**Life PROGNOSES – Action 1.25**

# WP1 - Compilation of final outputs: definition, mapping and evaluation of old-growth beech forests through field surveys and remote sensing

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# 1. Introduction

## 1.1. Policy context of Life Prognoses project: The EU Biodiversity Strategy and the strict protection of European primary and old-growth forests

The LIFE project PROGNOSES aims to contribute to the implementation of the EU Biodiversity Strategy to 2030, and EU Forestry strategy for 2030, and more specifically on the implementation of the goals on definition, mapping and strict protection of all remaining primary and old-growth forests in Europe (Directorate-General for Agriculture and Rural Development (European Commission), 2021; Directorate-General for Environment (European Commission), 2020).

The EU Biodiversity Strategy 2030 targets to protect at least 30% of the EU's land area and to have an effective management regime in place. Of this 30%, 10% must be under strict protection. All remaining primary and old-growth forests should be included in these strictly protected areas to protect them against any form of logging and safeguard their specific ecosystem services. At the moment, primary and old-growth forests only cover about 3% of the EU's forested area and exist of small, fragmented patches in the landscape.

Relevant challenges on the path to strict protection of all old-growth and primary forests are:

- The absence of a harmonized definition and criteria for European primary and old-growth forest, and a lack of knowledge regarding the structural features that allow identification (Barredo et al., 2021).

- The lack of overarching threshold values : threshold values to determine a forest to be old-growth forest are site, forest type and country dependent : even when criteria are set, and indicators defined (e.g. presence of large amounts of coarse woody debris), we will need threshold values to delineate what is old-growth. As the implementation of the strategy is a national authority, thresholds will be set at country level, but should be in line with reference values from natural forests.

- Incomplete information about the locations of the remaining primary and old-growth forests (incomplete and inaccurate mapping) (Barredo et al., 2021).

One of the main goals of the Life Prognoses project is to provide helpful tools to address the aforementioned barriers on the path to strict protection. For the development of these tools (definition, criteria, mapping etc.) the project focusses on beech forests. The reason for this focus is that most of the remaining old-growth and primary forests are beech forests, given the competitive strength of the species since the last glacial period (about 12.000 years ago). Furthermore, the project partners enjoy good connections with the world heritage site 'Ancient and Primeval Beech Forests of the Carpathians and other Places in Europe' comprising exemplar forests of the kind that should fall under strict protection throughout almost all biogeographic regions of Europe. The serial heritage site provides excellent study areas from which determining features can be distilled.

The project objectives concerning defining, identifying, and mapping old-growth forests are contained within Work Package 1 (WP1). This report brings together all major outputs of WP1, that will provide an overall 'state of knowledge' and deliver a valuable and significant contribution to a European-wide, scientifically sound, high resolution mapping of old growth forest in Europe.

## 1.2.Overview of objectives in WP1 of LIFE Prognoses

With WP1, the Life Prognoses project contributes to the development of a definition of, and criteria and indicators for primary and old-growth forests, with a focus in European beech dominated forests. Based on a preliminary literature review, determining features were listed that could serve as indicators. In a second phase, the proposed indicators were assessed in field. The definition and indicators should apply to the whole of Europe. A guidance has been developed for this assessment to provide a European-wide protocol that results in comparable results on the one hand, but leaves room for tailoring to the regional context on the other hand.

The ten test sites, where the assessment according to the field protocol has been conducted, provided the already existing mapping of the area. These maps were compared to the results from the newly collected data. The Joint Research Centre of the European Commission has compiled the existing mapping on old-growth and primary forests for Europe. The accuracy and precision of the compiled JRC mapping is assessed through sample-wise comparison with the results from the field mapping. The results from these validation procedures can be consulted in the report by Posch et al. (2025).

Furthermore, a screening of mapping methods based on remote sensing (RS), instead of an assessment in the field, has been conducted. The results of this screening can be consulted in the review paper by Hirschmugl et al. (2023). A RS method was developed to identify and delineate patches of old-growth forest. This RS method was validated against the results of four of the test sites. The results of this exercise for these four sites is to be published in a scientific paper (Hirschmugl et al., in prep.)

