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ABBREVATIONS

AIS	Areal Information System
FAO	Food and Agriculture Organization

INTRODUCTION

Historical forest mapping is essential for understanding long-term changes in forest cover, landscape structure, and land-use dynamics. It provides an important foundation for spatial analyses, environmental research, as well as policy assessments. In Denmark, the earliest available nationwide orthophotos date back to 1954. These aerial photographs were captured in May 1954 at a spatial resolution of 25 × 25 cm and cover the entire country in 5 × 5 km tiles. This dataset offers a unique opportunity to reconstruct tree crown cover and forest cover in Denmark in 1954, which is the primary objective of this project. See more details in Tsatsakis et al. (2026).

The final output of this study is a national forest map representing forest cover in Denmark in 1954, providing a baseline for quantitative analyses of afforestation, deforestation, and broader landscape changes over the past decades. In addition, the 1954 forest map is compared with a comparable national forest map from 2018. Through spatial analyses of the two datasets, we assess forest development in Denmark over the past seven decades and establish a foundation for further, more detailed investigations of long-term forest dynamics and their implications for the Danish landscape.

TREE CROWN COVER IN 1954

The 1954 dataset is compiled from COWI, the international, Danish based engineering, environmental and economics consultancy group, and is distributed by the multinational, Stockholm based IT group specialized in metrology and geospatial equipment and software, Hexagon. The 1954 aerial photographs were first analyzed by Tsatsakis et al. (2026), who developed a spatially explicit dataset of tree crown polygons using modern deep learning techniques. A convolutional neural network based on a U-Net architecture was applied to the grayscale aerial imagery to identify and map individual tree crowns across Denmark (Photo 1).

Due to the absence of forest inventory data from the 1950s, Tsatsakis et al. (2026) constructed a dedicated training dataset through manual delineation of tree crowns in selected reference areas. Two separate models were trained and subsequently combined to improve robustness. To enhance model generalization, extensive data augmentation techniques were applied, including image rotation, mirroring, and geometric distortion, enabling the model to recognize trees under varying

illumination and viewing conditions (Tsatsakis et al., 2026). The final model was applied pixel by pixel to the complete national image archive, producing a comprehensive map of tree canopy cover for Denmark in 1954 (Photo 1).

The resulting dataset includes all tree-covered areas, such as forests, shelterbelts, orchards, garden trees, and urban vegetation, and estimates that 407,937 hectares of Denmark's land area were covered by tree canopies in 1954 (Tsatsakis et al., 2026).

Photo 1. The 1954 aerial photograph (left) and the tree crown polygons derived from the 1954 aerial imagery (right) (from Tsatsakis et al., 2026).

Model performance was evaluated using independent validation points and yielded a specificity of 91 % and a true positive rate of 66 % (Tsatsakis et al., 2026). This indicates that the model is highly effective at minimizing false positives, while approximately one-third of actual tree-covered areas were not detected.

Although the tree crown dataset provides a detailed representation of vegetation structure, it does not directly correspond to forest area as defined by the Food and Agriculture Organization (FAO). According to the FAO (2020), forests are defined as land spanning at least 0.5 hectares, with a minimum width of 20 meters, a tree cover of at least 10 %, and trees capable of reaching a height of 5 meters, excluding urban parks, orchards, nurseries, and other non-forest land uses. To produce a historical forest map suitable for comparison with modern datasets, a post-processing workflow was therefore applied to the 1954 tree crown polygons to ensure compliance with the FAO forest definition.

METHODOLOGY

Forest cover in Denmark in 1954 was reconstructed from a high-resolution binary tree canopy dataset (1 m spatial resolution), in which forested areas were coded as 1 and non-forest areas as 0. All spatial analyses were conducted in the ETRS89 / UTM Zone 32N coordinate reference system. Vector-based spatial operations were carried out in QGIS.

Multipart polygons were first converted to single-part features using *Multipart to Singleparts*. Geometric errors, including self-intersections and invalid topology, were corrected using *Fix Geometries*. Polygons sharing boundaries were merged using *Dissolve* to create contiguous forest patches, ensuring that coherent forest units were treated as single landscape entities.

