Discussion of Simulation Results

The results demonstrate the potential of targeted forest management to significantly reduce fire risk. The strategic placement of **firewalls**, the promotion of **mature forest stands** contribute to a more fire resilient landscape. The integration of **urban and WUI zones** into fire models will make simulations more accurate and provide actionable insights for the local stakeholders in Nouvelle-Aquitaine, allowing them to tailor management strategies to specific risk zones.

A5.3.3 Conclusion and Next Steps

This report presents the detailed methodology and results of the IA 2.2 implementation in the Nouvelle-Aquitaine Living Lab (LL AQT). By integrating advanced fire simulation tools like Prometheus and BURN P3 with forest management strategies, LL AQT has developed a framework for reducing fire risk and enhancing landscape resilience. The simulations demonstrate the effectiveness of various land-use arrangements and forest management interventions in mitigating fire spread across the region.

Next Steps:

1. **Integration of WUI Zones**: A key priority moving forward is to integrate Wildland-Urban Interface (WUI) zones into the fuel map. These areas, where human settlements meet forested regions, represent a critical factor in wildfire risk management. Future simulations will incorporate WUI zones to ensure that fire prevention and resilience strategies account for the proximity to urban areas.
2. **Applying Simulations to the fusion of Landes and Gironde**: The immediate priority is to apply forest management simulations to the combined landscape of the Landes and Gironde departments. This will involve running new fire simulations that integrate both departments, allowing for more comprehensive risk assessment and management strategies tailored to the larger landscape.
3. **Linking with other Work Packages:** The simulations resulting from this work package (WP2) will be used in **WP4**, specifically for the fires forum. We will present fire risk assessments at the landscape level for the **Pays de BORN** and **Pays BARVAL** municipalities. The simulations are also providing insights into the free evolution of wildfires, which is crucial for municipalities to consider when revising urban planning strategies to create more fire-resilient landscapes. Additionally, this information will be used in policy clinics to discuss necessary adjustments to legal instruments at the regional level, promoting resilience as identified through our modeling efforts.
4. **Visit to Canada and upgrade to BURN P3+**: A critical next step is meeting in person the developers of BURN P3, including **Marc-André Parisien**, in Canada. This visit will focus on upgrading the current fire simulation tools to **BURN P3+**, which offers enhanced modeling capabilities. The upgrade will allow for more precise simulations and the ability to incorporate additional variables such as climate projections and more complex land-use configurations.

5. **Publication of results**: Once the updated simulations with BURN P3+ are completed, the results will be published in relevant scientific journals and shared with stakeholders. The publication will include detailed analyses of the simulations and their implications for forest management practices in fire-prone landscapes. This will ensure that the knowledge gained through this project can contribute to broader efforts in wildfire risk reduction and landscape resilience across Europe.

3.10 References

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4. Land use change (LUC) suitability analysis (Section 2)

4.1 Introduction

4.1.1 Expected climatic impact

The latest IPCC report (Arias et al., 2021) highlights the increasing frequency of heat extremes and a reduction in colder extremes. These climatic shifts are expected to have a more significant impact on crop yields than factors like soil type or cultivar (Blanco-Ward et al., 2017). Projections indicate substantial challenges for rural systems, with changes in production areas and the need for adaptation strategies, such as selecting cultivars better suited to future conditions. In the Mediterranean, agriculture is especially vulnerable to rising temperatures, extreme weather, droughts, and soil salinity, leading to altered growing cycles (Funes et al., 2016), increased water demands (Funes et al., 2021; Savé et al., 2012), water scarcity (Montsant et al., 2021; Vicente-Serrano et al., 2017), and reduced yields (Zhao et al., 2015), as well as soil salinity constraints (Connor et al., 2012). Numerous studies have documented the negative impacts of climate change on vineyards (Bernardo et al., 2018; Lorenzo et al., 2015; Xyrafis et al., 2022) and apple cultivation (Ahmadi et al., 2018; Li et al., 2019; Pfleiderer et al., 2019).

Mountain regions, once limited by short growing seasons and cooler temperatures, may benefit from warmer conditions, allowing for a broader range of cultivars (Blanco-Ward et al., 2019; Mosedale et al., 2016). As a result, mountainous agriculture has gained prominence as a response to global warming, offering the potential for high-quality produce (Arias et al., 2022; Modina et al., 2023; Sahu et al., 2020). However, these areas also face challenges due to their more variable environmental conditions. Frost risk is particularly concerning, as it can severely damage crops (Campos et al., 2017; Dami et al., 2012; Iglesias et al., 2020), and the rugged terrain complicates the use of agricultural machinery, making cultivation labour-intensive and less efficient.

