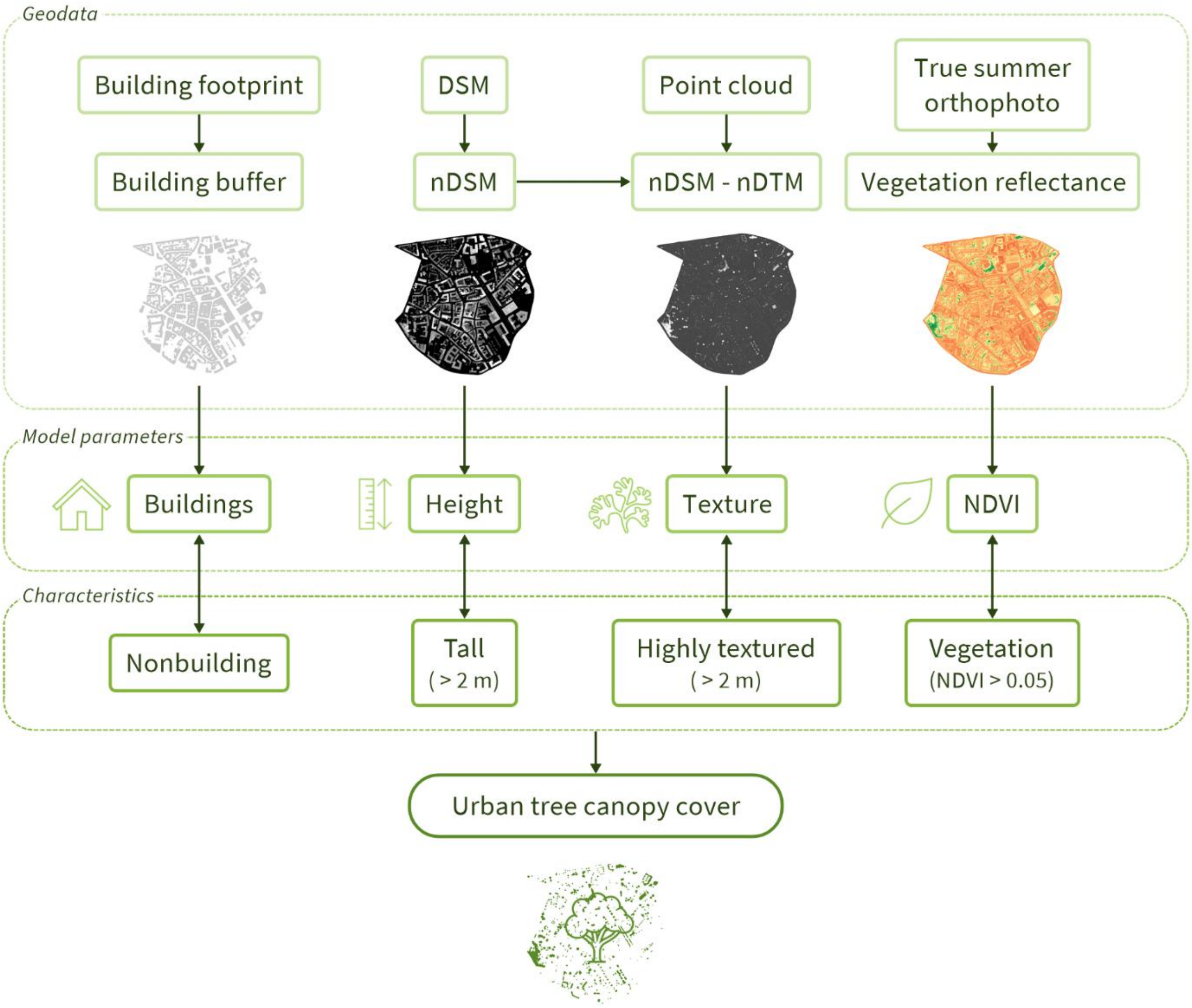


Figure 1: Overview of the developed geospatial model for mapping the UTC cover of Randers, including the geodata, model parameters, and characteristics of the UTC used and the linkages between them.

The mapping of UTC cover is performed by equal weighting of the four model parameters in a weighted overlay spatial analysis in ArcGIS Pro 3.3. Before the spatial weighting, each raster cell of the layers is assigned a scaled value of either 10 or 1 corresponding to whether the cell respectively matches or not a threshold for the UTC characteristic associated with that geodata. All thresholds for the model parameters in the final model (Figure 1) are set based on the literature, local context, and visual iterative interpretation of the geodata and resulting maps, and can likewise be altered according to the spatial context and purpose of a given UTC map.