# 2. Definition, criteria, indicators and benchmarks for European old-growth beech forests

## 2.1. Defining European old-growth beech forests

At the beginning of the Life Prognoses project's implementation period in 2021, several terms and corresponding definitions existed for the forest types that should be strictly protected. Variations are forest 'undisturbed by man', 'primary', 'virgin', 'ancient', 'old-growth', and 'primeval' forest. The different concepts are listed in the JRC report *Mapping and assessment of primary and old-growth forests in Europe* (Barredo et al., 2021). These concepts and definitions were subject to discussion in the expert Working Group on Forests and Nature (WGFN). The working group was established to develop several sets of guidelines, among which the *Guidelines for Defining, Mapping, Monitoring and Strictly Protecting EU Primary and Old-Growth Forests*, eventually published in 2023 (Directorate-General for Environment (European Commission), 2023b). The ongoing work within the Life Prognoses project supported the discussions during the meetings of this working group with expert information. The project examined the different relevant concepts in detail, closely investigated the idea of old-growth and what the distinction with primary forest should be (Vandekerkhove et al., 2022).

The Life Prognoses partners actively participated in the following meetings of the WGFN:

- 3rd meeting: October 22-23, 2020
- 4th meeting: January 25-26, 2021
- 5th meeting: October 21-22, 2021
- 6th meeting: February 7-8, 2022
- 7th meeting: May 12-13, 2022
- 8th meeting: October 5, 2022

On January 21st, 2021, the LIFE-prognoses partners contributed to the Commission's webinar on old-growth forests with a presentation about the ongoing related work in project. On September 27th, 2022, an additional meeting was held with the 'co-leads' of the primary and old-growth forests file to finetune the final version of the Commission guidelines.

The Life Prognoses project contributed with insights into the relevant aspects of the forests we want to protect and how these aspects relate to one another. The European Commission decided to employ the definition of the Food and Agricultural Organisation (FAO) for primary forests and to develop a new definition for old-growth forests, tailored to a Europe-wide context. The Life Prognoses project contributed to the development of this new European definition for old-growth forests. The development of the definition of old-growth is explained in the Life Prognoses report *Old-growth criteria and indicators for beech forests (Fageta)* (Vandekerkhove et al., 2022).

The Europe-wide defining characteristics of old-growth forests relate to their current structural features. This is the first important distinction between old-growth forests on the one hand, and primary, ancient, or virgin forests on the other hand. The latter group of concepts is characterized by a history without significant human disturbance and land-use change. Although it cannot be said that the history of an old-growth forest is irrelevant, it is not a criterium per se. The management history of an old-growth forest can be an explanatory

factor for why it has developed the structural features that make it an old-growth forest now. Forest continuity is not a criterium for a forest to be identified as old-growth.

The structural attributes that define old-growth forest are those that are associated with late-seral stages of stand development, such as the presence of deadwood and old trees. The second important distinction between old-growth forest and the group of forest concepts mentioned above is their maturity: old-growth forest are characterised by structural attributes of late-seral stages while an ancient forest is still an ancient forest in case it is in an early developmental phase after a large-scale disturbance, for example. Old-growth characteristics may develop in both primary and secondary forests, provided natural processes dominate over extended periods. This flexibility allows for a broad application in Europe, where forests often have diverse management histories.

The third important insight regarding the idea of old-growth is that in reality there is no sharp delineation between old-growth and not old-growth. The defining structural features develop over time at rates varying with the local context. This means that the features that characterise and old-growth forest do not appear all at once, but gradually. This is the reason the project publication on this topic talks about 'old-growthness', allowing to characterise a forest as having a certain level of old-growthness instead of being either fully old-growth or not at al.

## 2.2.Identifying European old-growth beech forests

Old-growth forests are identified based on their structural and ecological complexity. Unlike primary forests, old-growth characteristics can also develop in areas with historical human disturbance, provided natural processes dominate over time. Key criteria for old-growthness were extracted from an extensive literature review and include:

- **Presence of large and old trees**
  - High densities of very large or overmature trees.
  - Trees surpassing half their natural lifespan or exhibiting unique growth patterns.
- **Volume and diversity of deadwood**
  - Significant amounts of standing and fallen deadwood, with a range of decay stages.
- **Structural complexity**
  - Uneven-aged stands with multiple canopy layers and natural gaps:
  - Horizontal diversity (random or clumped spacing of trees/different canopy density)
  - Vertical diversity (Layering and vertical continuity of the canopy)
- **Tree species composition**
  - Dominance of late-successional species and a lack of invasive or non-native plants.
  - Tree species diversity
- **Soil microstructures (micro-relief)**
  - Density and size of pit-and-mound structures
- **Microhabitats**
  - Density of habitat trees (=trees bearing Tree related Microhabitats (TreMs)) with e.g. cavities, bark crevices, or epiphytes.
- **Indicator species**
  - Presence of indicator species of late seral stages with overmature trees and large dead wood.

