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Climate data for the European forestry sector: From end-user needs to opportunities for climate resilience

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ABSTRACT

The aim of this study is to assess the potential of Earth Observation and climate data for the forestry sector focusing on the Copernicus Climate Change Service (C3S). Although forestry researchers recognize the importance of Earth Observation and climate data, forestry practitioners currently work mainly with land cover information, largely neglecting climate data. Understanding its potential for the forestry sector becomes thus important, as to align the vast offer of climate services in Europe to different forestry users and stakeholders' necessities. Interviews, surveys, and dedicated workshops were used to collect a series of forestry end-users' needs and requirements regarding climate data. End-user's requirements were categorized through a SWOT analysis, which allowed to identify perceived internal strengths and weaknesses, external opportunities and threats to the increased use of the C3S. Results indicate that improved climate services for the forestry sector based on C3S data would benefit from enhanced training on the use of climate data, improved provision of services integrating climate with non-climate data, the provision of new variables and indicators, and the integration of machine learning techniques for developing data and information in support of the deployment of climate services. These findings are relevant to close the gap between demand and supply of climate services for the forestry sector and provide a basis for further exploring the value of climate data in serving a wide array of forestry stakeholders. Going forward, increased knowledge on user requirements from both forest practitioners and policy-makers can be beneficial to develop accessible tailored services.

Practical implications

The forestry sector plays a paramount role in achieving a climate neutral economy based on sustainability and resilience. In Europe, policies addressing environmental sustainability, biodiversity loss, and climate action place forests as a central pillar for strengthening biodiversity preservation, achieving carbon sequestration and ensuring the provision of multiple ecosystem services. At the same time, countries are pushing for a digital transformation of the forestry sector, introducing innovative tools at the service of scientists and practitioners. When seeking preparedness and adaptation to risks linked to climate variability, past and future climate conditions are fundamental variables for improving forest planning or guiding forest disturbances risk management. Although climate data are commonly used by scientists, forestry practitioners still make a limited use of such data.

The integration of climate data in forestry decision-making processes can lead to targeted and more accurate services which can contribute to the ecological resilience of European forests at the local and national scale. Seasonal forecasts can inform forest

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managers in their routine practices anticipating or postponing the planting or the harvesting operations based on the frost period. Firefighters can also be better prepared to manage forest fire risk through climate services providing local fire projections. Climate information can also support forest policy-makers in defining practice-oriented adaptation strategies and targets. However, to provide accessible and accurate climate services, their demand in the forestry sector needs to be understood. A close interaction between users and providers for building integrated climate services is crucial, as it enhances user engagement in the service delivering process.

The presented study aims at identifying user requirements to assess the potential of Earth Observation and climate data for the forestry sector focusing on the Copernicus Climate Change Services (C3S). The C3S is run by the European Center for Medium-Range Weather Forecast (ECMWF) on behalf of the European Commission. Exploring its potential for forestry-related operations and planning become thus relevant for developing tailor-made services for forestry based on historical climate data, seasonal forecasts and/or long-term projections. Through an online survey, semi-structured interviews, and workshops with forestry end-users, we collected users' requirements on C3S data. End-user's requirements were categorized through a SWOT analysis. Strengths, weaknesses, opportunities, and threats of the currently provided C3S were discussed to identify the main user needs from the forestry sector as to align them to the vast offer of climate services in Europe.

Through this assessment, the article introduces the main features demanded by the forestry sector to ensure the accessibility to high quality climate information in a user-friendly manner. Training on the use of climate data is crucial to raise awareness of the potential of climate data among practitioners, scientists and policy-makers. Training sessions can guide the selection, application, and interpretation of climate data and scenarios, besides improving the connection between demand and supply of climate data. There is also a demand for alternative pricing models of the climate services, to ensure data accessibility by small and medium enterprises and to foster the cooperation between private and public entities. Among the opportunities that foresee a positive engagement of users in using climate services, the integration of climate with non-climate data (land, atmosphere, ground, soil, and socio-economic data) is largely demanded by forestry end-users. Intermediate climate services providers can thus be guided in improving and developing climate services targeted to the forestry sector, such as projected future species distribution maps, emergency risk management platforms and predictions on bioenergy consumption, services identified in this study. For instance, the information collected in this study was used by purveyors to develop a prototype of tree species distribution map providing digested and user-friendly information to business owners and technical staff about the effects of climate change on forests.

Additionally, the findings of this research present the main internal and external barriers in the usage of climate information. The low temporal and spatial resolution is one of the main limitations identified by users when using climate data for their work. However, this requirement can be fulfilled only through higher computational power and improvements of the downscaling models. Subseasonal-to-seasonal (S2S) predictions are also becoming key, especially in the development of rapid detection services, for fire management as well as insect outbreaks and wind throw risk. Moreover, the low specialisation of non-technical forest staff can lead to misinterpreted data when consulting climate services. A User Learning Service tailor-made to the forestry sector can thus be developed to increase the knowledge on the use of climate data.

Finally, this study contributes to the alignment of service provision with user engagement to support the generation of technologically sound and user-centered services. This increased integration would support win-win solutions for both the C3S, through increasing the uptake of its data repositories by a growing and diversified body of European actors, and the European forest sector creating new job opportunities and enhancing the climate resilience and adaptation to climate change within the sector. We consider that the lessons learned in this study can assist researchers in the field of climate service research, and forestry practitioners interested in applying climate services. This paper provides insights into how new governance regimes and the development of new integrated climate services can be of crucial importance to further extend the uptake of C3S in the forestry sector.

Introduction

Impact of climate change on forest ecosystems is an important contemporary concern (Dyderski et al., 2018; Lindner et al., 2014). Besides affecting forest productivity, observed effects of climate change on forest ecosystems include changes in tree growth patterns, drought induced mortality and species distribution shifts (Lindner et al., 2014), as well as additional effects on water availability, increasing pests and diseases, and the rise of detrimental effects of natural disasters (e.g., mega-fires) (Adams, 2013). Recent extreme events such as the most extreme drought and heat wave on record in Central Europe (Brun et al., 2020; Buras et al., 2020) led to widespread tree decline and decreased productivity (Bastos et al., 2020). Climate observations indicate that such extremes have substantially increased over the past decades (Lorenz et al., 2019). Despite being dramatically impacted by climate change, forests also play a major role in mitigating its detrimental effects. Forests are important carbon reservoirs and harbour most terrestrial biodiversity (FAO and UNEP, 2020). Moreover, they provide a wide array of ecosystem services like production of goods, recreation, and soil and water protection (Duncker et al., 2012; Maes et al., 2020).

For all the above-mentioned points, the forestry sector plays a paramount role in achieving a modern, competitive, and climate-neutral economy by 2050, as recommended by the European Commission in its "*A Clean Planet for All*" vision (European Commission, 2018). When ensuring sustainability and resilience in the forestry sector, the deployment of a new circular bioeconomy can be enhanced, focusing on resilient and healthy forest ecosystems, and positively contributing to the overall European economy. The EU Green Deal provides the main guidance to the European Commission's legislative work for the period 2019–2024 (European Commission, 2019b). Climate change mitigation and adaptation are central in this policy line, as to increase the effort towards carbon neutrality by 2050.

Among the key actions to achieve carbon neutrality, the European Commission explicitly mentions that a European-wide digital transformation must be supported as "*a key enabler for reaching the Green Deal objectives*" (European Commission, 2019b). Both the agenda of the European forest-based sector 2030 (European Technology Platform, 2020) and the vision of the EU forest-based industries for 2050 (CEPI, 2019) indicate the key role of Earth observation (EO) for reaching their targets. Although forestry researchers recognize the importance of EO and climate data for forest planning and management, forestry practitioners currently work with mainly land cover information, largely neglecting climate data (Bruno Soares et al., 2018). Land cover data is used to map forest area, assess canopy health, and execute forest inventories, among other uses (European Commission, 2018, 2019b). Climate data is deemed necessary by forestry researchers, advocating its use in forest simulation modelling and forestry impact assessment for developing climate scenarios (Fontes et al., 2011; Reyer et al., 2020). Therefore, coupling EO and climate data has a huge potential for the forestry sector, as to integrate climate change effects into forestry decision-making processes and thus improving the ecological resilience of forests.

Forest scientists use EO and climate data in assessing the habitat suitability of different tree species and give an insight on ecosystem services like climate regulation, flood protection, and water and air

Table 1
Overview of the forest end-users participating to semi-structured interviews (N = 9) and workshops (N = 3).

