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OPINION PAPER **Open Access**

Advancing forest inventorying and monitoring

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Key message

Evolving societal demands and accelerated ecological dynamics due to global change are rapidly altering forest ecosystems and their services. This has prompted the need for advancing forest inventorying and monitoring initatives to expand their scope, improve data collection, foster scientific understanding, and better inform policy responses. Here, we discuss the collaborative processes followed to develop an Advanced Inventorying and Monitoring (AIM) system for Swiss forests. Further, we provide the key messages that emerged from this process which can be of interest to those involved in similar processes at the national/international level.

Abstract

Forests are under pressure and going through rapid changes. However, current inventorying and monitoring (IM) programs are often either disjointed, too narrow in their scope and/or do not operate at fine enough temporal resolutions, which may hinder scientific understanding, the timely supply of information, fast decision making, and may result in the sub-optimal use of resources. For these reasons, there is an urgent need for Advanced Forest Inventorying and Monitoring (AIM) programs to (i) achieve expanded relevance (by augmenting data/information across ecosystem properties and trophic levels), (ii) have increased temporal resolution (by tailored data collection frequency), and (iii) make use of technological advances (by incorporating novel tools and technologies). The Advanced Inventorying and Monitoring for Swiss Forests (SwissAIM) initiative was launched in 2020 to address these needs. SwissAIM builds upon the foundation offered by the existing programs (e.g., national forest inventory, long-term forest ecosystem research, biodiversity monitoring). It aims to offer a collaborative and adaptive framework to enable integrated data collection, evaluation, interpretation, analysis, and modeling. Ideally, it will result in a more responsive system with respect to current and predicted biotic/abiotic stressors that will challenge Swiss forests. Developing such a system implies identifying the information needs of different stakeholders (e.g., science, policy, practice), related

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technical requirements, and governance frameworks. Here, we present (i) the main features of the SwissAIM initiative (vision, scientific questions and variables, governance and engagement), (ii) the main outcomes of the participatory design process (measurements, sampling, and plot design), (iii) the potential transferability of AIM initiatives outside Switzerland (timing, relevance, practicability), and (iv) the key messages that emerged (i.e., need for advancement, integration and transdisciplinarity, statistical underpinning). Since similar needs related to forest inventorying and monitoring are emerging throughout Europe and elsewhere, the objective of this opinion paper is to share our experience and promote a dialog with those interested in developing AIM initiatives in other countries and regions.

Keywords Forest biodiversity, Global forest change, Integrated monitoring, Participatory design, Sampling and plot design, Switzerland, Terrestrial and remote monitoring

"Forest science relies on the long-term data that scientists wring from forests over decades. Our chances of overcoming climate change are small, but they will diminish further if we forget the basics of monitoring our home planet" (Editorial in Nature—18th August 2022, 608: 449).

1 Introduction

Forests constitute an immense resource globally (FAO 2020) and are key for climate change mitigation (Jackson et al. 2008; Masera et al. 2003), protection of biodiversity, and providing a variety of services for people across the world (Díaz et al. 2015). In this context, the role of forest inventorying and monitoring (IM) programs is of paramount importance to obtain baseline data, track changes, provide data for modeling and model validation, and inform policy and management, so that science-based actions and strategies can be implemented and their results monitored (Ferretti and Fischer 2013; Forest Europe 2020; Lovett et al. 2007; Vidal et al. 2016). IM has become even more crucial at a time of rapidly evolving scientific and societal demands (Armstrong et al. 2023; European Commission, 2023; Hegetschweiler et al. 2020) and accelerated global change, for example, as a result of droughts, storms, pest and disease outbreaks, and invasive species (Frei et al. 2022; Jakoby et al. 2019; Liebhold et al. 2017; Rohner et al. 2021; Trumbore et al. 2015; Valentin et al. 2020).

While existing IM systems have led to substantial advances in evaluating the response of our forests to environmental changes (e.g., Alberdi et al. 2020; Liang et al. 2022; Jaime et al. 2022; van der Linde et al. 2018), they are now facing several interrelated challenges, including (i) their ability to provide timely information at the time of accelerated forest dynamics, (ii) using resources efficiently, and, (iii) having technological readiness. In part, the first two challenges reflect the different origins of and the disconnection among current IM initiatives. For example, sampling density, temporal resolution, and timing of current IM initiatives were designed decades ago and they were optimized to estimate the extent (in different respects) of forest resources and identify changes based on some assumption on their pattern of occurrence (e.g., rather faint changes due to forest management policy, background air pollution). Events outside these target patterns, for example, repeated drought episodes with a patchy spatial distribution as the one caused by the 2018 megadrought in Europe, may "fall through the mesh," and not be immediately quantifiable by existing regular surveys (Rohner et al. 2021; Schuldt et al. 2020). Given that climate change–related disturbances will likely increase in frequency and dimension (e.g., pest outbreaks; Jakoby et al. 2019), the ability of a monitoring system to respond rapidly drawing on a wide array of measured attributes will become more and more important. In addition, although the terms inventorying and monitoring are frequently used synonymously (e.g., Morrison et al. 2008), they originally constituted two approaches with important differences, which, however, do have potential complementarities and some overlaps (Ferretti 2013). In Europe, this situation is typically represented by two distinct systems constituted by the international forest monitoring carried out under the United Nations Economic Commission for Europe (UNECE) ICP Forests (hereafter ICPF) (Ferretti 2010; Ferretti and Fischer 2013) and by national forest inventories (NFIs) coordinated under the European National Forest Inventory Network (ENFIN) (ENFIN 2021; Tomppo et al. 2010a). Differences (and therefore potential complementarities) include the origin (periodical assessment of national forest resources in NFIs; annual assessment of spatio-temporal changes in international forest condition and its response to environmental stressors in ICPF), sampling density (higher in NFIs), temporal resolution (higher in ICPF), statistical design (stronger in NFIs), ecological coverage measurements (broader in ICPF), scope of field methodologies, quality control, data access, and governance (nationally oriented in NFIs; internationally oriented in ICPF) (Ferretti 2013, 2021). Overlaps include the fact that in several countries NFI and the ICPF Level I network[1] share the same sample plots (Travaglini et al. 2013), although in many cases they use different field teams who visit plots at different times. The differences/complementarities and overlaps between the ICPF forest monitoring and NFIs clearly show that the current situation is sub-optimal: as such, building synergies will create added value between different IM initiatives, improve understanding and efficient use of resource, and permit us to go beyond the obsolete distinction/segregation between forest inventories and forest monitoring (Ferretti 2013; Kovač et al. 2014; Wulff et al. 2012). Ultimately, this will also allow us to better evaluate the effectiveness of policy and forest management actions, respond to the parallel increase and diversification of societal demands (e.g., biomass, biodiversity, recreation) and the augmented impact of different stressors (e.g., droughts, storms, pest and disease outbreaks).

Together with evolving societal and scientific demands and accelerated ecological changes, rapid technological advances also create new needs and opportunities for IM to advance. Besides classical remote sensing approaches, traditional forest mensuration on IM plots can now be supplemented by, for example, close-range remote sensing tools and technologies (Abegg et al. 2017; Calders et al. 2020; Kukenbrik et al. 2022; Tomppo et al. 2021), environmental DNA (eDNA) (Sales et al. 2020) and in-site sensors (Zellweger et al. 2019; Zürcher et al. 2023; Zweifel et al. 2023). In short, and ideally, what is currently being measured on statistically representative networks on an annual (e.g., ICPF Level I) or multi-annual basis (e.g., NFIs), in the future should be (i) measured with higher temporal frequency, (ii) supplemented by additional measurements that today are typical only for case-studies (e.g., ICPF Level II plots), and, (iii) better connected and integrated with close-range and remote sensing and other novel techniques (Ferretti et al. 2013; Ferretti 2021). Conceptual and technological development towards a new generation of Advanced Inventorying and Monitoring programs (AIM) will favor a better connection and integration between existing systems, an option that deserves consideration in view of scientific, operational, political, and financial benefits (Ferretti et al. 2013; Noon et al. 1999).

Switzerland can be a useful working example for developing AIM systems. Firstly, there is a variety of IM initiatives covering Swiss forests (Rigling et al. 2015), including the Swiss National Forest Inventory (NFI) (Fischer and Traub 2019), the Long-term Forest Ecosystem Research (LWF), encompassing Sanasilva forest condition survey (Schwyzer et al. 2015), and the Biodiversity Monitoring Switzerland (BDM) driven by the Federal Office for the Environment (FOEN) (BDM Coordination Office 2014). Secondly, these programs have important connections and similarities but also differences. They are connected from the point of view of their design: they are all based on the original 1 × 1 km systematic sampling grid developed for the first Swiss NFI (NFI1) (EAFV 1988; Fischer and Traub 2019) but are now installed on different sub-grids with only partial overlap, have different frequencies of data collection (from 1 to 5 and 9 years) and different measurement timings within the year (Ferretti et al. 2021). Thirdly, as in many other countries, there is a substantial segregation between large-scale surveys and intensive studies, with LWF plots (i.e., the Swiss realization of ICP Forests Level II with installed monitoring instruments) being located on purposefully selected sites outside the NFI network. While these different IM approaches, grids, sites, measurement frequencies, and variable of focus can be ideal for individual surveys, they appear sub-optimal when considering the overall perspective of data integration and use of resources.

In summary, emerging environmental issues, accelerated forest dynamics, new information needs, novel technologies, changed spatial and temporal scales of concern and more efficient use of resources require the development of a new generation of transdisciplinary AIM programs. Such programs would be beneficial to incorporate comparable, long-term, multiscale, near-real-time high-quality data able to detect forest ecosystem status and changes with increased temporal resolution. Realizing this fact prompted a new initiative towards an Advanced Inventorying and Monitoring system for Swiss forests (SwissAIM) (Ferretti et al. 2021). This paper (i) summarizes the participatory processes undertaken to develop SwissAIM, (ii) describes the design concepts that emerged from the process, (iii) discusses the potential for relevance and transferability of SwissAIM concepts outside Switzerland, and, (iv) identifies relevant key messages that emerged from the process. We consider it useful and timely to share our experience and promote a dialog with those interested in developing future forest monitoring, especially when considering important initiatives like the proposal for a new regulation on a monitoring framework recently launched by the European Commission (see European Commission 2023).