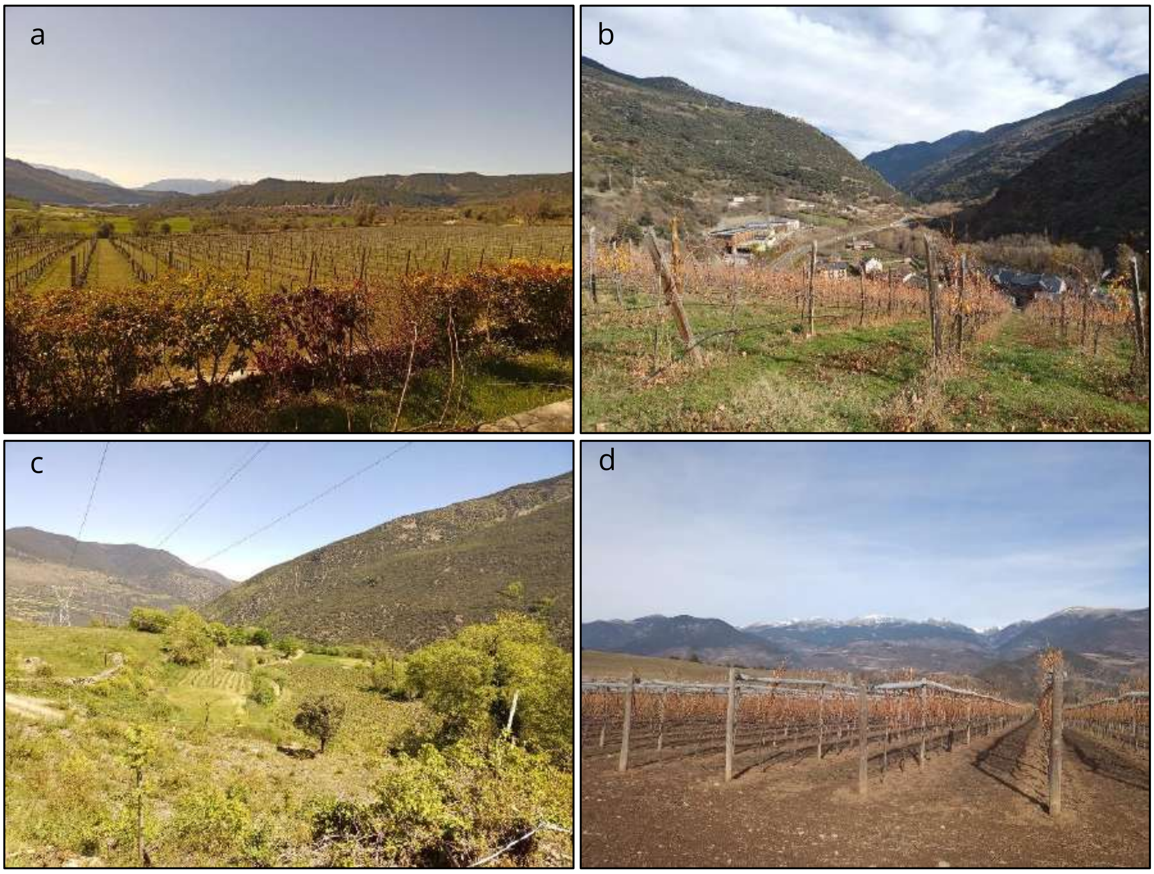


Figure 35. Vineyards in mountainous regions. a) Solana Roivert winery (605 m.a.s.l.); b) Cota 730 winery (760 m.a.s.l.); c) Celler Batlliu de Sort (880 m.a.s.l.); d) Cal Mandrat winery (1,230 m.a.s.l.).