No.	Organisation type	Country	Sector	Interest in climate data
Semi-structured interviews				
1	Association	Spain	Forest productivity and bioenergy	Interests in climate data to improve forest management and to know, in advance, bioenergy demands for heating systems.
2	Private company	Spain	Private forest manager	Interest in climate data for forest productivity projections and risk prevention regarding extreme winds and droughts.
3	Public research centre	NA[1]	Ecosystem services provision (mushrooms and truffles)	Interest in climate data for forecasting mushroom productivity in forest stands.
4	Public research centre	Italy	Disaster management (fires, floods)	Interest in climate data for building integrated wildfire forecasting models.
5	Private company	Finland	Integrated forest management, remote sensing	Interest in climate data for (i) integrated wildfire forecasting models, (ii) developing land use monitoring tools. Current user of the C3S.
6	Private company	Spain	Disaster management (fires, volcanic eruption)	Interest in climate data for (i) integrated wildfire forecasting models, as well as (ii) simulating other natural disasters. Current user of the C3S.
7	Public research centre	Germany	Disturbance risk management	Interest in climate data for developing multi-criteria modelling forecast of disturbances (storm).
8	Private company	Finland	Forest management consultant	Interest in climate data for forest management plans and forest extension services.
9	National research centre	Slovenia	Forest genetic	Interest in climate data for long-term species distribution modelling.
Workshops				
I	Forest genetics[2]	Pan-European	Forest genetics	Interest in climate data for monitoring conservation units of forest genetic resources.
II	Bioenergy[3]	Spain	Bioenergy	Interest in climate data to improve forest management and to know, in advance, bioenergy demands for heating systems.
III	Wildfire community[4]	Pan-European	Wildfire management	Interest in climate data for multiple uses (modelling, improve predictions, create user-friendly wildfire risk products, etc.).

[1] Information not provided by the user
[2] 7 participants
[3] 9 participants
[4] 11 participants

purification, which have important indirect economic implications. Climate data are also useful when coupled with phenological data to understand the duration of the growing season and how tree species distribution are affected by minimum temperatures (Kramer, 1994; Menzel & Fabian, 1999). Besides, EO and climate data are important to inform managers and practitioners when responding to increased droughts, frosts and pests (Allen et al., 2010, 2015; Vitasse et al., 2019). As forest productivity is expected to shift with climate variation, the provision of climate change projections to this sector is valuable for long-term decisions on planting strategies and exploitation plans (Keenan, 2012). In the case of wildfires, climate data supports wildfires projections, climate-fire models and the influences of fuel load/structure, essential for the prevention of forest fires (Dupuy et al., 2020). Medium-term decisions as harvest operations, postponed/anticipated planting, soil treatment methods, timber transportation etc., can also be informed by seasonal forecasts (e.g. 1 to 6 months) (Jönsson & Lagergren, 2017). Forest managers need to predict heavy precipitation and unfrozen soil before the harvesting operations to avoid the use of heavy machineries, which can increase soil compaction and erosion (Cambi et al., 2015; Stone, 2002). Finally, the increasing frequency and intensity of extreme events like wildfires, heat waves, and extreme precipitation (IPCC, 2014), require forestry stakeholders to anticipate their detrimental effects as to improve the resilience of forestry operations. Climate data is thus critical for both researchers and practitioners allowing to map tree species vulnerability, guide risk management and plan accurate long-term forest restoration and conservation strategies (Fremout et al., 2020).

To improve the integration of climate data in forestry operations, we assess the potential of EO and climate data for the forestry sector focusing on the Copernicus Climate Change Services (C3S). We do this by conducting interviews and workshops with forestry end-users interested to or dealing with C3S data. A users' perspective for assessing evolving climate data requirements is highly relevant, as it improves our understanding on how users are employing climate information in their decision-making processes. This is especially important when end-user numbers are rising, due to growing demands for climate data in the forestry sector and more diversified applications among forest managers and practitioners. Assessing systematically sector specific users needs on climate data can support the development of integrated climate services which can in turn close the gap between the demands of the sector and the offer of climate services. Our review revolves around the following research questions:

- What are the strengths, weaknesses, opportunities, and threats of the currently provided climate services to the forestry sector?
- What are the main user needs of the forestry sector when it comes to the integration of climate data with non-climate data?

By further analysing the identified opportunities, we were able to shortlist several climate services integrating climate and non-climate data, with direct potential in supporting forestry operations to reach Europe-wide climate change policy targets.

Materials and methods

Data collection

This study assesses the potential of EO and climate data for the forestry sector focusing on the Copernicus Climate Change Services (C3S). The Copernicus Programme is the cornerstone of the EU's efforts to monitor the Earth and its diverse ecosystems through satellite EO and in situ (non-space) data. The Programme is coordinated and managed by the European Commission. Copernicus is the largest EO data provider in the world, currently producing 12 terabytes per day of data. The vast majority of data delivered by the Copernicus Space infrastructure and the Copernicus services are made available to any citizen and organisation around the world on a free, full, and open access basis (Copernicus, 2019). The information services provided by Copernicus are divided in six themes: Atmosphere, Marine, Land, Climate Change, Security and Emergency (Copernicus, 2021). C3S provide information about the past, present and future climate through the Climate Data Store (CDS). The CDS functions as both a data storage and service provider. The CDS contains climate observations, reanalyses (through ERA 5), climate projections (through CORDEX and CMIP5/6), and seasonal forecasts. Both in-situ observation, satellite data reprocessed, and outputs from climate models are available for users. This service is in place since 2018 as a supporting tool for EU private and public actors in developing adaptation and mitigation plans to climate change. C3S provide a series of key climate variables and indicators based on temperature, precipitation, humidity, and drought events data (Marconcini et al., 2020).

Whilst the focus of this study is on C3S data, the scope was enlarged to two additional services of the Copernicus Programme relevant for the forestry sector: Copernicus Land Monitoring Service (CLMS), and Copernicus Atmosphere Monitoring Service (CAMS). CLMS provide geographical information on land cover and its changes, land use, vegetation state, water cycle and earth surface energy variables. CAMS provide continuous data and information on the atmospheric composition.

To identify the most prominent needs and requirements of the forestry sector in relation to climate data, a series of end users has been contacted and interviewed. This perspective allowed gathering the requirements of the sector interacting with a limited number of players which best represent the different necessities of climate information for the European forestry sector. Table 1 summarizes the users from the forestry sector which have been interviewed in the study. Each user was consulted using a semi-structured interviewing online tool (see Appendix), which was carefully designed to ease and support a standardized conversation between the user and the interviewer. The focus of these interviews was on identifying the users' needs concerning C3S for performing forestry-related activities and the users' requirements concerning forestry-related variables. Additionally, the interviews also focused on CLMS and CAMS related variables to understand the importance of this information for forestry-related activities. The main outcome of the interviews was to identify how current users' needs are fulfilled by the C3S, and how current climate services can be improved to support users decision-making processes. All interviews were performed online using a virtual meeting software. Interviews were also video recorded with the user's consent.

Along with the user interviews, a short structured online survey was also developed. The aim of this survey was collecting general end-users' requirements on C3S data. The survey had 22 questions (20 structured questions, and two open questions), and it was launched and disseminated between May and August 2020. The target groups of this survey were any relevant users (from small private holdings to large state-owned companies, from research centres to policy makers) including areas such as: forest genetics, forest management, disaster management, pest control, and urban forestry, which make use, or are expecting to make use of climate data in their daily work. Forty-three complete answers from European end-users were included in the analysis.

Three virtual workshops were also organised. The workshops involved users previously interviewed and additional potential users from the respondents' network. The aim of these workshops was building collective knowledge around strategic gaps in climate data jointly with the invited experts. The ultimate objective was identifying new integrated C3S services, and their technical and operational requirements, which can support a closer collaboration between the participants and the service providers. The all-in-one digital facilitation platform "HowSpace", specifically designed for facilitator-led workshops and events (Howspace, 2021), was used to facilitate the discussion. All interviews, survey and virtual workshops were designed as to comply with the EU General Data Protection Regulation (Additional Information about Data Protection - Annex, 2020), and all interviewees were asked for their consent for participating in the study.

Data analysis

Qualitative data analysis was conducted to identify and classify end-user requirements for climate data. MAXQDA was used to find patterns on the users' needs throughout the surveys (VERBI Software, 2019). The minutes of the semi-structured interviews and workshops, as well as the report with the results from the short structured online survey were uploaded on MAXQDA. Trough MAXQDA, the documents were screened to identify explicit statements defining feedback, requirements, or needs related to C3S and climate variables. Four main categories were used to code the statements: Strengths, Weaknesses, Opportunities, and Threats according to the SWOT analysis nomenclature (Sinha et al., 2020).

SWOT analysis

The SWOT analysis is a widely used tool to prioritize organisation cores competencies and develop business strategies. It can also be applied for exploring and classifying the factors impacting positively and negatively on the achievements of strategic objectives (Sinha et al., 2020) or for systematically assessing analytical and overarching frameworks (e.g. Ecosystem Services framework), as to identify main influencing factors (Bull et al., 2016). In this study, we used the SWOT analysis to classify perceived strengths and weaknesses, external opportunities, and threats of C3S data for selected forestry end-users. We operationalised the SWOT elements using the following definitions:

- *Strengths* (S) are existing features of the C3S that are currently supporting the forestry sector in their research, planning, managerial and consultancy activities.
- *Weaknesses* (W) involve internal barriers to the C3S that obstacle the usage of the climate service by the forestry sector. They might refer to missing features or further elaboration of existing parameters.
- *Opportunities* (O) are elements in the C3S which are not yet available but could be developed according to users requirements. Opportunities also refer to positive external aspects, such as economic, technical, social, political, legal, and environmental factors that might positively facilitate and encourage the usage of C3S (e.g. demand of climate information, or demand for C3S training).
- *Threats* (T) refer to user's perceived resistances in using C3S due to external barriers. They may include features that are not currently implementable due to technological limitations (e.g. satellite limitations in detection) or existing market barriers, such as competitiveness.