The accuracy of the model and thus its ability to correctly map UTC cover is qualitatively and quantitatively assessed. Due to the lack of ground control and reference data of suitable spatial resolution for both more comprehensive quantitative and qualitative assessment, the applied approaches are based on visual interpretation of comparable imagery.

The qualitative accuracy assessment is conducted through visual inspection and interpretation of the generated UTC cover geodata as visualised in the derived model map in comparison to the true orthophoto (TOP). The comparison is based on criteria of presence and extent of UTC cover: Firstly, whether UTC is mapped where trees are (corresponding to true positives and false negatives) and are not (corresponding to true negative and false positive) visibly present in the TOP. Secondly, to what degree the extent of the mapped UTC cover corresponds to the contour of canopy cover visible in the TOP for (groups of) trees.

For the quantitative accuracy assessment, 500 points are randomly sampled with an equal distribution in numbers between the areas mapped and not mapped as UTC: 250 points are sampled within the total area identified by the model as UTC, and likewise, 250 points are sampled within the total area that is not mapped and thus identified by the model as not constituting UTC. For each point, the presence or absence of UTC is manually annotated based on visual interpretation of the TOP and additionally the oblique aerial imagery from *Skråfoto* covering all of Denmark from all four points of the compass. *Skråfoto* is managed by the Danish Agency for Climate Data and is freely available online as a web application (https://skraafoto.dataforsyningen.dk). From the annotated point sample, spatial statistics are calculated using four metrics to quantitatively assess the model performance: user accuracy (UA), producer accuracy (PA), overall accuracy (OA), and Kappa coefficient (Kappa).

### *2.3 Geodata*

The specifications of the geodata used as input for the model presented in Figure 1 are summarised in Table 1.

| Model parameter | Input data source | Data provider | Original spatial resolution | Raster resolution in model |
|---|---|---|---|---|
| Buildings | GeoDanmark | Danish Agency for Climate Data | Polygon | 0.4 m |
| Height | Danish Height Model (DHM) | Danish Agency for Climate Data | 0.4 m | 0.4 m |
| Texture | Danish Height Model (DHM) | Danish Agency for Climate Data | 4.5 points/m$^2$ | 0.4 m |
| NDVI | Summer true orthophoto | PRIMIS | 0.2 m | 0.4 m |

Table 1: Specifications of the input geodata for the developed model.

For the non-building aspect, a thematic building footprint vector layer is applied to indicate areas that, because of buildings, have a low likelihood of constituting area of canopy cover to be mapped with the model. A buffer of 1 m is applied to the building footprints in the model to take building-edge features into account, and the layer is afterwards rasterised to match the data format of the other layers.

Tall objects are identified from a normalised DSM (nDSM) which is created by subtracting the DTM from the DSM for the area, both derived from the 0.4 m resolution DEMs which are part of the Danish Height Model (DHM). According to the FAO definition, trees outside forests, which includes urban trees, are in terms of height defined by being able to reach a minimum of 5 m at maturity (Bellefontaine et al., 2002). However, the study area contains newly planted street trees, which have thus not reached the height of maturity. Based on inspection of the study area through the input geodata, a threshold for the height of trees as tall objects is therefore set at 2.0 m to ensure that the young trees within the study area are included in the mapping of UTC cover.

The nDSM is furthermore applied to construct a texture layer to map the vertical complexity for distinguishing between smooth and impervious objects, like buildings, and highly textured and partially pervious objects, like tree canopies. The texture corresponds to the difference between the nDSM and a normalised DTM (nDTM) of the last returns ($nDTM_{last}$) which are filtered in ArcGIS Pro from the LiDAR point cloud (Lichtblau & Oswald, 2019; O'Neil-Dunne et al., 2014). Additionally, the texture parameter contributes to map canopies that overhang buildings, which might otherwise be excluded by the building footprint layer (O'Neil-Dunne et al., 2014). To align with the threshold set for the height, the threshold related to the textured tree canopies is likewise set at 2.0 m to ensure inclusion of the young trees in the study area.

To further distinguish between the urban features, vegetation is identified by NDVI which is derived from high-resolution multispectral imagery using the red and near-infrared (NIR) spectral bands to represent the vegetation reflectance. For the imagery, a TOP is used to ensure the spatial consistency of objects in the DEMs and the NDVI layer, because an orthophoto (OP) can contain perspective distortions. In an OP objects can appear tilted, which causes geospatial displacement of, for instance, rooftops and tree canopies. In a TOP the perspective distortions are rectified, which thus enables more geospatially accurate mapping of the UTC cover. The TOP used in the present study is generated with the available workflow in ArcGIS Reality for ArcGIS Pro, based on metadata of the original aerial imagery and a DSM.

