

Separating measurement from definition: an object-based workflow for national forest mapping

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Abstract

Forest is defined rather than observed, and definitions are written to serve different management objectives. In Norway, four authoritative datasets place forest between 35 and 43% of the mainland because each encodes a different rule. Categorical forest maps inherit this problem, since each serves only the definition it was built on. We present a documented object-based workflow that separates measurement from definition. Very high-resolution imagery, Sentinel-2, and a laser-derived canopy height model are combined with the existing national masks in a spatial database, and the result is segmented in two steps into tree crowns, tree points derived from them, and forest-stand segments carrying height, crown cover, species, and site index. A rule-based expert system then classifies the tree points. Applied to mainland Norway, the workflow produced 2.72 billion tree crowns and 57.8 million forest-stand segments covering 144,755 km². Because structure is stored as attributed objects rather than a single class, thresholding one dataset reproduces forest areas from 15.8 to 44.7% and brackets all four national estimates. Independent interpretation of 702 sampled points gave a commission error of 0.6% for the accepted tree points. The resulting dataset is called Skogmaske.

Keywords

Forest definition, object-based image analysis, individual tree detection, canopy height model, forest mapping

1. Introduction

Forests cover close to a third of the global land area and store a large share of terrestrial carbon, alongside much of the world's biodiversity and a range of provisioning and cultural services (FAO, 2025). Managing these ecosystems begins with accurately mapping tree distribution and forest extent. This foundational knowledge relies on a forest mask, a spatial record of tree presence and extent that underlies area statistics, carbon accounting, and change detection. Therefore, the quality of the mask limits the quality of everything built on it. Yet forest is not a physical fact but a definition, and definitions are built to serve particular management objectives, from timber production to carbon accounting to the conservation of biological diversity (Chazdon et al., 2016). Because these objectives differ, many definitions coexist, and the same land can qualify as forest under one rule and not under another. Separating what is measured from how forest is defined is therefore the starting point for a mask that can serve more than one definition.

Remote sensing offers a way to make that separation. Forest definitions rest on a few physical quantities, mainly how much ground the crowns cover, how tall the trees are, and how large a contiguous patch must be (Chazdon et al., 2016). Cover and height can now be measured from above across whole countries (Brandt et al., 2025). Very high resolution (VHR) satellite imagery records the horizontal extent of tree cover, and airborne laser scanning gives the vertical

1 structure. Neither measurement carries administrative status, so what is recorded is structure, to
2 which a definition can be applied afterwards.

3 Existing products sit at two extremes. On one side are continuous canopy surfaces, which now
4 span a wide range of resolutions. Tree cover change is mapped at 30 m (Hansen et al., 2013),
5 canopy height is mapped at 30 m and at 10 m by fusing spaceborne lidar with optical imagery
6 (Lang et al., 2023; Potapov et al., 2021), and tree cover density across Europe at 10 m (European
7 Environment Agency, 2024), while the newest global product reaches about 1 m and resolves
8 canopy edges and gaps well (Brandt et al., 2026). However, these surfaces remain pixel-based
9 rasters. They do not delineate crowns as objects, carry stand attributes such as species or site
10 index, or tie to an operational forest definition. Furthermore, their accuracy falls where the sun
11 sits low and the vegetation is short, conditions common in northern forest (Brandt et al., 2026).
12 On the other side, individual tree detection from VHR imagery and laser data is a mature field (Ke
13 and Quackenbush, 2011), but it is typically applied from plot to landscape scale. Between the two
14 lies the intermediate scale at which forest is actually managed and reported, where the crown,
15 the stand, and the patch of cover are the working units.

16 Working at this intermediate scale requires more than labeling pixels one by one, which yields
17 noisy and fragmented maps. Object-based image analysis (OBIA) groups neighboring pixels into
18 segments that behave as real-world objects and classifies them from their spectral values, shape
19 and context (Blaschke, 2010; Karan et al., 2025). Segments can be nested, so a single dataset can
20 represent forest at several scales, from individual tree crowns to stand-like segments. Such
21 methods already underpin operational forest resource mapping, including the Norwegian forest
22 resource map SR16 (Astrup et al., 2019).

23 The components are therefore mature, but their integration remains undeveloped. Segmentation
24 is established, measured structure is available, and the categorical masks that encode existing
25 forest definitions already exist. We are not aware of a documented workflow that integrates these
26 components, resolves the result at the object scales used in forestry, and runs reproducibly at
27 national scale. Fusing measurement with definition, while keeping the representation flexible
28 enough to serve more than one definition, is the methodological gap this paper addresses.

29 Norway offers a well-documented case, and the data needed to address it. The country maintains
30 several authoritative forest datasets, each built for a different purpose. AR5 treats forest as land
31 able to grow trees to 5 m with at least 6 trees per 1,000 m², assessed within a minimum mapping
32 unit (MMU) of 2,000 m² (Ahlstrøm et al., 2019). SR16 maps forest based on remote sensing with a
33 2 m height threshold and a 256 m² MMU (Astrup et al., 2019). N50 provides a qualitative forest
34 outline with no fixed height or density limit but a 4,000 m² MMU. In contrast, the National Forest
35 Inventory (NFI), running since 1919, is sample-based and defines forest as areas over at least
36 1,000 m² with a crown cover of at least 10% from trees capable of reaching 5 m in height (Tomter,

2019). National forest area estimates therefore range from 35% under AR5 to about 43% under the NFI, with intermediate figures near 38 to 39.5% from N50 and official statistics (Gjertsen et al., 2025). Most of the disagreement lies in sparse, low productivity tree cover near the tree line, along the coast, and in the north, where stands stay short and open (Bryn and Potthoff, 2018). These are the conditions global products handle worst, and they recur across boreal and montane regions worldwide.

This paper builds on a national feasibility study that developed and evaluated the approach on eight test areas covering just 1% of the mainland (Gjertsen et al., 2025). The study established the three-level product concept, the segmentation design, and the comparisons against reference datasets on which this work builds. Here we report the method with its production parameters, extend it with a rule-based classification of the detected tree points, apply it to full national coverage, and assess how the resulting dataset responds to different forest classifications.

We present an object-based workflow that combines VHR and Sentinel-2 satellite imagery with a laser-derived canopy height model and national categorical forest masks and produces three products: (i) individual tree crowns, (ii) the tree points derived from them, and (iii) forest-stand segments attributed with tree height, crown cover, species, and site index. Because the structure is stored as objects with measured attributes rather than a single binary class, the dataset decouples measurement from definition and can be re-thresholded to represent different forest definitions rather than committing to a single one. The contributions of this work are threefold: (1) a documented pipeline, implemented in Python and SQL and driven by eCognition rule sets, that integrates six raster and eight vector sources into a multi-scale forest representation; (2) an object hierarchy that reconciles several mutually inconsistent forest definitions within one product; (3) a demonstration that the approach scales to full national coverage, resulting in the Skogmaske dataset for Norway.

2. Data and study area

The study area is mainland Norway, about 324,000 km², spanning alpine and boreal vegetation zones. The land runs through strong gradients, from the coast to the alpine zone and from the south to the far north. A large share of the tree cover is sparse and low in productivity, and it is variably included by the different definitions (Gjertsen et al., 2025). Production runs on a national grid of square tiles, processed in batches (Figure 1). Method development and validation used eight test areas, each 250 km², laid out across landscape gradients. Together they cover just under 1% of the mainland (Gjertsen et al., 2025).

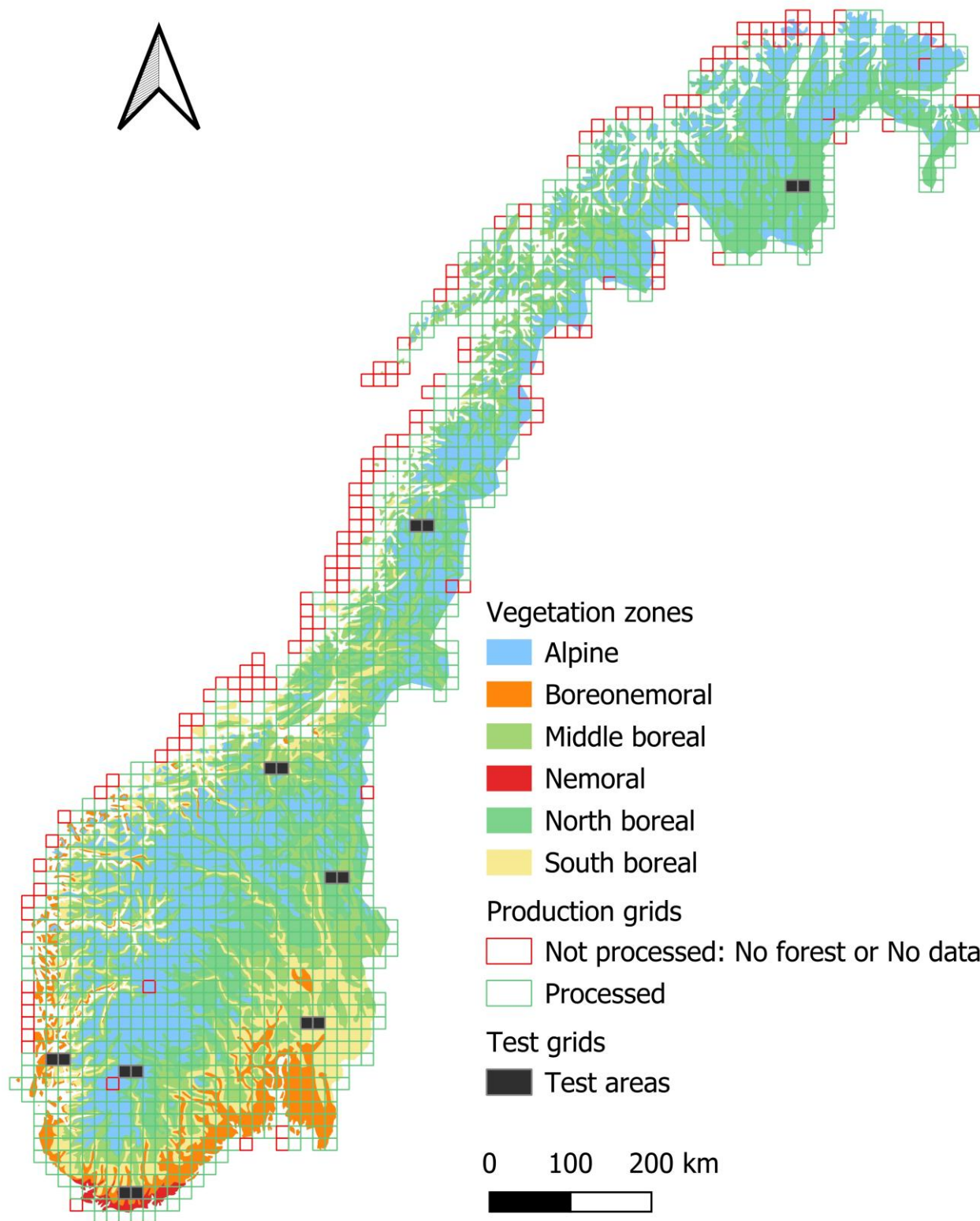


Figure 1: Study area. Mainland Norway, showing vegetation zones and the square production grid used to organize input data into production tiles. Basemap adapted from (Moen, 1998)

Two optical datasets provide spectral information on vegetation. The VHR mosaic comes from the Copernicus Contributing Missions and has a ground sample distance (GSD) of 2 to 4 m in four bands: blue, green, red and near infrared. It is a nearly cloud-free national mosaic built from several sensors acquired between June and September 2021, calibrated to reflectance (Copernicus Data Space, n.d.). The nearly cloud-free Sentinel 2 national mosaic has a GSD of 10 m in the same four bands and dates from July to August 2021 (Kartverket, 2026a; Norwegian Space Agency, 2026).

The national high-resolution elevation model (Kartverket, 2024) provides a 1 m digital surface model and a 1 m digital terrain model, from which a canopy height model (CHM) was derived. The underlying laser scanning was collected between 2010 and 2024, and each forest-stand segment carries the acquisition date of its source data.

Three existing forest masks anchor the dataset to national practice. AR5 (Ahlstrøm et al., 2019), SR16 (Astrup et al., 2019), and N50 (Kartverket, 2026b) each define forest under their own rules, and their union marks land already recorded as forest. SR16 also supplies tree species and site index, which are attached to the final forest-stand segments. A set of topographic vector layers refines the result. FKB (Felles kartdatabase), the national database of detailed topographic map data in Norway (Geonorge, 2026), provides layers for buildings, roads, water, and agricultural land. Together with a powerline buffer, these layers were used to remove false tree detections on buildings and power lines and to define boundaries against non-forest land.

All layers are held in a spatial database. Full details of each source, version, resolution, reference system, and preprocessing steps are given in Supplementary information.

3. Methods

3.1 Overview

The Skogmaske dataset was produced in a documented pipeline that integrates the input layers in a spatial database, derives individual tree crowns and tree points, and delineates forest segments. Figure 2 shows the complete workflow. Processing was carried out tile by tile using the production grid and executed on eCognition Server, allowing the workflow to scale to national coverage while keeping individual processing tasks within manageable sizes.

We define the image as a domain Ω that comprises all pixels. Segmentation produces a set of contiguous subsets $\mathcal{S} = \{S_1, \dots, S_n\}$ where all $S_i \subset \Omega$. Pixel based measures, such as vegetation indices and canopy height model (CHM), are defined for all $x \in \Omega$, while classifications and further analyses are defined on the segment levels.

A complete listing of model parameters is provided in the Supplementary Information. The workflow was implemented using eCognition Developer, eCognition Server, PostGIS, and QGIS.

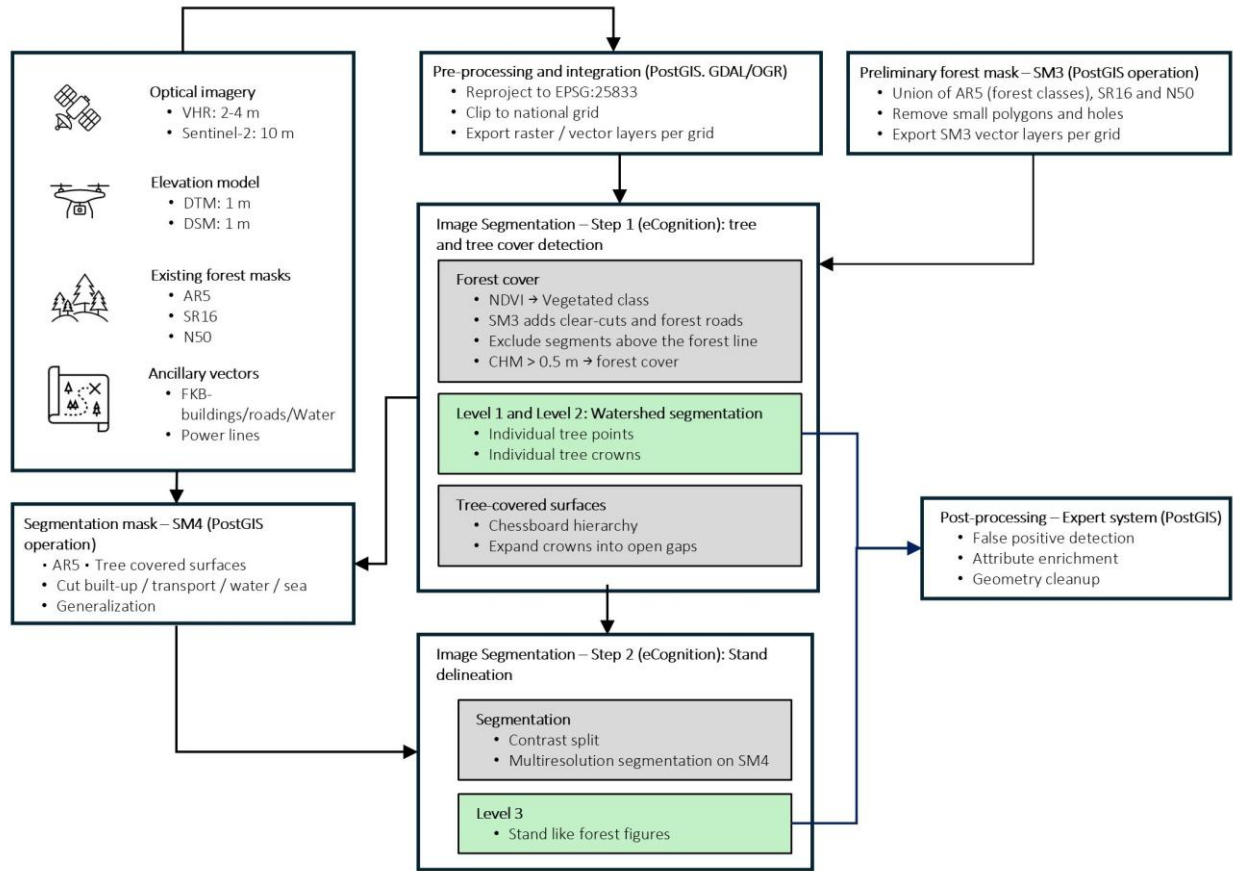


Figure 2: Workflow for producing the Skogmaske dataset. Multi-source remotely sensed data and national forest masks were integrated in a spatial database to create the SM3 and SM4 base masks. Object-based segmentation processed these into three outputs: (i) tree crowns, (ii) tree points, and (iii) attributed forest-stand segments. A rule-based expert system then classified the tree points to remove false detections.