Analytical procedure

According to the above-mentioned definitions, end-user requirements identified as already fulfilled were categorized as strengths of the C3S. Conversely, end-user requirements referring to a possible improvement of already existing features were placed under the weakness category. Needs referring to external factors and features not yet developed by the C3S were considered as opportunities. The external barriers, technical limitations or requirements that are currently not fulfilled by the C3S were categorized as threats. Interviewee's statements in the minutes were categorized in the four above-mentioned SWOT categories, through coding references in MAXQDA. This analysis was applied to two main subsectors of interviewed end-users from the forestry sector: forest risk management and bioenergy users. All other interviewed end-users (including forest consultants, forest genetic researchers and ecosystem services researchers) were classified as "Other sectors".

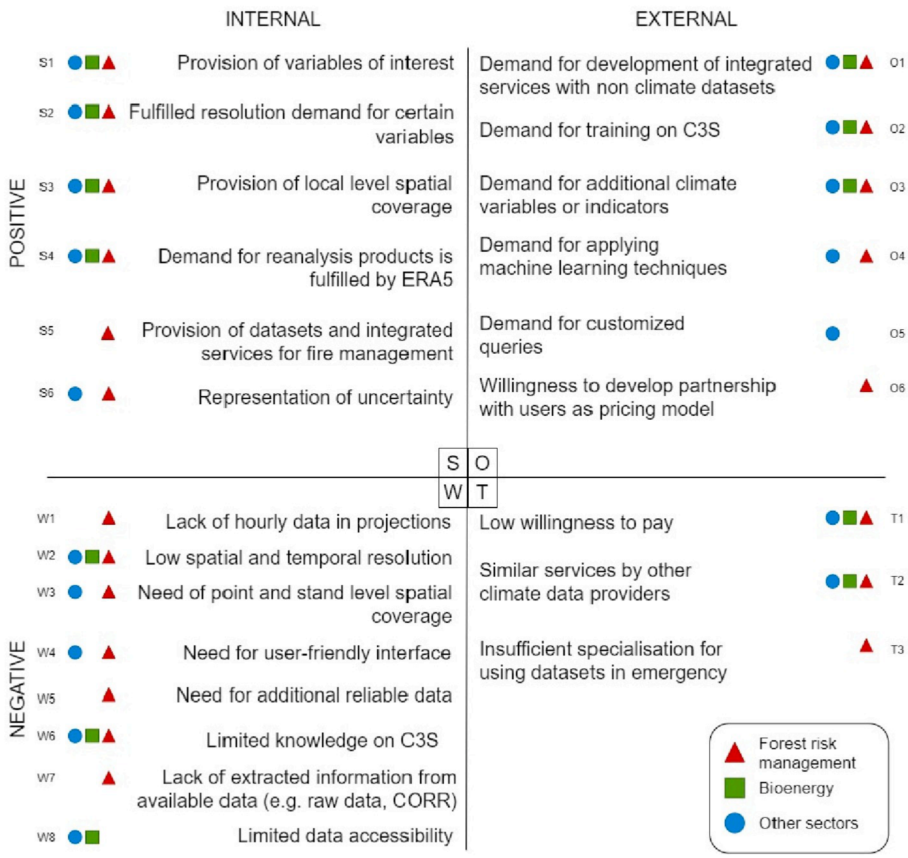

Fig. 1. Representation of the SWOT analysis of the Copernicus Climate Change Service (C3S) for the subsectors forest risk management, bioenergy and a remaining class for other sectors. S: strengths, W: weaknesses, O: opportunities, T: threats. (CORR stands for correlation). Internal requirements refer to positive and negative factors of the C3S offer, while the external requirements are those factors related to any existing climate information providers and users, external to the C3S.

Results

SWOT analysis

Fig. 1 summarises the main findings of the SWOT analysis, disentangling users' requirements into main perceived strengths, weaknesses, opportunities and threats. In the following sections, each SWOT component is further elaborated presenting the end-user requirements that emerged from the interviews and workshops.

Strengths

Five main strengths associated to climate data provision for the forestry sector were identified. Four of them were mentioned by all groups: provision of variables of interest, satisfaction with the resolution and coverage provided of certain variables, and provision of reanalysis products. Precipitation, temperature, wind, humidity, snow cover and forest fires are those variables available in the CDS which emerged as highly important for supporting forestry end-user operations, when forecasting forest disturbances, estimating forest damages, planning harvesting activities, or monitoring ecosystem services. Interviewed end-users were overall satisfied with the spatial and temporal resolution and coverage provided by C3S for certain variables of interest. However, few relevant differences have emerged across the subsectors. For instance, the bioenergy sector requires spatial low resolution (around 10x10 km) for the temperature and relative humidity variables. A 3 h' temporal resolution and a local spatial coverage, as provided in the CDS (through CORDEX and CMIP5), fulfil the users demand of sub-daily local data. The forest risk management sector demands a resolution around 25x25 km for ash cloud simulations. However higher resolution may be needed for wildfire modelling, as further described in the weaknesses section (3.1.2). The forest risk management sector has particular interest in historical climate data (available in the ERA5 reanalysis dataset) and seasonal weather forecasts (available in the C3S Seasonal Forecasts dataset) for modelling past and future development of disturbance and for the implementation of emergency warning systems. The ERA5[1] reanalysis component provided by C3S was positively evaluated by fire researchers and forest information providers, for past forest conditions analysis, identifying for instance fire burnt area, as well as by the bioenergy sector. Uncertainty representation, confidence of the data and accuracy were pointed as fundamental characteristics to have in the C3S by all users interviewed. The fact that there is a quality assessment and a documentation tab in every dataset of the CDS can be evaluated as a strength. Finally, the provision of datasets and integrated services for fire management was identified as a strength by the forest risk management sector. The EFFIS[2] dataset was developed as part of the C3S, creating synergies within the Copernicus Programme (in this case between the Emergency programme and the Climate programme), providing several indices on wildfire danger reanalysis, such as burnt

[1] ERA5 is a comprehensive reanalysis, from 1979 to near real time, combining historical observations using advanced modelling and data assimilation systems. It provides hourly estimates from atmospheric, land and oceanic climate variables. Currently, there is also available a preliminary back extension for 1950–1978.

[2] The European Forest Fire Information System (EFFIS) has been established by the European Commission collaborating with the national fire administrations and a Forest Fire Experts Group since 1998. It became operational in 2000. By providing near real time and historical forest fire information, EFFIS aims at supporting forest protection against fires and harmonization of information systems on forest fires in Europe (European Commission, 2017).

area from fires which was found relevant by the forestry sector (ECMWF, 2019).

Weaknesses

Nine weaknesses (or possible improvements from the user perspective) associated with climate data provision have been pinpointed. Five of them refer to technical requirements, such as temporal and spatial resolution and coverage (depending on variables and the type of analysis users must conduct), and uncertainty representation. The remaining four are transversal weaknesses linked to data visualization and provision through C3S interfaces. Concerning technical requirements, among all subsectors there is an explicit request for higher resolution of certain variables. While users are occasionally satisfied with the resolution provided, for specific analysis finer spatial and temporal resolution are required. Data on wind average speed, maximum, and direction are required at a spatial resolution of at least 1x1 km, instead of the 9x9 km that Copernicus is currently providing. Data on wind is critical for risk models to understand storm damages, as well as to predict the spread of a wildfire. If provided at a finer spatial resolution, wind is also an important variable for forest genetics researchers in gene flows studies, to predict species distribution shifts through pollen dispersal. A similar request was raised by the bioenergy sector demanding mean precipitation data at a medium resolution (100mX100m), a requirement currently not fulfilled by C3S. Other technical needs include the need for a higher frequency of updates for wind forecasts that have a daily cycle, as mentioned by end-users forecasting forest disturbances. Additionally, the forestry sector often conducts research at stand level or individual tree level, especially when monitoring tree health or phenology. Therefore, forest risk management users mentioned the need of obtaining finer local coverage, through stand level and point level climate data.

Other weaknesses are related to certain features of the C3S interface. Firstly, a user-friendly interface was requested allowing multiple selection criteria when downloading data. Multiple selection criteria would allow to download specific sets of raw data from a given location, such as a genetic conservation unit, without having to download the whole set of data. The demand for a user-friendly interface and the data accessibility are two weaknesses strongly interrelated. Providing access to data requiring high level skills and advanced computing is seen as a barrier to the usage of C3S by expert users, who still have high costs to bare, and non-expert users that lack the knowledge on how to use the platform and its related data. Specific features demanded by the forest risk management sector to ease the access to data is the provision of estimates calculated from the variables, such as correlation, and the availability of raw data behind the indices composed with multiple parameters. Another barrier to the increased usage of C3S data reported by all subsectors is the lack of knowledge on the data and the extent to which it can support the end-users activities. Some respondents were not aware of the existences of C3S, while others did not know about latest updates of the C3S. Overall, it emerged that C3S was not widely known and its potential poorly used.