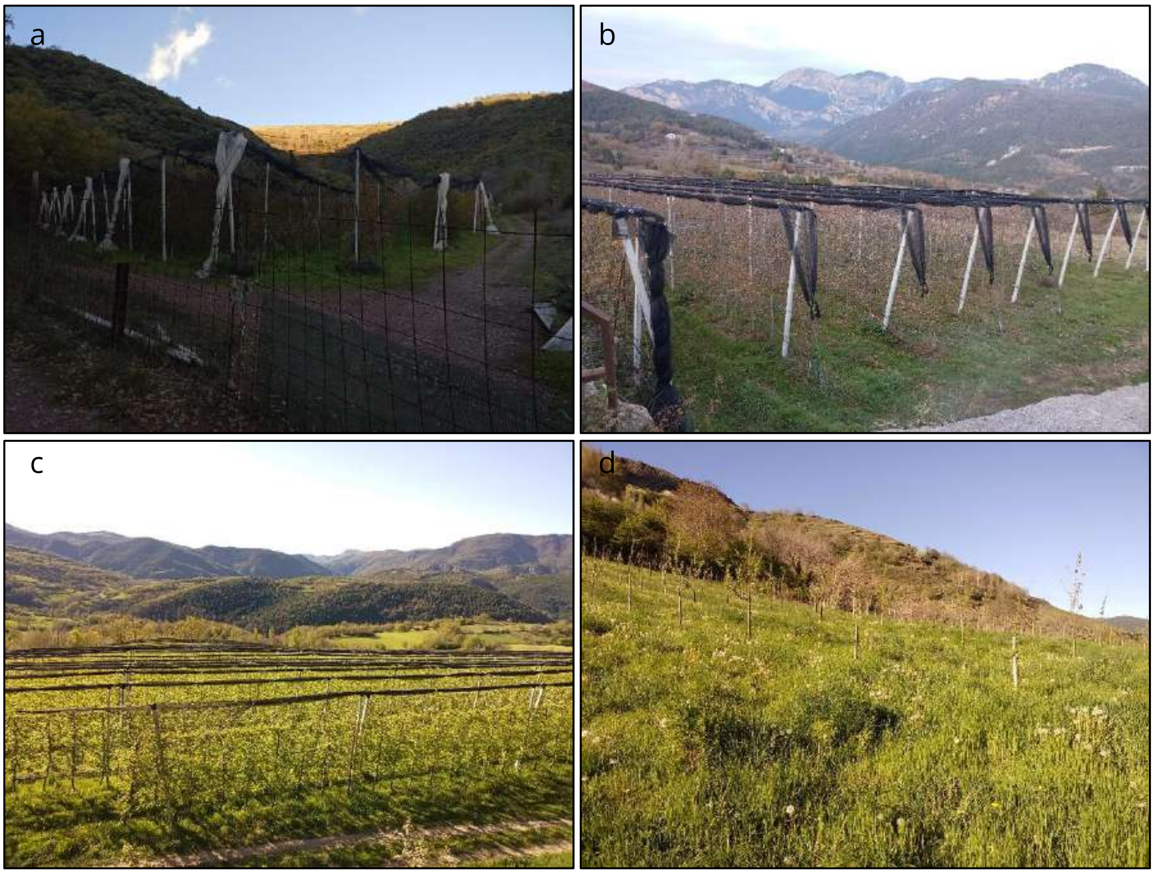


Figure 36. Apple orchards in mountainous regions. a) Escós (825 m.a.s.l.); b) Sant Llorenç de Morunys (907 m.a.s.l.); c) Gotarta (1200 m.a.s.l.); d) Saurí (1225 m.a.s.l.).

4.1.2 Wildfire events

The escalating drought conditions under global warming have exacerbated the frequency and distribution of Extreme Wildfire Events (EWE, as defined by (Castellnou et al., 2009)), particularly in Mediterranean regions (Fernandez-Anez et al., 2021; Ruffault et al., 2018). These events exert profound economic, social, and ecological impacts (Schoennagel et al., 2017). While EWE have been primarily associated with extreme weather conditions, they may also be influenced by landscape-level characteristics, such as land use/land cover composition and configuration (Rego et al., 2021). Patch size distribution may determine the resilience of landscapes to future fires (Hessburg et al., 2007) and the presence of agricultural plots has been seen to effectively buffer increased wildfire risk (Moreira et al., 2011; Nunes, 2012). Different studies highlighted the relevance of developing mosaic-landscapes with patches of agricultural land as an important strategy to promote fire-resistant and resilient landscapes (Acácio et al., 2023; Lecina-Diaz et al., 2023; Moreira and Pe'er, 2018).