[1] ICP Forests is a multilevel monitoring system organized with two complementary networks: Level I (on a systematic grid) and Level II (on a case-study basis) (details under: Outline of Part 1 (icp-forests.org).

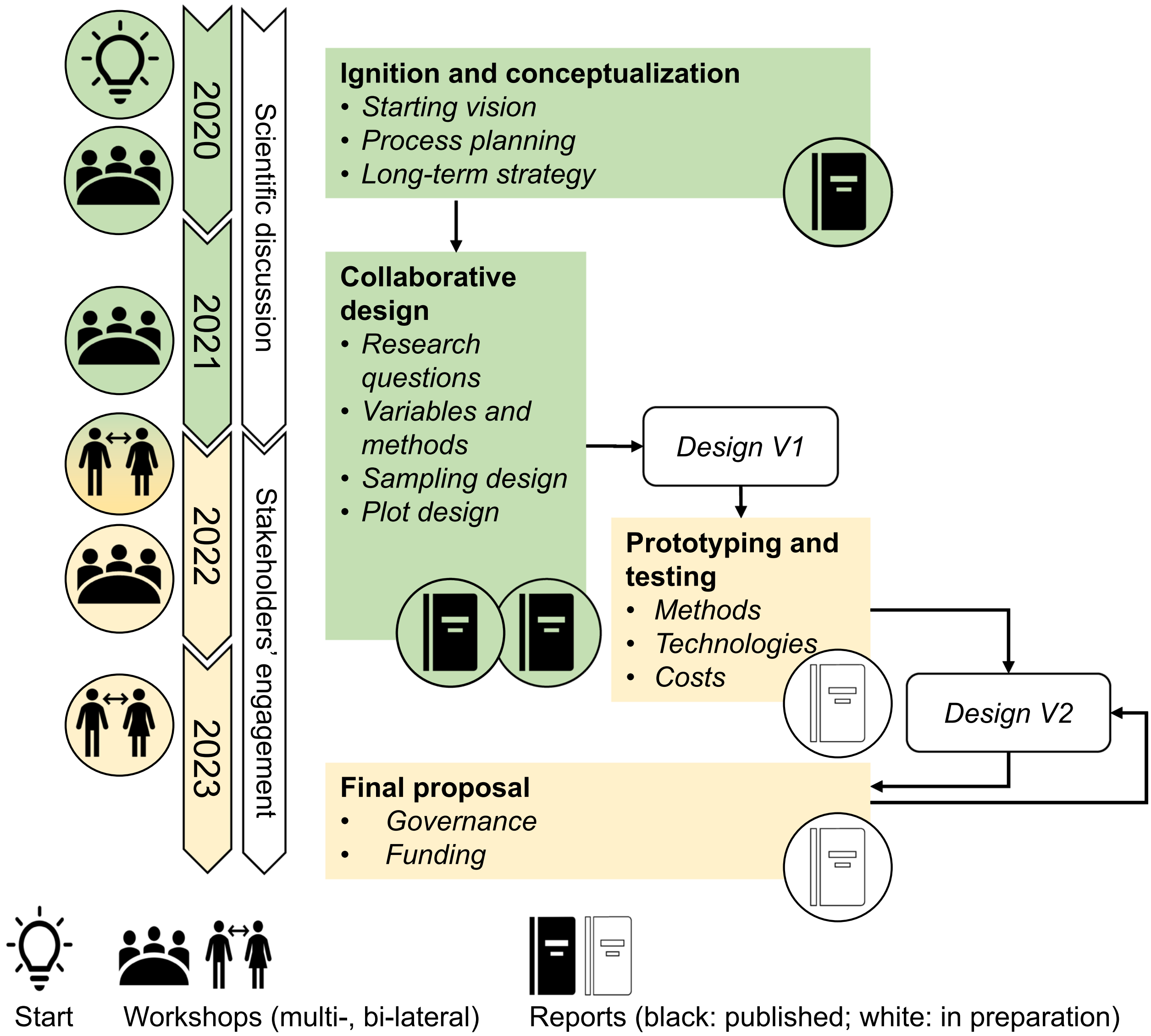


Fig. 1 Development of the SwissAIM (Advanced Inventorying and Monitoring for Swiss Forest) initiative with the main steps undertaken in the design process. The colors indicate those years/events/phases with mostly internal institutional science-driven activity (green) and when/where actual interactions with different stakeholders took place (yellow). The steps are described in the text. "Design V1" and "Design V2" mean subsequent revision of the design after input and feedback from different stakeholders. (Ferretti et al. 2021b; Shackleton and Ferretti, 2022)

2 Primary steps undertaken to develop SwissAIM

Envisioning, developing, and designing the SwissAIM initiative was a collaborative and participatory process (Fig. 1) with different steps including (i) a starting phase to conceptualize and develop a vision and long-term strategy involving scientists from different disciplines and with different backgrounds, (ii) a phase for collaborative design, (iii) a concurrent phase for prototyping and testing the design, and, (iv) a final phase, including starting developing a governance vision through the identification and engagement relevant stakeholders.

Although SwissAIM was initially science-driven to explore its scientific and strategic relevance and technicalities (e.g., sample size, plot design, and survey methods), in subsequent steps, numerous stakeholders involved in policy and management (e.g., the Forest Department of the Swiss Federal Office for the Environment – FOEN; Cantonal forest offices) and environmental non-governmental organizations (NGOs) were also engaged in the conceptualization and design of SwissAIM.

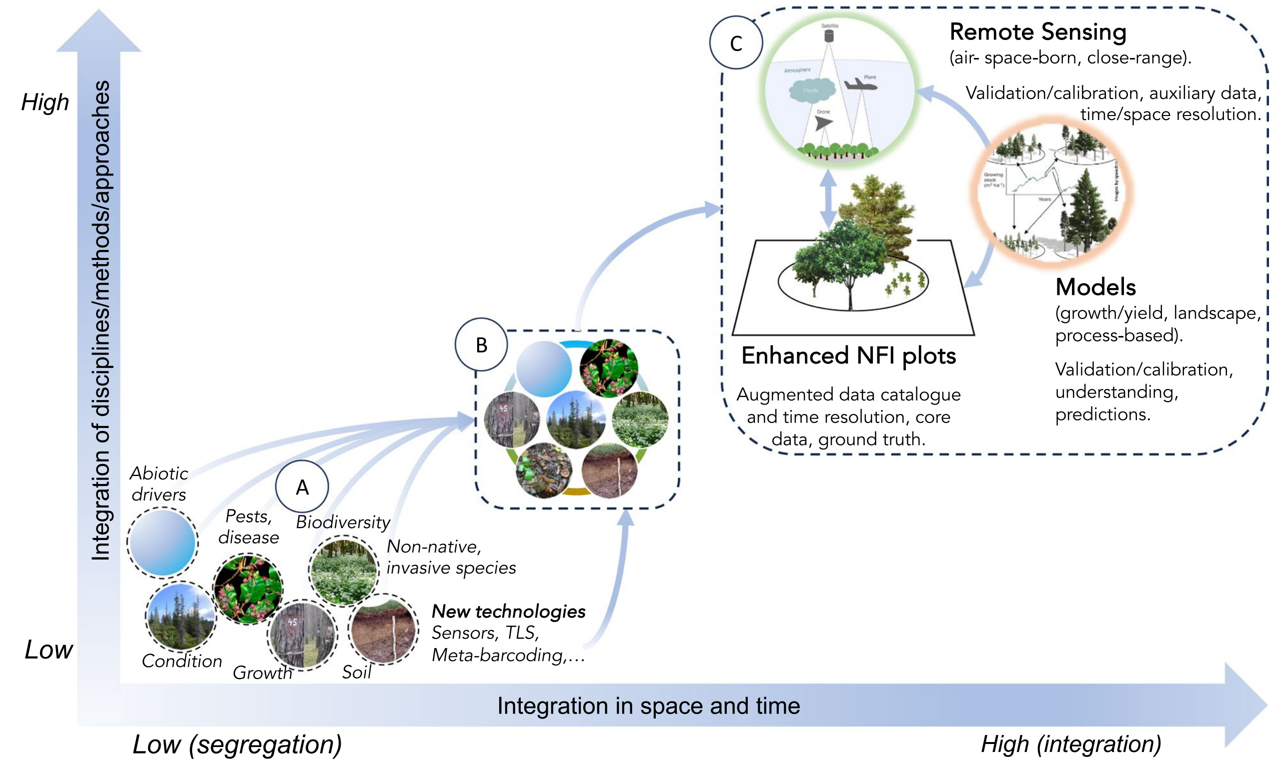


Fig. 2 Conceptual vision for the SwissAIM as an integrated inventorying and monitoring system. Moving from existing spatially and/or temporally segregated individual IM activity (bottom left, **A**) to co-located terrestrial measurements (middle, **B**) to highly integrated terrestrial, remote sensing, and model-oriented AIM (top right, **C**)

2.1 Developing an innovative vision and long-term strategy

The vision for the SwissAIM initiative was developed taking into account the input of scientists from different disciplines (forest ecology, dynamic, management; forest health; forest inventory and monitoring; biodiversity; soil and biogeochemistry; remote sensing and land change science; social sciences—see Ferretti et al. 2021) and the following overarching requirements that can be considered of relevance for AIM initiatives in general:

(i) Statistical perspective. AIM has to provide defensible results with known uncertainty. Here, a sound statistical perspective is essential for forest status and change estimation.

(ii) Holistic and integrative nature. AIM should consider all compartments of forest ecosystems (e.g., atmosphere; vegetation—from trees to lichens; soil), the different trophic levels (from producers to consumers), and the social dimensions (e.g., recreation, cultural values, management, and policy needs). Therefore, AIM initatives need a transdisciplinary, multifaceted perspective and will make use of terrestrial, close-range and remote sensing observation, and advanced tools and techniques (e.g., sensor networks, eDNA).