3.2 Data preparation

All input layers were brought into the common coordinate reference system ETRS89 / UTM zone 33N (EPSG 25833) and clipped to the production grid. The CHM was filtered by setting values below 0 m or above 50 m to zero. The filtered layer was used for all subsequent segmentation and attribution. Terrain slope in degrees was derived from the terrain model and canopy slope in percent from the filtered CHM, both using the Zevenbergen and Thorne operator (Zevenbergen and Thorne, 1987). For each tile in the production grid, the optical mosaics, the CHM, the forest attribute rasters, and the ancillary vector layers were exported to a dedicated working folder for segmentation.

3.3 Preliminary forest mask (SM3)

The existing national datasets encode established forest definitions that no single sensor can observe directly. We therefore combined them into a preliminary forest mask, SM3, denoted Ω_{nf} , formed as the union of the three national masks:

$$\Omega_{\text{nf}} = \bigcup_{k=1}^3 \Omega_{\text{nf}}^{(k)}$$

where the three contributions are the forest classes of AR5 (coniferous, deciduous, and mixed forest), the forest polygons of SR16, and the forest class of N50. The union was created by clipping each source to the production tile and dissolving the three layers into a single geometry. The resulting geometry was generalized to remove small holes and polygons introduced by artifacts in the source data.

3.4 Forest cover delineation

Segments based on FKB layers for roads, buildings, water bodies, and transformer stations were first created with the *vector-based segmentation* algorithm, $S_m = \Omega \cap V_m$, where V_m is a map polygon, and the resulting segments S_m were classified based on attributes in those layers.

To separate vegetated areas (green class) from non-vegetated areas (grey class), we used the normalized difference vegetation index (NDVI) derived from the VHR mosaic. Instead of applying a fixed NDVI threshold, the threshold was estimated adaptively from the scene. Large land objects were used to exclude water bodies from threshold estimation and to ensure that the NDVI histograms contained both vegetated and non-vegetated surfaces. For each land object larger than 10 ha, an Otsu threshold (Otsu, 1979) was computed from the NDVI histogram and constrained to the interval [0.1, 0.35]. The resulting object-specific thresholds t_m were combined into a single scene threshold t^* using an area-weighted mean:

$$t^* = \frac{\sum_m A(S_m) t_m}{\sum_m A(S_m)},$$

where $A(S_m)$ is the area of land object S_m and t_m is the corresponding Otsu threshold. Vegetated area was then defined as

$$\Omega_{\text{veg}} = \Omega \cap \{x \mid \text{NDVI}(x) > t^*\},$$

and extracted by applying the *multi-threshold segmentation* algorithm applied to the VHR NDVI. A second pass applied the same procedure to the Sentinel-2 NDVI, with the Otsu threshold constrained to [0.35, 0.5], so that vegetation missed in the VHR pass could still be captured.

In addition to the spectral rule, the preliminary mask Ω_{nf} (SM3) was used to assign all segments within the union to the green class, ensuring that forest areas lacking vegetation, such as recent clear-cuts and forest roads, were retained. These are recorded as forest in the national masks and are within-forest features rather than separate land types, so excluding them would fragment otherwise continuous forest. A locally defined upper elevation limit for tree detection was used to exclude high-elevation segments and suppress false detections on rock and scree where trees

cannot occur. The limit was derived from NFI observations of the highest recorded trees and assigned per production tile with a conservative margin. Its purpose is to bound the search space rather than to delineate a vegetation boundary. To separate woody perennial vegetation (shrubs and trees) from low vegetation, green-class areas were segmented with the multi-threshold segmentation algorithm applied to the CHM. A threshold of 0.5 m was applied, and all areas exceeding this height were classified as forest cover:

$$\Omega_{fc} = \Omega_{veg} \cap \{x \mid CHM(x) > 50 \text{ cm}\}.$$

3.5 Tree crowns and tree points

With forest cover defined, tree crowns were delineated using the *watershed segmentation* algorithm applied to the inverted CHM, yielding the set of tree-crown segments:

$$\mathcal{S}_{tc} = \text{Watershed}(-CHM(x)), \quad x \in \Omega_{fc}$$

$$\mathcal{S}_{tc} = \{S_{tc}^1, \dots, S_{tc}^m\}.$$

False detections were removed using a set of structural and contextual rules based on object geometry, terrain characteristics, and proximity to infrastructure. Segments unlikely to represent trees, including small artifacts, detections associated with power lines, detections on steep terrain, and detections above the upper elevation limit, were excluded.

In dense stands, particularly spruce forests, a crown segment may represent a group of trees rather than an individual crown. The centroid of each crown segment was recorded as a tree point.

3.6 Forest-cover segments

Forest comprises both tree crowns and the open areas between them. In sparse forests, particularly at high elevations, open areas may dominate, making crown segments alone a poor representation of forest cover. To address this, a hierarchical segmentation based on the *chessboard segmentation* algorithm was used to delineate forest-cover segments comprising both tree cover and open areas.

At the coarsest segmentation level, square image objects with sufficient tree cover were identified and retained. The objects were then recursively subdivided into smaller objects through progressively finer chessboard segmentation levels. At each level, image objects adjacent to accepted forest-cover objects were evaluated and, where appropriate, merged with them. This recursive expansion allowed open areas between neighboring forest patches to be included, improving connectivity, reducing fragmentation, and producing forest-cover segments $\mathcal{S}_{fc}$:

$$\mathcal{S}_{fc} = \mathcal{F}(\mathcal{S}^{(1)}, \mathcal{S}^{(2)}, \dots) \subset \mathcal{S}, \quad \Omega_{fc} = \bigcup_{S_i \in \mathcal{S}_{fc}} S_i$$

where $\mathbf{S}^{(1)}$, $\mathbf{S}^{(2)}$, ... denotes successive chessboard segmentation levels and $\mathcal{F}$ denotes the hierarchical expansion across levels.

The resulting forest-cover segments were separated into two cover classes, forestPatch and openForest, where openForest represents sparsely wooded areas with low tree-cover density.

3.7 Segmentation mask (SM4)

Delineating stand-like segments requires a mask that combines observed tree cover with forest areas defined by the national forest masks while excluding obvious non-forest land. We therefore constructed a combined forest mask, SM4, denoted Ω_{fc}^* , as a union of the preliminary forest mask and the derived forest-cover segments:

$$\Omega_{fc}^* = \Omega_{nf} \cup \Omega_{fc}$$

SM4 was created by first combining SM3 with the derived forest-cover segments and then removing built-up areas, transport infrastructure, and water bodies. Neighboring polygons of the same class were merged, and the resulting mask was generalized to remove small artifacts and improve geometric consistency. The mask retained the two cover classes and served as the input for the delineation of forest-stand segments.

3.8 Forest-stand segments

To obtain a product that can be adapted to different forest definitions, the combined mask Ω_{fc}^* was subdivided into small, homogeneous segments $\mathbf{S}_{fs}$ analogous to forest stands, but delineated on structure alone rather than on the species composition, age and site conditions used in operational forest stand delineation.

Initial boundaries were placed at pronounced changes in tree height using the *contrast split segmentation* algorithm applied to the rasterized tree-crown layer:

$$\mathbf{S}_{cs} = \text{ContrastSplit}(\mathbf{S}_{tc}^r),$$

where $\mathbf{S}_{tc}^r$ denotes a rasterized tree-crown layer with crown heights derived from the CHM.

The purpose of this step was to identify major structural boundaries rather than to create small segments. The resulting regions were subsequently refined using the *multiresolution segmentation* algorithm (MRS) applied to the CHM to produce forest-stand segments:

$$\mathbf{S}_{fs} = \text{MRS}(\mathbf{S}_{cs}, \text{CHM}(x)), \quad x \in \Omega_{fc}^*.$$

Each segment was assigned structural and forest-resource attributes. Tree height and crown cover were derived from the detected crown segments, while species and site index were transferred from SR16. Additional metrics describing the spatial distribution of tree crowns were also calculated.

The measured attributes served as the primary record. For convenience, each forest-stand segment was additionally assigned a structural class based on tree height and crown cover (Table 1). This classification is one example of a rule applied to the measured attributes rather than a property of the data itself. A user requiring different definition can apply different thresholds to the same attributes. Obvious artifacts and segments with implausible attributes were removed. The final dataset stores additional segment attributes, including the 50th, 95th, and 99th percentiles of normalized surface height.

Table 1: Structural classes of the forest-stand segments.

<i>Class</i>	<i>Mean tree height</i>	<i>Tree-crown cover</i>
<i>scrubForest</i>	below 2 m	no minimum
<i>lowForest</i>	2 to 5 m	at least 10%
<i>mediumForest</i>	5 to 10 m	at least 10%
<i>tallForest</i>	10 to 15 m	at least 20%
<i>veryTallForest</i>	above 15 m	at least 20%
<i>openForest</i>	inherited from SM4, not structurally classified	

3.9 Post-processing

The segmentation outputs were refined before release. Because object-based detection is sensitive to surfaces that mimic the spectral and structural characteristics of trees, a rule-based expert system was applied to classify each tree point as a definite tree, a possible tree, or not a tree. The classification combined evidence from the national forest datasets and ancillary layers with information on vegetation, height, terrain, and proximity to infrastructure. Tree-crown segments inherited the classification of their associated tree point. The classification was retained as an attribute rather than used to remove tree-crown segments, allowing users to apply their own filtering criteria. The score terms and thresholds were developed iteratively on 55 production tiles and distributed across the country, spanning vegetation zones, terrain types and climatic regions.

Forest-stand segments were further refined in a subsequent step. Where tree points indicated forest but no forest-stand segment had been produced, additional segments were created from clusters of tree points and attributed using the same procedure as for the forest-stand segments. These segments were labelled *bufferTP* to distinguish them from the primary segmentation output. Full details of the scoring system, thresholds, and decision rules are provided in the Supplementary Information.

3.10 Validation

Tree-point classification was assessed against independent visual interpretation. The 55 rule development tiles used for rule development were excluded, and 60 production tiles were

randomly selected from the remaining tiles. Within these tiles, 702 tree points were sampled using a stratified random design based on classifier label and terrain type.

Each point was interpreted visually from aerial orthophotos with a GSD of 25 cm available through Norge i bilder (Statens kartverk, 2026), without access to the classifier output or the attributes used by the expert system. Points were classified as tree, shrub/scrub, non-woody vegetation, or undetermined. Because tree points represent crown centroids rather than stem positions, the interpretation assessed the presence of a woody crown at the sample location. Undetermined points were excluded from the accuracy calculations and reported separately.

Accuracy was estimated using a design-based estimator, with strata weighted according to their population frequencies. Ninety-five percent confidence intervals were calculated with production tiles treated as the primary sampling units.

Additional evaluation of the forest-stand segments against NFI plots and the pan-European Tree Cover Density layer is reported by Gjertsen et al., (2025).

3.11 Application of forest definitions

To assess how the dataset responds to different definitions of forest, the forest-stand segments were thresholded on their height and crown-cover attributes. National forest area was then computed for combinations of a minimum height between 0 and 20 m and a minimum crown cover of 5, 10, 20, and 30%. Height was taken as the 95th percentile of normalized surface height within each forest-stand segment. The resulting areas approximated the structural criteria of the national definitions and were compared with published national estimates of forest area.

Minimum area criteria, which several definitions apply to contiguous forest in addition to height and crown-cover thresholds, were assessed separately. Qualifying forest-stand segments were dissolved into contiguous patches within each production tile, and patches below 1,000, 2,000, 4,000, and 5,000 m² were removed in turn, corresponding to the minimum area criteria used by the NFI, AR5, N50, and FAO forest definitions.

4. Results

4.1 The Skogmaske dataset

The national Skogmaske dataset contains three object-based layers. The workflow shown in Figure 2 produced 2,716,919,817 tree crowns and an equal number of associated tree points in Step 1, and 57,840,803 forest-stand segments covering 144,755 km² (44.7% of mainland Norway) in Step 2. The forest-stand segments are classified into six structural classes and one constructed class (Table 2 and Figure 3). Figure 3 shows an example production tile with an aerial orthophoto and the resulting forest-stand classification. MediumForest and tallForest together account for nearly three-fifths of the forest-stand area, with most of the remaining area classified as

lowForest or veryTallForest. The constructed class, bufferTP, covers 1,072 km² (0.7% of the mapped area) and consists of additional segments derived from tree-point clusters where no forest-stand segment was produced.

Table 2: Composition of the national forest-stand layer. Height values are area-weighted means of segment-level percentiles of normalized surface height. Shares may not sum to 100% because of rounding.

Class	Segments (n)	Area (km ²)	Share (%)	P50 (m)	P95 (m)	P99 (m)
lowForest	7,281,316	24,580.0	17.0	0.4	2.8	4.4
mediumForest	20,455,798	49,129.7	33.9	1.4	6.4	9.1
openForest	3,738,540	14,452.6	10.0	0.2	1.3	3.8
scrubForest	236,143	476.2	0.3	0.3	1.3	1.9
tallForest	16,185,835	35,866.0	24.8	4.6	11.8	14.4
veryTallForest	9,340,840	19,179.1	13.2	9.6	17.9	20.3
bufferTP	602,331	1,071.9	0.7	4.9	11.5	15.1
Total	57,840,803	144,755.5	100.0			

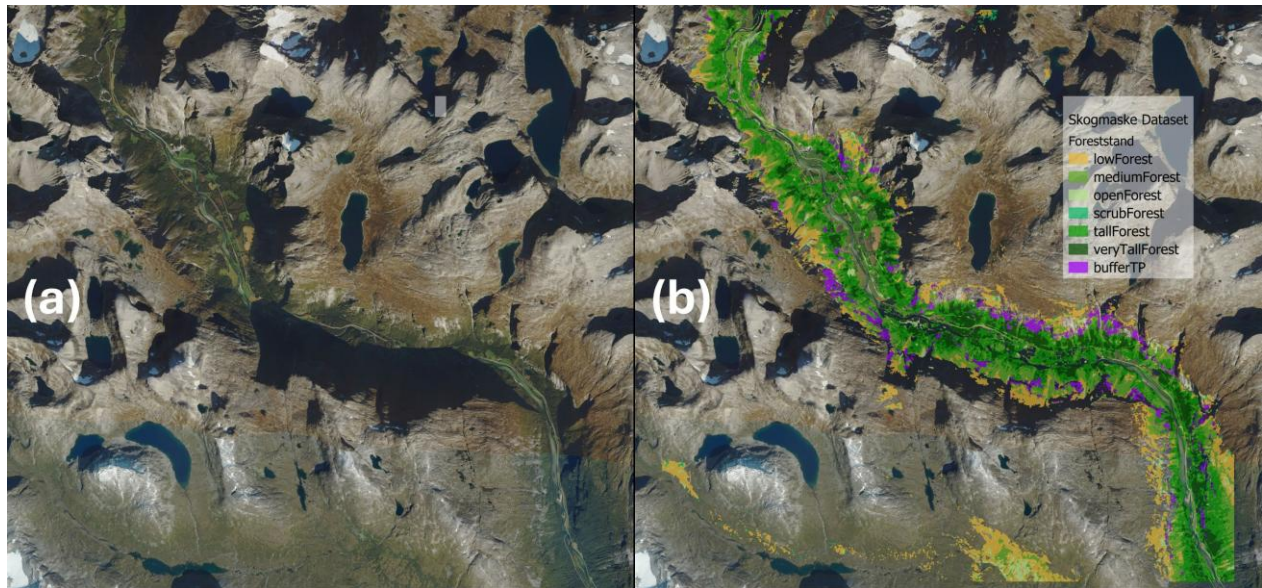


Figure 3: Example of the forest-stand classification for a production tile. (a) Aerial orthophoto. (b) Corresponding Skogmaske forest-stand map. Forest-stand segments are classified into six structural classes and one constructed class (bufferTP).