Opportunities

Six opportunities reflecting the positive engagement and interest of the respondents for the future development of C3S were identified. Three of them were raised by all three user categories: demand for new variables and indicators, need for training on the use of C3S data, and demand for climate services integrating non-climate data with the climate ones.

Among the additional variables and indicators, the Land Surface Emissivity (LSE) was demanded by forest risk management end-users. LSE is the average emissivity of an element on the Earth́ surface calculated from the measured radiance and land surface temperature (LST). It is used to perform retrieval, which can be applied to wildfire simulations, or is used to combine satellite data and climate data to estimate for instance the mass of an ash cloud after a volcanic eruption. Forest genetic researchers would like to have a combined index with precipitation and temperature data based on the vegetation period through which they can calculate drought stress indicators. Heat wave days[3] and frost days are variables demanded by genetic researchers, the bioenergy sector, and forest private owners. An opportunity that is addressing the above-mentioned weakness “lack of knowledge on C3S” is the demand for training. All subsectors have shown interest in joining training programmes focused on unfolding the potential of C3S data, through tailored hands-on activities.

Other opportunities that would directly address innovative deployments of Copernicus data are: (i) the demand for integrated services with non-climate data, (ii) the demand for new variables and indicators, and (iii) the request for integrating machine learning techniques. The demand for products integrating climate data with land, atmosphere, ground, soil, and socio-economic data is described in detail in the next section. Furthermore, the integration of satellite datasets with machine learning technology is now raising interest among researchers to perform rapid fire detections and European hazards map. The provision of updated information from C3S would allow improving information systems for wildfire risk and hazards mapping. Genetic researchers suggested the use of machine learning techniques to identify correlations and patterns across variables at stand level, so that key variables relevant for their research can be automatically selected.

One last opportunity relates to the C3S pricing system. Some of the interviewed wildfire researchers suggested the possibility to develop a partnership with research centres and business where C3S could provide services for a convenient price in exchange for some royalties on the final product delivered by the company. Another pricing opportunity suggested was to provide different levels of pricing depending on the type of data used by the users, in a way that small organisations can also have access to this service. The development of this pricing system could reach new users and involve them directly in the development of product improvements. The opportunity to add customized queries was expressed by the genetics sector, which would find having an interactive interface useful, where data could be manipulated directly, allowing users to upload additional information to compare trends.

Threats

The SWOT analysis suggests three main perceived threats related to C3S data provision: (i) low willingness to pay, (ii) the availability of other climate services mentioned by all user subsectors, and (iii) the insufficient specialisation mentioned only by the forest risk management subsector. The most mentioned threat for the increased usage of C3S is the low willingness to pay by climate service users supported by the CDS, developed by intermediate users (or purveyors) such as private companies or projects financed by the European Commission. The full value chain that users deal with to obtain climate data involves large investment costs. The forestry sector would thus like to maintain the service as freely accessible, as CDS is a free and open source. However, this element could limit the capacity of C3S to implement new technologies and increase the usage in Data and Information Access Services (DIAS), platforms that provide simplified access to the C3S data and other Copernicus services with different pricing options. Another threat to the increased usage of C3S data is the existence of other climate data providers that are better known by the forestry sector. The end-users stated two main reasons linked to the use of these different climate providers: (i) familiarity and (ii) satisfaction with the provideŕs spatial and/or temporal resolution, especially when working at national or regional level. Some examples of climate data providers commonly consulted are national and regional meteorological stations such as

[3] According to the Climatological EURO-CORDEX heat waves are a period of at least three consecutive days on which the daily maximal temperature exceeds the 99th percentile of the daily maximal temperatures of the May to September months for the control period of 1971 to 2000 (Copernicus, 2020).

Table 2
List of potential services that integrate climate and non-climate data.

Name of the potential services	Examples fulfilling users̈ needs	Type of data needed	Times that the product has been mentioned[1]	Subsectors
Projected future species distribution map under climate change scenarios[2]	(Dyderski et al., 2018; Pecchi et al., 2019; Takolander et al., 2019)	Climate, land cover, and forest structure	6 interviews and 1 workshop	All
Emergency wildfire management platform	(NWGC, 2019)	Climate, land cover, atmosphere, ground data	1 interview and 1 workshop	Wildfire sector
Bioenergy consumption and demands under climate change scenarios	(BizEE Software, 2021; EnergyCap Software, 2021)	Climate, social, economic	1 interview and 1 workshop	Bioenergy
Distribution of biotic and abiotic risks (specific for droughts, insects and fire risk)[3]	(Albert et al., 2017; Jönsson et al., 2009)	Climate forecasts, land cover, forest health, ground data	2 interviews and 1 workshop	Genetics, forest planners, bioenergy sector
Operations planning[3]	(Hyvärinen et al., 2020)	Climate (as snow), soil conditions, land changes	3 interviews and 1 workshop	Bioenergy and forest consultant

[1] The products were listed based on the level of details provided by the users during the interviews and the workshops.
[2] A first prototype has been developed for Spain, Indonesia and Sweden and it is publicly available at https://forest-forward.com/. This demonstrator uses C3S data to inform business owners and technical staff about the impacts of climate change on the distribution of species of value to the forestry industry. The information is communicated using maps and charts that synthesise and facilitate the access to high quality scientific data.
[3] This service will not be described due to lack of detailed information provided by the users.

WorldClim and the regional Climate Model Remo for downscaling. Thus, the existence of other climate service providers in Europe can be considered as a commercial threat to the C3S for attracting additional users from the forestry sector. Another factor limiting the usage of C3S by the forest risk management sector is the lack of competence and familiarity with the datasets. Firefighters, civil protection units, and local authorities do not often make direct use of climate data as provided in the CDS. They would rather have user-friendly climate applications that provide them already digested supporting information for emergency management.

Potential services integrating climate data with other types of data

The most mentioned opportunity in the SWOT analysis referred to the demand of services integrating climate data with non-climate data. This opportunity highlights the importance of land, atmosphere, on-field, and socio-economic data for the forestry sector, and allows Copernicus to further connect its programmes, for instance C3S, CAMS, and CLMS, similarly to what has been done with EFFIS. In Table 2, the most mentioned services that users would like to have available are presented.

A species distribution map is a highly demanded service by all the subsectors that is gaining increasing attention as a support tool in forest management. This service, in the form of an app, would relate data from the satellite imagery on land cover, altitude variation, and forest structure, with different climate change models impacting tree growth. End-users would use this product to assess with a dynamic approach how the climate is affecting tree species distribution and their growth in a specific geographical area. However, users (in particular forest genetic researchers) require that uncertainty in species distribution and in forecasts is indicated to avoid inaccuracy when using these databases. Further developments of these maps may include assessment of climatic suitability of trees, specific to forest disturbances to understand for instance how species can be affected by emerging biotic and abiotic risks in a climate change scenario. This type of information can support forest managers in selecting suitable tree species to plant, considering potential extreme droughts, or wind damages. It can also support decision makers in relation to risk forecasts across Europe. Interviewees also mentioned that a species distribution map as such would need high-resolution data on forest structure and forest composition at stand level. This resolution is complex to retrieve due to the limited computational power. Moreover, land data, as the ones from CORINE, often cannot distinguish specific forest types (e.g. between tree juveniles and shrubs) and thus is not always reliable.

The utility of a user-friendly early warning system for wildfire management was widely discussed during the wildfire workshop. This climate service could provide reliable assessment of fire impact in Wildland Urban Interfaces (WUI) and vulnerable forest areas. End-users suggested that these systems can make use of machine learning and satellite images, as well as other data, such as consequent emission dispersions, GHG, and vegetation to improve the rapid detection of wildfires, and to permit an integrated response to wildfires allowing interoperability between first respondents across different European geographical locations in an emergency situation. This platform would be essential to improve the management of other phases of the disaster management cycle, including preparedness, prevention, and recovery. It would serve end-users as public authorities, fire fighter units, and civil protection bodies.

From the interviews and the workshops with bioenergy users, it emerged that a climate service providing information on local bioenergy consumption linked to energy demands would be relevant for supporting sectorial operations. Such service requires the integration of climate data, including temperature, snow, and humidity, with socio-economic data, such as information on energy consumption. Its aim is forecasting the short- and long-term demand of bioenergy for biomass-based producers. Forecasts on the emissions derived from heating systems, comparing burning fuels and bioenergy could be provided. This prediction would support transparency in energy regulations and, possibly, the promotion of the wood-based bioenergy.

Discussion

The aim of this analysis was identifying and assessing opportunities for boosting the potential of climate data in supporting forestry operations. In this section, we will first discuss the findings of the SWOT analysis on user requirements considering similar and comparable user engagement studies on climate services, as well as existing integrated applications in the literature and elsewhere. We then examine our results in the light of the current policy changes as to identify a series of recommendations on how integrated climate services targeting forestry can support reaching overarching policy targets.

Success factors for C3S uptake in the forestry sector

The classification based on the SWOT framework helps exploring success factors that can increase the usage of C3S among end-users from the forestry sector. By looking jointly at the W-O-T components it is possible to illustrate how deploying opportunities can support in addressing identified weaknesses and threats of the C3S.