(iii) Temporal resolution. AIM should increase the temporal resolution of measurements as compared to the traditional, multi-annual NFI cycles (e.g., 9 years for the Swiss NFI), allowing for effective and timely detection of status and changes. For those attributes potentially subject to changes over the growing season (e.g., tree canopy and vegetation attributes) annual or even repeated intra-annual measurements should be considered. This will favor timely reporting, able to catch the pulse of forests, and tailor to the needs of all stakeholders for timely management and policy responses.

The overall SwissAIM vision then emerged as follows (Fig. 2):

> *"An integrated terrestrial and remote sensing observation system based on a permanent panel of enhanced NFI plots, that will provide high quality periodical (intra-annual, annual, multi-annual) results with known statistical errors for status,*

change and response of forests to biotic and abiotic drivers".

The innovative part of this vision includes the idea of combining the statistical perspective (typical of the NFIs) with an expanded set of ecosystem-oriented measurements and with high temporal resolution (typical of ICPF) and integrating all these different terrestrial measures with close- and remote sensing in plots with enhanced design. Altogether, this will permit (i) expanding the scope of existing IM systems across ecosystem compartments and properties, (ii) closer connection with remote sensing and modeling, and, (iii) better validation, calibration, understanding, and prediction. In this vision, the role of the Swiss NFI is central, because it (i) offers a robust and consistent nationwide statistical framework, (ii) has an already well-installed remote sensing component, and, (iii) is based on a systematic grid that has been used as the basis for other monitoring initiatives, like the forest condition survey Sanasilva and the BDM initative (see above). In particular, the Sanasilva provides a direct connection with the international dimension, as it represents the Swiss realization of the ICPF Level I assessment. Potentially, connecting NFIs and ICPF would provide an additional benefit (Ferretti 2010; Ferretti et al. 2013; Gasparini et al. 2013; Travaglini et al. 2013). A further important aspect inherent to the above vision is related to the need for comprehensive data for model calibration and validation.

There are several features inherent to the above vision. They include the following:

(i) SwissAIM should be a collaborative and participatory effort. On one side, development and implementation should include the perspectives and expertise of different stakeholders. On the other side, it will need, and will be conducive to, synergies and coordination between scientists of existing IM initiatives, and ideally result in enhanced scientific performance.

(ii) SwissAIM intends to be based on a permanent panel of NFI plots with an enhanced design. While this will place some challenges in the design and operability dictated by the nature of the NFI (e.g., the need to keep plots anonymous, see Sects. 2.2.3 and 2.2.4), it will offer the basis for national-scale, annual data, and estimates for status and change of key attributes linked to forest response to biotic and abiotic drivers, including extreme events. With annual data on, e.g., growth, SwissAIM will also enhance the interpretation of changes detected between subsequent 9-year NFI cycles.

(iii) SwissAIM has the ambition to be exemplary at the national/international level. Its vision, structure, and inherent collaborative nature will permit high-quality results and outputs, especially models relevant from local to national scales. It will be inspired by and will inspire development in the field of forest IM.

(iv) SwissAIM intends to serve science, practice, and society at large and will help to respond to the challenges posed by climate and global change. It will open research opportunities and will permit timely and closer monitoring of forests from a broad range of scientific perspectives. This will desirably lead to faster identification, upscaling and reporting of possible problems and prompt science-based solutions to better promote management, resilience, and resistance of our forests to accelerated environmental changes.

2.2 Collaborative design

The design process started with the identification of scientific questions, the related variables of interest and associated methods, the sampling design (including sample size), and the plot design.

2.2.1 Identifying research questions of interest

Ninety-two research questions were identified by scientists from different disciplines (Shackleton and Ferretti, 2022) (Appendix). These questions of interest covered aspects related to both research and application and were categorized into three broad categories including (i) better quantifying forest status and changes (i.e., the most typical set of questions for IM programs) (total: 29 questions), (ii) improving the understanding forest processes and dynamics (especially relevant when considering the foreseen acceleration of several processes induced by global change issues) (44 questions), and (iii) questions related to developing enhanced monitoring and inventorying techniques (an enduring concern for any IM perspective) (19 questions). The 100 most common words relating to the original questions (overall, and for each of the above three categories) are in the world clouds in Fig. 3: besides terms that can be expected given the context (e.g., "Swiss", "forests", "NFI", "LFI" – the German acronym for NFI), others like "status", "change", "biodiversity", "climate", "drought", "ecosystem", "biotic", "abiotic", "remote sensing", and "close range" emerged in the various clouds. Examples of topics related to the various questions are reported in Table 1.

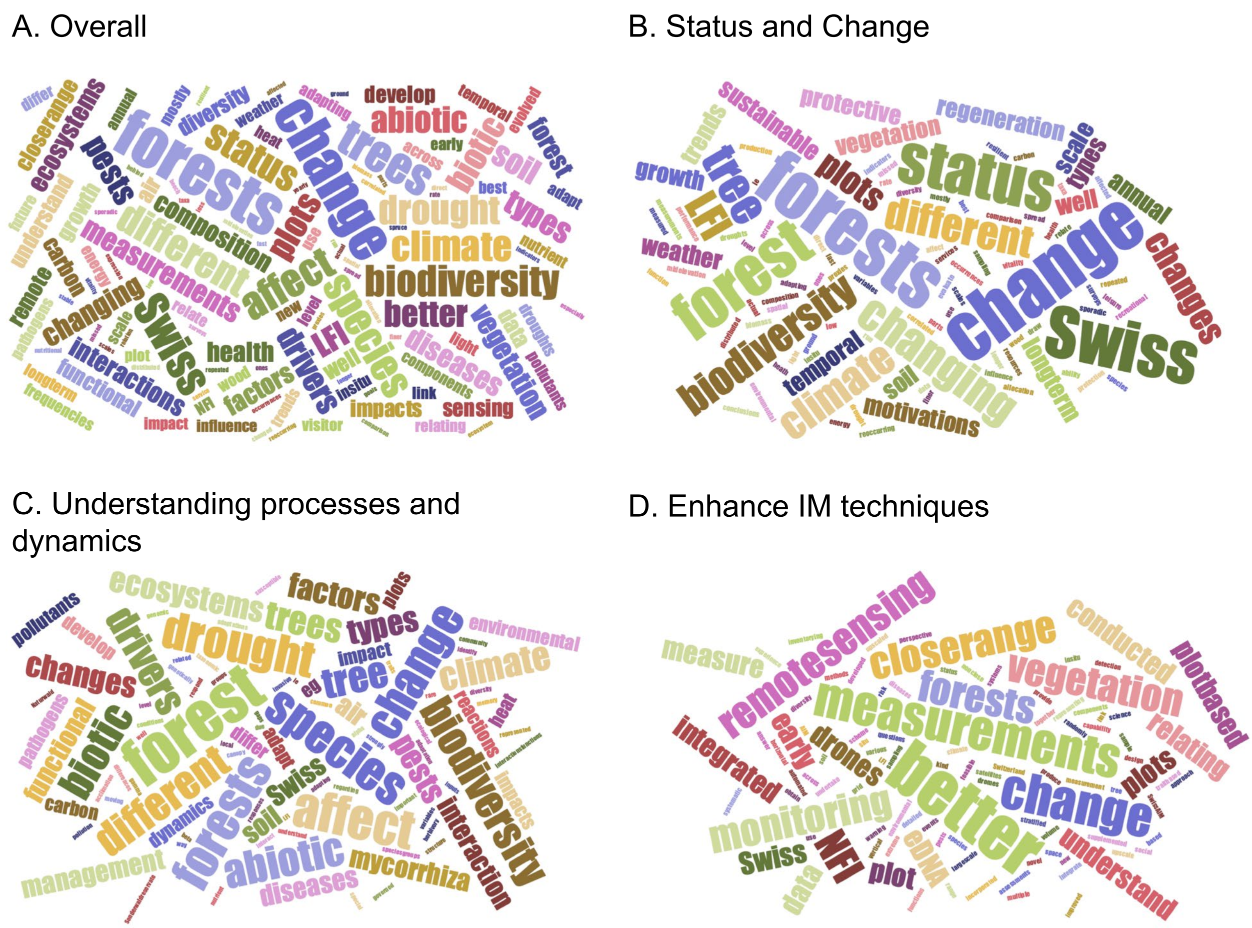


Fig. 3 The 100 most common words relating to (**A**) the entire set of 92 questions, and the sets of questions related to the quantification of status and change (**B**), understanding processes and dynamics (**C**), and enhancement of inventorying and monitoring techniques (**D**)

2.2.2 *Variables and methods*

Table 2 provides a summary of the main categories of attributes to measure that were mentioned through participatory processes (see full list in Appendix). Although measuring at least parts of the "traditional" forest attributes on NFI and LWF/Sanasilva plots, which is considered necessary also for comparative purposes, SwissAIM is conceived to go far beyond this and will include a broad range of target measurements (from the atmosphere to trees, vascular plants, other taxa, and soils) and collection of specimens for dedicated investigations (e.g., eDNA). Accordingly, measurement methods will be diverse and based on different platforms, from terrestrial to close-range and remote sensing.

Overall, we identified four priorities that measurements/activity to be undertaken for AIM initiatives should consider the following:

(i) Permit building better links among close-range, "traditional" remote sensing and terrestrial measurements. This will enable more diverse, accurate, quantitative and repeatable ground measurements, integration of data from below and above the canopy for more complete information at plot level (e.g. habitats, structures, ecophysiology), calibration/validation of models, and upscaling.

(ii) Improve/expand biodiversity-related assessments. Ground vegetation (at least vascular plants indicating changing site conditions) and other organismal groups, not just trees (e.g., insects, birds, bats, fungi, lichens, and bryophytes) should be considered to better evaluate biodiversity.

(iii) Collect specimens to assess, for example, soil and tree nutrition via foliar sampling, past annual growth using tree cores, eDNA for biodiversity, and pests and pathogens for demography and damage evaluation, and detection of non-native invasive species. This point received large interest to better evaluate and understand forest dynamics and responses to current and past disturbances and extremes.