Contrarily to what is needed to implement a better adapted landscape towards EWE, there has been a tendency over the past decades to land abandonment in almost all European countries (Pointereau et al., 2008). Mountainous areas are particularly vulnerable, presenting a three times higher risk than non-mountainous (Dax et al., 2021). Consequently, natural forest re-growth is increasingly replacing antique agricultural or pastural lands (Baldock et al., 1996; Gellrich and Zimmermann, 2007; Nikodemus et al., 2005). Those two combined factors lead, among other outcomes, to a higher probability of wildfires (Estoque et al., 2019; Romero-Calcerrada and Perry, 2004). Useful preventing practices traditionally applied in rural communities such as fire as a tool for land management (Tedim et al., 2016) diminished due to its perception as a threat rather than an ecological process, which reinforced fire exclusion and suppression policies. Another useful but recently less applied technique is shrub clearing combined with livestock farming (Lasanta et al., 2018; Muñoz-Ulecia et al., 2024). The increasing investment in fire suppression as the main tool, at the expense of prevention, has paradoxically contributed to fuel accumulation (Moreira et al., 2020). Consequently, rural mountain landscapes have become more homogeneous and flammable and, in turn, more susceptible to EWE (Moreira et al., 2011). All that recent information gathered about EWE suggest the need to change the paradigm in fire management policies from suppression to prevention, addressing the interlinked social, ecological, and economic systems behind the ignition and spread of wildfires (Moreira et al., 2020). Fire-smart management has been proposed as “an integrated approach primarily based on fuel treatments through which the socio-economic impacts of fire are minimized while its ecological benefits are maximized” by Hirsch et al. (2001) (Fernandes, 2013; Lecina-Diaz et al., 2023). In that sense, agricultural solutions can contribute to the increase of landscape heterogeneity, reducing fire spread and lowering the continuity of fuel, accumulated due to rural abandonment and fire exclusion policies (Ascoli et al., 2023; Lecina-Diaz et al., 2023; Moreira and Pe'er, 2018).

High Nature Value farmlands (HNVf; as described by Beaufoy et al. (1994)) in mountainous rural landscapes compose low-intensity agricultural and livestock activities, which are often associated with areas rich in biodiversity. Lecina-Diaz et al. (2023) results suggest that the potential net suppression cost savings can be substantial under HNVf scenarios. The most efficient scenario combines both HNVf with fire-smart management. Pais et al. (2023) results suggest that a landscape-oriented approach (e.g., random burning) combined with HNVf areas and HNVf areas with prescribed fire conversion will have greater overall effects on reducing wildfire areas over a 30-year period than under business-as-usual (which represents the most recent rural abandonment trend) scenarios. Focusing treatment efforts on areas with a medium–high fire hazard appears to be the option with the greatest impact on future fire mitigation, especially when combined with landscape transformations. Consequently, combining prescribed burning with “fire-smart” land-use policies, such as the promotion of HNVf and the restoration of native woodlands, can significantly enhance efficiency. This synergistic approach can reduce the area requiring annual treatment. However, agriculture practices in mountainous regions may be uncompetitive and difficult for local people to perform due to the demanding conditions in comparison to habitual cultivation areas. In addition, farmers are only financially rewarded for commodity production, but not for the societal benefits derived from the provision of public good ecosystem services and their contribution to suppressing wildfires. Limited financial resources are a prominent barrier to wildfire prevention in southern Europe, especially when fuel management is decoupled from the market, and agro-forestry land uses with a fire regulatory capacity are not integrated into wildfire risk management planning (Ascoli et al., 2023). Ascoli et al. (2023) provide a set of experiences that successfully applied fuel management practices in different territories, thus surpassing part of the economic limitation factor and achieving valuation on fire-marketing products.

The complex interactions between crops and climate, fire-vegetation dynamics, and LUC under climate change hinder the efficient management of rural landscapes (Oliveira et al., 2016; Thompson et al., 2017). Therefore, agricultural land management in mountainous areas should consider multiple objectives and needs. In addition, any decision regarding crop potential should be based on marketable production and sustainable management strategies to guarantee maintained production and provide long-term economic benefits.

4.2 Objective

The aim of this deliverable is to provide suitability maps for two woody crops (vineyards and apple orchards) in mountainous regions in the central-west region of the Southern Pyrenees and Pre-Pyrenees. Those could give an example of the range of possibilities to strategically introduce HNVf solutions in mountainous regions to reduce wildfire areas. Moreover, suitability maps were overlapped with the results from the IA 2.3 to better specify where those woody crops could be planted to enhance landscape resistance and resilience against wildfire events. Finally, main socio-economic limitations to develop the farming activity were also identified and summarized.