A vector-based morphological filtering approach described by Nord-Larsen (2024) was applied to operationalize the FAO forest definition. A positive buffer of 10 m was applied to all forest polygons using *Buffer* to connect neighboring tree crowns located within 20 m of each other. This step ensured that spatially proximate canopy elements were merged into continuous forest units.

A negative buffer of 20 m was subsequently applied to remove narrow extensions and linear features with a width of less than 20 m, thereby enforcing the minimum width requirement. A final

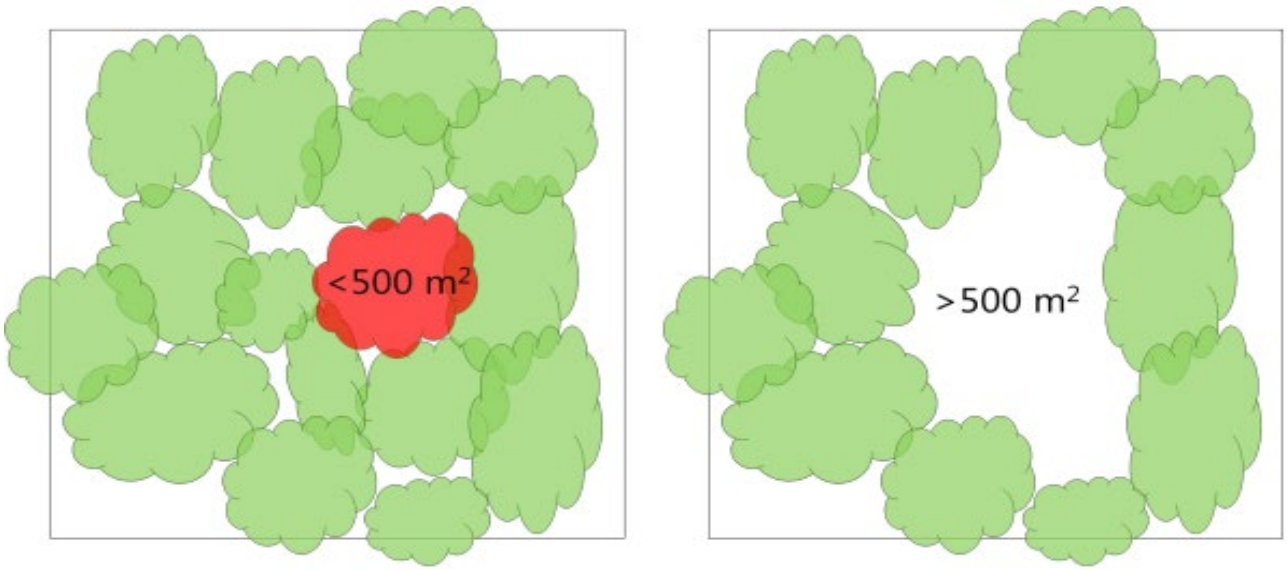

Photo 2. Areas smaller than 500 m² are filled to avoid artificial fragmentation caused by canopy gaps (from Nord-Larsen, 2024).

positive buffer of 10 m restored the outer boundaries of the polygons while maintaining the removal of sub-threshold narrow sections.

The polygons were then merged again using *Dissolve* to ensure spatial coherence. Polygon areas were recalculated in hectares using *Field Calculator* to enable accurate size-based filtering. Interior holes smaller than 500 m² were removed using *Delete Holes*, following the methodology described by Nord-Larsen (2024), to eliminate minor gaps likely caused by classification artefacts (Photo 2). Forest patches were subsequently filtered according to the FAO minimum area criterion of 0.5 ha, and all polygons below this threshold were removed. Finally, the total forest area was calculated by summing polygon areas in hectares (Table 1).

Exclusion Layers

In forest mapping, exclusion layers are commonly applied to remove areas that are known not to constitute forest, such as gardens, summerhouse areas, roads, agricultural fields, and urban parks. Nord-Larsen (2024) emphasizes that exclusion layers are essential for reliably removing areas that can confidently be classified as non-forest during post-processing. For 1954, however, no nationwide historical exclusion layers are available. A pragmatic approach was therefore adopted, combining modern geospatial datasets with informed assumptions.