Table 1 Examples of topics/goals mentioned for the three broad categories of research questions. For the full-list questions of interest please see the Appendix

1. Quantifying status and changes	2. Understanding processes and dynamics	3. Enhancement of monitoring and inventorying techniques
Obtaining time-integrated representative data/information on status and changes on key attributes related to the growth, health, biodiversity, performance in terms of climate protection, adaptation/acclimation, and use of the Swiss forest	Understand the effects of drought and climate change–induced acceleration on several ecosystem processes (e.g., health, mortality, nutrients, C-cycle, water availability, etc.)	Enlarge data portfolio, augment time frequency, and enhance data connection, integration, and use on a set of NFI plots
Assessing long-term trends in tree/ecosystem responses, functioning, and regeneration in relation to defined biotic and abiotic stressors and their interactions	Understand how biotic and abiotic variables affect forest biodiversity and functional traits	Explore and create linkages among close-range and non-close-range remote sensing data to in situ measurements on vegetation, soil, microclimate for upscaling in situ measurements
Assessing current and lagged effects of extreme drivers and their combination on growth, health, mortality, regeneration, and diversity	Understanding genomic adaptation of forest trees and functional reaction of mycorrhiza to environmental change such as climate change or drought	Include genomic and metagenomic techniques into monitoring schemes
	Relationship between different types of forest management, all levels of forest biodiversity, and forest structure	
	Development of biodiversity in common and special forests (e.g., forest reserves)	
	Identifying factors driving recreational preferences and how forest management may influence it	

Table 2 Measurement targets, data needs and sources and nature of measurement/sampling mentioned during the design process

Measurement target	Data need mentioned	Data source identified	Potentially destructive/invasive activity
Atmosphere/environment	Nutrients, ozone, climate, other environmental characteristics collected onsite	Terrestrial measurements/models	In-site measurements and installation of devices
Area and plot	NFI/LWF/Sanasilva catalogue plus additional site characteristics (e.g., Leaf Area Index, roughness of terrain)	Terrestrial and remote	Trampling for terrestrial measurements
Trees	NFI/LWF Sanasilva catalogue plus: Additional attributes/traits/damage symptoms and agents/causes/browsing/… Tree-rings, genetic analyses	Terrestrial and remote	Trampling for terrestrial measurements Collection of specimens for lab identification and tree-ring analyses
Vascular plants	Species richness/diversity	Terrestrial	Trampling for terrestrial measurements
Other organismal groups (insects, birds, bats, fungi incl. lichens, bryophytes, soil microbiota)	Species richness/diversity	Terrestrial	Trampling for terrestrial measurements and for installation of recording devices—sound monitors, camera traps
Soil	Nutrient availability, carbon sequestration, organic biomass pool, physical characteristics, matric potential	Terrestrial	Installation of devices, digging of soil cores and pits

(iv) Add in-site automated recording of environmental variables (e.g., atmosphere, soils) with near real-time access to data (i.e., via remote upload).

Whether all of these additions will be possible, and which trade-off will be necessary, will be clarified during the final steps of the design process and prototyping, especially in consideration of the need to protect NFI plots from bias due to visitation and monitoring activities and budget constraints (see 2.2.4).

2.2.3 Sampling design

Sampling and plot design drive the precision of estimates of status and changes in relation to the attributes being measured. The design is closely related to the spatial and temporal scales of interest, and the ecological targets scales (from genes to ecosystems) (Table 2). In particular, the possibility to draw conclusions valid for (i) the forest tree population, (ii) at the level of the entire country, and, (iii) in the short, medium, and long term were most frequently mentioned as important during the design process. Interest in deriving estimates at the level of biogeographic regions and/or over-defined environmental gradients was also mentioned. Related to temporal scales, there is the need to ensure the optimal frequency of measurements of different attributes in agreement with their expected rate of change. For this reason, SwissAIM will generate data with different temporal resolutions, ranging from continuous automated measurements (e.g., soil matric potential), to intra-annual and annual (e.g., tree diameter and crown condition) and to multi-annual measurements (e.g., soil solid phase, ground vegetation, tree genetics).

Three main aspects of sampling design were considered: the network scheme, its sample size in terms of number of plots and the plot design (see below). As for the network scheme, two main components were identified: a systematic component and a thematic component, both based on the NFI grid which offers a consistent operational framework across Switzerland. The systematic component would provide national-scale, statistically representative data and information on an expanded set of attributes and at higher time resolution than IM programs in place so far. The thematic component would concentrate on defined themes and stressors (e.g., drought). Both components would, however, be connected by using the same enhanced plot design (see below). This also represents an innovative feature, as it incorporates, since the beginning, the idea to use a common system for two purposes: status and change detection, and understanding of forests' response to defined stressors.

In detail, the SwissAIM thematic component would be based on a sub-sample of the NFI plots selected according to defined environmental gradients/strata. As environmental gradients of interest can always vary according to changing priorities (e.g., disturbance, nitrogen deposition, and forest protection and conservation gradients), the selection of relevant NFI subsamples will happen only upon the definition of the

Table 3 A summary of different sampling design options, with pros and con, as emerged from the participatory design process (Shackleton et al. 2023)

Use current/active NFI grid		Use old "dormant" (no more in use) plots of the NFI grid or shifted NFI grid		Use new grids/other options	
Pros	**Cons**	**Pros**	**Cons**	**Pros**	**Cons**
Cost saving, as several measurements, is already performed there	Limitation of measures on the plot (non-invasive or destructive)	No limitations on measures and approaches	More costly, as current IM will have to start new measurements campaign	Can focus on core needs then choose the right grid to achieve the goals	Statistical option not clarified
It will help build synergies with existing monitoring and inventorying initiatives (NFI, Sanasilva, BDM, soil inventory, etc.)	Impact of regular and frequent site visits	New plots for comparison with existing annual NFI panels	No connection with long-term data	Best to have representative and relevant gradients	Risk of poor statistical representativity at country level
It will value long-term historical measures					
(Potentially) higher political support—will not be starting a new initiative	Mistrust in NFI data from these plots (linked to impacts on the site). Possible loss of (some) long-term NFI plots	No impact on current NFI plots	Perceived as a new initiative—less political backing		
Possible related option: use the current NFI grid but add "satellite" plots nearby, to not bias the actual NFI plots					

Table 4 Number of plots necessary to achieve different statistical power for detecting changes in different variables

Power	(a) Multi-annual changes in species richness. dz = 0.206 (effect size) was used			(b) Annual basal area increment (BAI) dz = 0.18 (effect size) was used			(C) Annual changes in the mean trees with > 25% defoliation per plot. dz = 0.14 (effect size) was used		
	p value			*p value*			*p value*		
	0.01	*0.05*	*0.1*	*0.01*	*0.05*	*0.1*	*0.01*	*0.05*	*0.1*
70	230	147	112	300	192	147	494	316	241
75	252	165	128	329	216	167	542	356	275
80	279	187	147	364	244	192	599	403	317
85	311	214	171	406	279	223	669	460	368
90	354	250	203	463	326	265	762	538	438
95	423	308	256	553	402	351	912	665	554

gradient of concern and the required sample sizes on a case-by-case basis. These thematic sub-grids could therefore be included whenever necessary, can be temporary or permanent, will densify the SwissAIM systematic component, and will contribute to the flexibility of the entire SwissAIM system. As the thematic sub-grids will be developed upon demand, their individual design will not be discussed further here.

The SwissAIM systematic component would be based on a sub-sample of plots on the NFI grid selected to cover the whole of Switzerland. While the final layout and sample size of the systematic grid are currently being defined, the most favored option is to use plots on the currently active NFI grid over the use of "dormant" plots (Table 3).

Such a choice will permit better synergies between different IM initiatives in Switzerland using the same grid and allow SwissAIM to draw on existing long-term data. On the flip side, this option will limit destructive or invasive measures or excessive visitation which could introduce biases on the plots (e.g., Ferretti 2014; Semboli et al. 2014) and in the plot management and therefore affect the representativity of NFI estimates and potentially jeopardizing the 40-year long time data series (see below). Another option suggested to mitigate possible impacts on NFI plots is to use the current NFI grid, but add “satellite” plots nearby, enabling frequent, invasive/destructive measurements.

As for sample size, suggestions already exist to identify the minimum necessary sample size to assess the status of Swiss forests (e.g., forest health status based on tree crown defoliation, Köhl et al. 1994; Travaglini et al. 2013). Much less information is available about sample sizes needed to detect changes at defined probability levels. We conducted an ad hoc power analysis focusing on temporal changes and considered three attributes with different time windows for change detection and for which there were data available. The attributes included plant species richness (connected to biodiversity; changes over multiple years), basal area increment (connected to productivity and carbon sequestration; changes between subsequent years), and, tree crown defoliation (connected to forest health; changes between subsequent years). Using available data for each of the three attributes (species richness—Kull and Kuechler dataset; Thimonier et al. 2011; Küchler et al. 2015), basal area increment—RapiDbeeCH dataset (see details in Rohner et al. 2018), and annual changes in the frequency of trees with > 25% defoliation per plot—Sanasilva dataset), we calculated *dz* values (effect sizes), which were then used in the power analyses instead of more traditional Cohen’s d values. *dz* values account for high levels of correlation within paired sample designs (Lakens 2013). We used the open-source software R and G-Power for analysis. The preliminary results of the analysis suggest that ideally, the SwissAIM should have between 200 and 400 plots to achieve a reasonable statistical power of 80% to detect change for the considered variables at $p = 0.05$ (Table 4).

Two-hundreds plots correspond approximately to an 8 × 8 km grid for Switzerland (e.g., Fig. 4), which can be considered as the minimum acceptable sampling density. Table 4 also shows that higher power can be achieved with a considerable increase in the number of plots (and relevant denser grids) that will come with a major increase in the costs related to field work. With the above estimates of potential sample size, we can also conclude that if a bias will emerge after more intensive measurements on the selected plots, such a bias will affect ca. 200 plots, i.e., 3.3% out of the 6000 + plots of the NFI.