4.2 Definition flexibility

Because each forest-stand segment carries a measured tree height and crown cover, the dataset can be thresholded to approximate the structural criteria of different forest definitions rather than committing to a single one (Figure 4). Applying thresholds to the height attribute (95th percentile of normalized surface height) and crown cover, the mapped forest area ranges from 15.8% of mainland Norway (height ≥ 10 m, cover $\geq 10\%$) to 44.7% (no thresholds applied).

A crown-cover rule of $\geq 10\%$ alone yields 39.2%, almost exactly the N50 estimate of 39.5%. A height rule of at least 2 m combined with 10% cover, approximating SR16, yields 38.4%. A rule approximating the NFI and FAO structural criteria (height ≥ 5 m and cover $\geq 10\%$) yields 28.7%.

The dataset therefore reproduces the range spanned by the four national forest definitions, which individually place Norwegian forest area between approximately 35% and 43%.

Minimum area criteria had little effect on these estimates. Applying the criteria to contiguous patches formed by dissolving adjacent qualifying forest-stand segments, the rule approximating the NFI and FAO structural criteria yielded 28.6% under a minimum area of 1,000 m² and 28.0% under a minimum area of 0.5 ha, compared with 28.7% with no minimum area requirement. The minimum area thresholds used by AR5 and N50, 2,000 m² and 4,000 m², yielded 28.4% and 28.1%, respectively. Across all tested thresholds, the total variation was only 0.7 percentage points.

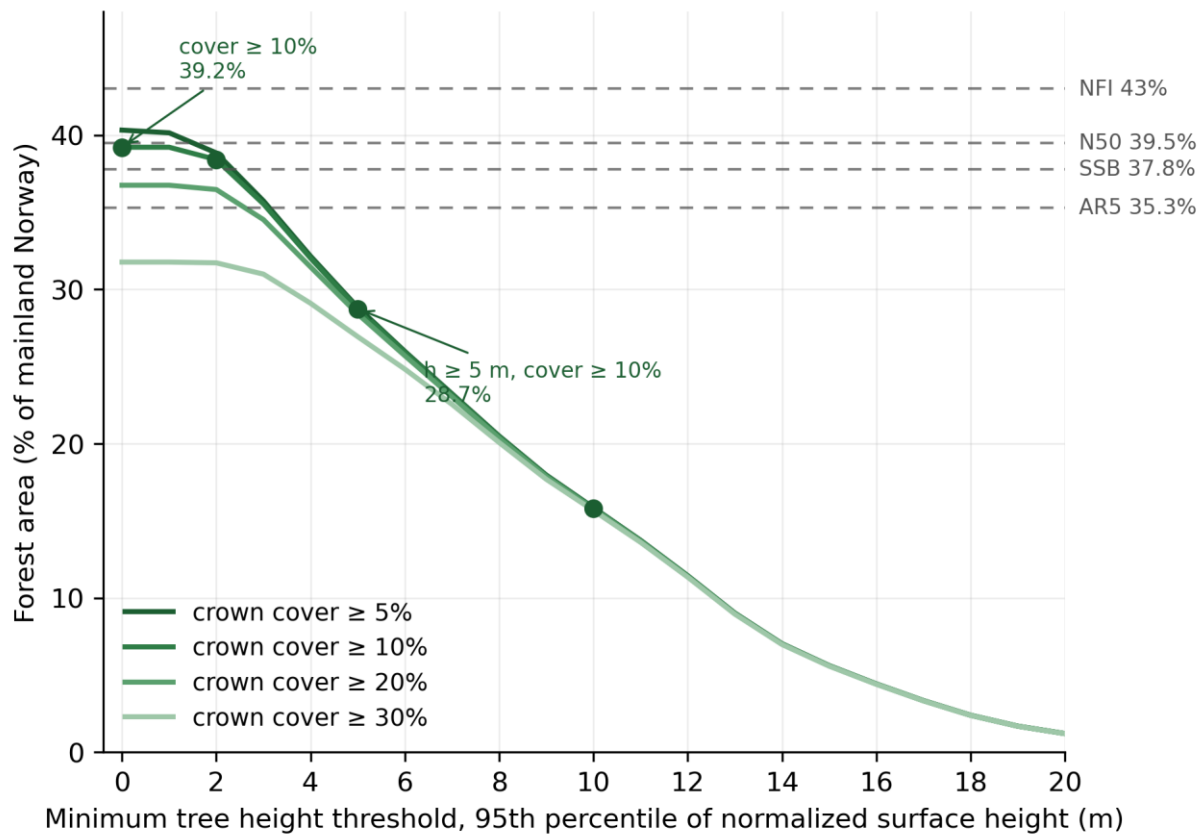


Figure 4: Definition flexibility of the Skogmaske forest-stand layer. Each curve shows the national forest area obtained by thresholding forest-stand segments using a minimum tree height (x-axis, 95th percentile of normalized surface height) and a minimum crown cover (curves). Filled markers represent values computed from the final dataset, whereas dashed lines indicate published national forest-area estimates. A single dataset reproduces the range covered by all four national forest definitions.

4.3 Tree-point accuracy

Tree-point classification was assessed using 702 points interpreted from aerial orthophotos in 60 production tiles outside the rule-development set. Accuracy estimates were weighted to represent the national dataset using the stratum populations, and 95% confidence intervals were

estimated using a design-based approach with production tiles treated as the primary sampling units (Table 3).

Among points classified as definite trees ($er_definitiv_tre = 1$), 99.4% (95% CI 98.8–100) were interpreted as woody vegetation and 98.5% as trees specifically, corresponding to a commission error of 0.6%. Among points classified as rejected ($er_definitiv_tre = -1$), 96.3% were confirmed as non-tree or low scrub, whereas 3.7% were interpreted as trees.

Points interpreted as possible trees ($er_definitiv_tre = 0$) resolved to a near-even mix of tree (28%), shrub (28%), and non-woody (30%) references. Thirty-nine points (5.6%) could not be interpreted from the imagery, mostly in deep shadow, and were excluded from the accuracy denominators.

Table 3: Tree-point classification accuracy. Design-based estimates were weighted using national stratum frequencies, and 95% confidence intervals were estimated using production tiles as the primary sampling units ($n = 702$ points from 60 production tiles).

<i>Classifier label</i>	<i>Reference agreement</i>	<i>Value</i>	<i>95% CI</i>
<i>Definite tree (= 1)</i>	woody (tree or shrub)	99.4%	98.8–100
<i>Definite tree (= 1)</i>	tree only	98.5%	96.6–100
<i>Rejected (= -1)</i>	non-tree or scrub	96.3%	93.6–99.0
<i>Rejected (= -1)</i>	real trees rejected	3.7%	1.0–6.4

The proportion of tree-point detections rejected by the expert system varied strongly with terrain (Table 4; Figure 5). Figure 5 illustrates an example in which the expert system removed a large number of false detections above the tree line while retaining detections classified as possible or definite trees. The share of raw detections rejected by the expert system increased from 2.8% in lowland forest to 23.6% on steep terrain and 76.1% in open mountain terrain near the tree line. After classification, the definite-tree class achieved user's accuracies of 100%, 95.9%, and 97.9% in lowland forest, steep terrain, and open mountain terrain, respectively. Rejection correctness showed the opposite pattern, reaching 97.0% and 98.5% in lowland and steep terrain but only 81.5% in open mountain terrain, where 12 of 65 points rejected by the expert system were interpreted as small trees. Misclassification between trees and shrubs was likewise largely confined to open mountain terrain, where 15% of points classified as definite trees were interpreted as shrubs, compared with 1% or less in lowland and steep terrain.

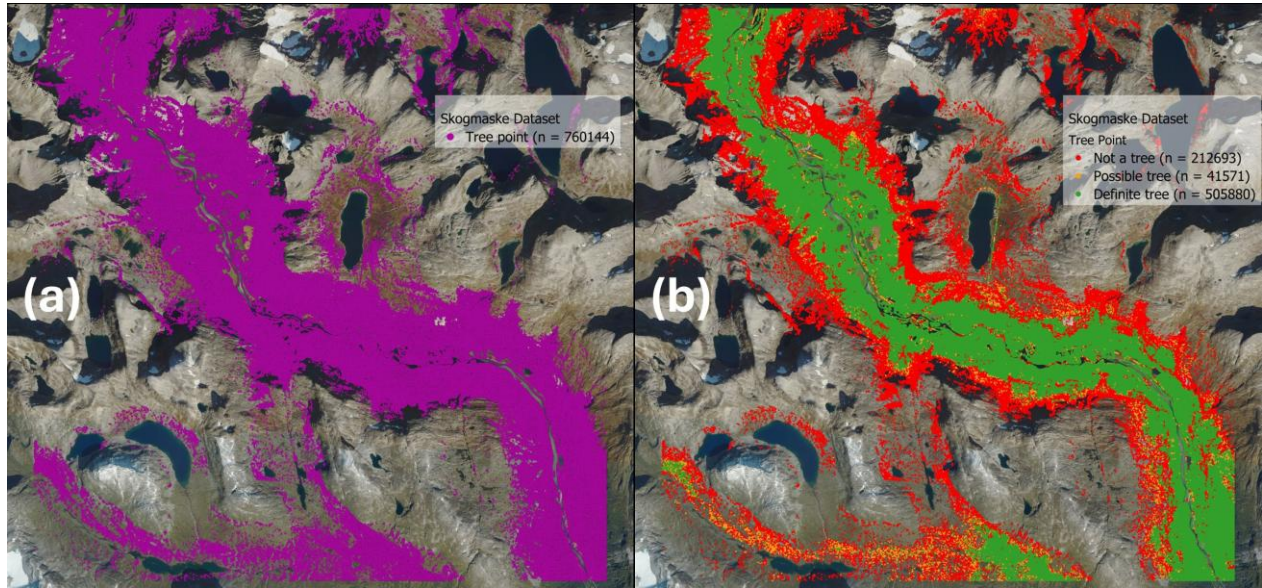


Figure 5: Example of expert-system classification of tree-point detections in open mountain terrain near the tree line. (a) Raw tree-point detections. (b) The same detections after expert-system classification as Not a tree, Possible tree, and Definite tree.

Table 4: Rejection rate and classification performance by terrain group.

<i>Terrain group</i>	<i>Share of points (%)</i>	<i>Rejection rate (%)</i>	<i>Definite-tree UA (%)</i>	<i>Rejection correctness (%)</i>
<i>Lowland forest</i>	80.6	2.8	100.0	97.0
<i>Steep terrain</i>	18.4	23.6	95.9	98.5
<i>Open mountain</i>	1.0	76.1	97.9	81.5

4.4 Comparison with reference data

Comparison with NFI plots and the pan-European Tree Cover Density layer showed strong agreement with both references (Gjertsen et al., 2025). Against 144 NFI plots within the test areas, the Skogmaske forest mask agreed with the reference classification for 90% of plots, rising to 94% when plots representing large trees in built-up or agricultural settings were counted as correct detections, and to 99% when only a single unambiguous disagreement remained.

Against the pan-European Copernicus High Resolution Layer Tree Cover Density-2018 (European Environment Agency, 2024), segment-level crown cover showed a mean difference of 0.93% (95% CI 0.85–1.01), a standard deviation of 18.42%, and a Pearson correlation of 0.766.

5. Discussion

5.1 A measurement-based, definition-flexible forest mask

Skogmaske separates the measurement of tree cover and canopy structure from the definition of forest. The three output layers record where trees are, how large their crowns are, and how they aggregate into forest-stand segments, and these segments carry the height and crown-cover attributes needed to apply a forest definition afterwards. Applying different thresholds to a single

dataset reproduces forest areas spanning 15.8 to 44.7% of the mainland and brackets all four national estimates. This addresses the problem set out in the Introduction: Norwegian forest area estimates differ by up to eight percentage points because each source encodes a different definition. Rather than adding a further definition, Skogmaske provides a measurement-based dataset to which structural criteria can be applied.

One discrepancy is systematic. Applying a literal 5 m height threshold yields 28.7%, below the AR5 estimate of 35%. AR5 and NFI define forest by the capacity of land to grow trees to at least 5 m, whereas Skogmaske measures current height, and the discrepancy therefore largely reflects young and regenerating forest that is definitionally forest but has not yet reached that height. The comparison is also influenced by limitations in AR5 (Gjertsen et al., 2025), which remains incomplete in parts of the country, so the 35.3% figure is not a fully mapped reference.

5.2 The expert system and marginal forest

The tree-point validation shows that 99.4% of points classified as definite trees were interpreted as woody vegetation, corresponding to a commission error of 0.6%, and that the expert system does most of its filtering in the terrain where object-based detection is most challenging. In open mountain terrain near the tree line, 76% of raw detections were rejected, and the retained detections had a commission error of 2.1%. Rock, scree, and low scrub in this terrain mimic the spectral and structural signature of trees. The pattern is consistent with the finding of Gjertsen et al., (2025) that the greatest disagreement among the existing masks lies near the tree line, and with the broader observation that sparse, low, marginal forest is where definitions and sensors diverge most (Bryn and Potthoff, 2018).

The correction has a cost. In open mountain terrain the filter also discards genuine low trees, and 12 of the 65 interpreted rejections there were trees, giving a rejection correctness of 81.5% against 97% or more in lowland and steep terrain. For most applications, which concern productive forest, this trade-off is favorable, because the errors are concentrated in a terrain class that accounts for about 1% of detections. For applications targeting the tree-line ecotone, the possible-tree class retains these ambiguous detections rather than discarding them. The validation confirms that this class is genuinely mixed, with a near-even split between trees, shrubs and non-woody vegetation.

5.3 Consistency with independent reference data

Agreement with 144 NFI plots (90–99%, depending on the treatment of edge cases) and the low bias relative to HRL TCD (0.93%, $r = 0.766$) indicate that the forest-stand layer is consistent with both field-based and satellite-based references. The near-zero mean difference in crown cover is notable because the two products are derived from different sensors and apply different definitions of cover. This suggests that the segmentation does not introduce a systematic bias in canopy cover at the scale of forest-stand segments.

5.4 Relation to global canopy products

Global canopy products have improved rapidly, and the most recent generation reaches a spatial resolution of about 1 m while preserving canopy edges and gaps (Brandt et al., 2026). Two differences remain particularly relevant. First, these products are rasters of height or cover. Skogmaske represents canopy as delineated objects rather than raster cells. The resulting forest-stand segments have a mean size of 2,503 m², carry attributes such as species and site index, and can be linked to national forest definitions. Second, Norwegian marginal forest presents some of the conditions that global products handle least well. Brandt et al., (2026) report that agreement with spaceborne lidar falls where sun elevation is below 45 degrees, that about a third of their input imagery falls below that threshold, and that short vegetation remains difficult. Both conditions are common in Norway, and they coincide with the terrain where the national definitions disagree most.