Areas outside the terrestrial land surface were first removed using a polygon layer representing all Danish municipalities (Kommune_område_10k_GeoDanmark-KDS_2025), eliminating erroneously mapped tree crown polygons in marine areas (Photo 3).

The earliest nationwide land-use dataset available, the Areal Information System (AIS) from 1996–1999 (Nielsen et al., 2000), was used to exclude permanent water bodies and urban areas. Lakes were masked using the AIS lake layer (Sø_25k_AIS_1996–1999). Lake polygons were subtracted using *Difference*. Urban areas were excluded using the AIS urban zone layer (Byzone_25k_AIS_1997–1999), subtracted using *Difference*. After these overlay operations, forest area was recalculated to provide a consistent estimate of forest cover in 1954 (Table 1).

Photo 3. Example of tree crown polygons incorrectly mapped over the sea (from Tsatsakis et al., 2026).

Comparison with the 2018 Forest Map

Following the production of the national forest map for 1954, a contemporary national forest map from 2018, obtained from the Forest Plan project, was included in the analysis. As the 2018 map was also derived from remote sensing data, it is methodologically comparable to the 1954 dataset (Nord-Larsen et al., 2023).

To identify forest persistence, a spatial intersection between the 1954 and 2018 forest polygons was performed using *Intersection*, producing a polygon vector layer representing forest areas present in both years. Newly established forest areas were identified by subtracting the 1954 forest polygons from the 2018 forest polygons, while deforested areas were identified by subtracting the 2018 polygons from the 1954 forest polygons. For all resulting layers, forest area was calculated in hectares using QGIS geometry tools.

RESULTS

The final product represents a reconstruction of forest cover in Denmark in 1954, derived from historical tree crown mapping and subsequently processed in accordance with the FAO forest definition.

To assess the influence of exclusion layers, forest area was calculated under multiple masking scenarios (Table 1).

Year	Source	Processing step	Forest area (ha)	% of land area
1954	INNO4EST project	Before masking	366,614	8.5 %
1954	INNO4EST project	After masking with lake polygon	364,356	8.5 %
1954	INNO4EST project	After masking with lake and urban zone polygons	356,392	8.3 %

Tabel 1. Forest area estimates derived from the 1954 tree crown dataset under different masking scenarios. The table illustrates the effect of excluding lakes and urban zones on the final forest area estimate.

As shown in Table 1, the application of spatial masking layers incrementally reduces the estimated forest area. The final estimate, excluding both lakes and urban zones, amounts to 356,392 hectares, corresponding to 8.3 % of Denmark's land area. The percentage was calculated using a total Danish land area of 4,309,831 hectares (including lakes), based on official statistics from Danmarks Statistik (2025).

An overview of forest area estimates derived from different data sources and methodological approaches is presented in Table 2.

Year	Source	Data	Forest area (ha)	% of land area
1954	INNO4EST project	Aerial photographs deep learning + GIS	356,392	8.3 %
1951	Danmarks Statistik	Questionnaire survey	370,670	8.6 %
1965	Danmarks Statistik	Questionnaire survey	404,573	9.4 %
2018	Forest Plan project	Satellite-based remote sensing	581,262	13.5 %
2023	Danmarks Skovstatistik	Field-based National Forest Inventory	651,757	15.1 %

Tabel 2: Overview of forest area estimates in Denmark from different data sources and methodological approaches (Danmark Statistik, 1968; Danmarks Statistik, 1954; Nord-Larsen et al., 2023, 2025).

As shown in Table 2, forest area in Denmark has increased substantially over the past seven decades. The 1954 estimate of 356,392 hectares (8.3 %) contrasts with 651,757 hectares (15.1 %) reported in 2023, indicating that national forest area has nearly doubled since the mid-20th century. Estimates of the questionnaire-based surveys from 1951 and 1965 report 370,670 hectares forest area in 1951 (8.6 %), and 404,573 hectares forest area in 1965 (9.4 %). Finally, the 2018 Forest Plan map reports 581,262 hectares (13.5 %).