While the above sample size can be an acceptable trade-off in terms of statistical requirements, it will be necessary to achieve a sustainable balance (technically and financially) between spatial and temporal resolution. For example, since some measurements will require either frequent visits or relatively expensive technical

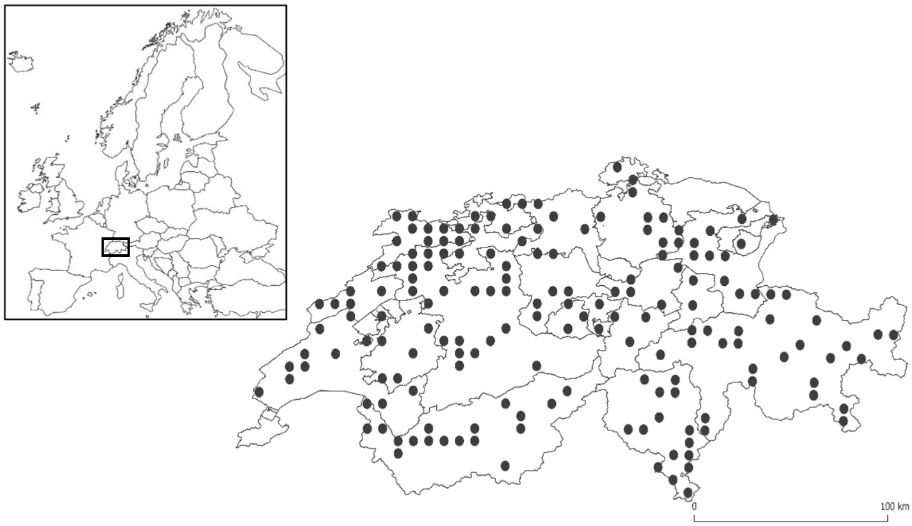


Fig. 4 Map of Switzerland with an example of one possible layout of the systematic component of the SwissAIM on an 8×8 km grid sub-sample of the National Forest Inventory

equipment (e.g., soil sensors and their associated remote connection), it may become necessary to consider more relaxed grid densities for certain investigations.

2.2.4 Enhanced plot design

Plot design is a long-lasting challenge for forest IM initiatives (e.g., Häbel et al. 2019; Henttonen and Kangas, 2015; Kuhel et al. 1995; Zeide 1980), and there are various options and trade-offs that need to be considered in the development of any AIM initiative. The most favored option for SwissAIM was to enhance the design of NFI plots (Fig. 5) to accommodate more intensive and integrated monitoring.

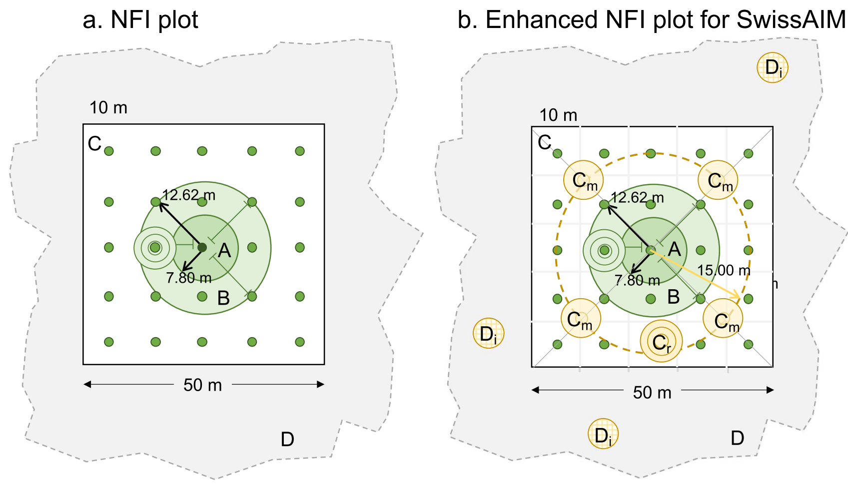
Current designs for NFI plots in Europe seldomly include frequent (annual, intra-annual) visits, invasive measurements/destructive sampling and/or automated measurements, and are very focused on tree growth, as opposed to multi-level integrated forest monitoring initiatives (e.g., ICPF , long-term ecological research) where such measures and considerations are more common (Ferretti 2013). By building on the AIM vision, we want to bridge this gap. As such, the option for an enhanced plot design will be to keep the traditional circular Swiss NFI plots as the base plus the current NFI interpretation area as a "large plot" for connections with remote sensing (which requires a larger area than the circular plots), drone-based measurements, TLS or MLS (terrestrial or mobile laser scanning) and their integration. The large plot can be supplemented with sub-plots for additional, minimally invasive or destructive measurements and specimen collection (e.g., tree coring, see Portier et al. 2023) (Fig. 5).

2.3 Prototyping and testing

The SwissAIM initiative is being prototyped and tested. This step is critical for guiding decision-making on many aspects of the design, especially those that come with constraints and trade-offs. In particular, this step is needed (i) to optimize methods and plot designs which are not yet fully tested (e.g., the use of terrestrial laser scanning to identify forest gaps for regeneration assessments; the sub-plots for semi-destructive measurements); (ii) to estimate costs, in order to prioritize options, assessing possible trade-offs in view of budget constraints, and developing strategies for co-funding between various institutions and stakeholders (see below); and, (iii) to have technological readiness, to ensure increased accuracy or efficiency of measurements, and to allow for better integration between measures and automated data analysis, also through Artificial Intelligence.

2.4 Engagement and governance

Identifying clear governance structures and mechanisms is critical to the long-term success of any collaborative initiative and these need to be adaptable in time to overcome challenges, improve and remain relevant (Lindenmayer and Likens 2009). While SwissAIM was prompted by a multidisciplinary scientific community, relevant stakeholders across academia, policy, and practice at the national and regional levels were engaged at an early stage to define and promote their involvement. For



Plot component	*Use in the NFI*	*Intended use in SwissAIM*
A. Inner circular plot (radius of 7.98 m) with transects for deadwood assessment.	**Measurement plot.** ● NFI catalogue measurements of trees with a DBH ≥ 12 cm on a 9-year basis.	**Measurement plot.** Same as in NFI plus: ● Part of NFI catalogue on **annual basis.** ● **Forest health** (e.g., Sanasilva catalogue) on annual basis.
B. Outer circular plot (radius of 12.62 m) with transects for deadwood assessment and circular subplot for regeneration assessment.	**Measurement plot.** ● NFI catalogue of trees with a DBH ≥ 36 cm. ● Regeneration assessments (small sub-plots to the left). ● Deadwood transects (3 lines) on a periodic (9-year) basis for all three points.	**Measurement plot.** Same as in NFI plus: ● Part of NFI catalogue on an **annual basis**. ● **Forest health** (Sanasilva catalogue) on annual basis. ● **Ground vegetation** assessments on a periodic (5-9 year) basis.
C. Large area (50 x 50 m) with raster points for tree cover assessment.	**Interpretation area.** ● For field observations and aerial photo assessment and interpretation.	**Large plot. Sampling and remote sensing connection.** Same as in NFI plus: ● Extended **remote sensing**. ● **Drone-based and TLS (terrestrial laser scanning)** measurements. ● **Sub-plots for additional measurements** (see C_m, C_r).
C_m, C_r. Sub-plots within the large area.	**Not considered.**	**Sub-plots.** ● C_m: minimally-destructive sampling **(e.g., soil and DNA samples, tree coring)** and measurements **(e.g., soil sensors, climate sensors, sound recorders).** Located along the diagonals. ● C_r: **regeneration assessment in canopy gaps.**
D. Outside of the large area.	**Not considered.**	**Larger area.** ● **Invasive and destructive** measurements/ sampling (e.g., insect trapping) (see D_i).
D_i. Sub-plots outside the large area.	**Not considered.**	Sub-plots for **invasive and destructive** measurements/ sampling (e.g., insect trapping). Haphazard location.

Fig. 5 Top: Comparison of current NFI plot design (**a**) with the enhanced design for the SwissAIM plots, with additional plot components in yellow (**b**). Bottom: list of plot components. For each plot component, its current use in NFI and the foreseen use in SwissAIM are described. NFI catalog refers to measurements already conducted by the Swiss NFI (Düggelin et al. 2020); the same applies to the Sanasilva catalog (Methods of the Sanasilva Inventory—WSL). See alphabetic capital keys (**A**, **B**, **C**, **D**) for connecting the top and bottom parts of the figure

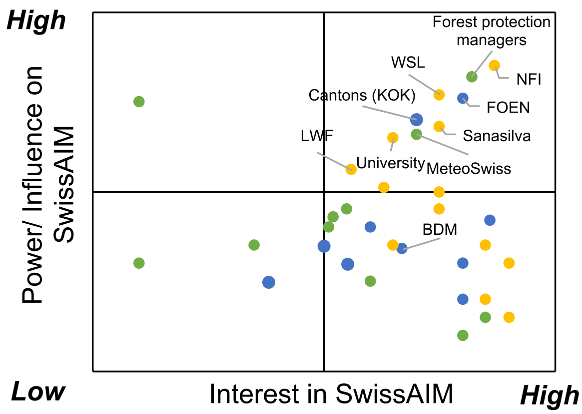


Fig. 6 Map of stakeholders and their power/influence on, and their interest in SwissAIM as emerged from an exercise carried out during a co-design workshop (Shackleton et al. 2023). Yellow dots: academic stakeholders; blue dots: policy/practice-related stakeholders; green dots: other stakeholders (e.g., Industry, NGOs). Note that stakeholders may have received more than one mention and different positioning by different workshop participants—in such a case, we have taken an average ranking between them. Only stakeholders specifically mentioned in the text are labeled (after Shackleton et al. 2023)

this purpose, we carried out a stakeholder mapping exercise to identify interests in and potential contributions to SwissAIM (Fig. 6). Overall, such an exercise showed that in Switzerland numerous institutions were perceived to have both, high power/influence and interest (38% of stakeholders listed), or high interest in SwissAIM (49% of stakeholders listed). Stakeholders identified with the highest power and interest included the Federal Office for the Environment (FOEN – national level policy and decision makers), several Research Units at WSL (WSL), existing forest IM programs (including the NFI, LWF/Sanasilva, BDM), MeteoSwiss (institution engaged in weather monitoring, forecast and plant phenology), forest protection managers in Switzerland, Swiss Universities, and the forest divisions of different Cantons (regional level decision makers) in Switzerland (Fig. 5). Of key interest for the further development and implementation of SwissAIM is to engage stakeholders with high power and/or high interest and a broad mix of stakeholders from different backgrounds (science, policy, and practice) interested in the initiative. The implementation of SwissAIM would build synergies and collaborations between different institutions and existing networks, and this needs to be reflected in the governance structure and its bodies. While in Switzerland inspiring governance models may come from, e.g., the Swiss NFI, at the international level, a good example of a combination of bottom-up and top-down approaches may come from the ICPF (see: Bodies & Structure—ICP Forests (icp-forests.net)).