A complete overview of the structural attributes of old-growth forest, and the corresponding literature review, can be found in the report *Old-growth criteria and indicators for beech forests (Fageta)* (Vandekerkhove et al., 2022).

## 2.3.From the listed criteria to a measure of ‘old-growthness’

The ‘old-growth indicator’ defines an aggregated score combining multiple indicators for old-growth. This way, a comprehensive assessment of ‘old-growthness’ can be obtained.

The indicators were organised into nine thematic groups:

1) Deadwood
2) Decay stage
3) Development stages
4) Microhabitats
5) Native species
6) Stand density
7) Successional status
8) Tree dimensions
9) Tree species richness

The preliminary results for this indicator show a significant difference between managed and primary forests and an intermediate position of set aside and long untouched stands.

The idea of the old-growth indicator for the attribution of old-growthness to assessed forest stands was examined more closely by comparison with the results from the field mapping (see § 4). The narrative and preliminary results from this investigation can be consulted via scientific posters and conference slides on the project website. Meyer et al. (2021) provide detailed insights into the idea of the old-growth Indicator for quantifying old-growthness of European beech forests.

# 3. Evaluation of the existing mapping of old-growth forests

The existing mapping of primary and old-growth forests in Europe has been compiled by the JRC (Barredo et al., 2021) primarily based on the reference database by Sabatini et al. (2021) *European Primary Forest Database V2.0* (EPFD2).

The resulting database comprises the mapping that was available before the definition of old-growth and the guidelines on identifying and mapping were developed. Therefore, it is necessary to assess the extent to which this database aligns with what is currently considered old-growth.

The Life Prognoses project evaluated the database against a set of known patches of old-growth that were also selected for the field sampling. This way, 50 polygons located in beech forests from the EPFD2 were confronted with aerial photographs and maps from the test areas of the project that are also comprised in the serial world heritage *Ancient and Primeval Beech Forests of the Carpathians and Other Regions of Europe* (Posch et al., 2025).

## 3.1. Evaluation of the European Primary Forest Database v2.0

The EPFD2 currently is the most comprehensive and complete database on European primary and old-growth forests. The database comprises information on these kinds of forests from 48 datasets and includes 18,411 individual patches (41.1 Mha) spread across 33 countries. It is a geodatabase: for each entry, coordinates are saved. The attributes recorded for each entry (forest patch) include naturalness, dominant tree species etc.

The question remained whether the information from the EPFD2 can be used as reference data for the location, extent and state of European old-growth forests. As a part of the Life Prognoses project the database was evaluated for this purpose.

To assess whether the EPFD2 is a suitable reference for old-growth forests, two main criteria were examined to select the polygons that would be assessed:

(1) whether the data was collected by another method than only remote sensing (this would result in circular reasoning) and
(2) whether it concerns a beech-dominated polygon. For the selected polygons.

The precision of the delineation was divided into four categories.

- A: Precise delineation of pure and mixed beech old-growth forests (OGF). These polygons represent well-defined areas of old-growth beech forests without significant management influences or inclusion of other land cover types.
- B: Polygons containing a mix of managed and old-growth beech forests.
- C: Polygons that include mixed beech forests with other forest types or land cover types (such as rocks, lakes, meadows, roads, or buildings). These polygons are less accurate as reference datasets for pure beech forests.
- X: Polygons containing no or hardly any beech trees: These areas are unsuitable for further analysis of old-growth beech forests.

The evaluation highlighted both the strengths and limitations of the existing datasets. While there is a wealth of data available for many countries in Europe, the quality of the datasets varies significantly: Many datasets still require further refinement to be used as reliable reference datasets for beech forest studies. The study emphasizes the importance of careful data selection and categorization when working with large, complex geodatabases, and it suggests that future efforts should focus on improving the accuracy of the delineation of polygons and ensuring that they contain representative beech forest areas.

