



Deliverable 2.1

Criteria for adaptive single tree level management



D2.1: Criteria for adaptive single tree level management

Deliverable details

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Adaptive forest management, biodiversity, forest health, wood quality, sustainable forestry, LiDAR, point clouds

Executive Summary

This deliverable sets out the criteria and indicators for adaptive forest management at the single-tree level within the SingleTree project, supporting the EU Forest Strategy and broader European Green Deal objectives to enhance biodiversity, reduce greenhouse gas emissions, and strengthen forest resilience under increasing disturbance pressure (windstorms, bark beetles, drought, forest fire, and root rot). The core premise is that implementing adaptive management at the single-tree level, supported by high-resolution remote sensing, artificial intelligence (AI), and forest digital twins, allows for more precise, data-driven and targeted interventions compared to traditional stand-level practices, with an expected increase in overall forest multifunctionality compared to Business-as-Usual (BAU).

The work establishes a shared conceptual framework across three regionally distinct Living Lab Value Chains (LLVCs): North (Sweden), Central (Switzerland), and South (Spain), while ensuring indicators (and thresholds) reflect region-specific hazards and management contexts. LLVC North and Central prioritize resistance and resilience to wind damage and European spruce bark beetle outbreaks, whereas LLVC South focuses on reducing forest fire risk under drought, fuel accumulation, and changing socio-landscape conditions, aligned with a fire-smart mosaic approach. Despite these differences, all LLVCs apply common decision criteria spanning (1) biodiversity, (2) tree health status and hazard risk, and (3) stem/wood properties linked to economic return.

Methodologically, the deliverable links adaptive management principles with precision forestry enabled by remote sensing. It specifies how single-tree attributes derived from remote sensing feed into actionable indicators. These data support targeted interventions at single-tree and micro-stand scales (aggregation of trees in a particular small area where the species composition, structure, size, age, ... are homogeneous), integrating productivity goals with biodiversity and resilience outcomes.

Key outputs include a structured criteria set that operationalizes multifunctional management based on a variety of ecosystem services: biodiversity indicators (tree species diversity, habitat elements, and animal diversity proxies), tree health and risk indicators (crown condition metrics and region-specific risk levels), and wood quantity/quality indicators. Overall, the deliverable concludes that clearly defined, measurable criteria, rooted in established sustainability frameworks and adapted to local conditions, are essential to translate adaptive management into practical guidelines. This approach enables consistent yet regionally tailored decision-making that enhances forest resilience, supports biodiversity conservation, and improves economic viability.

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1. Introduction

The EU Forest Strategy, as one of the flagships in the European Green Deal and the EU Biodiversity Strategy for 2030, is pivotal for achieving the ambitious goals for enhancing the EU's biodiversity and reducing greenhouse gases (GHG) emissions in the near future. While it advocates small-scale sustainable forest management and the use of wood-based resources, European forests are facing increasing natural disturbances, such as windstorms, forest fires, drought, European spruce bark beetle (*Ips typographus* L.) outbreaks and wood decaying (*Heterobasidion* spp) root rot. Recent advances in remote sensing enabling detailed forest data acquisition at the individual tree level provide significant opportunities for developing adaptive and multifunctional forest management based on single-tree information. Such approaches are crucial for supporting a sustainable bioeconomy, counteracting biodiversity loss, and enhancing the resilience of European forests.

Adaptive management in forestry has emerged as a critical area of inquiry due to the increasing pressures of climate change, biodiversity loss, and escalating natural disturbance regimes such as forest fires and pest outbreaks (Govedar et al., 2023; Temperli et al., 2012). Forest management paradigms have evolved from static, single-objective approaches to more dynamic, integrative frameworks that emphasize resilience and multifunctionality (Bolte et al., 2009; Yousefpour et al., 2017). For instance, natural disturbances exacerbated by climate change increasingly threaten forest carbon storage and biodiversity, demanding adaptive strategies to sustain these ecosystem functions (Mina et al., 2022; Repo et al., 2025). Projected increases in forest fire severity, pest outbreaks, and shifts in tree species distributions further reinforce the urgency of developing resilient forest management approaches (Liang & Hurteau, 2023; Mary Petritan & Beloiu Schwenke, 2023).