3 Relevance and transferability of AIM initiatives outside Switzerland

The essential role of forests in mitigating climate change and achieving climate targets, and the augmented frequency and effects of disturbances have prompted a renewed interest and debate around forest IM (Bontemps et al. 2022; Ferretti 2021; Nabuurs et al. 2022; Päivininen et al. 2023). In Europe, for example, this renewed interest has resulted in the launch of several scientific projects under the Horizon Europe framework (e.g., PathFinder (pathfinder-heu.eu); Forwards – Healthy trees translate to healthy citizens (forwards-project.eu)), in the European Commission, a new proposal for a framework regulation on forest monitoring (European Commission 2023) as well as other initiatives (e.g., https://www.greens-efa.eu/en/article/event/forests-hidden-secrets). All these projects and initiatives involve many European countries (i.e., 15 in PathFinder; 11 in FORWARDS) plus the European Commission and its Joint Research Center. Thus, the timeliness and broad relevance of the subject and suggestions provided in this paper are obviously important beyond Switzerland.

Besides the relevance and timeliness of SwissAIM, the practical transferability of the concepts adopted here to other countries with largely different environmental, organizational, and political conditions is important. Here, it is worth noting that, like in Switzerland, many European countries, and several countries outside Europe (e.g., Breidenbach et al. 2021), have existing forest IM in place with, e.g., (i) both NFI and ICPF networks running, (ii) sometimes in connection, sometimes not (see Travaglini et al. 2013), but (iii) always with different time resolutions and (iv) with non-forest attributes almost always measured on different, segregated networks based on haphazard or ad-hoc sampling design. Under this situation, we believe that the concepts proposed here (clear statistical perspective, augmented time resolution, expanded data catalog, synergies among existing IM systems, improved connection and integration between terrestrial measurements, remote sensing, and models by means of enhanced plot design) are of general value and can be adopted (or adapted) in relation to the situation of individual countries: a typical example is the case of required sample size. It is important to acknowledge that since much of the process described here involved an intense dialogue among scientists from different disciplines and other stakeholders at various institutional levels, its practicability depends on the situation of individual countries. Yet, just because countries from across Europe and the European Commission itself are now demonstrating interest in the subjects (see above), we are also convinced that the above concepts reflect a generalized direction of development and can help inspire an international, pan-European vision about forest IM.

4 Key messages for the development of advanced inventorying and monitoring initiatives (AIM) emerging from our experience

We identified four main messages emerging from the SwissAIM design process which may be useful for developing AIM programs elsewhere:

4.1 Message 1: It is time to do it. There is ample interest in and a great need for advanced forest inventorying and monitoring (AIM)

There is a clear need and interest for AIM concepts and systems at both the Swiss and the international level. In scientific terms, the main drivers of interest were the potential for better detection and quantification of status and changes and improved understanding of forest dynamics that can be achieved by (i) highly integrative enhanced plots, combining "traditional" mensuration with cutting-edge technologies on (ii) a sound statistical basis, and, (iii) higher temporal resolution. In Switzerland, where for example the NFI is the basis also for other networks (e.g., the ICPF Level I and BDM survey), AIM can originate from concentrating investigations on (a selection of) NFI plots with enhanced design to expand the measurement catalogues, better connect with remote sensing, and improve models. In other countries, the statistical basis offered by locally existing networks (NFIs, ICPF, others) can play a similar role.

4.2 Message 2: Be transdisciplinary. Advanced inventorying and monitoring (AIM) initiatives should go across scales and disciplines and involve multiple stakeholders

There was a consensus that covering different spatial and temporal scales, environmental gradients, and different ecological and social targets by integrating different expertise through multi-, inter-, and transdisciplinary approaches were essential for any AIM initiative (see also below). For example, assessing status and change in the short as well as in the long-term was the focus of most scientific questions, especially in relation to climate change, and AIM could help to fulfill these shorter-term needs which are a big gap in current IM initiatives. Furthermore, the inclusion of several other organismal groups (e.g., ground vegetation, insects, birds), social aspects (e.g., recreation and management) and ecosystem compartments (e.g., atmosphere, soil) was seen as a desirable addition for AIM to improve overall understanding and to obtain baseline data also from other perspectives such as biodiversity conservation, forest use and management, cultural services and invasions by non-native species. On the same line, together with the national scale, other administrative scales (from enterprises to Cantons) and environmental gradients (e.g., drought sensitivity, nitrogen deposition gradients, forest protection, conservation, and management) were mentioned. The extent to which a single initiative can actually address all stakehoholder needs and scales is unclear. However, it is unlikely that SwissAIM will be able to cover all possible scales at all levels with acceptable statistical confidence and sustainable cost, and, trade-offs will likely be necessary.

4.3 Message 3: Promote integration. Integrated measurement approaches are increasingly necessary

The set of measurements and observations carried out under the traditional IM is large, but it still suffers some limitations and disconnection. There is a need to overcome existing limitations to better understand broader forest dynamics and processes and to improve models. The starting vision for SwissAIM also highlighted the intention to better integrate ground and remote measures. Similarly, the need to collect specimens (e.g., soil, cores for tree ring measurements) and install measurement devices (e.g., meteorological sensors, soundscape recorders for biodiversity) in or nearby NFI plots was mentioned several times during the workshops. Such activity would provide valuable additional data and information to better interpret the current and future development of the Swiss forest. However, destructive sampling and devices may collide with the fundamental need to protect NFI plots from disturbances related to monitoring and from visible installation that can also introduce unwanted bias as plots become visible to managers. For this, the design process considered this issue carefully and defined what can be done, and where.

4.4 Message 4: Be statistically sound. A robust sampling design is needed

For any AIM initiative to provide relevant scientific evidence, there is a need for robust statistical designs. This point was reiterated as important by various stakeholders across the entire design process. NFIs and ICPF Level I with their probabilistic sampling design offer a solid basis for building AIM initiatives upon, although we still recommend that dedicated studies are undertaken on the topic. An enhanced plot design should be adopted—and has been defined for the SwissAIM—to accommodate measurements traditionally not carried out, or not with the necessary temporal resolution, and the collection of samples into a consistent, optimized statistical framework (see Message 3).

5 Conclusions

There is an urgent need for timely and comprehensive information on the status, changes and drivers of forest health, productivity, biodiversity, and conservation in Europe. This information is relevant to address key challenges for our forests and our society, such as climate change mitigation and adaptation, energy and the biodiversity crisis, and, is necessary to better inform and evaluate policy and management responses to these challenges. Much has been already accomplished by running IM programs. Yet, addressing the above information needs involves overcoming the obsolete distinction between forest inventorying and monitoring programs by favoring their operational integration, expanding the suite of measures taken, and promoting the combination of terrestrial measurements, close-range and remote sensing, and modeling. The SwissAIM initiative has the ambition to put this into practice. It intends to be a collaborative effort to concentrate key measurements on a statistically representative set of plots to cover a wide range of attributes across all trophic levels and ecosystem properties at increased temporal resolutions. This will mark progress towards a new generation of forest AIM programs that—while keeping a probabilistic approach—are able to provide multi-level (atmosphere, vegetation, soil), multi-source (terrestrial, close-range-, aerial-, and space-borne remote sensing) data and information. AIM will permit addressing an augmented range of scientific questions beyond the traditional tasks of forest IM and will open new avenues for scientific investigation, enhanced reporting, data integration, and modeling, which will benefit both scientific understanding and developing policy responses - enabling us to better respond to global change challenges.

We identified a series of scientific questions at a variety of temporal, spatial, environmental, and ecological scales (from single sites to the entire country and from single cells to ecosystems) and developed a comprehensive list of possible novel measurements and sampling approaches that can be useful for inspiring other AIM initiatives. At the international level, several recent initiatives (see above) clearly highlight the need for more effective IM to be able to evaluate changes in carbon sequestration, forest health, productivity, and biodiversity including the causes and time dynamics of these changes. The extent to which synergies among different IM systems are actually considered across Europe is not clear yet. For this reason by favoring a better integration and dialogue between IM programs, SwissAIM is timely and may also promote development, advancements, connections and cooperation at the international level.

Appendix

Scientific questions of interest for SwissAIM

Questions related to the "Status and Change" of forests

Relating to the topic of better quantifying the status and change of Swiss forests, there were a total of 29 different questions[2] (see below, in alphabetic order), five of which were of general broad-scale/cross-cutting interest, followed by subject areas relating to climate and forests (4), biodiversity (4), health and vitality (4), and social-economic (4).

(1) **Abiotic factors**. How are light and energy distributed in different parts of the forest and how does this change?
(2) **Biodiversity**. How well are the biodiversity proxies of LFI correlated with direct biodiversity data (i.e., actual occurrences of different taxa)?
(3) **Biodiversity**. What are the finer-level vegetation types on the LFI plots? How do they change and which ones are missed (sporadic surveys of ground vegetation)?
(4) **Biodiversity**. What is the status and change of soil biodiversity?
(5) **Biodiversity**. What is the status and change of Swiss forest biodiversity?
(6) **Broad-scale/cross-cutting.** Are Swiss forests sustainable and resilient to change?
(7) **Broad-scale/cross-cutting.** Are Swiss forests sustainable?
(8) **Broad-scale/cross-cutting.** How have forests changed and evolved in relation to different forest ecosystem service types?
(9) **Broad-scale/cross-cutting.** Is forest health, growth diversity, and regeneration changing across different temporal and spatial scales?
(10) **Broad-scale/cross-cutting.** What is the status and change of forest resources in Swiss forests?
(11) **Climate and forests.** How are forests adapting to climate change?
(12) **Climate and forests.** How do changes in LFI indicators relate to in-situ measurements of weather (climate) on LFI plots? (in the longer run: changes in weather and climate)?
(13) **Climate and forests.** How fast does repeated drought affect tree composition: comparison of plots at low- and mid-elevation?
(14) **Climate and forests.** Which tree species are affected mostly by reoccurring droughts?