Furthermore, the applied TOP is from leaf-on season in summer to be suited for NDVI calculations to identify the extent of urban canopies. Yearly updated spring OPs are freely available at *Dataforsyningen*, but these are from the leaf-off season in spring and they are not TOPs. Summer OPs are also generated for Denmark yearly for specific administrative purposes, but these are generally not freely available to the public. Therefore, a current summer OP in leaf-on season from 2023 with 0.2 m spatial resolution that covers the study area and the appertaining imagery and metadata for generating a summer TOP are provided by PRIMIS for the purpose of this study.

The ArcGIS Pro NDVI raster function is applied to the TOP to calculate the NDVI based on Equation 1:

$$\text{NDVI} = \frac{\text{NIR - Red}}{\text{NIR + Red}} \qquad (1)$$

In the literature, the threshold for vegetation is generally defined by NDVI ≥ 0.2 (Esau et al., 2016; Gascon et al., 2016; Hashim et al., 2019). However, through visual inspection of the imagery and NDVI layer for the study area, some young urban trees were found to have lower values of NDVI, which presumably is due to the more sparse canopy structure and thus relatively high surface reflectance from urban fabric below the young trees (X. Li et al., 2024; Nichol & Lee, 2005). For that reason, the threshold for vegetation in the study area is set at NDVI ≥ 0.05 to give a more accurate map of the place-specific UTC cover to be managed.

## 3. Results

The UTC cover mapped from the developed geospatial model from Danish geodata is visualised in the map in Figure 2.


Figure 2: Map of the UTC cover (mapped in green) based on the developed model for the study area of Randers.

From the map in Figure 2 the percentage UTC cover can be calculated to 4.57% of the study area of Randers. The map further indicates that the spatial distribution of this UTC is a few areas with larger continuous canopy cover and several smaller, scattered patches.

Based on the visual interpretation of the UTC model map, in comparison to the TOP, the developed model demonstrates promising performance for mapping UTC cover in the study area. Throughout the study area, the model maps UTC for a significant amount of the trees present. Additionally, the visible extent of the canopies is correctly bounding it from the surroundings and highly corresponds to the contour of the UTC cover visible in the TOP, as can be observed in the zoom-in examples of the model map in Figure 3.