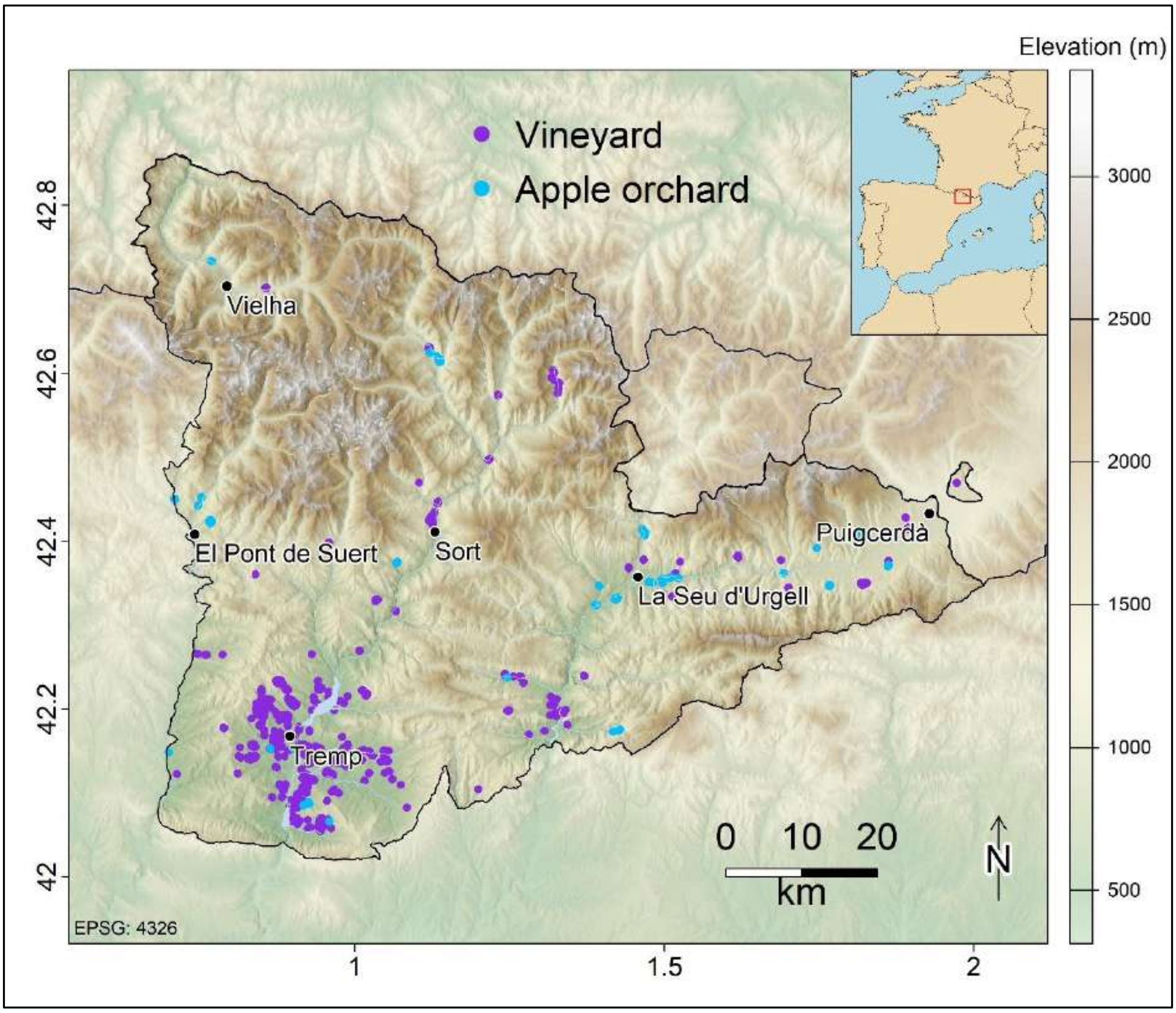


Figure 37. Study area with vineyards and apple orchards according to SIGPAC (2022) and DUN (2022).