[2] A few original questions are very similar and will be merged at the operational stage.

(15) **Growth/wood/carbon.** What is the annual change in tree growth, biomass, and carbon allocation on an annual scale?
(16) **Growth/wood/carbon.** What is the status and change of wood production in Swiss forests?
(17) **Growth/wood/carbon.** What is the yearly expression of change components (growth, loss, etc.)?
(18) **Health and vitality.** Is soil nutrient availability stable in Swiss forests?
(19) **Health and vitality.** Is the tree nutritional status changing?
(20) **Health and vitality.** What is the rate of spread of new pests and diseases, especially for beech and spruce?
(21) **Health and vitality.** What is the status and change in Swiss forest health and vitality?
(22) **Protection.** How is protective forest performance changing?
(23) **Protection.** What is the protective function of forests and how is it changing?
(24) **Protection.** What is the status and change of forest climate protection services in Swiss forests?
(25) **Regeneration.** What is the status and change in tree regeneration in Swiss forests?
(26) **Social-economic.** Are leisure and recreational use of Swiss forests changing?
(27) **Social-economic.** What are the impacts of visitors as well as researchers on forests?
(28) **Social-economic.** What are the long-term forest management motivations, goals and trends in Switzerland and the motivations behind this?
(29) **Social-economic.** What are the long-term trends and changes in forest visitor frequencies, needs, preferences, and behaviors?

Questions related to "understanding processes and dynamics"

In total, there were 43 different questions[3] relating to a better understanding of processes and dynamics in Swiss forests (see below, in alphabetic order). Climate and forests (10 questions), abiotic factors (7), and biotic-abiotic interactions (7) and health and vitality (6) were the most frequent subject areas in the thematic sub-classifications.

(1) **Abiotic factors.** How do atmospheric drivers (nitrogen deposition, ozone) affect forests?
(2) **Abiotic factors.** How do climate-related drivers, including wind and wet snow affect forests?
(3) **Abiotic factors.** How do light and energy affect processes and dynamics in different forest compartments?
(4) **Abiotic factors.** How do site and stand properties and their change affect forests?
(5) **Abiotic factors.** What are the impacts of abiotic stressors (drought, heat, and VFP) on forest trees?
(6) **Abiotic factors.** What are the impacts of air pollutants and nutrients on trees and ecosystems?
(7) **Abiotic factors.** What are the interactions between drought and air pollutants?
(8) **Biodiversity.** How does biodiversity affect forest functioning?
(9) **Biodiversity.** How do the abiotic conditions, the functional composition of the LFI plots as well as alpha, beta, and gamma diversity change?
(10) **Biodiversity**. How does biodiversity develop and how is it represented in common and special forests (e.g., Naturwald-Sonderwaldreservate, rare forest types)?
(11) **Biotic and abiotic interactions.** How do changes in soil and interaction with other drivers impact forest services?
(12) **Biotic and abiotic interactions.** Are important biotic interactions (herbivory, invasive species) related to abiotic and biotic changes—i.e., moving from species level to interactions/functions governed by species interactions?
(13) **Biotic and abiotic interactions.** Do different taxonomic groups respond in the same way to biotic and abiotic drivers?
(14) **Biotic and abiotic interactions.** How do biotic and abiotic variables affect forest biodiversity and functional traits?
(15) **Biotic and abiotic interactions.** What are the interactions among biotic and abiotic drivers of forest change?
(16) **Biotic and abiotic interactions.** What is the link between biotic and abiotic factors and factors and tree pests and diseases?
(17) **Biotic and abiotic interactions.** Which factors influence the soil biota, mycorrhiza and vegetation, biodiversity, and vice versa?
(18) **Biotic and abiotic interactions?** How can we better understand the link between biotic and abiotic factors and disease processes?
(19) **Broad-scale/cross-cutting.** Can we understand differences in species responses and identify which species/groups are susceptible to which types of change?
(20) **Climate and forests.** Do forest trees genetically adapt to climate or drought?
(21) **Climate and forests.** Does the mycorrhiza community change due to climate change or drought?

[3] A few original questions are very similar and will be merged at the operational stage.

(22) **Climate and forests.** How are forests adapting to climate change?
(23) **Climate and forests.** How do droughts impact tree species and ecosystems?
(24) **Climate and forests.** How does acclimation, local adaptation, and ecological memory affect trees' reactions to heat and drought?
(25) **Climate and forests.** How have iconic tree species evolved to global environmental changes?
(26) **Climate and forests.** What are the genomic adaptations of forest trees and functional reactions of mycorrhiza to environmental changes, such as climate change and drought?
(27) **Climate and forests.** Where and when do water availability constraints occur in Swiss forests (near-real-time assessments) and how do these constraints relate to above-ground observations (defoliation, die-back, infection with pathogens)?
(28) **Climate and forests.** Which forest plant species shift along elevation gradients, and by how many meters per decade?
(29) **Climate and forests.** Which species adapt to climate change best?
(30) **Growth/Wood/carbon.** How do soil carbon pools develop?
(31) **Growth/Wood/carbon.** What is the carbon sequestration and wood production capacity provided by different species and forest ecosystems?
(32) **Health and vitality.** Are diverse forests more resistant to pests and diseases?
(33) **Health and vitality.** Does forest biodiversity improve forest health and reliance?
(34) **Health and vitality.** How do biotic drivers (e.g., pests, pathogens, ungulates) affect Swiss forests?
(35) **Health and vitality.** How does drought interact with air pollution and nutrient inputs into ecosystems?
(36) **Health and vitality.** What are key mortality mechanisms in Swiss forests?
(37) **Health and vitality.** What is the interaction between drought and pests and diseases?
(38) **Management.** How do different types of forest management affect forest biodiversity?
(39) **Management.** How do different types of forest management affect forest biodiversity and forest structure?
(40) **Management.** How does different silvicultural management affect forests?
(41) **Regeneration.** How strongly does regeneration under the canopy differ from that in gaps regarding principal tree composition in samples?
(42) **Regeneration.** What will forest regeneration and dynamics look like in the future?
(43) **Regeneration.** Which tree species differ mostly withstand tree composition in gap regeneration plots?
(44) **Social-economic.** What factors determine visitor frequencies in different forest areas?

Questions related to "enhanced monitoring"

In total, there were 18 different questions[4] related to enhanced forest monitoring techniques (see below, in alphabetic order). Integrated monitoring (7 questions) and sampling and design (5) were the most frequent subject areas mentioned.

(1) **Integrated monitoring.** Are there new measurements that could be conducted in the NFI (use the experience of any kind of measurement conducted in the AIM)?
(2) **Integrated monitoring.** Does a trait-based approach allow us to better understand forest dynamics and change?
(3) **Integrated monitoring.** How can close-range and non-close-range (remote sensing/drones) measurements be improved and incorporated and upscaled to produce in situ plot-based data?
(4) **Integrated monitoring.** How can eDNA, automated monitoring of diversity, and other novel methods be integrated together?
(5) **Integrated monitoring.** How can we better integrate remote sensing (close-range; drones; satellites) into monitoring and inventorying?
(6) **Integrated monitoring.** How can we better link close-range and remote sensing data to in situ measurements relating to vegetation, soil, and climate?
(7) **Integrated monitoring.** What environmental variables should be measured to best evaluate change?
(8) **Modeling/upscaling/estimation.** How can we better upscale plot-based measurements?
(9) **Modeling/upscaling/estimation.** If we understand the mechanisms of change can we develop a predictive model to anticipate future changes and/or change in localized plots?
(10) **Modeling/upscaling/estimation.** What is the detailed volume of the various tree components?
(11) **Risk assessment/early warning.** Can SwissAIM provide early detection capability for pests, diseases, and other extreme events?

[4] A few original questions are very similar and will be merged at the operational stage.

(12) **Risk assessment/early warning.** How can we better monitor the rate of spread of new pests and diseases especially for beech and spruce?
(13) **Risk assessment/early warning.** How can early warning systems be developed for (the health of) Swiss forests?
(14) **Risk assessment/early warning.** How can we better undertake large-scale risk assessments relating to Swiss forests?
(15) **Sampling and design.** Can the sampling scheme of LFI be supplemented by randomly stratified plots better representing the environmental space of forests in Switzerland?
(16) **Sampling and design.** How do we better measure horizontal and vertical vegetation on an NFI plot?
(17) **Sampling and design.** How do you design monitoring across multiple species and functions to obtain an integrated perspective of status and change?
(18) **Sampling and design.** How does the temporal scale of sampling influence our ability to draw conclusions on status and change?
(19) **Sampling and design.** Is it feasible to answer social science questions based on a systematic forest plot sample grid?

Variables of interest for SwissAIM

Table 5 outlines the list of variables of interest for SwissAIM, as well as the broad-scale approach or methods needed and the number of times the variable was mentioned in the series of in-depth interviews with experts from different disciplines. Table 6 outlines the current list of NFI measures. A large portion of these will also be included in SwissAIM, importantly with many having annual measures instead of being on a 9-year cycle.