The workflow is not specific to Norway. The same approach can be applied wherever very high-resolution imagery, a laser-scanning-derived elevation model, and categorical forest masks are available.

5.5 Limitations

The validation is subject to several limitations. The tree points are crown centroids rather than stem positions, so detection is assessed at the level of the crown and its classification rather than the individual stem, and a single tree-crown segment may represent a small group of trees. The distinction between woody and non-woody vegetation was based on independent interpretation of orthophotos. However, the distinction between trees and shrubs relies partly on the canopy height model, which also forms part of the classifier input. The sample was drawn from 60 production tiles so points cluster within tiles. Design effects estimated from the tile-level results were modest, 1.15 for the definite-tree class and 1.32 for the rejected class, and the reported intervals were adjusted accordingly. The crown cover and inventory plot comparisons derive from the eight test areas rather than the full national dataset (Gjertsen et al., 2025).

The threshold analysis applies height and cover criteria directly to the forest-stand segments. Several definitions also impose a minimum area on contiguous forest. This criterion cannot be applied directly to individual segments because they are segmentation units, with a mean size of about 2,503 m², rather than contiguous forest patches. Assessed on contiguous patches at national scale, the four national minimums change the mapped area by between 0.1 and 0.7 percentage points, so this does not affect the comparison with the national estimates. Finally, the CHM was derived from data acquired between 2010 and 2024, and its temporal mismatch with the 2021 imagery may affect rapidly changing stands such as recent clear-cuts.

Data availability

The Skogmaske dataset is produced and maintained by NIBIO and is not publicly available in its entirety. A demonstration subset covering one production tile, including the tree-point, tree-crown, and forest-stand layers in GeoParquet format is deposited at <https://zenodo.org/records/22080835> (Gjertsen et al., 2026) to enable inspection of the data model and attribute schema. The input datasets remain the property of their respective owners and are subject to the corresponding licenses; they are listed in the Supplementary Information.

CRedit authorship contribution statement

Arnt Kristian Gjertsen: Conceptualization, Methodology, Software, Data curation, Investigation, Project administration, Writing – review & editing. **Shivesh Kishore Karan:** Data curation, Software, Formal analysis, Validation, Visualization, Project administration, Writing – original draft, Writing – review & editing. **Knut Bjørkelo:** Methodology, Software, Data curation, Project administration, Writing – review & editing.

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Supplementary Information

This document contains the technical details behind the Skogmaske dataset. It is organized in order of the production workflow. Several of the input datasets are license-restricted and the segmentation depends on commercial software, so the dataset cannot be regenerated from public sources. Section S7 sets out what is available and what is not, and which components can be replicated independently.

S1 Dataset definition

S1.1 Scope

Skogmaske integrates optical satellite imagery, an airborne laser scanning elevation models, forest attribute rasters and several authoritative national vector datasets into three object layers: individual tree crowns, the tree points derived from them, and stand-like forest segments. This document covers dataset development from source extraction through to export. Vector data and intermediate products are held in a PostgreSQL database with the PostGIS extension. Raster and vector export use GDAL and OGR. Orchestration is in Python. Image segmentation uses Trimble eCognition and eCognition Server.

S1.2 Spatial framework

All processing is carried out in ETRS89 UTM zone 33N, EPSG: 25833. Production runs on a national grid of square tiles. The master grid table carries, per tile, the tile name, the processing batch, the local forest line elevation, data-presence flags for elevation model, land and forest, the land area, and the tile geometry. Tiles that lack elevation, land or forest data are flagged through the presence fields and excluded from production. Of the national grid, 1 837 tiles contained tree-point data and were processed; a further 128 were flagged as having no data. Method development and validation used eight test areas of 250 km² each across landscape gradients, together covering just under 1 percent of the mainland land area.

S1.3 Input datasets

Table 1 lists each input dataset with its owner, version, native resolution or geometry type, reference system and role in the workflow.

Table 1: Input datasets. GSD is ground sample distance.

Dataset	Owner	Version	Resolution / geometry	Role
VHR mosaic (Copernicus Contributing Missions, VHR-IMAGE 2021)	ESA	2021	Raster, 2–4 m GSD, 4 bands (B,G,R,NIR)	Primary optical source; crown detection and NDVI
Sentinel-2 cloud-free national mosaic	Kartverket, from ESA data	2021	Raster, 10 m GSD, 4 bands	Second NDVI pass
Digital terrain model (DTM)	Kartverket	2010–2024	Raster, 1 m GSD	Ground surface; input to CHM; terrain slope
Digital surface model (DSM)	Kartverket	2010–2024	Raster, 1 m GSD	Canopy top surface; input to CHM

Canopy height model (CHM)	Derived (DSM – DTM)	Derived	Raster, 1 m	Canopy height; watershed crown segmentation
SR16 tree species raster	NIBIO	2023	Raster, from 16 m product	Species attribute for forest figures
SR16 site index raster	NIBIO	2023	Raster, from 16 m product	Site index attribute for forest figures
AR5 (FKB-AR5)	Geovekst, NIBIO	2024	Vector polygon	Forest mask component
SR16 forest polygons	NIBIO	2023	Vector polygon	Forest mask component; bufferTP subdivision
N50 land cover	Kartverket	2023	Vector polygon	Forest mask component (class Skog)
FKB-Bygning (buildings)	Geovekst	2024	Vector polygon	Remove false detections on buildings
FKB-Veg (roads)	Geovekst	2024	Vector polygon	Segment boundaries against roads
FKB-Vann (water)	Geovekst	2024	Vector polygon	Exclude water from NDVI threshold estimation
FKB agricultural land	Geovekst	2024	Vector polygon	Boundaries against agricultural land
Power line buffer	NVE	2025	Vector polygon	Remove false detections under transmission lines
Open mountain land (ArFjell)	NIBIO	2024	Vector polygon	Penalty term in tree-point classification
Forest line grid	Derived from national forest inventory	2025	Vector, per-tile attribute	Upper elevation limit for tree detection

S1.4 Notes on individual data sources

VHR mosaic: A cloud-free national mosaic assembled from several sensors acquired between June and September 2021 (a small number of areas are from 2020, Figure 1), calibrated from digital numbers to reflectance and stored as a GDAL VRT. Images were prioritised by resolution, 2 m ahead of 4 m, and by proximity to 15 July 2021. Resampled to 2 m on export.

Sentinel-2 mosaic: Cloud-free national mosaic from July and August 2021 in the four 10 m bands, atmospherically corrected to surface reflectance, stored as a VRT and kept at native 10 m on export.

Elevation models: The national detailed elevation model provides 1 m DTM and DSM. The CHM is the difference DSM – DTM. Acquisition spans 2010 to 2024 (Figure 1).

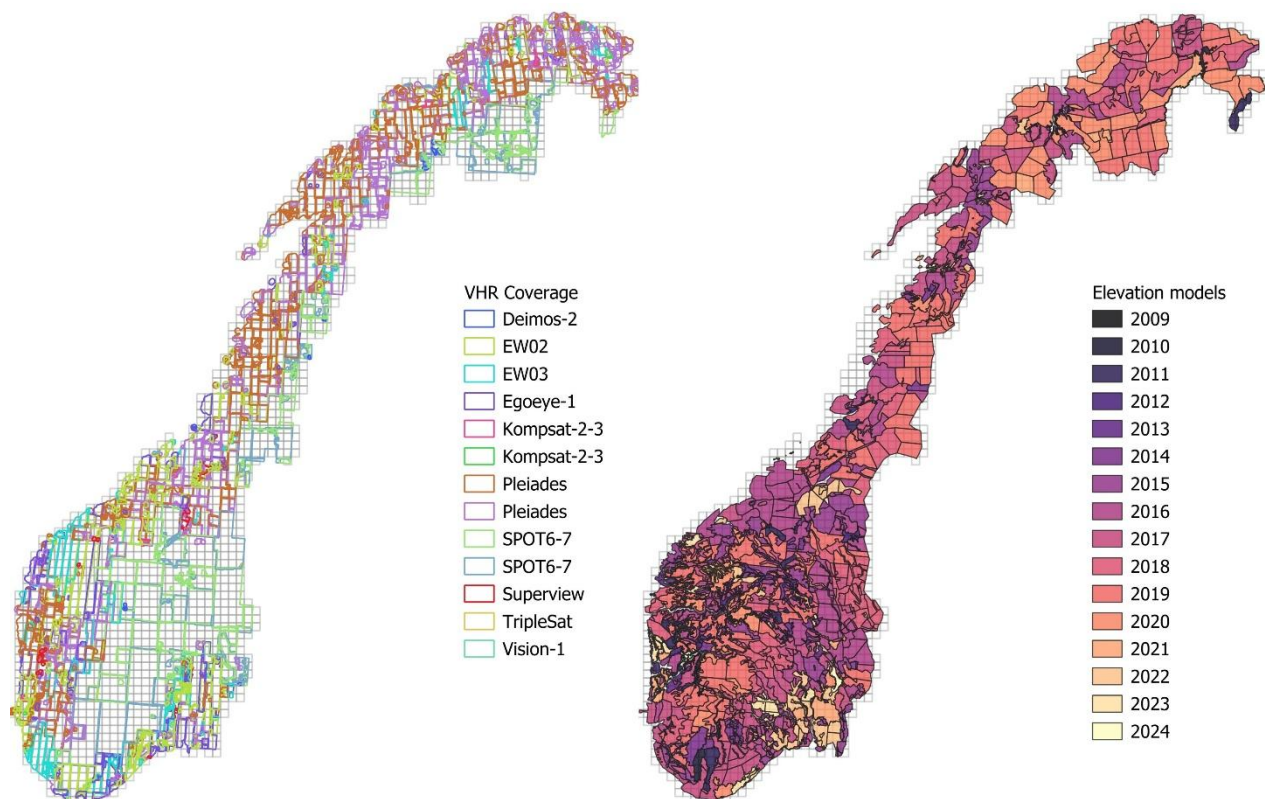


Figure 1: Figure showing a two-panel map of VHR satellite sensors (Left), and elevation acquisition year (Right).

S2 Data preparation

Preprocessing brings every layer into EPSG:25833, clips it to the production grid, builds the preliminary forest mask, and exports the per-tile inputs that feed segmentation. Steps are given in execution order.

S2.1 Preliminary forest mask (SM3)

SM3 is the union of the three existing national forest masks and represents land already recorded as forest under at least one national definition. Forested AR5, SR16 and N50 are extracted per tile and unioned in two stages, AR5 with SR16 first, then that result with N50. For any tile lacking one of the three sources, a small dummy object (a 2 m buffer around the tile centroid) is inserted so that the union is never empty. Interior rings smaller than 99 m² are removed with the helper function `fjerne_holes`, and polygons smaller than 128 m² are deleted. The result is written as single polygons with an object type, an area attribute and a source tag.

A robustness measure applies at this step. A collection extract is used when building the union polygons, because a micro-geometry can otherwise produce line geometries.

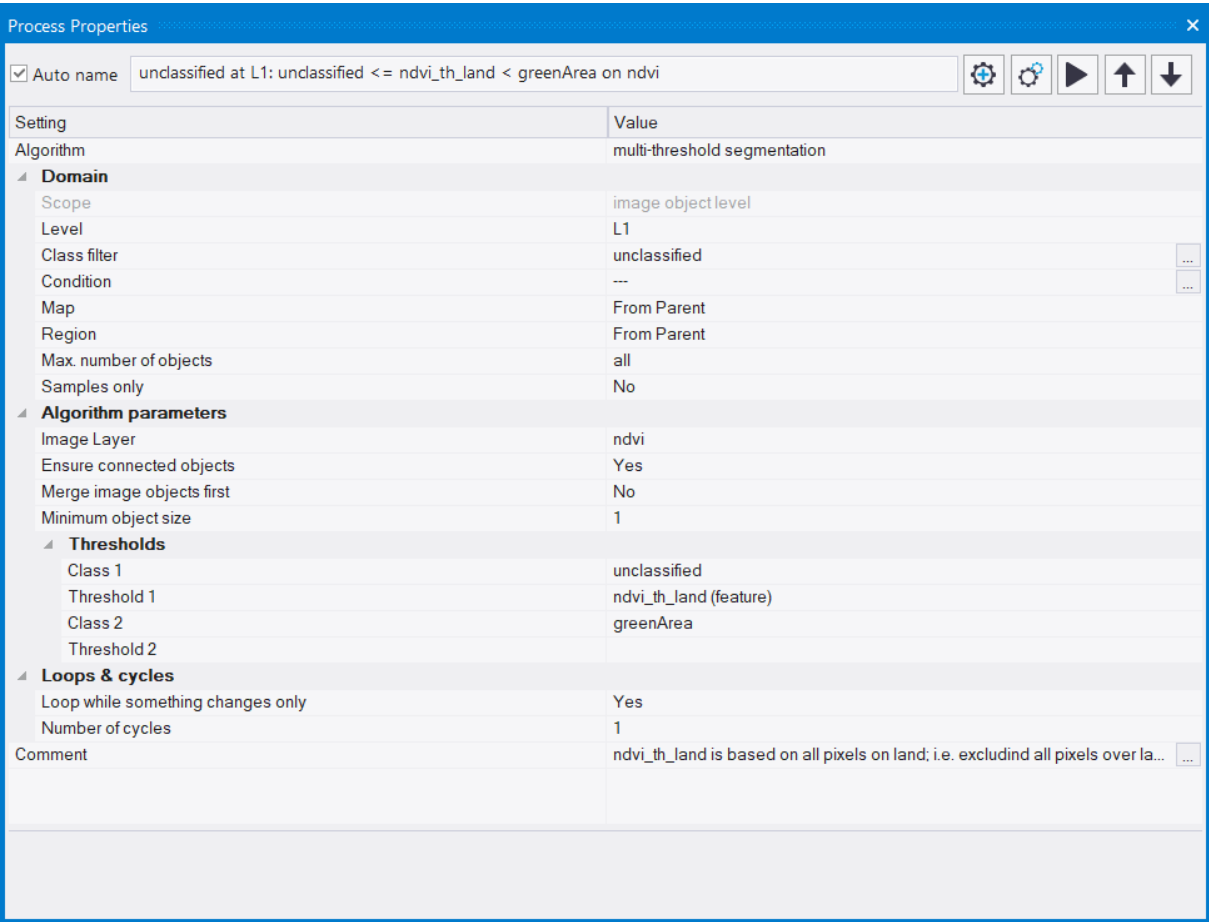
S2.2 Raster export per tile

Raster layers are exported per tile with gdalwarp, cutting each layer to the tile buffer polygon. Source and target CRS are EPSG:25833, output type is Float32 with DEFLATE compression, source nodata 0 and destination nodata –9999, BIGTIFF enabled, and the tile polygon supplied as both cutline and crop-to-cutline. Ground sample distance on export is 1 m for the terrain and surface models, 2 m for the VHR mosaic and the SR16 species and site index rasters, and native 10 m for Sentinel-2.

S3 Segmentation methodology

Image segmentation is carried out in two eCognition steps. Step 1 detects vegetation, forest cover, tree crowns and tree-covered surfaces. Step 2 subdivides the segmentation mask (SM4) into stand-like forest segments. SM4 is the combined forest mask that defines where stand segmentation is performed. It is formed by uniting the preliminary forest mask SM3 with the forest-cover segments produced in Step 1, and then removing built-up land, transport, freshwater, and sea using AR5, so that the mask covers observed tree cover together with land recorded as forest in the national masks, but excludes land that is clearly not forest. Processing runs on eCognition Server and is tiled within each tile to 1500 m by 1500 m tiles processed independently and stitched, with objects on tile borders reprocessed after stitching.