To assess forest dynamics between 1954 and 2018, the constructed 1954 forest map was integrated with the 2018 forest map. By comparing these two forest maps, we see that the national forest area has increased by 224,870 hectares over this period, corresponding to a net increase of 5.2 % over 66 years.

Further spatial comparison between the two maps shows:

- **Forest persistence:** 288,037 hectares of the forest areas present in 1954 remained forest in 2018, corresponding to 80.8 % of the 1954 forest area.
- **Afforestation:** 323,030 hectares were established between 1954 and 2018, representing a 90.7 % increase relative to the 1954 forest area.
- **Deforestation:** 68,355 hectares of forest present in 1954 had been cleared by 2018, corresponding to 19.2 % of the 1954 forest area.

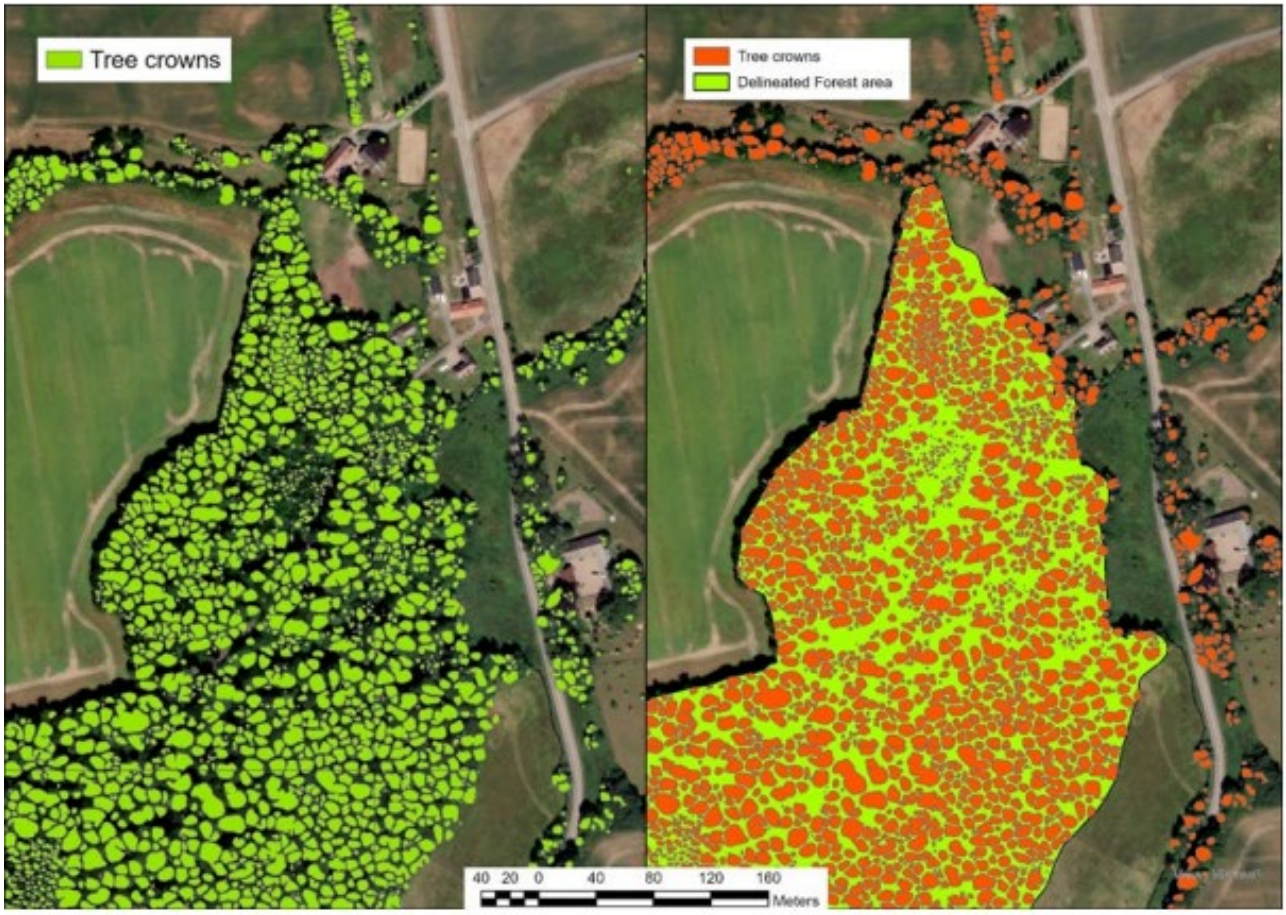

Photo 4. Tree crown cover (left) and the delineated forest area (right) (from Nord-Larsen et al., 2025).

DISCUSSION

Data Limitations

Several limitations are inherent to the 1954 aerial photograph dataset and should be considered when interpreting the forest map.