Table 5 Variables of interest-based on broad-scale clusters of similarity

Broad-scale target variable entity (in alphabetic order)	Specific variables mentioned	Nature of data collection *see descriptions below	No. of times mentioned
Atmosphere	Local meteorological/microclimate data	Device	7
	Light penetration/regime	Device; remote	2
	Modelled climate data	Model	1
	Pollutants	Sampling	1
	Modelled climate and air pollutant variables	Model	1
Bryophytes, lichens	Number of bryophyte and lichen species	Observation	1
Deadwood	Deadwood	Observation	4
Entire ecosystem	Water budget	Observation; device; model	1
Fungi	Richness of deadwood fungi	Observation	1
Insects	Richness and/or abundance of insects or specific groups of insects	Observation; measure	6
Plot/Stand	Stability and shallow landslides	Observation	1
	Visitor uses (soundscapes)	Observation; measure	2
	Visitor counts	Measure	1
	Terrain roughness	Observation	1
Soil	Soil compaction	Measure	1
	Soil profile	Observation	1
	Soil type	Observation	1
	General soil data (chemical analysis, texture, etc.)	Sampling	2
	Soil organic matter pools	Observation; measure	1
	Physical soil properties at greater soil depths	Observation	1
	Organic layer	Observation; measure	1
	Soil moisture and temperature	Device	1
Soil biota	Soil biota/Mycorrhiza diversity	Sampling	4
Stakeholders	Stakeholder needs and interests	Social survey	2
Stand	Forest physiological measures	Remote	2
	Forest structure	Remote	2
	NDVI	Remote	1
	Stem number/distribution	Remote	1
	Vegetation layer density	Observation; remote	1
	"Openness" of the canopy	Observation; remote	1
Trees	Defoliation (e.g., Sanasilva)	Observation	5
	Beech-bark exudation	Observation	1

Broad-scale target variable entity (in alphabetic order)	Specific variables mentioned	Nature of data collection *see descriptions below	No. of times mentioned
	Galls and witch-es'-brooms	Observation	1
	Bark necrosis	Observation	1
	Genetic inventory of tree provenience	Sampling	1
	Allele frequency changes	Sampling	1
	Tree history	Observation	1
	Origin of the tree	Observation	1
	Tree phenology	Observation; device	1
	Tree volume	Measure	1
	Symptoms of pests and pathogens (leaf damage)	Observation	2
	Disease on young trees	Observation	1
	Tree nutrition status	Sampling	1
	Annual tree growth (preferably historical too)	Measure	5
	Habitat trees	Observation	1
	Tree regeneration	Observation	7
	More frequent measures of trees from the NFI catalog (see Table 6)	Observation; measure	5
	Social position	Observation	1
	Competition	Observation; measure	1
	Canopy traits related to forest health	Observation, remote	2
	Crown condition/mortality per tree	Observation, remote	2
	Tree shape/structure	Observation; remote	4
	Tree mortality	Observation	2
	Crown diameter	Observation; remote	1
Vascular plants	Ground vegetation (richness and/or abundance)	Observation; measure	6
Vertebrates	Vertebrate richness and/or density (e.g., birds, bats, and/or mammals)	Observation; measure	2

*Observation: simple terrestrial, observational assessment. Measure: simple terrestrial measurement. Device: installation of device needed. Sampling: destructive sampling is needed. Model: data obtained from models. Remote: data obtained from remote sensing. Social survey: data collected using interviews or questionnaires

Table 6 List of current Swiss NFI measures

Data collection method	Feature	Data collection method	Feature
Aerial photo	Pre-determined data for 'Forest/non-forest' decision	**Terrestrial tree (dbh ≥ 12 cm) continued**	Crown class (length)
	Reference points for the field plot location		Crown class (shape)
	Altitude		Social position
	Forest boundary line		Height where crown starts
	Degree of crown cover		Crown dimensions
	Forest gaps		Damages (type, location, dimensions)
	Deciduous/evergreen tree cover at 25 raster points		Mistletoe
	Land cover class at 25 raster points		Stem quality
	Vegetation height/altitude at 25		Lopsided or bent tree
	Stage of development		Fork
	Degree of closure		Height of fork or main branch
	Relief		Stump shoots
	Stocking element outside the forest		Seed trees in regeneration, pioneer planting
	Single trees outside the forest		Dry parts > 20%
	Potential forest use		Coppicing above 2 m height
Terrestrial area	Forest/non-forest decision		Reaction to bark marking of dbh position
	Reason for forest decrease		Stem heights of broken snags
	Reason for forest increase		Woodpecker cavity
	Previous use before forest increase		Fungus species (perennial fruiting bodies)
	Photos of the sample plot		Lichen species
	Accessibility and walkability		Length of lying tree

Data collection method	Feature	Data collection method	Feature
	Soil samples from topsoil		Twigs on dead tree/Deadwood twig
	Thickness of soil horizon in topsoil		Bark cover on a dead tree
	Slope		Hardness of dead tree
	Aspect		Ground contact of dead tree
	Relief		Degree of moss cover on dead tree
	Landslide		Degree of lichen cover on dead tree
	Erosion		Number of shrubs on a dead tree
	Rockfall		Number of saplings on a dead tree
	Boulder-axis lengths		Microhabitats (cavities, holes, cracks, bark pockets, fungal fruit bodies, cover with ivy, moss, and lichens)
	Boulder shape	**Terrestrial regeneration (dbh < 12 cm)**	Tree species
	Snow movement, Avalanches		Height class, dbh
	Traces of fire		Damage, browsing
	Pasturing (type, intensity)		Length of leading shoot (next plant)
	Ecological pressure, Disturbances		Regeneration type (next plant)
	Tracks from skidding during wood harvesting		Natural or artificial regeneration (next plant)
	Vehicle tracks from wood harvesting (length, depth, width, degree of cover, stand or skid track, age, puddles)		Measures to protect against game (next plant)
	Type of damage to soil		Substrate (next plant)
	Obstacles to and constraints on logging		Silvicultural assessment (next plant)

Data collection method	Feature	Data collection method	Feature
	Presence of stumps	**Terrestrial subplot regeneration**	Degree of shading
	Category of use		Proportion naturally poor regeneration conditions
	Special sites and water bodies		Proportion anthropogenically poor regeneration conditions
	Water bodies		Proportional area with good regeneration conditions
	Azonal site types		Proportional area with competing vegetation
	Vegetation type		Competing plant species
	Heaps of branches		Main type of topsoil
	Snags	**Lying deadwood (line intersect sampling)**	Broadleaved/coniferous wood
	Places without vegetation		Cross diameter
	Dry stonewalls, heaps of stones		Length $</\geq$ 1 m
	Geomorphological objects		Slope
	Recreational facilities		Degree of decomposition
	Root plates		Length of intersect with heap of branches
	Ants (presence, species)		Piece of deadwood in a heap of branches
	Ant-heaps (number, dimensions)	**Terrestrial forest edge**	Exposition of forest edge
	Number of tree cavities with detritus		Composition of forest edge
	Problematic herbaceous neophytes		Width of shelterbelt
Terrestrial stand	Forest type		Width of shrub belt
	Forest origin and management type		Width of herbaceous fringe
	Stage of development		Shape of forest edge
	Stand age		Density of forest edge

Data collection method	Feature	Data collection method	Feature
	Degree of mixture		Condition of forest edge
	Degree of cover of tree species in the upper layer		Barrier delimiting forest edge
	Degree of crown closure		Immediate neighborhood of forest edge
	Type of gap		Woody species along the forest edge
	Stand structure	**Interview survey and forest road assessment**	Ownership
	Degree of cover of stand layers		Forest road network
	Type of cover of stand layers		Width of forest road
	Stand's top height		Vehicle type
	Stand stability (loads, resilience)		Obstacles on forest road
	Type of areal forest damage (areal damage)		Connection of forest roads to the main road network
	Extent of areal damage		Concept for opening-up forest land
	State of clearing		Intentions concerning the concept of opening-up forest land
	Stocking border, forest edge		Pre-hauling distance
	Stand border		Hauling distance
	Inner edges		Means of hauling
	Stand size		Limitations in choice of means of hauling
	Type of regeneration		Marking of skid roads
	Protection of regeneration		Hauling destination
	Distribution of regeneration		Hauling direction
	Degree of cover of regeneration		Hauling route
	Degree of cover of established regeneration		Altitude of the helicopter timber depot
	Main tree species in established regeneration		Length of cable line

Data collection method	Feature	Data collection method	Feature
	Degree of a cover of shrub layer		Location of mobile tower yarder
	Degree of cover of ground vegetation		Timber sorting (short, long)
	Degree of cover of berry bushes		Year of last use
	Main species of berry bush		Type of last use
	Urgency of silvicultural treatment to be done next		Year and type of silvicultural treatment since the previous inventory
	Type of silvicultural treatment to be done next		Salvage cuts (proportion, reason)
	Presence of woody plant species (200 m^2 plot)		Date of next silvicultural treatment
	Proportion of woody plant species in shrub forest		Type of next silvicultural treatment
Terrestrial tree (dbh ≥ 12 cm)	Tree species		Principle goal of plentering in mountain forests
	dbh up to 60 cm, circumference if diameter > 60 cm		Conditions for the next silvicultural treatment
	Circumference		Timber harvesting (type, in-/outsourcing)
	Diameter at 7 m tree height (d7), tree height		Basis for local planning (type, year of establishment)
	Distance, azimuth from center		Regional Forest Development Plan (status)
	Inclination towards center		Certification (type, label)
	Living/dead/standing/lying		Size of managed unit
	Date of death		Forest functions
	Tree age		Primary functions
	Stem height of broken snag		Location in catchment area of drinking-water source
	Treetop used		Intensity of recreational use (visitor frequency)
	Growth form		Seasonality of recreational use

Data collection method	Feature	Data collection method	Feature
	Tree status		Type of recreational use
	Tree-rings on stumps of used trees		Type of forest origin
	Height of stumps of used trees		Year of afforestation
	Diameter of stumps of used trees		Type of stand origin
	Inventory of stumps		Year of the last pasturing
	Layer		

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Authors' contributions
MF conceived the project idea and raised money for the project. MF and RTS collected and analyzed the data and co-wrote the first draft of the manuscript. CF, AG, CG, and KM provided substantial support and intellectual contributions as part of the SwissAIM committee. All other authors provided intellectual insights for the development of the SwissAIM initiative, provided valuable time in workshops and meetings, and edited and contributed to advanced drafts of this manuscript.

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Availability of data and materials
The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
All the authors included in the manuscript agree to the publication of the article.

Competing interests
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