- 1
- S3.1 Parameter summary
- 2
- Multi-threshold segmentation



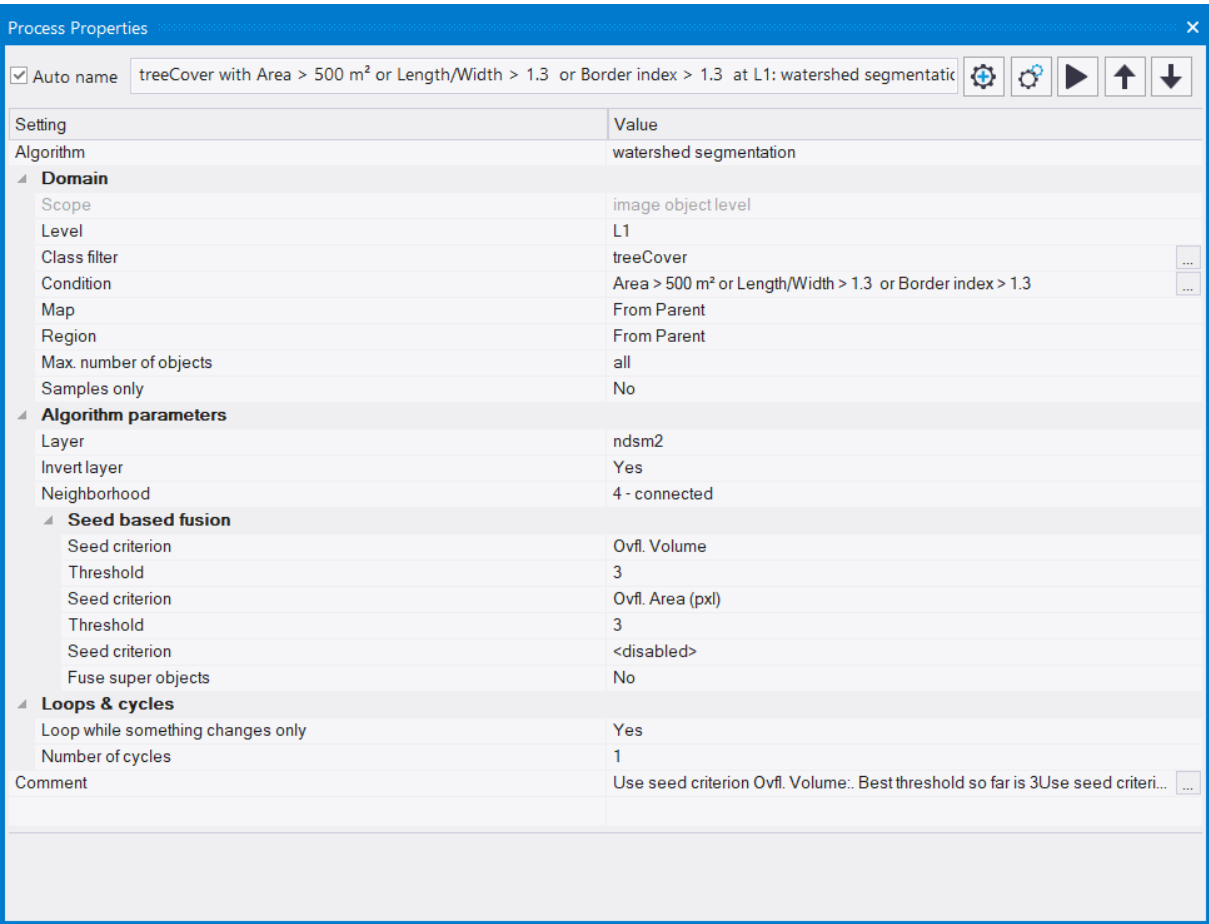
3

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5

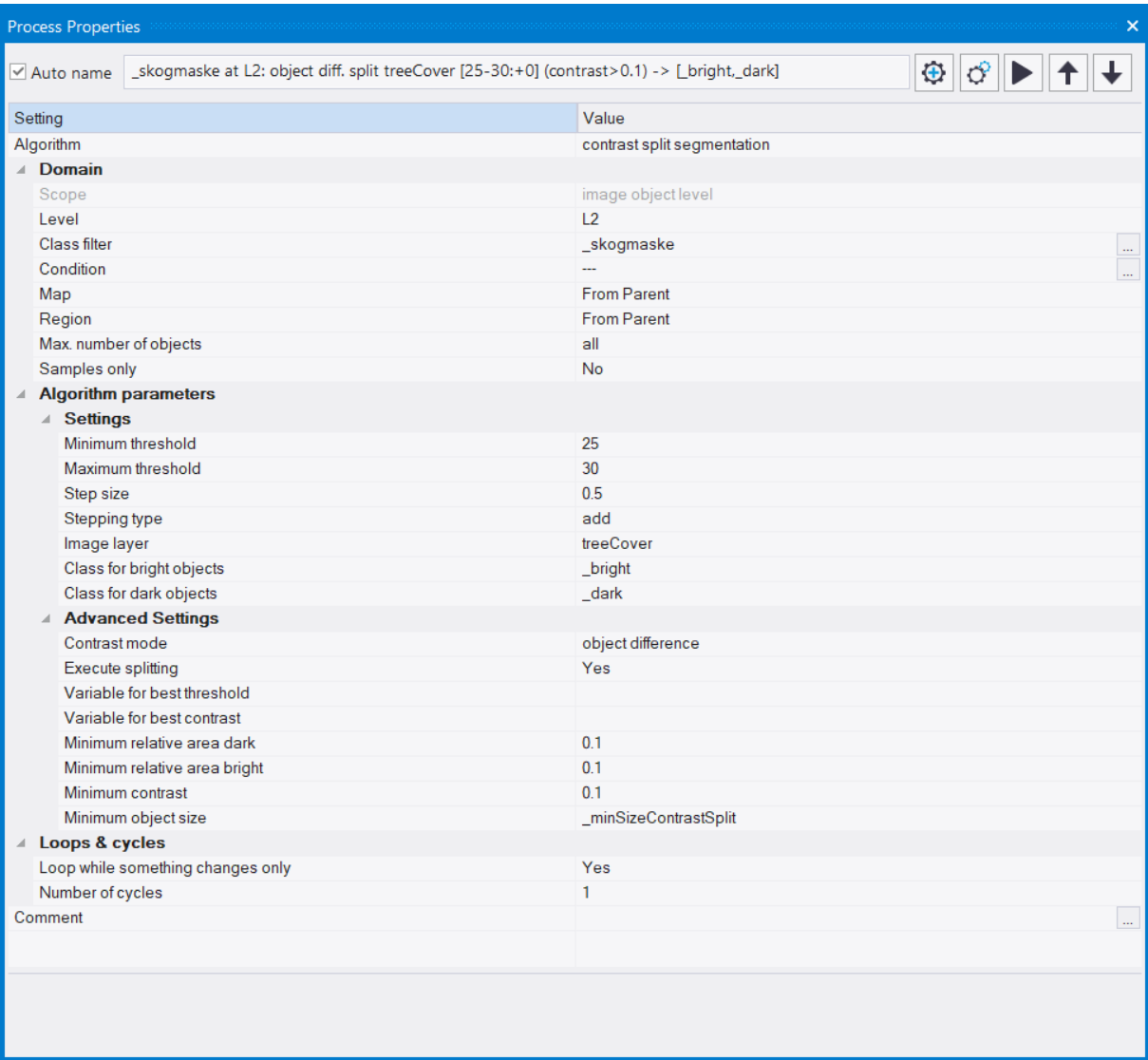
Figure 2. Process properties and parameter settings of the multi-threshold segmentation algorithm used to delineate the vegetated areas shown in Figure8.

1 Watershed segmentation



2
3 Figure 3. Process properties and parameter settings of the watershed segmentation algorithm used to delineate the tree-crown
4 segments shown in Figure 21.

1 Contrast split segmentation



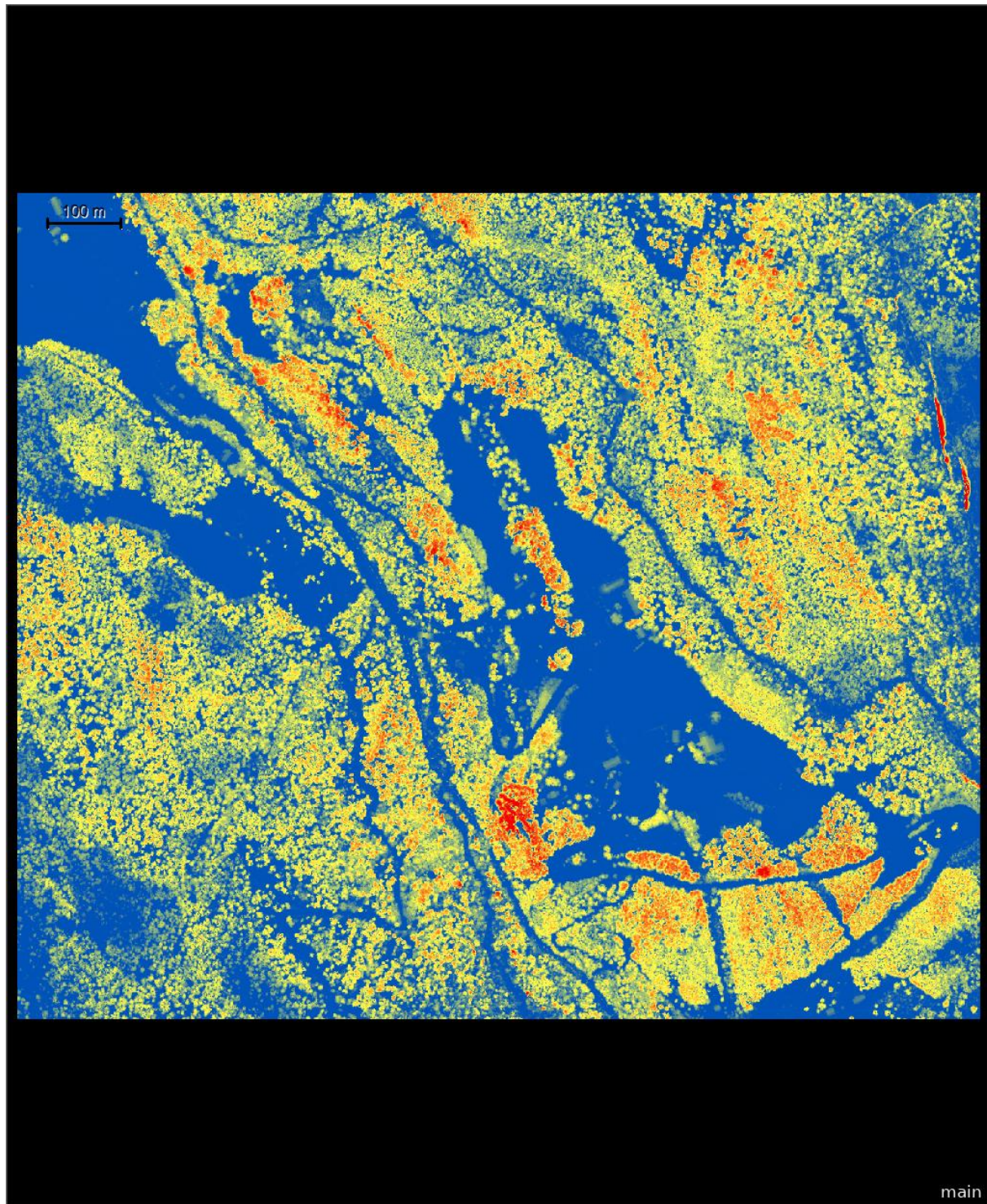
2
3 Figure 4. Process properties and parameter settings of the contrast split segmentation algorithm used to identify the initial
4 boundaries shown in Figure 54.



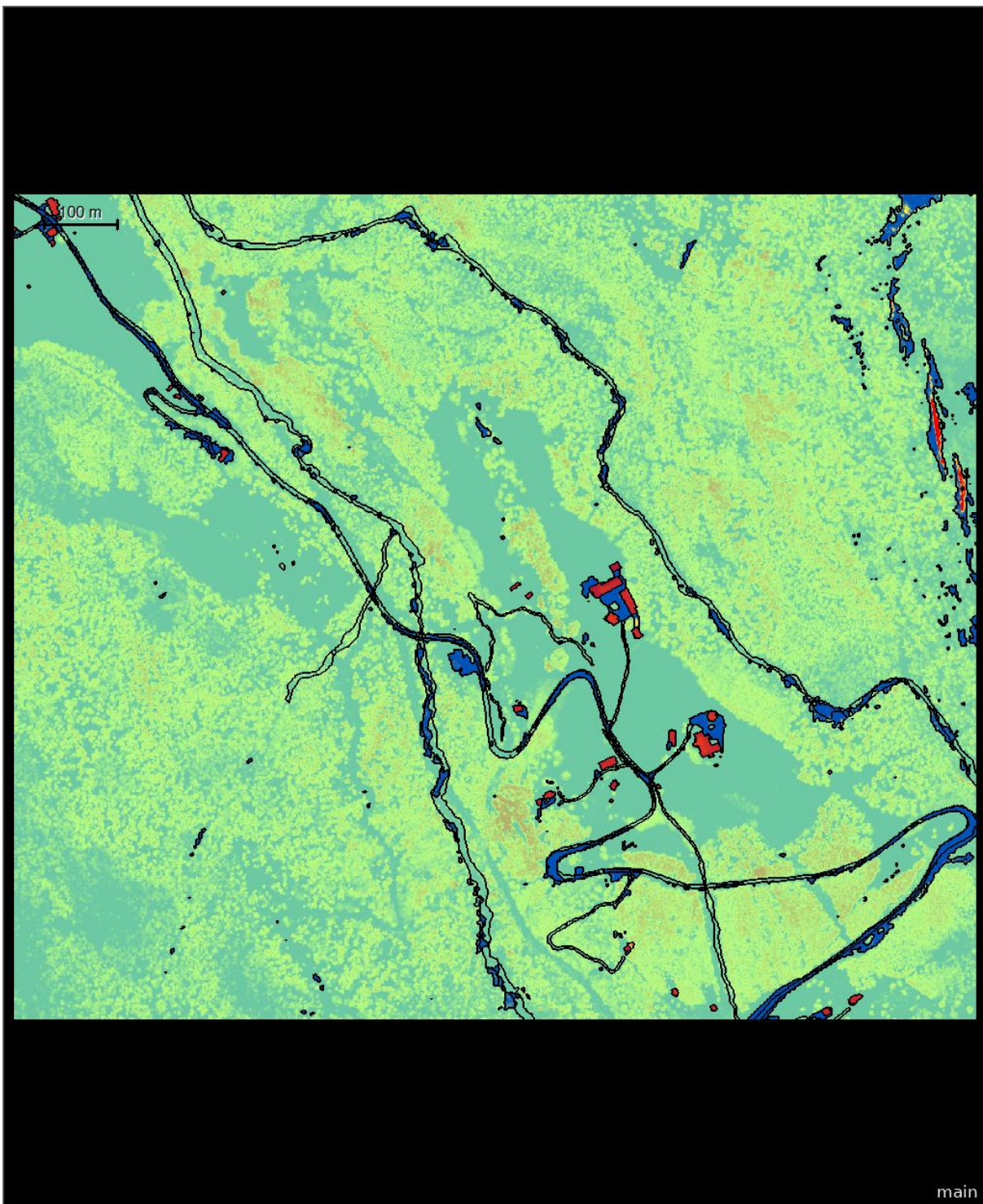
1

2

Figure 6. Example subset of the 2021 VHR imagery.



1
2 Figure 7. Example subset of the canopy height model (CHM). Colors represent canopy height, from low values (blue) to high values
3 (red).