Adaptive forest management offers a structured, iterative approach that enables forest managers to respond flexibly to uncertainties caused by climate change and associated increase in natural disturbances. It integrates monitoring, continuous learning, and feedback loops to guide decision-making under changing environmental conditions (Govedar et al., 2023; Kneeshaw et al., 2021). By following this approach, operational foresters can tailor their management strategies to generate resilient forests to confront future climate conditions while the management remains socially and economically viable. Adaptive strategies preserve biodiversity, sustain ecological functions, and enhance forest structure, aligning with evolving societal expectations of forests as multifunctional landscapes (Repo et al., 2025; Temperli et al., 2012).

A critical knowledge gap exists in understanding how adaptive management strategies can simultaneously enhance provisioning of multiple ecosystem services, while considering risks and uncertainties related to climate change (Borges et al., 2014; Marques et al., 2017). Controversies persist regarding the balance between active interventions, such as forest conversion and fuel reduction, and passive approaches that emphasize natural processes

and non-intervention (Adamopoulos et al., 2024). Moreover, the efficacy of adaptive management in reducing pest damage without compromising biodiversity remains debated, with some studies highlighting potential conflicts between restoration and pest control objectives (Kärvemo et al., 2017; Kneeshaw et al., 2021). The consequences of these gaps include suboptimal forest resilience and increased vulnerability to natural disturbances, threatening long-term sustainability (Maxwell et al., 2022).

The overall conceptual approach and criteria for adaptive single tree management in the SingleTree project are common for all Living Lab Value Chains (LLVC) and consider wood quantity and quality (impacts on economic return), biodiversity, and health status and risks of hazards (affecting forest resilience) at the tree level. However, their indicators (and thresholds) consider region-specific settings such as specific forest management strategies and objectives, and risks to forests. They are defined by each LLVC, namely LLVC North (Sweden), LLVC Central (Switzerland), and LLVC South (Spain). The LLVCs North and Central are vulnerable to windstorms and bark beetle outbreaks, whereas the LLVC South (Spain) is vulnerable to forest fire, exacerbated by prolonged drought, fuel accumulation, and rural depopulation. This approach allows each LLVC to implement adaptive forest management strategies grounded in shared principles, while recognizing unique region-specific settings. Clearly defined criteria translate the complexities of adaptive management into practical, actionable guidelines.

2. Objectives

This deliverable focuses on defining the criteria for adaptive single-tree-level management, which forms the foundation for developing novel management solutions and tools to enhance forest resilience and multifunctionality. This requires approaches that effectively utilize detailed individual tree-level information (e.g. on wood quantity and quality, tree health, hazard risks, and biodiversity) derived using improved monitoring technologies. Such individual tree information can later be aggregated at micro-stand level to obtain relevant information for management. For this purpose, we have defined an overall conceptual approach and criteria for adaptive single-tree-level management to support multifunctional forest management and harvesting planning (Figure 1).