To protect old-growth forests effectively, the gaps in the mapping will have to be addressed. In §4 the assessment of old-growthness in the field is explained, and in §5; a method to assess this feature through remote sensing (RS) is presented.

# 4. Assessment of old-growthness in the field: a mapping guideline

The existing mapping of European old-growth forests is abundant but still incomplete and not always accurate. To fill the gaps in the mapping, methods need to be developed to assess old-growthness and identify old-growth patches. This assessment can be done by assessing the old-growth indicators in the field.

The Life Prognoses project contributed to the mapping of old-growth forests by developing a protocol that is applicable Europe-wide for the delineation and assessment of old-growthness of beech forest stands in the field (Kirchmeir et al., 2023).

Considering the large diversity of forest ecosystem across the biogeographic regions in Europe, developing a protocol that can be used everywhere on the European land surface is challenging. For this reason, the protocol leaves sufficient room for tailoring to national and regional standards and practices. Nevertheless, it tries to find a balance between regional *applicability* and interregional *comparability*. The field protocol is made to assess the selected Europe-wide criteria and indicators for old-growth forests, but without fixed thresholds for these indicators. This allows the national governments and organizations to tailor the assessment procedure to the national and regional context.

In what follows, we first explain the protocol itself, with a view to its Europe-wide application and in relation to the Commission guidelines that have been developed by the WGFN (Directorate-General for Environment (European Commission), 2023a). Afterwards, we briefly explain the development and evaluation of this protocol within the project.

## 4.1. Life Prognoses Mapping Guideline and Field Survey Protocol

The Mapping Guideline and Field Survey Protocol developed by the Life Prognoses partners provides instructions for every step in the process of the assessment of old-growthness, specifically for European beech-dominated stands, but sufficiently generalizable. The steps discussed are:

- Selection of the mapping area
- Delineation of homogenous forest patches/stands (pre-classification)
- Set up of the sampling design
- Collection of field data on sampling plots (including structural parameters and in a selection of sites also tree-cores, microhabitat inventory and soil samples)
- Final assessment of old-growth indicators of each polygon

Here, we briefly touch on the main points of every step[1].

[1] What is mentioned here is to illustrate the set-up and scope of the field protocol. It is not sufficient to actually execute the assessment of old-growthness and mapping of old-growth forest. For actual implementation of the protocol, please consult the dedicated document.

1. Selection of the mapping area

The mapping area is the area for which the old-growthness of the comprised patches will be assessed. It is important to include a sufficiently large area to ensure sufficiently large homogeneous patches can be delineated afterwards for assessment. For most sampling sites, a mapping area of at least 1000 ha is selected. For significantly smaller sites, such as Krokar, 250 ha to 500 ha is sufficient.

The mapping area should include potentially old-growth as well as managed forest for comparison. Preferably, a broad range of levels of old-growthness is included.

2. Delineation of field units or homogeneous forest stands

For the delineation of homogeneous field units criteria with respect to which the stands are homogeneous have to be defined. With the help of existing maps, the management plan of the area, and aerial imagery, the selected criteria can be evaluated for the mapping area and field units can be distinguished.

We propose the following criteria with view to the assessment of old-growthness:

- Dominance of beech
- Main admixed tree species
- Management type
- Age class (if managed or set-aside forest); developmental phase for primary forests
- Time since abandonment (for unmanaged forest)
- Upper canopy cover density (closed, spaced, half-open,…)

Each unique combination of these criteria is called a 'stratum'.

3. Required field data per stratum

The sampling of dendrometric features, needs to ensure the data sampled allows to be analysed by sound statistical methods to evaluate the level of oldgrowthness.. Some of these elements (like Very Large trees) are scarce, so the required sample size should be adequate. When using plots of 500 $m^2$, at least 5 to 10 plots per stratum are needed. If data has been collected for the relevant variables in the area previously, the data can be used only if it has been collected within the five years before the old-growth assessment will take place and in case the sampling size meets the requirements.

In all other cases, a virtual sampling grid with dimension 100 m to 300 m can be placed on the mapping area divided in strata. For each field unit or stratum, at least 5 to 10 sampling plots should be selected (coinciding with the nodes of the grid).

4. Collection of field data

For every sampling plot, data should be collected for a set of indicators and corresponding criteria for old-growthness. The criteria and indicators evaluated this way are the ones listed in the Life Prognoses publication *Old-growth criteria and indicators for beech forests (Fageta).* In the field protocol, criteria and indicators to assess carbon stock and biodiversity are included as well. This choice was made because the field protocol was also used to reach the other project objectives. To standardise the data collection across different mapping areas (comparability) and for areas without an established design, a basic plot design is developed.