4.3 Material and methods

Suitability assessment in agriculture is a multidimensional concept involving complex and interrelated factors (Purvis et al., 2018), necessitating the use of multi-criteria decision analysis (MCDA) approaches. These approaches must handle diverse sources of information, uncertainty, and expert knowledge and preferences (Banai-Kashani, 1989; Pashaei Kamali et al., 2017). The complexity of the indices involved in the model and their relationship with each crop implies that suitability thresholds are not abrupt but rather fuzzy (Cornelissen et al., 2001). Therefore, to establish the most suitable relationship between indicators and crop development, fuzzy logic is employed (Zadeh, 1988). Fuzzy logic allows for the integration of numerical and categorical variables of different scales, facilitating the expression of sustainability assessment indices (de Vos et al., 2013; Prato, 2005). Subsequently, to address the highly complex nature of the problem and integrate all selected indices in the MCDA, the Analytic Hierarchy Process (AHP) was utilized (Saaty, 1987). AHP is a mathematical method for resolving complex land management problems by identifying the best alternatives. It works through a pair-wise comparison matrix and relies on the judgements of experts to derive priority scales (Saaty, 2008). The comparisons are made using a scale of absolute judgements that represents how much more one element dominates another with respect to a given attribute. Experts are crucial in the MCDA to weight the importance of all the criteria conforming the model because not all of them are of equal importance (Gigović et al., 2017).

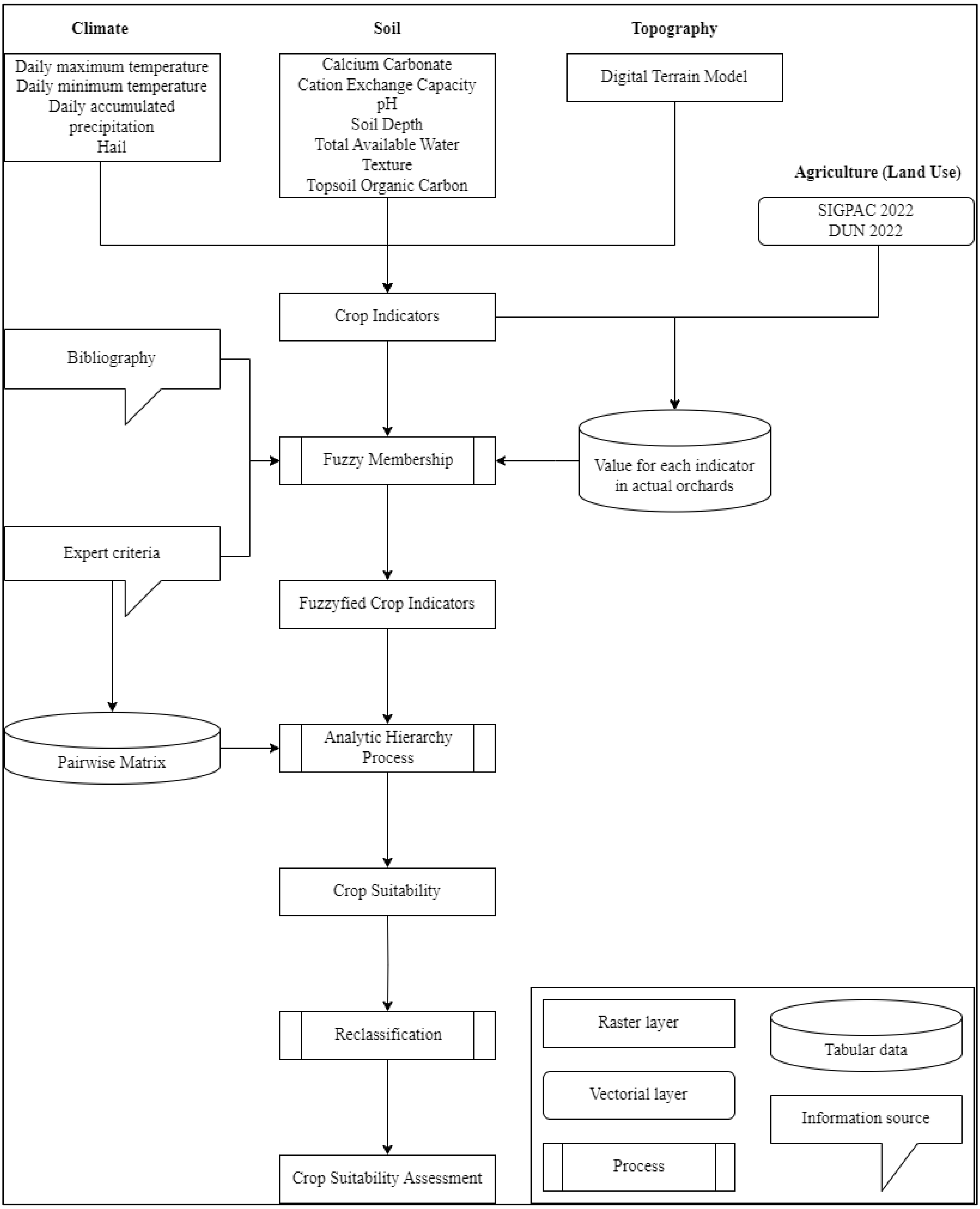


Figure 38. Methodological approach for the multicriteria analysis.