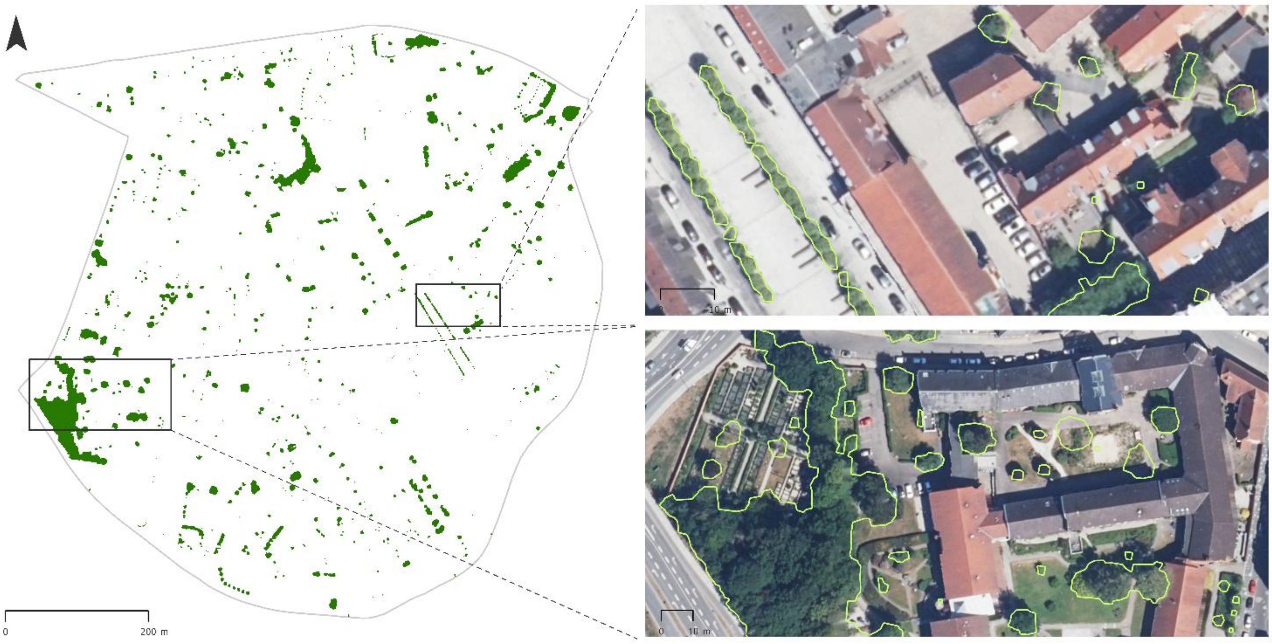


Figure 3: Zoom-in examples of the UTC cover mapped by the developed model (left, mapped in dark green) and its visual alignment with the underlying TOP (right, outlined in light green).

UTC falsely mapped by the model is very limited in the study area and mostly noticeable where changes in the landscape are occurring related to, for instance, renovation or construction sites.

The quantitative assessment from 500 randomly sampled points in the study area, equally distributed in numbers between UTC and non-UTC, indicates similar high accuracy of the UTC model. As listed in Table 2: User accuracy (UA), producer accuracy (PA), overall accuracy (OA), and Kappa coefficient (Kappa) calculated for the developed urban tree canopy cover model.

, the model's performance in all four quantitative metrics applied supports the reliability of the UTC cover map.

| **UA** | **PA** | **OA** | **Kappa** |
|---|---|---|---|
| 94.00% | 99.58% | 96.80% | 93.60% |

Table 2: User accuracy (UA), producer accuracy (PA), overall accuracy (OA), and Kappa coefficient (Kappa) calculated for the developed urban tree canopy cover model.

It should be noted, that because the UTC cover mapped constitutes a low percentage (4.57%) of the entire study area, it causes a high class-imbalance for the accuracy assessment presented in Table 2. The assessment can thus be biased by the relatively high density of points within the mapped UTC area compared to a relatively low density of points in the area identified by the model as not constituting UTC due to the equal distribution of sampling points in numbers per class. For instance, the very high PA in Table 2 could be biased by the relatively low spatial density of true and false negative sampling points assessed. However, alternatively distributing all sampling points for the accuracy assessment randomly across the study area, regardless of UTC mapped or not, would introduce bias of very few points being located within areas mapped as UTC due to the low UTC cover mapped in the study area.

Overall, the conducted UTC cover map both qualitatively and quantitatively illustrates high geospatial accuracy of the generated UTC geodata. Thus, the accuracy assessments indicate reliable model performance when applied in the study area.

## 4. Discussion

The potential value and limitations of the developed geospatial model based on model performance and replicability are discussed in the following. Based on the developed model, different maps are produced to support the discussion and compare the model-generated geodata to other geodata sources.

### *4.1 Model Performance*

From the visual interpretation and quantitative metrics, the model map demonstrated promising performance of the developed model in accurately mapping UTC cover in the study area.

However, the accuracy assessments are mainly based on the visual interpretation of TOP which is also part of the input geodata for the model and thus not an independent data source. To more comprehensively assess the accuracy of the model and generated UTC geodata, ground truth geodata would be required but are not currently available.

Alternatively, despite the limitations of the registration approach, the GeoDanmark geodata on trees does provide information indicating in Figure 4 that the developed model maps UTC where trees are registered according to a different source.


Figure 4: Location of individual and groups of trees according to GeoDanmark geodata (Danish Agency for Climate Data, 2023) compared to the UTC cover mapped by the developed model.

Yet, the suitability of the geodata for validation can further be questioned because of observable inconsistency with the TOP. For instance, several trees in the GeoDanmark map layer not mapped by the model seem not to be present in the TOP either.

Comparing the model map to maps of tree canopy from other open geodata sources for validation is also challenging due to the spatial scale in question; land cover maps and geodata on UTC cover are often of too coarse spatial resolution to be suitable for mapping at hyperlocal scale like the urban mesoscale in small cities. For the specific study area of Randers, land cover maps like the European *CORINE* from Copernicus, the Danish *INSPIRE* from the Danish Agency for Climate Data, the *Dynamic World* developed by Google and World Resources Institute, and Esri's *Sentinel–2 Land Cover* all show a UTC cover of zero in the area.