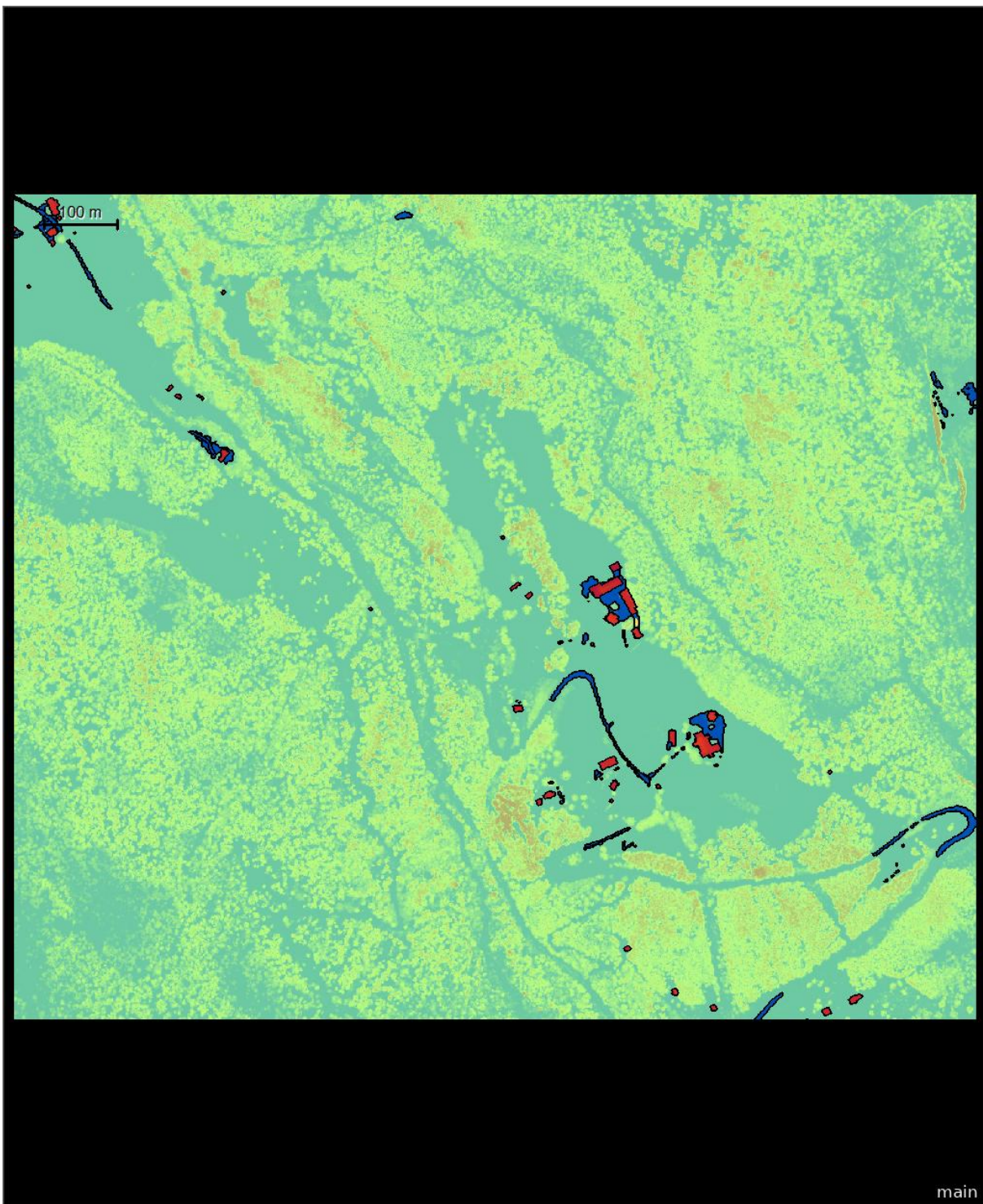


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Figure 8. Areas classified as vegetation cover based on NDVI. Vegetation cover is shown in semi-transparent green over the CHM, and buildings are shown in red.

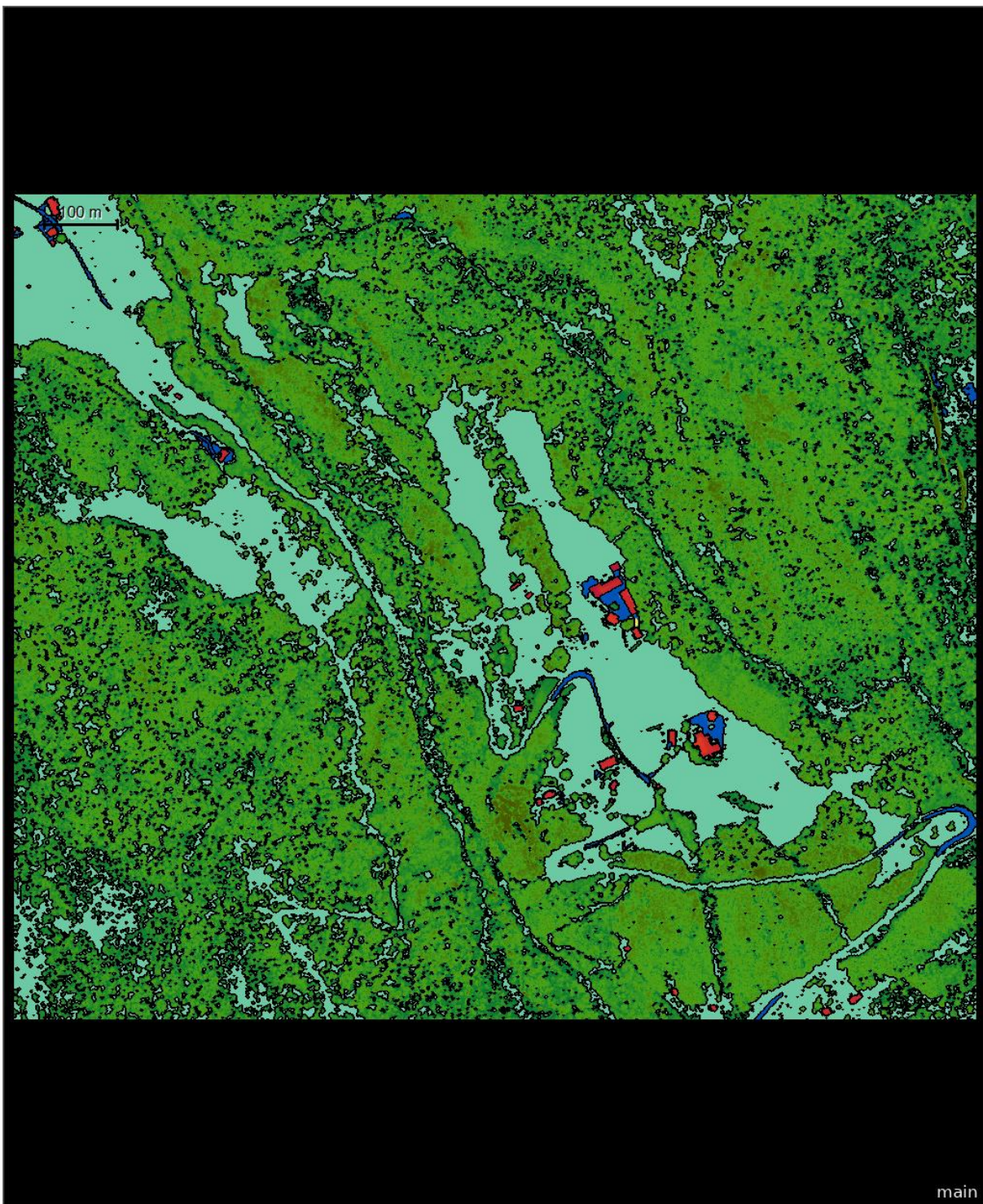


1

2

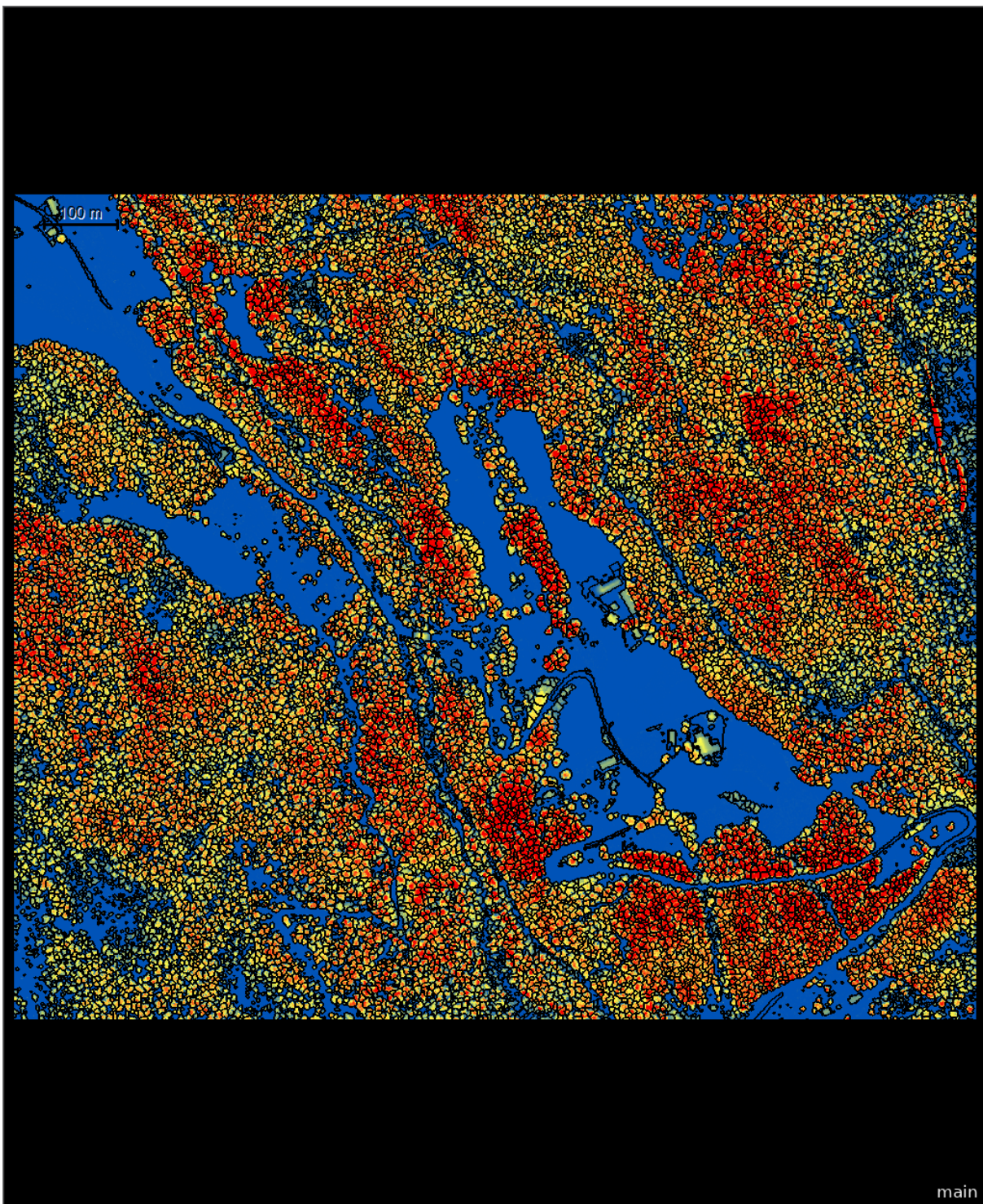
3

Figure 9. Vegetation cover extended with forest areas from the preliminary forest mask (SM3). Compared with Figure8, non-vegetated areas within forest, such as recent clear-cuts and roads, are retained.