The indicators used in the multicriteria analysis were selected based on their relevance in understanding general climate characteristics of vineyards and apple orchards regions, their ability to depict cultivar suitability, and their widespread acceptance and utilization in various regions (Alsafadi et al., 2020; Beyene et al., 2022; del Río et al., 2021). The complete set of indicators was categorized into three primary groups: a) climate, b) soil, and c) topography.

a) For climate: the *Hydrothermic index of Branas, Bernon, Levadoux* (BBL) accounts for the influence of temperature and rainfall on grape production; *Cold Days late spring* (CDls) represent cold waves that can induce flower abortion and pollen and ovule infertility, which cause fertilization breakdown and affect seed filling, leading to low seed production; *Frost Risk early autumn* (FRea) details the frost occurrence during the final stages of maturation and the start of harvest; *Frost Risk late spring* (FRls) has the same function as FRea but for flowering and the initial stages of fruit formation; *Growing Season Precipitation* (GSP) summarizes the total precipitation during all the annual development cycle; *Growing Season Temperature* (GST) measures the average temperature during the same period as GSP; *Hail* (Ha) represents the days with a high probability of hailstorms during flowering and the initial stages of fruit formation; the *Heliothermal Index of Huglin* (HI) provides information regarding the level of heliothermal potential and about the sugar potential according to variety; *Night Cold Index ripening* (NCIr) is a night coolness variable that takes into consideration minimum temperatures during ripening to improve the assessment of qualitative potentials of wine-production regions; *Net Hydric Needs* (NHN) shows how changes in land water balance result from the combination of changes in crop phenology, potential evapotranspiration, and crop distribution; *Stressful Hot Days ripening* (SHDr) represent heat waves that can cause burn scars or loss of fruits; the *Winkler Index* (WI) or *Growing Degree Days* (GDD) classifies regions based on the heat accumulation during the growing season.

b) For soil: *Calcium Carbonates* ($CaCO_3$) address some measure of the soil structure and aggregation, with an excess negatively affecting the mineralization rate of the soil organic matter (Virto et al., 2018); *Cation Exchange Capacity* (CEC) exhibits the soil's ability to retain cations; *pH* (pH) gives an indication of the nutrient balance and fertility; *Soil Depth* (SD) offers an estimation of the potential available volume for roots to expand into, but also indicates the soils' potential moisture holding ability; *Total Available Water* (TAW) is the volume of water that is nominally available for plant growth; *Texture* (Te) shows different soil properties in terms of agricultural use such as the drainage and nutrient retention capacity; *Topsoil Organic Carbon* (TOC) is measured in the first 40 cm and expresses the soil quality and fertility.

c) For topography: *Aspect* (As) affects the angle at which sunlight hits the vineyard and its total heat balance characteristics, which affect final fruit composition; *Growing season Solar Radiation* (GSR) affects the soil and air temperature, transpiration, soil moisture, and atmospheric humidity during the annual development cycle; *Slope* (Sl) is important to soil water drainage, but it also affects the daily maintenance of crops in direct relation to machine manoeuvrability.

Growing seasons were defined and divided into its most important phenological stages for each crop. For grapevines, bud break – flowering (April – June) and maturation –

harvest (August – October) were especially vulnerable to negative weather events (particularly frost) due to their importance to final production (Anastasiou et al., 2022; Tonietto and Carbonneau, 2004). For apple orchards, bud break – flowering (April – May) and maturation – harvest (September – October) were also especially vulnerable to negative weather events (Iglesias et al., 2020). The phenological stage of apple bloom precedes that of grapevine flowering, which makes them more susceptible to frost damage and, consequently, to a decrease in final yield. Various studies have corroborated total yield losses caused by late spring frosts (T° < - 5 °C) occurring towards the end of May (Iglesias et al., 2020).