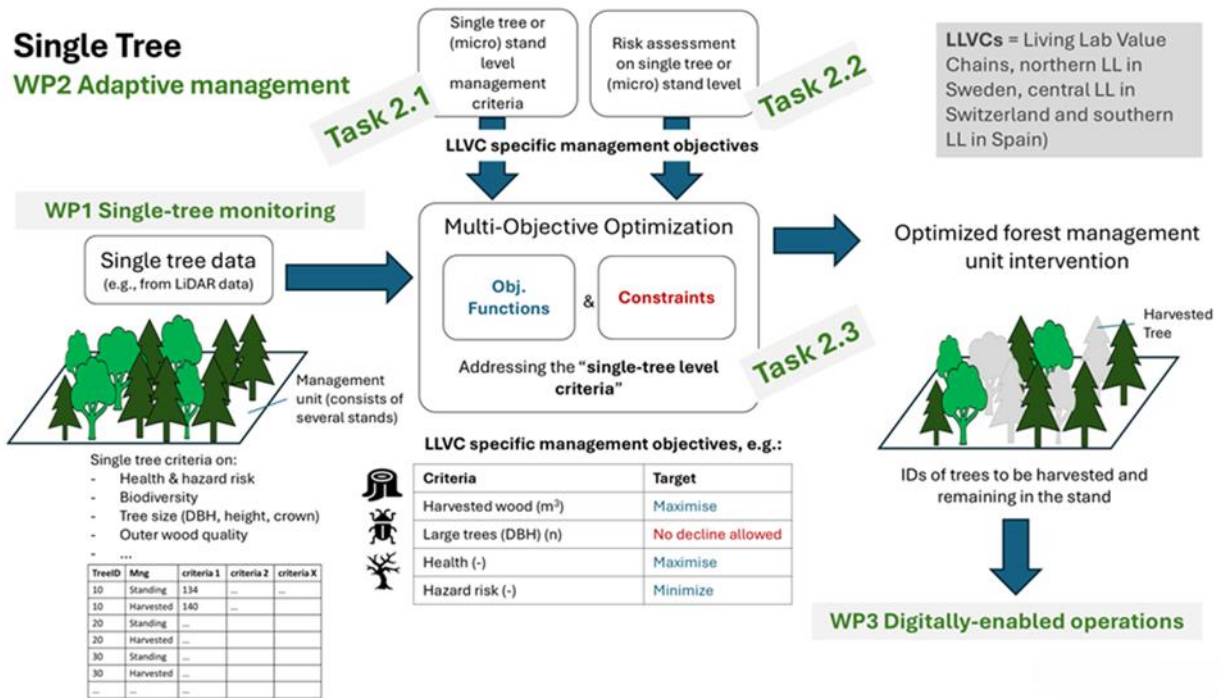


Figure 1: Outlines for WP2 and links between Tasks 2.1-2.3 and with other WPs

3. Living Lab Value Chains

Importantly, the need for adaptive forest management is not uniform across regions; it varies significantly depending on ecological context, land-use history, and social expectations. In the SingleTree project, this variability is addressed through three regionally distinct LLVCs, each characterized by specific forest types, hazard profiles, and management priorities.

Adaptive management strategies in each LLVC (Figures 2 and 3) are developed around key criteria – resilience, resistance, economic return, and biodiversity – tailored to their unique regional conditions.

- **Living Lab Value Chain North (Sweden):** encompasses boreal and semi-boreal forests, which are primarily dominated by Norway spruce and Scots pine. The region is highly vulnerable to windstorms and European spruce bark beetle outbreaks, especially as climate change amplifies disturbance frequency. LLVC North is managed by a large-scale, profit-driven company.
- **Living Lab Value Chain Central (Switzerland):** encompasses mixed temperate forests but often with dominance of spruce due to management legacies, which renders the region similarly susceptible to wind damage and bark beetle disturbances.

The state-run forest enterprise manages the LLVC central for multifunctional purposes, where trees are harvested on an individual basis, and clear-cuts are restricted. Due to steep slopes, only half of the harvest operations are mechanized.

- **Living Lab Value Chain South (Spain):** presents a contrasting profile, with Mediterranean and sub-Mediterranean forests primarily composed of oak woodlands (e.g. *Quercus pyrenaica* Wild) and pine stands (e.g. *Pinus nigra* Arn, *Pinus sylvestris* L.), embedded in mosaics of cropland and shrubland. The primary hazard here is forest fire, exacerbated by prolonged drought, fuel accumulation, and rural depopulation. Adaptive management emphasizes reducing fire risk through structural complexity, fuel discontinuity, and landscape-level planning following the “fire-smart mosaic” approach (Pulido et al., 2023). Management of LLVC South is structured around a mixture of public & private forest ownership, with a large share of unmanaged forests.