The protocol includes the collection of data for some descriptive parameters regarding soil, geography, management history, human disturbance, and stand developmental

phase and structure. For these parameters, the information can be gathered in the field, but mostly based on cartography and management plans. Collecting the data for the so-called 'dendrometric survey' happens in the field. The parameters essential to the assessment of old-growthness are indicated with 'required', while other indicators are 'additional. Including the indicators that fall under the latter category, however, will add to the robustness and precision of the assessment.

A chapter describing the protocol for the sampling and analysis of soil carbon content is included. As mentioned earlier, this is done with view to the other objectives of the project.

A detailed description of the measuring protocol is given in Kirchmeir et al. (2023). However, as several datasets were already existing, with slightly different methodologies (but meeting the basis requirements of the protocol), the data sampling was sometimes divergent. Calculations of variables such as tree volume is based on country-specific allometries. A detailed overview of all sites, plots and applied measuring and calculation procedures is given in Vanhellemont (2025).

5. Asessment of the indicators for old-growthness

   Based on the results of the field survey, reference values can be derived for all variables for the primary forests in the dataset. From these reference ranges, indicator values can be derived, based on the method by Meyer et al. (2021).

   Results of this exercise will be published in a scientific journal. The manuscript (Smith et al., in prep) is still in draft.

## 4.2.Relation of the field protocol to the Commission guidelines

The Life Prognoses field protocol is an important complement to the publication of the Commission *Guidelines for Defining, Mapping, Monitoring and Strictly Protecting EU Primary and Old-Growth Forests (Directorate-General for Environment (European Commission), 2023b)*.

The Commission guidelines focus on the bigger picture, running the reader through the policy context, the definitions for primary and old-growth forest etc. They give an overview of the definitions and their meaning, and list the selected indicators for old-growthness, but do not discuss these matters to the extent the scientific report of Life Prognoses, *Old-growth criteria and indicators for beech forests (Fageta)*, does.

The same goes for the mapping: the Commission guidelines briefly touch on mapping, mentioning the importance of combining remote sensing technologies with other assessment methods, the existence of the EPFD2 as a starting point, the importance of national inventories to fill the gaps, and some budget lines that could support the endeavour financially. The nature of the Life Prognoses field protocol is different; it focusses on the concrete execution of the assessment in the field, specifying which data should be collected and elaborating on the minimum requirements for the different samplings concerned.

## 4.3.Development and evaluation of the Life Prognoses Mapping Guideline

The sites used in the Life Prognoses dataset and analysis were selected from the total set of component parts of the serial world heritage site *Ancient and Primeval Beech Forests of the Carpathians and Other Regions of Europe* comprising primary old-growth and developing (secondary) old-growth forests.

The forests for developing and testing the field protocol are selected to cover all relevant biogeographic regions[2] Buffer zones that are still managed were also sampled, in order to cover the full range of TSA-contexts.

Table 1, from the descriptive report (Vanhellemont, 2025), gives an overview of the sampled sites.

*Table 1: Overview of the sampling sites (from: Vanhellemont, 2025).*

| site | country | lat | lon | beech forest region | biogeographic region | MAT (°C) | MAP [a] (mm) | altitude (masl) | soil [b] |
|---|---|---|---|---|---|---|---|---|---|
| Abruzzo NP | IT | 41.78 | 13.75 | Central Mediterranean | mediterranean | 6.2 | 1369 | 1500-1800 | PH, CH |
| Central Balkan NP | BG | 42.74 | 24.77 | Moesian-Balcanic | alpine | 5.8 | 890 | 960-1560 | CM |
| Hainich NP | DE | 51.08 | 10.44 | Subatlantic-Hercynic | continental | 7.3 | 761 | 270-480 | AL, AT, CM, KS, LP, ST, TC |
| Kalkalpen NP | AT | 48.22 | 13.79 | Alpine | alpine | 6.7 | 1327 | 460-1360 | CM, LP |
| Kellerwald NP | DE | 51.15 | 8.98 | Subatlantic-Hercynic | continental | 7.3 | 775 | 220-620 | CM |
| Klenovský Vepor | SK | 48.55 | 19.60 | Carpathian | continental | 6.2 | 754 | 540-1250 | CM |
| Krokar | SI | 45.54 | 14.77 | Illyrian | alpine | 8.9 | 1447 | 910-1180 | CM, LP |
| Sinca forest | RO | 45.66 | 25.17 | Carpathian | continental | 5.9 | 950 | 1000-1260 | CM |
| Snežnik | SI | 45.57 | 14.47 | Illyrian | alpine | 8.9 | 1447 | 1350-1450 | CM, LP |
| Sonian forest | BE | 50.75 | 4.42 | Atlantic | atlantic | 10.6 | 852 | 90-130 | CM, RT |
| Stara Planina | BG | 42.76 | 24.55 | Moesian-Balcanic | alpine | 6.8 | 612 | 1240-1480 | CM |
| Uholka forest | UA | 23.70 | 48.31 | Carpathian | continental | 7.7 | 1134 | 530-1200 | CM |