The demand for training on how to effectively use the C3S (O2) can be leveraged to address the low specialisation in climate data use (T3) expressed by users from the risk management sector. The low specialisation among non-technical users is complemented by a growing interest in climate services by decision makers without technical knowledge on the use of C3S raw data (PWC, 2019). Providing training on technical aspects of available datasets, climate services and on the potential of C3S data for forestry decision-making processes can improve the understanding on how climate data can support forestry operational decisions, especially among non-expert users. This would include as well the provision of guidance in selecting, applying, and interpreting climate data and scenarios (Máñez et al., 2014). Training sessions or workshops can create a space to connect climate knowledge to users, explaining how to use climate data and collecting feedbacks and requests on how users can further benefit from climate data. This latter information can support data providers in further enhancing climate services (Jönsson & Lagergren, 2017; Keenan, 2012). A User Learning Service tailor-made to the forestry sector could thus be developed, as is currently done for the agriculture sector users of C3S (Buontempo et al., 2020). This interface would support in expanding the C3S market, filling the gap between climate scientists and decision makers. Trainings and workshops can also improve the lack of awareness and knowledge on C3S (W6), expressed by all user subsectors. As earlier stated the low demand for climate services negatively affects the delivery of benefits expected by the users (Cavelier et al., 2017; Giuliani et al., 2017). While climate services are considered policy relevant and well appreciated by academia and the public sector, they are not yet fully mainstreamed into private businesses (Cortekar et al., 2020). Improving C3S awareness can thus increase multiple climate-based applications and meet current expectations of the forestry sector.

Finally, training and workshops can also support users that routinely make use of other climate providers (e.g. WorldClim), of getting acquainted with C3S as an additional working tool. As presented in the results, these users rely on other data providers because of both customary and satisfactory reasons (T2). Such users would make use of the C3S only if specific technical requirements would be provided. National climate service centres, such as meteorological departments, meet national needs for climate data demanded by users working at regional and local level (Vaughan & Dessai, 2014). Moreover, regional climate centres are also preferred thanks to the focus on specific locations and settings (Vaughan & Dessai, 2014) and to the direct focus on regional users needs. Studies at regional and local level showed preference for nearby observational sites when gathering meteorological variables at higher resolution (100x100 m) (Marchi et al., 2019). Climate services including C3S may not guarantee the same quality of data in all locations as this quality depends on the climate variability in each location, on the quality and the density of the observations, and on the interpolation results (Hijmans et al., 2005). Marchi et al. (2019) suggest establishing local up-to-date climate services networks that would provide data for constructing European level climate datasets and accurate interpolated climate data. Derived climate surfaces are fundamental in the forestry sector as they allow to plan the transfer of genetic resources across specific geographic areas. Collecting data from the established networks including errors, would be relevant for improving climate surfaces for the forestry sector. Climate service networks could thus be an opportunity to construct reliable European level climate datasets, when users are demanding resolutions that C3S cannot currently provide.

A weakness observed by the forestry sector is the unfulfilled demand for data at finer scales (W1-3 and W5). This could better support decision-making processes, especially when users need to combine data from different sources and locations in models (such as forest or hydrological models) requiring high resolution (Bessembinder et al., 2019). A higher resolution of the projected climate scenario datasets would improve the quality of forest growth simulations, supporting forest managers planning activities (Palma et al., 2018). Another typical application of higher resolution climate information is within wind damage risk projections, which requires stand or even tree-level information on the wind speed and damage risk (Jackson et al., 2021). Forest managers and owners would benefit from high-resolution maps to identify the wind damage vulnerability of forest stands and individual trees and therefore base their decision-making on disturbance prevention. Capturing the forest vulnerability through higher-resolution information could also support forest insurance companies to offer risk-based pricing services (Suvanto et al., 2019). Additionally, high-resolution climatic maps (e.g., 250x250 m) can inform practitioners regarding species suitability choices when relating drought risk and productivity, which are affected among others by the spatial configuration, slope exposure and elevational temperature differences (Hlásny et al., 2014). This information is fundamental also for biomass producers to understand the suitability of future species and support decision making on the type of species to be planted.

The provision of finer resolution data demands high computational power which C3S cannot provide. Good quality data is also affected by the acquisition conditions: for instance, when detecting windthrows, the season when the windthrows are happening and the topography can influence a proper detection of the parameters affecting the data accuracy (Dalponte et al., 2020). When lacking finer resolutions in the datasets, users resort to downscaling methods or other models which allow processing the data at the spatial and temporal resolution needed. However, observed data and interpolated data do not always match, adding uncertainty to future projections. The scale may be biased due to the several sources from which climate data are gathered and, therefore, accumulate errors. At the same time, this weakness can be considered as an opportunity to further develop downstream services provided by the purveyors using CDS to provide bias-corrected data.

Given the increased uncertainty due to downscaling models, several studies suggest focusing on the improvement of subseasonal-to-seasonal (S2S) prediction providing forecasts with a time range of 20–90 days (Keenan, 2012; Street, 2016). In the case of forest fire risk, S2S prediction would give to fire emergency units enough time in advance for preparation to the fire season, potentially reducing environmental and socio-economic impacts. Overall, the introduction of subseasonal and seasonal to decadal predictions in user-friendly climate services can support i.a. the development of rapid detection services, for fire management as well to insect outbreaks and windthrow risk. These services can provide a better understanding of the causes and consequences of near-term climate variability, building preparedness, enhancing good management practices, and eventually contributing to climate resilience and adaptation. Besides, climate information can also support forest policy makers in defining practice-oriented adaptation strategies and targets.

Climate-based services play an important role in climate change mitigation and adaptation. For this reason, these services need to be made available to a broad range of users. However, our results have shown that users have a low willingness to pay for new climate services developed through the CDS (T1), implicating that climate services should be provided for free or users must be incentivized to pay through alternative pricing models. A first solution would be public data providers directly satisfying users demands, which explicitly requested a user-friendly interface, digested data and additional information (as raw data or estimates on correlation). This refers to the need for public data providers to internalize additional steps of the climate services value chain. Differently from the current situation, the proportion of private to public providers would decrease further down in the value chain (Cortekar et al., 2020). When this suggestion is not achievable, the private data provider could offer a free probation period so that a company can assess if it is worth to pay for the climate services of interest (Giuliani et al., 2017). This is easy to implement for many private climate service providers as most of them follow an “e-business model”, where the service is provided in exchange for the payment of a monthly, seasonal, or yearly subscription (Larosa & Mysiak, 2019). Another possible pricing model consists of giving free access to only a part of the climate service. A company would then pay if they want to obtain the full functionality.

The same threat can be managed by the employment of mixed business models (O6), where the price is based on the size of the company. In this way, additional users could have access to the C3S data provided by the purveyors, including small organisations and enterprises. Innovative business models could bring forward the ongoing debate on how to achieve customized climate services without undermining their societal and economic benefits. It is fundamental to initiate a careful transition from a collaborative intergovernmental environment to a market driven service to ensure the non-excludability of the climate services together with the generation of solutions for target interest groups (Harjanne, 2017; Keele, 2019).

Through a systematic review of climate services for society, Vaughan and Dessai (2014) states that climate services must receive public funding to ensure their independence in knowledge generation. Public support is also essential to further strengthen the climate services market by developing clear regulation on data accessibility (Lourenço et al., 2016). This supports our suggestion for public data providers in internalizing user requirements in their datasets, and so contributing to climate service availability to a wider public. A recent market study shows that there is an unequal distribution of climate service providers among European countries (Cortekar et al., 2020). This fact also favours the provision of data from the EU-wide EO programme Copernicus. Besides, there are also opportunities for cooperation between public and private entities, especially when considering private companies able to bring innovative approaches and user-friendly interfaces (Harjanne, 2017). Collaboration could create synergies and support the joint-development of new climate services (European Commission, 2015; Mañez et al., 2014).

Policy implications

This study showcased that a systematic collection of end-user requirements can support practitioners and data providers in guiding the deployment of climate services into exploitable information for forestry end-users. Despite the predominantly descriptive nature of our results, this study suggests that a close interaction between users and providers for building integrated climate services is crucial, as it enhances user engagement in the service delivering process. Hewitt et al. (2017) illustrated three levels of user engagement when deploying climate services: (i) passive engagement, through web-based tools, (ii) interactive activities, through seminars and workshops, (iii) one-to-one relationships between data users and data providers. The degree of engagement, as well as the associated costs for the providers to establish such relationships change as participation becomes more direct. In this study we have followed an intermediate approach, which allowed to identify a series of specific and concrete user needs of the forestry sector.

User-centered strategies when dealing with climate data are growing in importance and the regulatory framework has a fundamental role in stimulating climate services emergence. The European Commission is following this path through its Roadmap for Climate Services as a response to the climate change challenge (European Commission, 2015). In the roadmap it is clearly indicated how "*understanding the demand for climate services*" is one of its main pillars as to adjust climate services future developments following a user-based perspective, rather than a provider perspective. Promoting greater private and citizen engagement as to co-design, co-implement, and finally co-evaluate integrated climate data derived services is also a main cornerstone of the European Green Deal, as to support innovations emergence and acceleration of best practices. The recent proposed Mission by the Directorate-General for Research and Innovation (European Commission, 2020) fully embraces user-led innovations for the development of new climate services to speed up the transformation to a "*climate-resilient Europe*". Greater citizen and user engagement are also central to those Green Deal areas mostly aligned with the forestry sector, such as the Biodiversity and Climate Action (European Commission, 2019a). This further indicates the importance of collecting forest user requirements for climate service deployment and positions our findings as highly relevant for closing the climate services potential gap for the forestry sector.