Figure 2: Captures of LLVC North, LLVC Central and LLVC South, respectively. (Photographs by Nial Perry).

Based on these general criteria, adapted to region-specific frameworks, each LLVC can implement adaptive forest management strategies rooted in shared principles-resilience, resistance, economic viability, and biodiversity conservation-while acknowledging distinct regional dynamics. Clearly defined criteria translate the complexities of adaptive management into practical, actionable guidelines.

A criterion, defined as a fundamental standard for judgment or evaluation, serves as a normative benchmark guiding sustainable forest management decisions. Institutional frameworks such as FSC, PEFC, FAO, and the Montréal Process operationalize criteria to structure sustainable governance through measurable indicators and continuous improvement processes. Clear criteria support informed decision-making, facilitate the evaluation of trade-offs, and ensure scientifically grounded, operationally feasible interventions across multiple scales.

The *SingleTree* project advances forest management by implementing strategies at the single-tree and micro-stand levels, marking an evolution from traditional stand-level practices that rely on aggregate indicators. Single-tree management enables precise, data-driven responses to structural, compositional, and vulnerability differences within forests. By leveraging high-resolution proximal remote sensing and artificial intelligence, the *SingleTree* project integrates detailed individual-tree data on tree health and hazard risks, biodiversity, and wood quality into decision-making processes. This precise, individualized management

enhances the effectiveness of silvicultural treatments and aligns timber production with biodiversity conservation and climate resilience objectives.

This methodology resonates with the concept of precision forestry, representing a technological extension of adaptive management principles applied at fine spatial scales. Precision forestry employs advanced tools – including terrestrial laser scanning (TLS), mobile laser scanning (MLS), UAV and aircraft-based sensors and satellite and aerial imagery – to achieve detailed, spatially explicit monitoring of forest conditions to optimize forest operations by improving efficiency, enhancing environmental protection and reducing waste. This approach rounds the circular economy from planting and monitoring to harvesting. These technologies improve forest inventories' spatial accuracy and support evidence-based decisions. Within the SingleTree project, precision forestry enables the design of targeted interventions, optimizing immediate forest conditions and long-term ecosystem resilience.



Figure 3: *Pinus pinaster* and *Pinus sylvestris* stands, respectively, in the LLVC south (Photographs by Chamodi Dissanayake).

4. Criteria for adaptive management

4.1. Available attributes

The *SingleTree* project generates detailed data sets essential for addressing the specific management criteria established for each LLVC. These attributes are expected from WP1 along with the risk assessment from Task 2.2, and other spatial data (Table 1). These detailed and spatially explicit variables and metrics provided by the *SingleTree* project will support adaptive forest management, allowing for precise interventions adapted to the ecological, economic and social contexts of each LLVC. This data-driven approach ensures the effective translation of complex adaptive management principles into actionable forest management strategies.

Table 1: Extracted attributes from remote sensing (RS) data

Extracted attributes from RS data	
Tree attributes	Tree positions, tree species, diameter (d), tree height (h), stem volume (v), crown size (volume, length), whorl position, branch size, stem taper, stem defects (crooks, sweep, forks), Derived: relative value increment, neighbourhood indices.
Stand attributes	Basal area (g), stem number (N), standing volume (V), dominant height, segmented deadwood, Derived by T2.2: Fire damage risk score, wind damage risk score, spruce bark beetle outbreak risk score.