[a] data from Di Fiore et al. (2022; Abruzzo NP), Abiota Compendium Annex to Central Balkan National Park Management Plan (Central Balkan NP), data from Gauer & Aldinger (2005; Hainich NP, Kellerwald NP), CHELSA data (Karger et al. 2018) (Kalkalpen NP, Sinca forest), E-OBS data v24.0e (Cornes et al. 2018, https://surfobs.climate.copernicus.eu/dataaccess/access_eobs.php; Klenovský Vepor, Stara Planina), meteorological station of Kočevje at 467 m altitude (Krokar, Snežnik), Uccle weather station of the Royal Meteorological Institute (Sonian forest), meteorological station of Carpathian Biosphere Reserve in Uholka at 430 m altitude: 1990-2010 for MAT, 1980-2010 for MAP (Uholka forest)

[b] based on the soil sample plots (Abruzzo NP, Klenovský Vepor, Stara Planina), forest inventory data (Central Balkan NP), unpublished forest site mapping and soil maps (Hainich NP, Kellerwald NP), national park inventory data (Kalkalpen NP), soil maps (Krokar, Snežnik), forest management plans (Sinca forest), soil maps and former soil sampling (Sonian forest), Brändli & Dowhanytsch (2003; Uholka forest)

In Ukraine, it was impossible to sample the original site of Chornohora due to the war context of the country. It was substituted by an already existing datasets of a site nearby (Uholka), kindly provided by WSL (Switzerland)..

The compiled dataset contains both data sampled during the project strictly following the field protocol, but also existing data with slightly different protocols, but meeting the basic

[2] This is without the boreal biogeographic region; for the simple reason that the serial world heritage does not include any component parts in that region (yet).

requirements of the protocol (for details see: Vanhellemont, 2025). Due to these differences, the data compilation required significantly more effort to align the data.

# 5. Assessment of old-growthness through remote sensing methods

## 5.1. Scientific screening of remote sensing-based mapping methods

On the possibilities and approaches to apply remote sensing (RS) in the identification and mapping of primary and old-growth forests, a scientific overview paper was produced by Life-PROGNOSES (Hirschmugl et al., 2023).

In summary, old-growth forests (OGF) provide valuable ecosystem services such as habitat provision, carbon sequestration or recreation maintaining biodiversity, carbon storage, or human well-being. Long-term human pressure caused OGFs in Europe to be rare and scattered. Their detailed extent and current status are largely unknown. This review aims to identify potential methods to map temperate old-growth forests (tOGF) by remote sensing (RS) technology, highlights the potentials and benefits, and identifies main knowledge gaps requesting further research. RS offers a wide range of data and methods to map forests and their properties, applicable from local to continental scale. We structured existing mapping approaches in three main groups. First, parameter-based approaches, which are based on forest parameters and usually applied on local to regional scale using detailed data, often from airborne laser scanning (ALS). Second, direct approaches, usually employing machine learning algorithms to generate information from RS data, with high potential for large-area mapping but so far lacking operational applications and related sound accuracy assessment. Finally, indirect approaches integrating various existing data sets to predict OGF existence. These approaches have also been used for large area mapping with a main drawback of missing physical evidence of the identified areas to really hold OGFs as compared to the likelihood of OGF existence. In conclusion, studies dealing with the mapping of OGF using remote sensing are quite limited, but there is a huge amount of knowledge from other forestry-related applications that is yet to be leveraged for OGF identification. We discuss two scenarios, where different data and approaches are suitable, recognizing that one single system cannot serve all potential needs. These may be hot spot identification, detailed area delineation, or status assessment. Further, we pledge for a combined method to overcome the identified limitations of the individual approaches.