Conclusions

Climate services, and in particular the C3S, are critical for mapping, projecting and predicting forest conditions for both scientists and practitioners. Our analysis suggests that: (i) new governance regimes which can facilitate the development and update of climate services by public and private actors should be favored and supported, (ii) integrated climate services including both climate and non-climate data should be promoted, (iii) developing key partnerships is crucial, especially when intermediaries between data providers and final users are missing. Aligning service provision with user engagement is a priority for deploying the future services derived from C3S. This would allow to generate both technologically sound (through upcoming enhancements of climate information as the new high-resolution reanalysis ERA5-Land, the outcomes of the Coupled Model Intercomparison Project Phase 6, etc.), and user-centered services (developing a diversified series of interactive activities with sectorial end-users). This increased integration would support win–win solutions for both the C3S, through increasing the uptake of its data repositories by a growing and diversified body of European actors, and the European forest sector creating new job opportunities and enhancing the climate resilience and adaptation to climate change within the sector. Moreover, economic costs to develop and integrate these additional services in the forestry-decision-making processes could be covered by leveraging new financial means, aiming at strengthening the European climate ecosystem through ad-hoc investments (e.g. the investment ambitions set forth by the European Investment Bank (EIB, 2020)).

CRediT authorship contribution statement

Fraccaroli Cecilia: Methodology, Software, Investigation, Formal analysis, Data curation, Writing – original draft, Visualization. **Marini Govigli Valentino:** Conceptualization, Methodology, Investigation, Data curation, Writing – original draft, Project administration, Supervision. **Briers Siebe:** Writing – original draft, Visualization. **Peña Cerezo Nieves:** Project administration, Methodology, Investigation, Data curation, Writing – review & editing, Funding acquisition. **Paz Jiménez Jorge:** Funding acquisition, Project administration, Investigation, Data curation, Writing – review & editing. **Romero Maria:** Investigation, Data curation, Writing – review & editing. **Lindner Marcus:** Supervision, Writing – review & editing. **Martínez de Arano Inazio:** Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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6. Appendix.

6.1. Initial open questions

1) What is the main forestry research area, related to climate data, you are currently working on?
2) Which type of input data do you need for your forestry activities (climate and non-climate)?

6.2. General questions

1. Where is your organisation located?
2. In which type of organisation do you work?
3. Indicate or estimate the size of your organisation: less than10, 10–49, 50–249, 250–499, 500–999, 1000–2500, >2500
4. What is your primary role within your organisation?
5. In which forestry subsector do you work?

☐ Logging	☐ Bioenergy
☐ Wood processing	☐ Forest genetics and restoration
☐ Wood supplier	☐ Forest planning and regulation
☐ Disaster management	☐ Research
☐ Ecosystem services provision	☐ Pest and disease management
☐ Urban forestry	☐ Other:

6. Has climate change affected any of your forest activities in the last 5 years? If yes, which have been the most affected activities?

☐ Planting	☐ Acquisition of raw material
☐ Management activities	☐ Sales and market
☐ Service Provision	☐ Research activities
☐ Disaster management activities (Fire, pests, floods, droughts)	☐ Other:
☐ Harvesting	

7. Which Earth Observation data (satellite imagery, sensors in drones/planes, lidar, etc.) do you use in your activities?

6.3. Data requirements

8. Copernicus Climate Change Service (C3S) provides valuable information about the past, present and future of several climate variables and indicators. Are you aware of how this information can help your business and forest activities? (yes/no)
9. Copernicus Atmospheric Monitoring Service (CAMS) can provide valuable information of air quality such as ozone, UV and other factors affecting forest growth, as well as products on wildfires. Are you aware of how this information can help your business and field work? (yes/no)
10. Copernicus Land Monitoring Service (CLMS) provides valuable information of land use, land cover and forests condition. Are you aware of how this information can help your business and field work? (yes/no)

11. Please mark the main variables that are relevant in your work for climate data, atmospheric data and land data. For the variables selected, indicate the desired temporal scale, spatial coverage, spatial resolution, temporal resolution and output.

TYPE OF DATA	VARIABLE	TEMPORAL SCALE[1]	SPATIAL COVERAGE[2]	SPATIAL RESOLUTION[3]	TEMPORAL RESOLUTION[4]	DESIRED OUTPUT[5]
Climate data	Precipitation					
	Temperature					
	Wind					
	Humidity					
	Atmospheric pressure					
	Visibility					
	Extreme events					
	Forest Fires					
Atmospheric data	Reactive gases					
	Particulate matter and aerosols					
	Greenhouse gas concentrations					
	Fire emissions					
	Radiations					
Land data	Land-use/land-cover maps					
	Vegetation status and cover					
	Energy Balance					
	Water					
	Cryosphere					
	Ground based Observation for Validation					

[1]Historical information based on weather stations, Reanalysis, Weather Forecast, Seasonal Forecast, Decadal, Long Projections.

[2]Point data, parcel size, municipality size, regional, national, global.

[3]More than 10x10km; around 10x10km, around 100x100m; between 1 and 5 m; less than 1 m.

[4]1) How often should this information be updated; 2) how much in advance you would need the information available to inform decisions; 3) what is the required temporal resolution (Subdaily, daily, weekly, monthly, annually).

[5]Graph/plot, map, table or file, processed statistics, other.

12. Please select the most important characteristics of the information required.

☐ User friendly

☐ Freely available

☐ Data is provided in a format that is easy to use/ compatible with organisation's software

☐ Access to user support

☐ Availability of supporting information

☐ Examples of uses of this information in potential applications

☐ Scientific quality and robustness

☐ Uncertainty representation

6.4. Forestry variables

13. For each variable indicate the importance that each one of them will have for your activities in the future.

FOREST VARIABLES	Minimal	Moderate	High
General infrastructure (trails, roads)			
Streams, waters channels and water reservoirs			
Logging infrastructures			
Forest species distribution			

(*continued on next page*)

(*continued*)

FOREST VARIABLES	Minimal	Moderate	High
Forest structure (height, age, leaf index, basal area, stand density)			
Fire risk areas/fire burnt areas			
Clear-cut areas			
Geophysical variables (DEM, aspect, geological substrate, etc.)			
Individual tree level measurements (diameter, health conditions, damages, mortality)			
Forest productivity (site index, biomass, volume)			
Wood quality			
Biotic damages (due to pests and diseases)			
Abiotic damages (due to frost, draughts)			
Regulating ecosystem services (CO_2 stocks, erosion, flood control)			
Provisioning ecosystem services (genetic resources)			
Supporting ecosystem services (biodiversity)			
Cultural ecosystem services (tourism)			
Other (please specify)			

6.5. *Qualitative final questions*

14. Are you considering increasing the use of any Land, Atmospheric or Climate Change product/service for any of your forest activities? Which ones?
15. Apart from the above-mentioned climate variables and indicators, is there any additional need, climate indicator, or combined index you would like to have?
16. Is there any other type of data you find useful for taking climate related decisions? Which one?
17. Do you use any additional information such as databases, simulation models, or algorithms that you consider interesting to research or take into account?
18. C3S data is free and open for use, would you be willing to pay for services and applications derived from C3S data that best suit your needs?

☐

I'm interested to pay for the services, depending on the price and the service offer

☐

I'm interested to pay for the services but only as part of a larger service offer to support my forestry operations

☐

Maybe I'm interested to pay for the services but I need more information on potentially saved expenses and benefits

☐

No, I'm not interested in paid services but I'm interested in free Copernicus services

☐

No, I'm not interested

☐

Not relevant for my activities

References

Adams, M., 2013. Mega-fires, tipping points and ecosystem services: Managing forests and woodlands in an uncertain future. For. Ecol. Manage. 294, 250–261. https://doi.org/10.1016/j.foreco.2012.11.039.

Albert, M., Nagel, R.-V., Nuske, R., Sutmöller, J., Spellmann, H., 2017. Tree Species Selection in the Face of Drought Risk—Uncertainty in Forest Planning. Forests 8 (10), 363. https://doi.org/10.3390/f8100363.

Allen, C.D., Breshears, D.D., McDowell, N.G., 2015. On underestimation of global vulnerability to tree mortality and forest die-off from hotter drought in the Anthropocene. Ecosphere 6 (8), art129. https://doi.org/10.1890/ES15-00203.1.

Allen, C.D., Macalady, A.K., Chenchouni, H., Bachelet, D., McDowell, N., Vennetier, M., Kitzberger, T., Rigling, A., Breshears, D.D., Hogg, E.H.T., Gonzalez, P., Fensham, R., Zhang, Z., Castro, J., Demidova, N., Lim, J.-H., Allard, G., Running, S.W., Semerci, A., Cobb, N., 2010. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. For. Ecol. Manage. 259 (4), 660–684. https://doi.org/10.1016/j.foreco.2009.09.001.