4.2 Management criteria and indicators

The formulation of criteria and indicators is focused on ecosystem services, tree health and vitality, and hazard risks, while integrating biodiversity promotion. These criteria and indicators promote adaptive management at the single tree level and the micro-stand level by providing desired conditions and benchmarking the current situation. When creating the criteria and indicators, we have considered several frameworks such as the Forest Europe, the Montréal Process for the Conservation and Sustainable Management of Temperate and Boreal Forests, and the Forest Stewardship Council (FSC) certification (Forest Stewardship Council, 2023a; Linser & O’Hara, 2015; *PEFC Benchmark Standard*, 2024; *The Montréal Process*, 2015). In the *SingleTree* project, the criteria and indicators (and their thresholds) are defined separately for each LLVC, considering the regional settings (Table 2).

Table 2: Criteria and indicators for adaptive single tree level management in different LLVCs.

Criterion	North, Central and South LLVCs - Ecosystem Services and Indicators
Biodiversity indicators	<p>Tree species diversity: Shannon index (H'), Species richness/ha</p> <p>Habitat elements: Deadwood - Snags/stumps/logs volume/ha, Buffer from water bodies</p> <p>Animal diversity: Presence/probability of holes and nests</p>

<p>Tree health status and risks of hazards</p>	<p>Crown and stem condition: tree crown and stem structure (snow damages, large herbivory damages, deformations due to nutrient deficiencies, stem damages, ...), Transparency of the crown, Defoliation %, Discoloration %</p> <p>Risk level: Wind damage risk score and European spruce bark beetle risk score (LLVCs North in Sweden and Central in Switzerland), Fire risk score (LLVC South in Spain)</p>
<p>Stem and wood properties traits</p>	<p>Wood quality and quantity (impacts on economic return): Basal area, Diameter distribution, Taper ratio, Crown base height, Tree leaning angle, Knots count</p>

5. Annex

5.1 Definition

Table 3: Definitions of some commonly used technical words

01	Criteria
	<ul style="list-style-type: none"> ▪ Standards by which you judge, decide about, or deal with something (<i>Cambridge dictionary</i>). ▪ The conditions necessary to achieve the principles of responsible forest management (<i>Forest Stewardship Council, 2023b</i>). ▪ A broad management objective reflecting essential ecological, economic, and social values that sustainable forestry must uphold (<i>PEFC Benchmark Standard, 2024</i>). ▪ The range of forest values to be addressed and the essential elements or principles of forest management against which the sustainability of forests may be assessed (<i>Food and Agriculture Organization of the United Nations, 2015</i>). ▪ Overarching goals representing desired outcomes of sustainable management, measured through corresponding quantitative and qualitative indicators. Collectively, these institutional definitions establish a comprehensive foundation for monitoring, evaluating, and adapting forest management practices within an iterative, evidence-based framework (<i>The Montréal Process, 2015</i>).
02	Risk
	<ul style="list-style-type: none"> ▪ The potential loss of life, injury, or destroyed or damaged assets which could occur to a system, society or a community in a specific period of time, determined probabilistically as a function of hazard, exposure, vulnerability and capacity (<i>UNDRR, 2007</i>).
03	Hazard
	<ul style="list-style-type: none"> ▪ A process, phenomenon or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption or environmental degradation (<i>UNDRR, 2007</i>).
04	Exposure
	<ul style="list-style-type: none"> ▪ The situation of people, infrastructure, housing, production capacities and other tangible human assets located in hazard-prone areas (<i>UNDRR, 2007</i>).
05	Vulnerability
	<ul style="list-style-type: none"> ▪ The conditions determined by physical, social, economic and environmental factors or processes which increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards (<i>UNDRR, 2007</i>).

5.2 Variables description

Table 4: Acronyms for common variables (International Union of Forestry Research Organizations, 1965)

Acronym	Full name
d	Diameter at breast height (cm)
V	Stand volume (m ³ /ha)
v	Tree volume (m ³)
g	Tree basal area (m ²)
cbh	Height to crown base (m)
N	Stem number per hectare

Upper-case letter representing stand level variables; lower-case letter representing tree level variables

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