## 5.2. Remote Sensing-based mapping method for the assessment of old-growthness in European beech forests

Within PROGNOSES, we mapped four sites in three bio-geographical regions and evaluated the potential for upscaling this classification for all beech forests in Europe. Based on the variety of different forms, which an old-growth beech forest can take in different regions, under different climatic conditions and in different phases of development, this is not an easy task. We therefore focussed our approach on identifying potential forest areas with old trees, as tree height and – to some extent also age – is mirrored in remote sensing data. We employed Sentinel-2 satellite data and, for two of the sites, additional airborne LiDAR (ALS) data.

More specifically, the aims of this study are: (i) to develop an RS-based direct mapping tool for old-growth beech forests in different bio-geographical regions in Europe and (ii) to apply a scientifically sound accuracy assessment. The latter is only possible through the homogeneous field measurements generated in our LIFE+ PROGNOSES project mentioned above. The intrinsic challenges to achieve the aims in this study are:

(i) different characteristics of old-growth beech forests in different bio-geographical regions
(ii) different input/training data available in terms of timeliness, quantity and reliability
(iii) different remote sensing data availability

The research questions therefore are:

(1) Is there a one-fits-it-all methodology to classify old-growth beech forests in Europe?
(2) What is the achievable accuracy for classifying old-growth beech forests from RS data by using independent field-measured plot data for validation?
(3) What is the benefit of including ALS data in that classification?

We could prove the assumption, that training data quality has a strong impact on the classification output and the related accuracy values. Training data, that was collected at a similar time as the plot data or in line with the prognoses field data collection guidelines, led to better results than training data collected long time ago or for different purposes. We reached high accuracies in the Sonian Forest and in Bulgaria, while the results for mountainous Kalkalpen National Park and Abruzzo National Park were much lower. We could further prove that the inclusion of ALS data improved the overall accuracy of the map by approximately 6%, but also varying according to site.

The methods and results are drafted in a scientific paper (Hirschmugl et al., in prep.).

# A. Technical annex :mapping products produced and compiled in the project.

1. *Polygon map of 9 test sites*
    a. *GIS-layer (polygon map) compiling existing stand maps of 9 UNESCO WH Components and their surrounding.*
    b. *Metadata and technical Specificities are described per site (projection, description of attributes).*
    c. *Result will be published in the repository Zenodo – open access (CC-BY-NC -ND)*

2. *GIS-layer with sample Plot location and metadata*
    c. *GIS-layer representing the location of the plot data produced and used in Prognoses*
    d. *The dataset is a shapefile with point features. Each plot is represented by its center coordinate. Each plot also has a unique ID, which allows to link it to the datafiles on dendrometrics, carbon, etc…that will also be deposited in a repository (zenodo). The attribute table contains metadata describing the plot (elevation, soil type, stand age,…). Description of the plot selection and sampling protocol is published in Kirchmeir et al. (2023) and further elaborated in Vanhellemont (2025).*
    e. *Result will be published in the repository Zenodo – open access (CC-BY-NC-ND)*

3. *RS result : RS-product for the Test sites (4) : result of the mapping exercise*
    c. *GIS-layer*
    d. *Technical details of the mapping result*
    e. *Result will be published in the framework of the publication– open access (CC-BY-NC-ND)*

Site overview for the mapping products

| Site | plot location map (point layer) | Polygon maps | RS result (Raster layer) |
|---|---|---|---|
| ab ... Abruzzen | OK | Yes | Yes |
| cb ... Central Balkan | OK | Yes | Yes |
| ka ... Kalkalpen | OK | Yes | Yes |
| so .. Sonian | OK | Yes | Yes |
| ha ... Hainich | OK | Yes | - |
| ke ... Kellerwald | OK | Yes | - |
| kr ... Krokar | OK | Yes | - |
| kv ... Klenovsky | OK | - | - |
| sz ...Sneznik-Zdrocle | OK | Yes | - |
| sp.. Stara Planina | OK | - | - |
| uh ... Uholka | OK | Yes | - |
| Si... Sinca | OK | - | - |

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