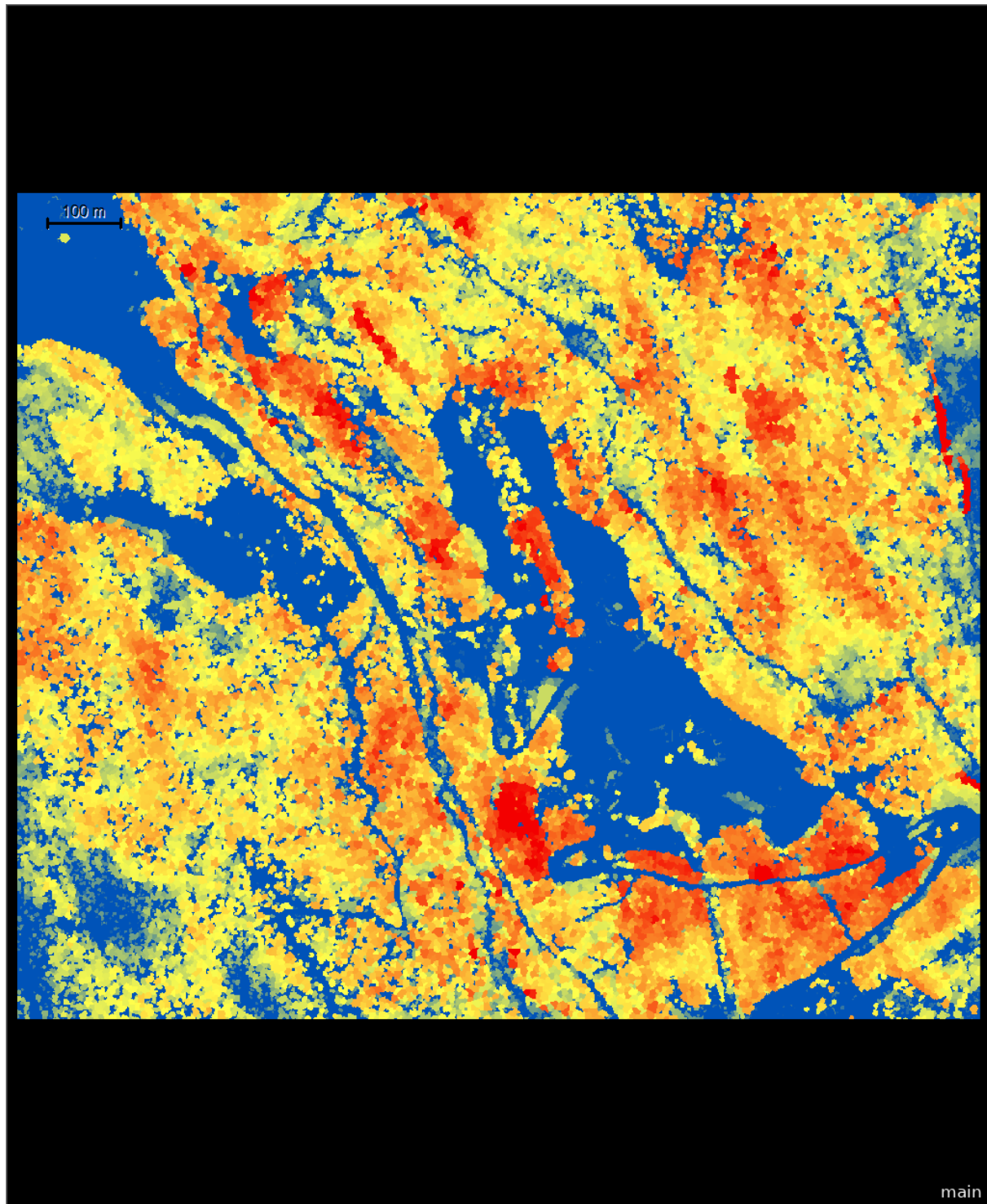


1

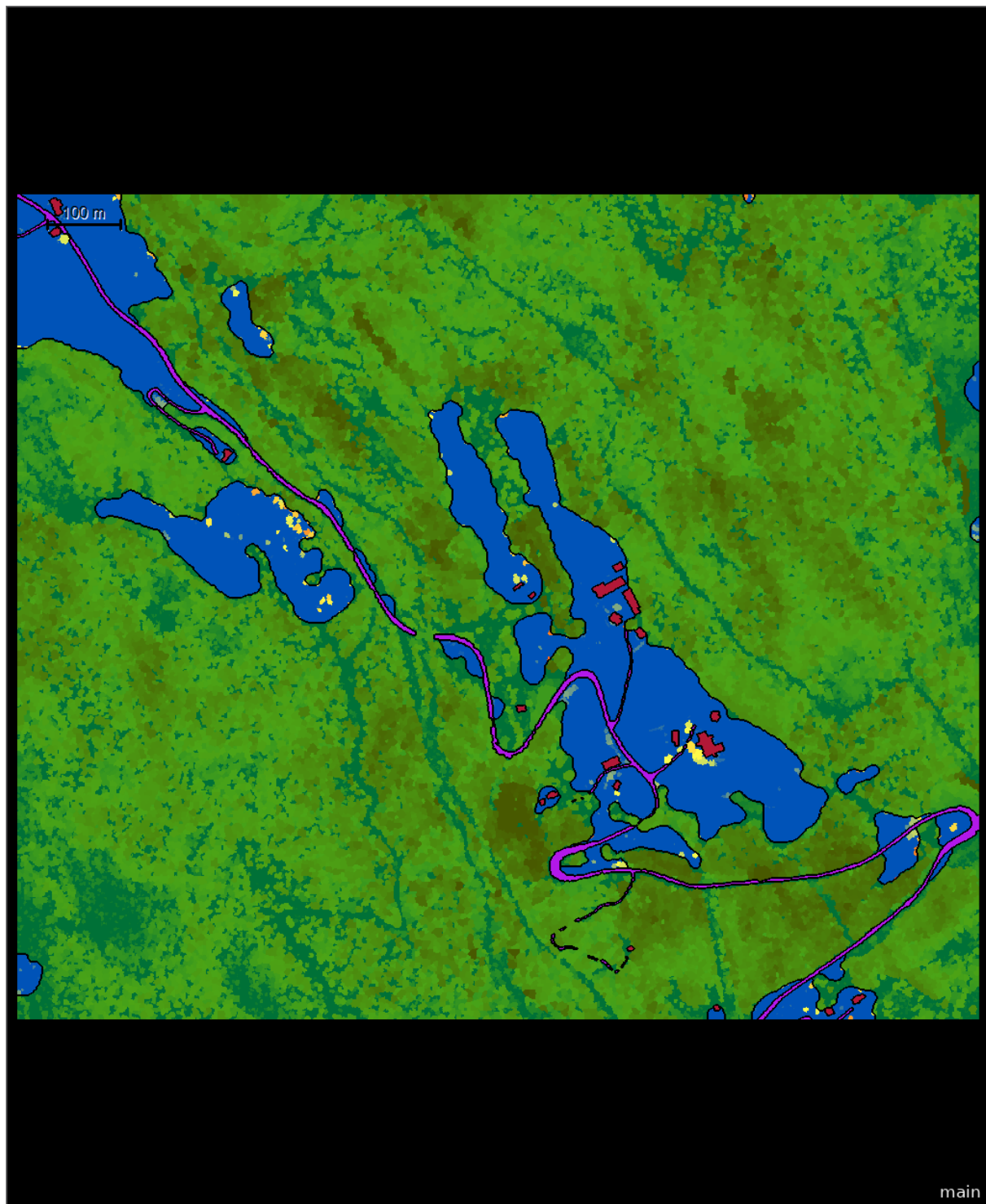
2 *Figure 10. Areas classified as tree cover, shown in dark green. Buildings are shown in red. The tree-cover areas form the basis for*
3 *the delineation of tree-crown segments.*



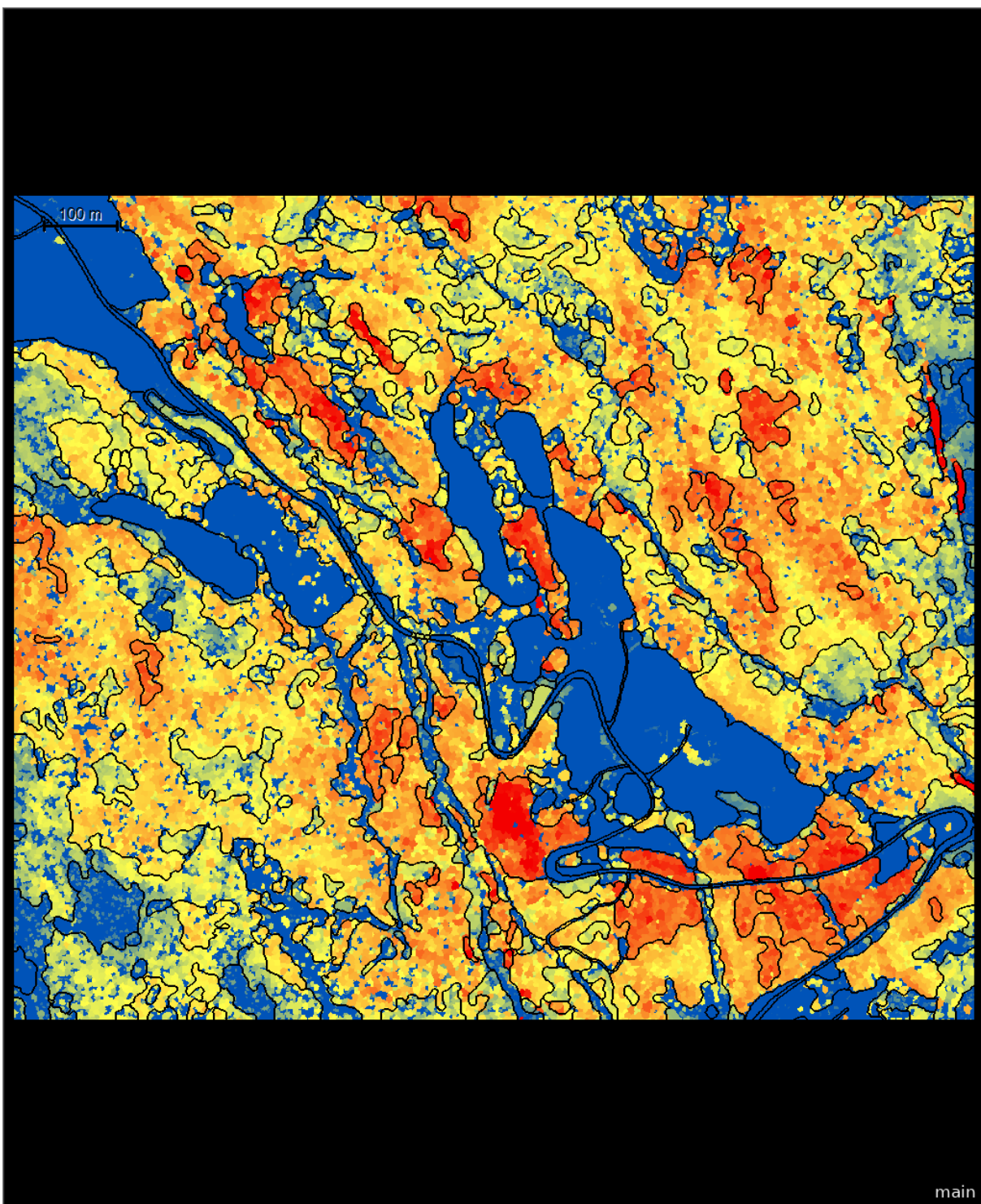
1
2 Figure 21. Tree-crown segments delineated using watershed segmentation, overlaid on the canopy height model (CHM). Colors
3 represent canopy height, from low values (blue) to high values (red).



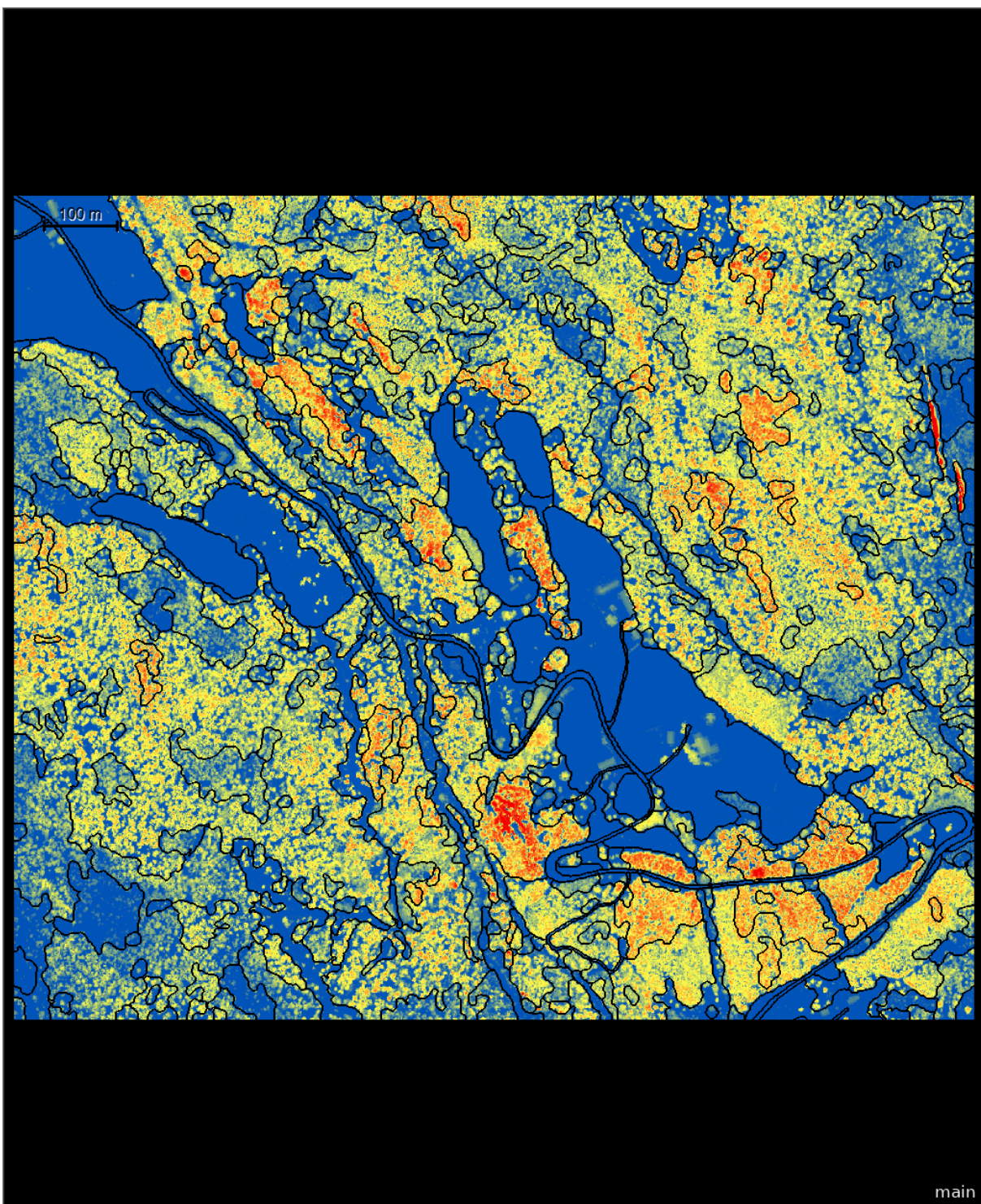
1
2 Figure 32. Rasterized tree-crown layer with crown heights derived from the canopy height model (CHM). This layer was used as
3 input to the contrast split segmentation algorithm. Colors represent crown height, from low values (blue) to high values (red).



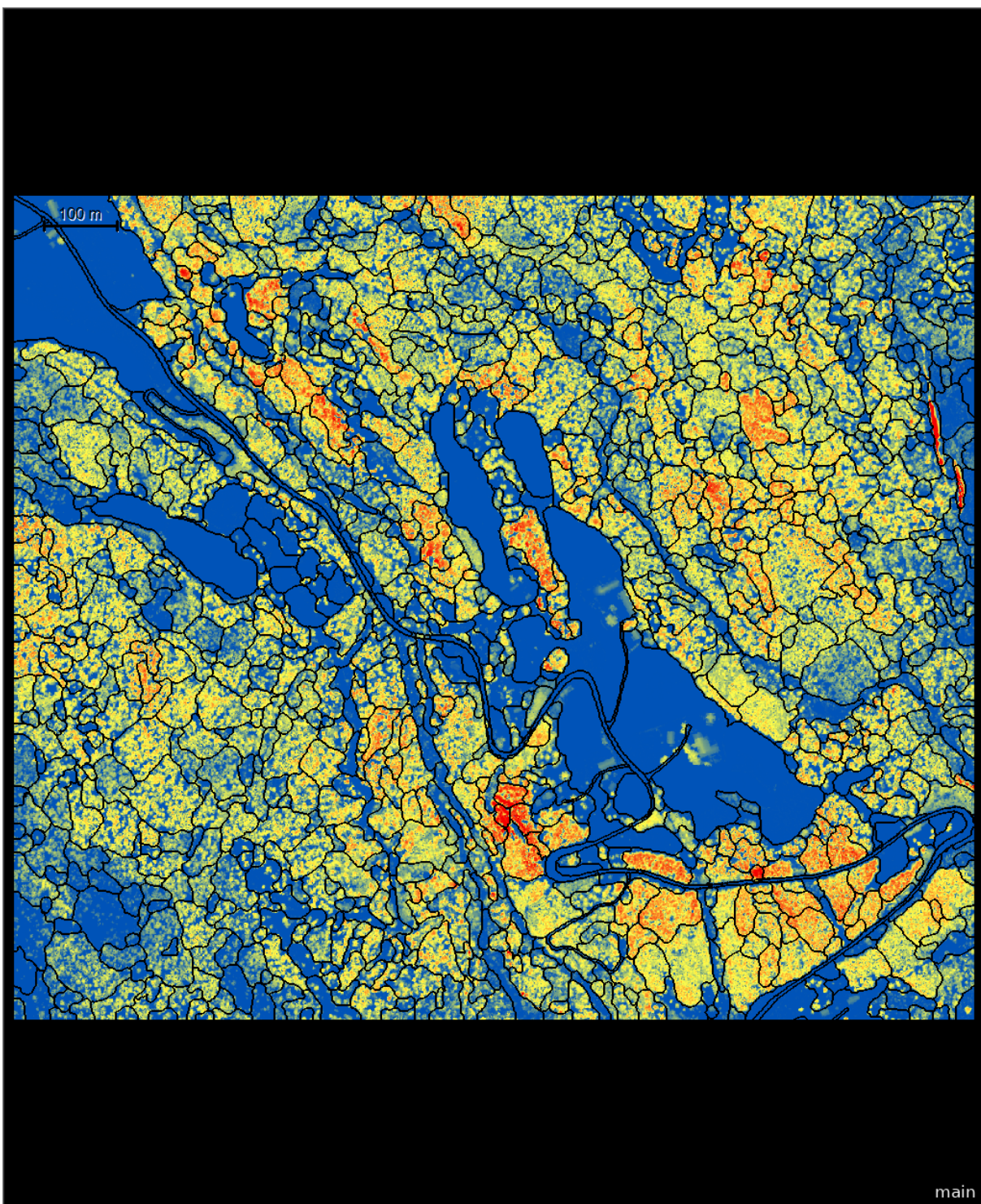
1
2 Figure 43. The segmentation mask (SM4) is shown in semi-transparent green on the rasterized tree-crown layer. Buildings are
3 shown in red.



1
2 Figure 54. Initial boundaries identified at pronounced changes in crown height using the contrast split algorithm. The image shows
3 a rasterized tree-crown layer with crown heights derived from the CHM. These boundaries served as the initial regions for the
4 subsequent delineation of forest-stand segments. Colors represent crown height, from low values (blue) to high values (red).



- 1
- 2 *Figure 65. The initial boundaries overlaid on the CHM. Colors represent canopy height, from low values (blue) to high values (red).*



1
2 Figure 76. Forest-stand segments overlaid on the CHM. Colors represent canopy height, from low values (blue) to high values (red).
3

S3.2 Construction of bufferTP figures

Segmentation does not produce a figure everywhere that confirmed trees exist, because the segmentation mask derives from SM3 and the Step 1 surfaces rather than from the tree points themselves. Stand polygons were therefore constructed from clusters of confirmed tree points falling outside the existing forest-stand layer. These figures are labelled bufferTP so they can be distinguished from segmented figures in downstream analysis.

The procedure runs per tile as a sequence of PostGIS operations through three working tables, and comprises four stages.

Stage 1: selecting eligible tree points

A tree point is eligible if it satisfies all of the following.

- Geometric criterion. The point does not fall within any existing forest-stand polygon in the same tile.
- Classification criterion. The point is classified as a definite tree (`er_definitivt_tre = 1`).
- Land type criterion. The point falls within an AR5 type that can carry forest (`artype` in 21, 22, 23, 30, 50, 60, 99), which excludes built-up land, water and glaciers.
- Height criterion. `max_ndsm` exceeds 1.5 m, so that shrub vegetation is not counted.
- Exclusion. Points within the power line buffer are removed.