First, the photographs were acquired in May, prior to full leaf-out of deciduous trees. This phenological timing reduces crown visibility, particularly for deciduous species, and limits the ability to accurately identify and delineate forested areas (Tsatsakis et al., 2026). Consequently, certain forested areas may be underrepresented in the dataset.

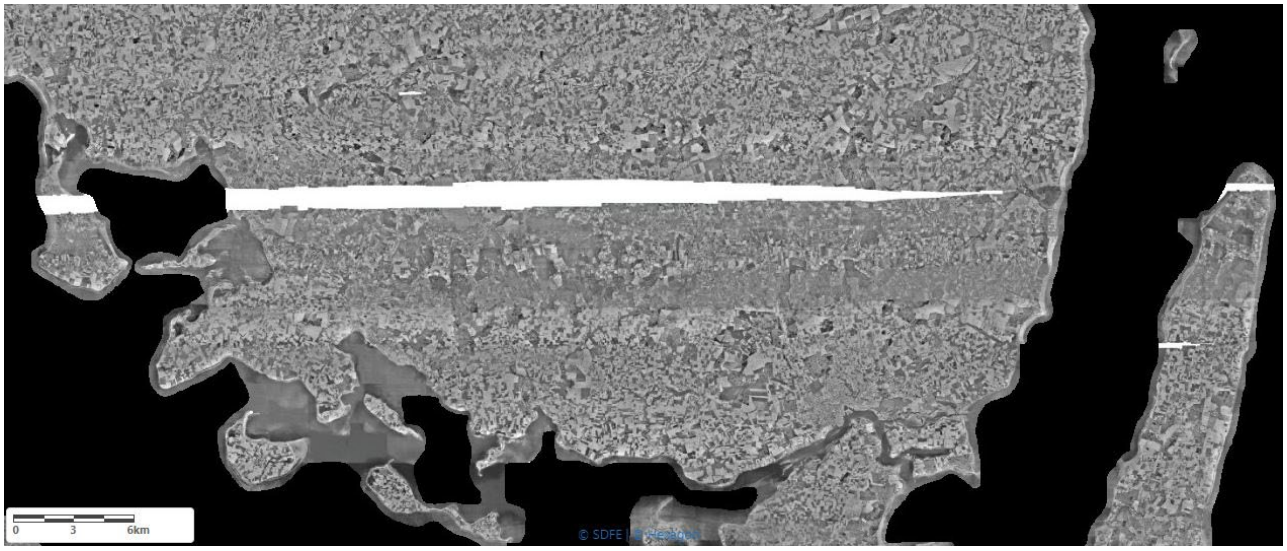

Photo 5. The band with missing imagery in southern Funen. Picture from Tsatsakis et al. (2026).

Second, the islands of Læsø and Anholt were not photographed in 1954. While historical sources suggest that Anholt had little or no forest at the time (Det Kongelige Bibliotek, 2026), Læsø had undergone afforestation beginning in the early 20th century, including the establishment of Læsø Klitplantage (Naturstyrelsen, 2026). Forested areas on Læsø in 1954 are therefore not represented in the dataset, leading to a slight national underestimation of forest extent. In addition, minor gaps in photographic coverage occur in a few places, resulting in a few localized areas with missing data (Tsatsakis et al., 2026) (Photo 5).