Bastos, A., Ciais, P., Friedlingstein, P., Sitch, S., Pongratz, J., Fan, L., Wigneron, J.P., Weber, U., Reichstein, M., Fu, Z., Anthoni, P., Arneth, A., Haverd, V., Jain, A.K., Joetzjer, E., Knauer, J., Lienert, S., Loughran, T., McGuire, P.C., Tian, H., Viovy, N., Zaehle, S., 2020. Direct and seasonal legacy effects of the 2018 heat wave and drought on European ecosystem productivity. Sci. Adv. 6 (24), eaba2724. https://doi.org/10.1126/sciadv.aba2724.

Bessembinder, J., Terrado, M., Hewitt, C., Garrett, N., Kotova, L., Buonocore, M., Groenland, R., 2019. Need for a common typology of climate services. Climate Services 16. https://doi.org/10.1016/j.cliser.2019.100135.

BizEE Software. (2021). BizzEE Degree Days, Weather data for energy saving. https://www.degreedays.net/introduction.

Brun, P., Psomas, A., Ginzler, C., Thuiller, W., Zappa, M., Zimmermann, N.E., 2020. Large-scale early-wilting response of Central European forests to the 2018 extreme drought. Glob. Change Biol. 26 (12), 7021–7035. https://doi.org/10.1111/gcb.v26.1210.1111/gcb.15360.

Bruno Soares, M., Alexander, M., Dessai, S., 2018. Sectoral use of climate information in Europe: A synoptic overview. Clim. Serv. 9, 5–20. https://doi.org/10.1016/j.cliser.2017.06.001.

Bull, J.W., Jobstvogt, N., Böhnke-Henrichs, A., Mascarenhas, A., Sitas, N., Baulcomb, C., Lambini, C.K., Rawlins, M., Baral, H., Zähringer, J., Carter-Silk, E., Balzan, M.V., Kenter, J.O., Häyhä, T., Petz, K., Koss, R., 2016. Strengths, Weaknesses, Opportunities and Threats: A SWOT analysis of the ecosystem services framework. Ecosyst. Serv. 17, 99–111. https://doi.org/10.1016/j.ecoser.2015.11.012.

Buontempo, C., Hutjes, R., Beavis, P., Berckmans, J., Cagnazzo, C., Vamborg, F., Thépaut, J. N., Bergeron, C., Almond, S., Amici, A., Ramasamy, S., & Dee, D. (2020). Fostering the development of climate services through Copernicus Climate Change Service (C3S) for agriculture applications. Weather and Climate Extremes, 27(June 2019). https://doi.org/10.1016/j.wace.2019.100226.