Stage 2: candidate polygons

Each selected point is buffered by the larger of its estimated crown radius and 6.0 m. Buffers are unioned and the result dumped to parts, so each polygon represents one connected cluster of buffered points. The polygon set is then cleaned in sequence: polygons below 128 m² are removed as noise; interior holes below 128 m² are filled; polygons below 256 m² are removed after hole filling; a concave hull with target percent 0.06 is computed to smooth the ragged outer edge of the buffer union into more natural stand boundaries; the hull is simplified with a topology-preserving simplification at 2.0 m tolerance; and any new interior holes below 256 m² are filled.

```
-- Stage 2, core of the candidate construction (illustrative)
WITH buf AS (
  SELECT ST_Buffer(geom, GREATEST(radius, 6.0)) AS geom
  FROM   rydd_trepunkt
  WHERE  fs_gid = 0           -- outside existing stands
        AND er_definitivt_tre = 1 -- confirmed tree
        AND artype IN (21,22,23,30,50,60,99)
        AND max_ndsm > 1.5
        AND har_kraftlinje = 0
)
SELECT ST_SimplifyPreserveTopology(
  ST_ConcaveHull(geom, 0.06), 2.0) AS geom
FROM (SELECT (ST_Dump(ST_Union(geom))).geom AS geom FROM buf) d
WHERE ST_Area(geom) >= 256;
```

Stage 3: subdivision and generalisation

To make the constructed polygons reflect real forest units rather than the shape of a buffer union, they are subdivided against SR16 forest polygons with `ST_Intersection`. Polygons that do not touch SR16 and exceed 512 m² are retained unchanged. The resulting set then passes through multi-stage neighbour generalisation using the established spatial procedures (Custom neighbour-consolidation procedures), which consolidate small polygons into larger neighbours on the basis of shared boundary length and a relative threshold.

Stage 4: overlap removal and attribution

Although the source points lie outside existing stands, buffering and generalisation can still push the constructed polygons into partial overlap with them. The union of all existing stands whose bounding boxes intersect the candidates is therefore computed, the difference is taken with `ST_Difference`, and polygons below 0.9 m² are discarded as numerical residue. Each surviving polygon is then attributed from the underlying tree points: counts of definite, possible and non-tree points; summed crown area and summed crown volume for confirmed trees; and the relative measures `tar_am2` and `vol_am2`, each capped at 9999.

The national run used five parallel workers, each with its own PostgreSQL schema so that the only shared resources were the accumulating national tables. Atomic tile assignment used `SELECT ... FOR UPDATE SKIP LOCKED`. The run produced 623907 candidate polygons, and subsequent cleaning to remove overlap with existing stands and with each other reduced this to the 602331 bufferTP figures reported in the manuscript.

S4 Expert rule-based system

S4.1 Rationale

Object-based detection is sensitive to surfaces that mimic the spectral and structural signature of trees. Rock outcrops, boulder fields, stone walls and steep slopes in the alpine zone all produce a raised normalized surface height, and where vegetation grows around them the vegetation index is also high, so both criteria that define a tree are satisfied where no tree exists. No single attribute separates these cases reliably. The classification therefore aggregates independent evidence from several sources into a numeric score, and applies a decision rule to the score together with terrain gradient.

A rule-based approach was chosen over a trained classifier for two reasons. The decision path for any individual point can be traced to the attributes that produced it, which matters where the dataset supports administrative use; and the rules could be developed from existing knowledge of

forest definitions and of the failure modes of the segmentation, without assembling a manually verified training set spanning the full range of Norwegian forest and terrain.

S4.2 Score computation

Each tree point is enriched by spatial overlay with AR5, SR16, N50, open mountain land and the power line buffer, and carries canopy height from the CHM, terrain slope from the DTM, aspect, and vegetation indices from both optical sources. The score is the algebraic sum of the terms in Table 2; each term is evaluated independently.

Table 2: Score terms. Positive terms are evidence for a tree, negative terms evidence against.

Group	Condition	Points	Reasoning
Primary forest evidence	AR5 artreslag in 31, 32, 33	+3	Point falls in land already mapped as forest
	AR5 unavailable and N50 objtype is Skog	+2	Fallback where AR5 is not mapped
Standing volume	SR16 srvolmb > 100 m ³ /ha	+2	Independent indicator of forest biomass
	SR16 srvolmb 50–100 m ³ /ha	+1	
Vegetation index	NDVI > 0.55 (Sentinel-2, or VHR as fallback)	+2	Strong vegetation response
	mean_ndvi ≥ 0.40	+1	
	Both sources available and sum > 1.1	+1	Agreement between independent sensors
	Both sources available and sum ≤ 1.1	−1	Disagreement between sensors
Height	mean_ndvi < 0.1 and s2_ndvi < 0.2	−4	Very low response; typical of rock
	max_ndsm > 3 m	+2	Height implausible for ground clutter
	max_ndsm ≤ 1.5 m	−2	Object effectively at ground level
Aspect	Slope facing S, SE or SW	+1	Favourable growing conditions in Norway
Penalties	Within power line buffer	−2	Cable and mast returns mimic canopy
	Open mountain land, sparse vegetation class 1	−3	Land known not to carry forest
	Open mountain land, sparse vegetation class 2	−1	
	N50 class snow or glacier	−3	Land cannot carry forest
	Mean terrain slope > 50°	−2	Steep terrain is a known source of artifacts

S4.3 Classification

Hard exclusions are evaluated first. Points on terrain steeper than 70° are always classified as not a tree. Points on terrain steeper than 60° with maximum height above 20 m are also excluded, since very tall objects on steep faces are almost always artifacts. On terrain steeper than 40°, points with a score of 2 or below are excluded. These thresholds reflect that steep terrain is a known source of false detections.

Definite-tree conditions are then evaluated.

- A score of 6 or above is a definite tree.

- An object with `max_ndsm` between 12 and 30 m and score at least 2 is a definite tree, because a height in this range is plausible for Norwegian forest and difficult to explain without vegetation.
- An object with `max_ndsm` above 30 m requires a score of at least 4, because very large height values can also arise from processing errors or spurious laser returns.

The possible-tree category takes points with score at least 4 and slope at most 50°, and points with score at least 3, height above 5 m and slope at most 40°. All remaining points are classified as not a tree.

```
-- Classification, structure of the decision (illustrative)
CASE
-- hard exclusions, evaluated first
WHEN mean_slope_dtm > 70 THEN -1
WHEN mean_slope_dtm > 60 AND max_ndsm > 20 THEN -1
WHEN mean_slope_dtm > 40 AND tree_score <= 2 THEN -1
-- definite tree
WHEN tree_score >= 6 THEN 1
WHEN max_ndsm > 12 AND max_ndsm <= 30 AND tree_score >= 2 THEN 1
WHEN max_ndsm > 30 AND tree_score >= 4 THEN 1
-- possible tree
WHEN tree_score >= 4 AND mean_slope_dtm <= 50 THEN 0
WHEN tree_score >= 3 AND max_ndsm > 5
    AND mean_slope_dtm <= 40 THEN 0
ELSE -1
END AS er_definitivt_tre
```

S4.4 Propagation and use

Tree crowns inherit the label from their seed point, which is possible because crowns and points are one to one by construction. The label is carried as an attribute rather than used to delete objects, so that users may apply their own threshold; the possible-tree class in particular retains ambiguous detections that a binary filter would discard. A separate flag `er_busk` marks probable shrubs, defined as `max_ndsm` below 1.5 m.

The classification also propagates to the stand layer, where each figure carries counts of definite, possible and non-tree points, and to bufferTP construction (S3.2), which uses only confirmed trees.

S4.5 Development and tuning

The score terms and thresholds were developed through iterative testing across regions, with conditions and threshold values added to address misclassification cases identified during testing, particularly on steep terrain, open mountain land and in alpine areas. Testing used 55 tiles distributed across the country, spanning vegetation zones, terrain types and climatic regions from lowland forest in the south-east to mountain and coastal regions in the north and west, comprising approximately 83.5 million tree points.

S5 Dataset export

S5.1 Exported datasets

Three datasets are exported per tile, all in EPSG:25833.

- **Tree points**, 27 attributes per point, including the score, the classification, the shrub flag, canopy height statistics, vegetation indices, terrain slope and the attributes acquired by spatial overlay.

Table 3: Attribute schema of the exported tree-point dataset. Columns are listed in the fixed export order.

#	Attribute	Type	Source / description
1	fid	Integer	Internal identifier from the source geopackage
2	uuid	Text	Unique identifier: fid concatenated with rute_name
3	max_ndsm	Real	Maximum normalized surface height (m)
4	mean_ndsm	Real	Mean normalized surface height (m)
5	min_ndsm	Real	Minimum normalized surface height (m)
6	mean_dtm	Real	Mean terrain model elevation (m)
7	area_m2	Real	Crown area (m ²)
8	radius	Real	Estimated crown radius (m)
9	s2_ndvi	Real	NDVI from Sentinel-2
10	mean_ndvi	Real	Mean NDVI from the VHR image
11	mean_slope_dtm	Real	Mean terrain slope from the DTM (degrees)
12	slope_dtm	Real	Terrain slope sampled at the point pixel (degrees)
13	aspect_dir_20m	Text	Aspect direction from the 20 m DTM, for example N, S, SE
14	artreslag	Smallint	AR5 tree species (-99 = none)
15	argrunnf	Smallint	AR5 ground conditions
16	arskogbon	Smallint	AR5 site index
17	artype	Smallint	AR5 land type (99 = outside AR5 coverage)
18	svolmb	Real	SR16 standing volume including bark (-99 = none)
19	n50_objtype	Varchar(32)	N50 land cover object type, for example Skog, Snølsbre
20	snaumark_val	Integer	Open mountain land class (-99 = none)
21	har_kraftlinje	Smallint	1 = within the power line buffer, 0 = outside
22	komid	Smallint	Municipality number from national administrative boundaries
23	rute_name	Text	Production tile name, for example 33-107-104
24	tree_score	Smallint	Aggregate tree score (Section S4.2)
25	er_busk	Smallint	1 = probable shrub (max_ndsm < 1.5 m), 0 = otherwise
26	er_definitivt_tre	Smallint	1 = definite tree, 0 = possible tree, -1 = not a tree
27	geom	Geometry	PointZ, EPSG:25833

- **Tree crowns**, 22 attributes per crown, including crown area, canopy height statistics, vegetation index, and the four categorical fields inherited from the paired tree point.

Table 4: Attribute schema of the exported tree-crown dataset. Columns are listed in the fixed export order. Where an attribute exists in both sources, the crown polygon is authoritative; five attributes are inherited from the paired tree point.

#	Attribute	Type	Source / description
1	fid	Integer	Internal identifier from the source geopackage (ObjectShapes)
2	uuid	Text	Unique identifier: fid concatenated with rute_name
3	area_m2	Double	Crown area recomputed from the polygon geometry (m ²)
4	atborder	Smallint	Tile-border indicator from the source geopackage
5	mean_slope	Real	Mean terrain slope, inherited from the paired tree point
6	max_ndsm	Real	Maximum normalized surface height (m)
7	mean_ndsm	Real	Mean normalized surface height (m)
8	min_ndsm	Real	Minimum normalized surface height (m)
9	q50ndsm	Real	50th percentile of normalized surface height (m)
10	q95ndsm	Real	95th percentile of normalized surface height (m)
11	q99ndsm	Real	99th percentile of normalized surface height (m)

12	mean_dtm	Real	Mean terrain model elevation (m)
13	nhm_tetthet	Smallint	Point density of the national elevation model
14	nhm_aar	Smallint	Acquisition year of the national elevation model
15	ndvi	Real	NDVI value for the crown
16	har_kraftlinje	Smallint	1 = within the power line buffer, 0 = outside
17	artype	Smallint	AR5 land type, inherited from the paired tree point
18	artreslag	Smallint	AR5 tree species, inherited (-99 = none)
19	er_busk	Smallint	Shrub flag, inherited from the paired tree point
20	er_definitivt_re	Smallint	Classification, inherited from the paired tree point
21	rute_name	Text	Production tile name, for example 33-115-134
22	geo	Geometry	Polygon, EPSG:25833

- **Forest-stand segments**, 22 attributes per figure, including area, structural class, height percentiles, crown-cover density, crown distribution, species, site index, tree-point counts, and source acquisition date.

Table 5: Attribute schema of the exported forest-stand dataset.

#	Attribute	Type	Source / description
1	gid	Integer	Internal identifier for the forest-stand polygon
2	uuid	Text	Unique identifier: gid concatenated with rute_name
3	area	Double precision	Polygon area (m²)
4	class	Varchar	Structural class from segmentation, or bufferTP for constructed polygons (Section S3.2)
5	dtm	Real	Mean terrain model elevation; object mean of DTM pixels (m)
6	ndvi	Real	Mean NDVI from the VHR image; object mean (red and near-infrared bands)
7	q50ndsm	Real	50th percentile of normalized surface height within the figure (m)
8	q95ndsm	Real	95th percentile of normalized surface height (m)
9	q99ndsm	Real	99th percentile of normalized surface height (m)
10	slope	Real	Mean terrain slope from the DTM (degrees)
11	srbonitet	Integer	SR16 site index (modal pixel value; nodata 0 excluded)
12	srtreslag	Integer	SR16 tree species (modal pixel value; nodata 0 excluded)
13	treedistrib	Real	Index in [0, 1] for spatial homogeneity of crown distribution (NULL where it cannot be computed)
14	sistflydat	Date	Acquisition date of the most recent source imagery
15	rute_name	Varchar	Production tile name, for example 33-107-102
16	n_ok_tre	Smallint	Count of definite trees (er_definitivt_tre = 1) within the figure
17	n_kanskje_tre	Smallint	Count of possible trees (er_definitivt_tre = 0)
18	n_ikke_tre	Smallint	Count of non-trees (er_definitivt_tre = -1)
19	n_busk	Smallint	Count of shrub points (er_busk = 1)
20	tar_am2	Real	Relative crown area (crown area per unit figure area)
21	vol_am2	Real	Relative standing volume (volume per unit figure area)
22	geom	Geometry	Polygon, EPSG:25833

Each figure carries both a polygon geometry and a guaranteed interior representative point, and a unique identifier formed from the internal identifier and the tile name.

S5.2 Production run

The national tree-point export ran on 2 and 3 May 2026 across 1 837 tiles with a 100 percent success rate. The exported dataset contains 2 716 919 817 tree points in 1 837 files. Mean processing time was 474.9 seconds per tile against a median tile size of 1 338 910 points, the largest single tile holding 4 673 710 points, for a total of 242.3 processor-hours.

S6 Software and data access

S6.1 Software

Vector processing and mask construction use PostgreSQL with PostGIS. Raster and vector export use GDAL and OGR. Orchestration, the export tools and the format benchmark use Python, with psycopg2, GeoPandas, PyArrow, Shapely and pyogrio. Image segmentation uses Trimble eCognition Developer and eCognition Server. All components except eCognition are open source.

S6.2 Availability of inputs and outputs

The Skogmaske dataset cannot be regenerated from publicly available sources. Most of the input datasets are held by their owners under licences that do not permit redistribution, and the segmentation depends on commercial software.

Table 6: Availability of the components required to run the workflow.

Component	Availability	Note
VHR mosaic	Restricted	Copernicus Contributing Missions; license held by the data owner
Sentinel-2 mosaic	Open	National mosaic published through the national ground segment
Elevation models (DTM, DSM)	Restricted	Published nationally.
AR5, FKB	Restricted	Published through the national geodata catalogue
SR16	Open	Published nationally
N50	Open	Published nationally
Power line buffer, open mountain land	Restricted	Held by the respective institutions
PostGIS and Python production scripts	Internal	Held in the project version control system
Skogmaske dataset	Restricted	Demonstration subset for one grid tile deposited; see the manuscript data availability statement