Furthermore, the imagery was acquired at varying flight angles and under changing illumination conditions throughout the day. This introduces spatial variability in image quality and shadow patterns, complicating consistent interpretation of tree structure. Because the imagery is grayscale and limited to a single spectral band, it lacks the spectral information available in modern multispectral datasets, reducing the ability to distinguish between vegetation types. Moreover, each location is represented by a single acquisition date, whereas contemporary forest mapping typically relies on multi-temporal imagery to capture seasonal variation and reduce classification uncertainty (Tsatsakis et al., 2026).

To mitigate these limitations, Tsatsakis et al. (2026) used supplementary data sources and incorporated them into the analysis, including historical topographic maps from 1901–1971, Luftwaffe aerial photographs from 1944-1945, and modern orthophotos (Det Kongelige Bibliotek, 2026). These

additional datasets were used to support interpretation in areas that were difficult to classify using the 1954 imagery alone and help ensure that the analysis is as robust as possible despite the inherent constraints of the historical dataset (Tsatsakis et al., 2026).

Methodological Considerations

Beyond the limitations of the source imagery, several methodological factors influence the estimated forest area. A central source of uncertainty relates to the performance of the deep learning–based tree crown detection model. The model demonstrates a high specificity (91 %), indicating a strong ability to minimize false positives. However, the true positive rate is 66 %, implying that roughly one-third of existing tree cover may not be detected. However, this omission primarily concerns small, narrow, or sparsely distributed tree elements, such as young plantations, shelterbelts, and scattered trees (Tsatsakis et al., 2023). As a result, the total tree-covered area in 1954 is likely underestimated. However, because the FAO forest definition emphasizes minimum area and width thresholds, the impact of underdetecting very small or fragmented canopy elements on the final forest area estimate is likely smaller than the overall omission rate suggests.

Conversely, some degree of overestimation may occur. Due to the absence of detailed historical land-use layers from 1954, it was not possible to fully exclude tree-covered non-forest land uses such as orchards, gardens, and certain urban tree stands. The earliest nationwide land-use dataset available, the Areal Information System (AIS) from 1996-1999 (Nielsen et al., 2000), was therefore used to exclude permanent water bodies and urban areas. However, the use of the AIS masking layer introduces a temporal mismatch of more than 40 years between the land-use data and the 1954 imagery.

Lakes were removed based on the assumption that they represent relatively stable landscape features whose spatial extent has not changed substantially since 1954. Urban zones were likewise used as a masking layer, based on the consideration that most urban expansion in Denmark has historically occurred on former agricultural land rather than at the expense of forest. This pattern is closely linked to the long-standing legal protection of Danish forests under the *Fredskovsforordningen*, which has been in force since 1805 (Helles et al., 2026).

Consequently, this procedure may have excluded some small forest patches that were located within areas classified as urban in the 1996-1999 dataset. At the same time, it effectively removes gardens, parks, and other tree-covered areas that do not meet the FAO forest definition. Nevertheless, despite the application of modern exclusion layers, some non-forest tree cover may remain in the final dataset due to the lack of historically consistent masking data.

Taken together, these uncertainties imply that the reconstructed forest map should be interpreted as a best-available, spatially explicit estimate rather than an exact measurement. Nevertheless, the approach provides a transparent and reproducible historical baseline for analyzing long-term forest dynamics.

Methodological Comparison between National Forest Estimates

The forest area estimates presented in this study derive from different methodological approaches, each with distinct strengths and limitations. Comparing them highlights how methodological variation influences reported forest extent.

The 1954 forest map presented here is based on historical aerial photographs combined with deep learning-based tree crown detection and GIS-based post-processing. This approach produces a spatially explicit dataset and ensures national coverage. However, as discussed previously in this report, it may underdetect small or fragmented tree elements due to image quality constraints and model sensitivity (Tsatsakis et al., 2026).
The questionnaire-based surveys conducted by Danmarks Statistik in 1951 and 1965 relied on self-reported information from forest and plantation owners, supplemented by administrative records (Danmark Statistik, 1968; Danmarks Statistik, 1954). These surveys achieved broad coverage of registered forest properties but did not produce spatially explicit maps. The estimates may therefore reflect reporting inconsistencies, biases or differences in interpretation of what constitutes forest.