Buras, A., Rammig, A., Zang, S., C., 2020. Quantifying impacts of the 2018 drought on European ecosystems in comparison to 2003. Biogeosciences 17 (6), 1655–1672. https://doi.org/10.5194/bg-17-1655-2020.
Cambi, M., Certini, G., Neri, F., & Marchi, E. (2015). The impact of heavy traffic on forest soils: A review. Forest Ecology and Management, 338, 124–138. https://doi.org/https://doi.org/10.1016/j.foreco.2014.11.022.
Cavelier, R., Borel, C., Charreyron, V., Chaussade, M., Le Cozannet, G., Morin, D., Ritti, D., 2017. Conditions for a market uptake of climate services for adaptation in France. Clim. Serv. 6, 34–40. https://doi.org/10.1016/j.cliser.2017.06.010.
CEPI. (2019). EU FOREST-BASED INDUSTRIES 2050: A vision of sustainable choices for a climate-friendly future.
Copernicus. (2019). Accessing data – the where and how-Copernicus.
Copernicus. The number of heat wave days for European countries derived from climate projections 2020.
Copernicus. (2021). Copernicus Services. https://www.copernicus.eu/en.
Cortekar, J., Themessl, M., & Lamich, K. (2020). Systematic analysis of EU-based climate service providers. Climate Services, 17(October 2019), 100125. https://doi.org/10.1016/j.cliser.2019.100125.
Dalponte, M., Marzini, S., Solano-Correa, Y.T., Tonon, G., Vescovo, L., Gianelle, D., 2020. Mapping forest windthrows using high spatial resolution multispectral satellite images. Int. J. Appl. Earth Obs. Geoinf. 93 (July), 102206 https://doi.org/10.1016/j.jag.2020.102206.
Duncker, P. S., Raulund-Rasmussen, K., Gundersen, P., Katzensteiner, K., De Jong, J., Ravn, H. P., Smith, M., Eckmüllner, O., & Spiecker, H. (2012). How Forest Management affects Ecosystem Services, including Timber Production and Economic Return. Ecology and Society, 17(4). http://www.jstor.org/stable/26269223.
Dupuy, J.-L., Fargeon, H., Martin-StPaul, N., Pimont, F., Ruffault, J., Guijarro, M., Hernando, C., Madrigal, J., Fernandes, P., 2020. Climate change impact on future wildfire danger and activity in southern Europe: a review. Annals of Forest Science 77 (2). https://doi.org/10.1007/s13595-020-00933-5.
Dyderski, M.K., Paź, S., Frelich, L.E., Jagodziński, A.M., 2018. How much does climate change threaten European forest tree species distributions? Glob. Change Biol. 24 (3), 1150–1163. https://doi.org/10.1111/gcb.2018.24.issue-310.1111/gcb.13925.
ECMWF. (2019). World's first wildfire and river flow reanalyses to be updated in near-real time.
EIB. (2020). EIB Group Climate Bank Roadmap 2021-2025 (Issue November 2020).
EnergyCap Software. (2021). Weatherdatadepot. https://www.weatherdatadepot.com/cooling-degree-days.
European Commission. (2015). A European research and innovation roadmap for climate services.
European Commission. (2017). About EFFIS.
European Commission. (2018). A Clean Planet for all. A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy. Com (2018) 773, 114.
European Commission. (2019a). A European Green Deal.
European Commission. (2019b). The European Green Deal. Communication from the commission to the European parliament, the European council, the council, the European economic and social committee and the committee of the regions.
European Commission. (2020). Proposed Mission: A Climate Resilient Europe: Prepare Europe for climate disruptions and accelerate the transformation to a climate resilient and just Europe by 2030. https://doi.org/10.2777/69766.
European Technology Platform. (2020). Strategic research and innovation agenda 2030 of the European forest-based sector.
FAO and UNEP. (2020). The State of the World's Forests 2020. In The State of the World's Forests 2020. FAO and UNEP. https://doi.org/10.4060/ca8642en.
Fontes, L., Bontemps, J.-D., Bugmann, H., Van Oijen, M., Gracia, C., Kramer, K., Lindner, M., Rötzer, T., Skovsgaard, J.P., 2011. Models for supporting forest management in a changing environment. Forest Systems 3 (4), 8. https://doi.org/10.5424/fs/201019s-9315.
Fremout, T., Thomas, E., Gaisberger, H., Van Meerbeek, K., Muenchow, J., Briers, S., Gutierrez-Miranda, C.E., Marcelo-Peña, J.L., Kindt, R., Atkinson, R., Cabrera, O., Espinosa, C.I., Aguirre-Mendoza, Z., Muys, B., 2020. Mapping tree species vulnerability to multiple threats as a guide to restoration and conservation of tropical dry forests. Glob. Change Biol. 26 (6), 3552–3568. https://doi.org/10.1111/gcb.v26.610.1111/gcb.15028.
Giuliani, G., Nativi, S., Obregon, A., Beniston, M., & Lehmann, A. (2017). Spatially enabling the Global Framework for Climate Services: Reviewing geospatial solutions to efficiently share and integrate climate data & information. Climate Services, 8, 44–58. https://doi.org/https://doi.org/10.1016/j.cliser.2017.08.003.
Harjanne, A., 2017. Servitizing climate science—Institutional analysis of climate services discourse and its implications. Global Environ. Change 46 (May), 1–16. https://doi.org/10.1016/j.gloenvcha.2017.06.008.
Hewitt, C.D., Stone, R.C., Tait, A.B., 2017. Improving the use of climate information in decision-making. Nat. Clim. Change 7 (9), 614–616. https://doi.org/10.1038/nclimate3378.
Hijmans, R.J., Cameron, S.E., Parra, J.L., Jones, P.G., Jarvis, A., 2005. Very high resolution interpolated climate surfaces for global land areas. Int. J. Climatol. 25 (15), 1965–1978. https://doi.org/10.1002/(ISSN)1097-008810.1002/joc.v25:1510.1002/joc.1276.
Hlásny, T., Mátyás, C., Seidl, R., Kulla, L., Merganičová, K., Trombik, J., Dobor, L., Barcza, Z., Konôpka, B., 2014. Climate change increases the drought risk in Central European forests: What are the options for adaptation? Forestry Journal 60 (1), 5–18. https://doi.org/10.2478/forj-2014-0001.
Howspace. (2021). Howspace.
Hyvärinen, O., Venäläinen, A., Vajda, A., 2020. Bias-adjusted seasonal forecasts of soil moisture for forestry applications in Finland. Adv. Sci. Res. 17, 23–27. https://doi.org/10.5194/asr-17-23-2020.
IPCC. (2014). Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.
Jackson, T.D., Sethi, S., Dellwik, E., Angelou, N., Bunce, A., van Emmerik, T., Duperat, M., Ruel, J.-C., Wellpott, A., Van Bloem, S., Achim, A., Kane, B., Ciruzzi, D. M., Loheide II, S.P., James, K., Burcham, D., Moore, J., Schindler, D., Kolbe, S., Wiegmann, K., Rudnicki, M., Lieffers, V.J., Selker, J., Gougherty, A.V., Newson, T., Koeser, A., Miesbauer, J., Samelson, R., Wagner, J., Ambrose, A.R., Detter, A., Rust, S., Coomes, D., Gardiner, B., 2021. The motion of trees in the wind: a data synthesis. Biogeosciences 18 (13), 4059–4072. https://doi.org/10.5194/bg-18-4059-202110.5194/bg-18-4059-2021-supplement.
Jönsson, A.M., Appelberg, G., Harding, S., Bärring, L., 2009. Spatio-temporal impact of climate change on the activity and voltinism of the spruce bark beetle, Ips typographus. *Global Change Biology* 15 (2), 486–499. https://doi.org/10.1111/j.1365-2486.2008.01742.x.
Jönsson, A.M., Lagergren, F., 2017. Potential use of seasonal forecasts for operational planning of north European forest management. Agric. For. Meteorol. 244–245, 122–135. https://doi.org/10.1016/j.agrformet.2017.06.001.
Keele, S., 2019. Consultants and the business of climate services: implications of shifting from public to private science. Clim. Change 157 (1), 9–26. https://doi.org/10.1007/s10584-019-02385-x.
Keenan, R.J., 2012. Adaptation of forests and forest management to climate change: An editorial. Forests 3 (1), 75–82. https://doi.org/10.3390/f3010075.
KRAMER, K., 1994. A modelling analysis of the effects of climatic warming on the probability of spring frost damage to tree species in The Netherlands and Germany. Plant, Cell Environ. 17 (4), 367–377. https://doi.org/10.1111/pce:1994.17.issue-410.1111/j.1365-3040.1994.tb00305.x.
Larosa, F., Mysiak, J., 2020. Business models for climate services: An analysis. Clim. Serv. 17, 100111. https://doi.org/10.1016/j.cliser.2019.100111.
Lindner, M., Fitzgerald, J.B., Zimmermann, N.E., Reyer, C., Delzon, S., van der Maaten, E., Schelhaas, M.J., Lasch, P., Eggers, J., van der Maaten-Theunissen, M., Suckow, F., Psomas, A., Poulter, B., Hanewinkel, M., 2014. Climate change and European forests: What do we know, what are the uncertainties, and what are the implications for forest management? J. Environ. Manage. 146, 69–83. https://doi.org/10.1016/j.jenvman.2014.07.030.
Lorenz, R., Stalhandske, Z., Fischer, E.M., 2019. Detection of a Climate Change Signal in Extreme Heat, Heat Stress, and Cold in Europe From Observations. Geophys. Res. Lett. 46 (14), 8363–8374.
Lourenço, T.C., Swart, R., Goosen, H., Street, R., 2016. The rise of demand-driven climate services. Nat. Clim. Change 6 (1), 13–14. https://doi.org/10.1038/nclimate2836.
Maes, J., Teller, A., Nessi, S., Bulgheroni, C., Konti, A., Sinkko, T., Tonini, D., & Pant, R. (2020). Mapping and assessment of ecosystems and their services: An EU ecosystem assessment. In JRC Science for Policy Reports. European Commission. https://doi.org/10.2760/757183.
Mañez, M., Zolch, T., Cortekar, J., 2014. Mapping of Climate Service Providers Theoretical Foundation and Empirical Results : A German Case Study - CSC Report 15. CSC Report 15, 54 pages.
Máñez, M., Zölch, T., & Cortekar, J. (2014). Mapping of Climate Service Providers Theoretical Foundation and Empirical Results : A German Case Study, CSC Report 15. Climate Service Center.
Marchi, M., Sinjur, I., Bozzano, M., & Westergren, M. (2019). Evaluating WorldClim Version 1 (1961 – 1990) as the Baseline for Sustainable Use of Forest and Environmental Resources in a Changing Climate. 1, 1–14.
Marconcini, M., Esch, T., Bachofer, F., Metz-Marconcini, A., 2020. In: Manual of Digital Earth. Springer Singapore, Singapore, pp. 647–681. https://doi.org/10.1007/978-981-32-9915-3_20.
Menzel, A., & Fabian, P. (1999). Growing season extended in Europe. Nature, 397(6721), 659. https://doi.org/10.1038/17709.
NWGC. (2019). Wildland Fire Decision Support System. National Wildfire Coordinating Group (US Government). https://wfdss.usgs.gov/wfdss/WFDSS_About.shtml.
Palma, J.H.N., Cardoso, R.M., Soares, P.M.M., Oliveira, T.S., Tomé, M., 2018. Using high-resolution simulated climate projections in forest process-based modelling. Agric. For. Meteorol. 263 (August), 100–106. https://doi.org/10.1016/j.agrformet.2018.08.008.
Pecchi, M., Marchi, M., Burton, V., Giannetti, F., Moriondo, M., Bernetti, I., Bindi, M., Chirici, G., 2019. Species distribution modelling to support forest management. A literature review. *Ecological Modelling* 411, 108817. https://doi.org/10.1016/j.ecolmodel.2019.108817.
PWC. (2019). Copernicus Market Report - February 2019. Luxembourg: Publications Office of the European Union, 2016. https://doi.org/10.2873/011961.
Reyer, C.P.O., Silveyra Gonzalez, R., Dolos, K., Hartig, F., Hauf, Y., Noack, M., Lasch-Born, P., Rötzer, T., Pretzsch, H., Meesenburg, H., Fleck, S., Wagner, M., Bolte, A., Sanders, T.G.M., Kolari, P., Mäkelä, A., Vesala, T., Mammarella, I., Pumpanen, J., Collalti, A., Trotta, C., Matteucci, G., D'Andrea, E., Foltýnová, L., Krejza, J., Ibrom, A., Pilegaard, K., Loustau, D., Bonnefond, J.-M., Berbigier, P., Picart, D., Lafont, S., Dietze, M., Cameron, D., Vieno, M., Tian, H., Palacios-Orueta, A., Cicuendez, V., Recuero, L., Wiese, K., Büchner, M., Lange, S., Volkholz, J., Kim, H., Horemans, J.A., Bohn, F., Steinkamp, J., Chikalanov, A., Weedon, G.P., Sheffield, J., Babst, F., Vega del Valle, I., Suckow, F., Martel, S., Mahnken, M., Gutsch, M., Frieler, K., 2020. The PROFOUND Database for evaluating vegetation models and simulating climate impacts on European forests. Earth Syst. Sci. Data 12 (2), 1295–1320. https://doi.org/10.5194/essd-12-1295-202010.5194/essd-12-1295-2020-supplement.

Additional information about data protection - Annex, 2 (2020). https://survey.tecnalia.com/Privacy_Policy/Copernicus-Forest-en.pdf.

Sinha, R., Shameem, M., Kumar, C., 2020. February). SWOT: Strength, weaknesses, opportunities, and threats for scaling agile methods in global software development. In: ACM International Conference Proceeding Series. https://doi.org/10.1145/3385032.3385037.

Stone, D.M., 2002. Logging Options to Minimize Soil Disturbance in the Northern Lake States. North. J. Appl. For. 19 (3), 115–121. https://doi.org/10.1093/njaf/19.3.115.

Street, R.B., 2016. Towards a leading role on climate services in Europe: A research and innovation roadmap. Clim. Serv. 1, 2–5. https://doi.org/10.1016/j.cliser.2015.12.001.

Suvanto, S., Peltoniemi, M., Tuominen, S., Strandström, M., Lehtonen, A., 2019. High-resolution mapping of forest vulnerability to wind for disturbance-aware forestry and climate change adaptation. BioRxiv. https://doi.org/10.1101/666305.

Takolander, A., Hickler, T., Meller, L., Cabeza, M., 2019. Comparing future shifts in tree species distributions across Europe projected by statistical and dynamic process-based models. Reg. Environ. Change 19 (1), 251–266. https://doi.org/10.1007/s10113-018-1403-x.

Vaughan, C., Dessai, S., 2014. Climate services for society: Origins, institutional arrangements, and design elements for an evaluation framework. Wiley Interdiscip. Rev. Clim. Change 5 (5), 587–603. https://doi.org/10.1002/wcc.290.

VERBI Software. (2019). MAXQDA 2020 [computer software]. maxqda.com.

Vitasse, Y., Bottero, A., Cailleret, M., Bigler, C., Fonti, P., Gessler, A., Lévesque, M., Rohner, B., Weber, P., Rigling, A., Wohlgemuth, T., 2019. Contrasting resistance and resilience to extreme drought and late spring frost in five major European tree species. Glob. Change Biol. 25 (11), 3781–3792. https://doi.org/10.1111/gcb.v25.1110.1111/gcb.14803.