Other freely available map products, including Copernicus' *Urban Atlas* and the European Space Agency's (ESA) *WorldCover*, do however show the presence of UTC in the study area. Yet, they are still of too coarse spatial resolution for accurately mapping green elements like individual street trees. This nevertheless emphasises the knowledge and data gap concerning UTC cover at the hyperlocal scale and thus the potential value of the developed model by addressing it.

### *4.2 Perspectives on Input Geodata and Accessibility*

The use of a not freely available summer TOP as input geodata for the model however limits the accessibility of the mapping. Because of the methodical approach chosen for mapping UTC in the present study, a summer TOP was required for the NDVI calculations and spatial consistency with the other input geodata to optimise the model performance for geospatial accuracy. However, applying the developed model with the available spring OP or a summer OP might also hold potential for providing UTC information at the hyperlocal scale, as illustrated in the zoom-in examples in Figure 5.


Figure 5: Zoom-in examples of the UTC cover only mapped by the developed model with the spring OP (red) and summer TOP (blue) as imagery input respectively and where the mapped UTC from the two overlaps (purple).

For the different imagery inputs the amount of UTC cover mapped in the study area by the model corresponds to 4.45% with the spring OP and 4.56% with the summer OP compared to 4.57% with the summer TOP (f). Thus, the difference amounts to merely 0.12 percentage points in UTC cover between the freely available spring OP and the summer TOP as input, where the latter requires both access to the current summer OP and processing it to a TOP.

The relatively small differences might be due to the high quality and spatial resolution of the DEM's and other input geodata supplementing the NDVI model parameter in representing UTC. Furthermore, as NDVI is chlorophyll sensitive and tree bark to some extent contains chlorophyll, like leaves, red light is still absorbed to some extent by the trees which might cause the detectable difference in the NDVI of urban elements even in a leaf-off spring OP (Natale et al., 2023; Pettorelli et al., 2005). In theory, NDVI of leafless trees does inherently not properly describe the canopy of the tree and is thus less suited for estimating the provision of ecosystem services. Additionally, the OP not being *true* also causes geospatial displacement between the input geodata regarding the model parameters. Moreover, the differences in UTC cover caused by the spring OP might be of greater magnitude for other cases with, for instance, more or less UTC cover.

Nevertheless, the exemplified mapping of UTC cover in Figure 5 indicates that applying the model with the spring OP might hold potential and value due to all input being open geodata. In future research, the applicability of more accessible NDVI data sources should therefore be quantitatively assessed to investigate the further potential of freely available geodata for mapping of local UTC cover. Exploring this further would moreover allow for and inform a discussion of: How accurate UTC cover maps are needed for a specific purpose and what level of model and map accuracy can be accepted relative to the cost of geodata?

Because of the research objective focusing on exploring model development, replicating the model with new cases is beyond the scope of the present study. However, investigating the replicability of the model remains a crucial next step for validating the model's potential value as a tool for providing geospatial information on local UTC cover at the hyperlocal scale.

## 5. Conclusion

In the present study, a geospatial model has been developed within ArcGIS Pro to demonstrate how urban tree canopy cover can be mapped with geospatial techniques from existing Danish geodata. Adding to the collection of existing tools, the study targets local practitioners in small cities by proposing an alternative to AI-based models and map products to acquire hyperlocal UTC cover information in cities with less resources required.

The developed model demonstrates promising performance through the UTC cover map of the study area in the smaller Danish city of Randers with high geospatial accuracy. However, both the qualitative and quantitative accuracy assessments are limited by the lack of UTC ground truth geodata.

Model maps showing UTC cover comparable to the imagery could be generated with summer TOP as imagery input. However, applying the model with the summer OP and freely available spring OP also indicated potential for mapping UTC without limited geodata accessibility. In future research, the spatial accuracy of applying available imagery for the NDVI model parameter should be further assessed to investigate its potential value for accessible mapping of UTC relative to the resources available and the purpose of use. Otherwise, adding recent summer OP or even TOP to the freely available basic Danish geodata could, based on the study findings, enable accurate mapping of hyperlocal UTC cover in Danish cities with the developed model.

For the purpose of mapping UTC cover of other cities, the model is, however, currently limited by being based on a single case. Consequently, a crucial next step is to apply the model to other study areas that are geographically similar or different to explore the replicability of the developed model. Enabling accessible mapping of hyperlocal information on UTC cover as a spatial metric and visually communicated through maps can thus hold value for supporting nature-based approaches to climate change adaptation in cities. Additionally, UTC cover maps can provide a baseline for planning and further investigation of climate-regulating ecosystem services provided by urban trees in a given city.

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