More recent mapping initiatives, such as the Forest Plan 2018 forest map, are based on automated canopy detection from multispectral satellite imagery. These approaches provide consistent, objective, and spatially comprehensive coverage, although young plantations and structurally heterogeneous stands may still be difficult to detect (Nord-Larsen et al., 2023).

Finally, the field-based National Forest Inventory, as reported in the 2023 forest statistics report, provides highly accurate structural and compositional information based on direct systematic plot-level measurements (Nord-Larsen et al., 2025). However, these data are sample based rather than fully spatial representations.

Overall, the comparison illustrates the trade-offs between spatial detail, structural accuracy, and methodological transparency. Despite differences in approach, all datasets indicate a substantial increase in forest area in Denmark since the mid-20th century. The merging of independent data sources strengthens certainty in the overall trend, even if individual estimates vary due to methodological differences.

Preliminary Analysis of Forest Development since 1954

The spatial comparison between the 1954 forest map and the 2018 forest map enables the identification of geographical patterns of forest change, including the distribution of newly afforested areas and regions of forest loss between 1954 and 2018 in Denmark.

The analysis shows that the Danish forest area increased by 224,870 hectares during this period 1954-2018, corresponding to a net gain of 5.2 % of the total land area over 66 years. Approximately 80 % of the forest area present in 1954 persisted as forest in 2018. However, 68,355 hectares of forest existing in 1954 had been cleared by 2018, representing a loss of around 19 % of the 1954 forest area. These findings call for further investigation into the drivers of deforestation since 1954. Potential explanations include urban expansion, infrastructure development, and agricultural conversion. However, the relative importance of these land-use changes has not yet been analyzed and remains a topic for future research.

The analysis further shows that 323,030 hectares of forest were established between 1954 and 2018, corresponding to a 90 % increase relative to the 1954 forest area. This substantial afforestation reflects structural changes in Danish land use. Future analyses could examine the landscape contexts in which afforestation primarily occurred in this period, the forest types and tree species established, and the geographical distribution of new forest areas across Denmark. Such investigations would provide deeper insight into the economic, ecological and policy drivers of afforestation.

These findings are highly relevant in the context of contemporary Danish forest and climate policy. Recent political agreements, including the 2024 Green Tripartite Agreement (*Den Grønne Trepart*), set ambitious targets for large-scale afforestation in the coming decades, including the establishment of 250,000 hectares of new forest on former agricultural land by 2045 (Regeringen et al., 2024). The historical evidence presented in this study demonstrates that substantial afforestation has previously taken place in Denmark. Although current policy ambitions imply a faster rate of forest expansion than observed historically, the results indicate that both the methodological capacity and land-use potential for large-scale forest development exist.

CONCLUSION

This study has constructed a national map of the forest cover in Denmark in 1954 based on historical aerial photographs and deep learning-based tree crown detection, combined with GIS-based processing in accordance with the FAO forest definition. The resulting spatially explicit forest map provides a consistent historical baseline for analyzing long-term forest dynamics.

The analysis estimates that Denmark's forest area in 1954 covered 356,392 hectares, corresponding to 8.3 % of the national land area. A spatial comparison with contemporary forest data demonstrates that forest area has increased substantially since 1954. Between 1954 and 2018, the total forest area expanded by approximately 224,870 hectares, while around 80 % of the 1954 forest persisted. At the same time, around 19 % of the 1954 forest area was lost, highlighting that forest development has involved both afforestation and deforestation.

Although the reconstruction is subject to uncertainties related to historical imagery and methodological constraints, it represents a robust and transparent estimate of the forest extent in 1954. By integrating historical aerial data with modern spatial analysis techniques, this study contributes a valuable long-term perspective on forest change in Denmark. The results provide an important empirical foundation for future research on land-use transitions and for evaluating contemporary forest and climate policy ambitions.

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