Table 53. Summary of indicators. Where T_{max} = Daily maximum air temperature (°C); T_{min} = Daily minimum air temperature (°C); T_x = Daily mean air temperature (°C); T_{mx} = Monthly mean temperature (°C); T_{base} = Base temperature (°C), which, for Vineyard physiological activities (such as photosynthesis and transpiration), is considered to be 10 °C (Winkler et al., 1974) and for apple 4 °C (González-Noguer et al., 2023); P = Daily total rainfall (mm); P_m = Monthly total rainfall (mm); D_{o35} = Day with a maximum temperature over 35 °C; D_{b0} = Day with a minimum temperature below 0 °C; D_{b15} = Day with a mean temperature below 15 °C; n = Number of days; D_{Ha} = Day with hail probability; d = Length of day coefficient (42°01' - 44°00') = 1.03.

Code	Units	Definition	Orchard	References
BBL	°C*mm	$\sum_{01.04}^{31.08} T_{mx} * Pm$	Vineyard	*Lorenzo et al. (2015)* *Alsafadi et al. (2020)* *Anastasiou et al. (2022)*
CDls	days	$\sum_{01.05}^{30.06} D_{b15}$	Vineyard	*Alsafadi et al. (2020)* *Vasconcelos et al. (2009)*
FRea	days	$\sum_{01.09}^{31.10} D_{b0}$	Vineyard Apple	-
FRls	days	$\sum_{01.05}^{30.06} D_{b0}\_vineyard \sum_{15.04}^{30.05} D_{b0}\_apple$	Vineyard Apple	-
GSP	mm	$\sum_{01.04}^{31.10} P$	Vineyard	*Blanco-Ward et al. (2019)* *Zito et al. (2023)*
GST	°C	$\frac{(\sum_{01.04}^{31.10} \frac{(Tmax + Tmin)}{2})}{n}$	Vineyard	*Admasu et al. (2022)* *Cardell et al. (2019)* *Jones et al. (2010)*
Ha	days		Apple	-
HI	°C	$\sum_{15.04}^{30.05} DHa$	Vineyard	*Alsafadi et al. (2020)*

		$\sum_{01.04}^{30.09}\left(\frac{((Tx-10)+(T_{max}-10))}{2}\right)*d$		*Tonietto and Carbonneau (2004)*
NCIr	°C	$\frac{(\sum_{01.08}^{31.10}T_{min})}{n}$	Vineyard	*Alsafadi et al. (2020)* *Tonietto and Carbonneau (2004)*
NHN	mm/year	*As described in Funes et al. (2021)*	Vineyard Apple	*Funes et al. (2021)* *Tonietto and Carbonneau (2004)*
SHDr	days	$\sum_{01.08}^{31.10}D_{o35}$	Vineyard Apple	*Alsafadi et al. (2020)* *Blanco-Ward et al. (2017)*
WI GDD	°C	$\sum_{01.04}^{30.09}\left(\frac{(T_{max}+T_{min})}{2}\right)-Tbase$	Vineyard Apple	*Alsafadi et al. (2020)* *Cardell et al. (2019)* *Jones et al. (2010)*
$CaCO_3$	%	*As described in Ballabio et al. (2019)*	Vineyard Apple	*Alsafadi et al. (2020)* *Garrido (1994)*
CEC	cmol/kg	*As described in Ballabio et al. (2019)*	Vineyard Apple	*Proffitt (2014)* *Rusjan et al. (2007)*
pH	-	*As described in Ballabio et al. (2019)*	Vineyard Apple	*Admasu et al. (2022)* *Jones et al. (2004)* *White (2003)*
SD	category (cm)	*Depth class of an obstacle to roots within the soil typological unit. As described in Panagos et al. (2022)*	Vineyard Apple	*Kim and Shim (2018)* *Manandhar et al. (2013)* *Wolf and Boyer (2003)*
TAW	mm	*((fc - wp) * SD) * 10* *fc and wp as described in Toth et al. (2015)*	Vineyard	*Funes et al. (2021)* *Oliver et al. (2013)* *Wolf and Boyer (2003)*
Te	category	*As described in Ballabio et al. (2016)*	Vineyard	*Kurtural et al. (2010)* *Chozom and Nimasow (2021)* *Kim and Shim (2018)*
TOC	%	*Depth class of an obstacle to roots within the soil typological unit. As described in Panagos et al. (2022)*	Vineyard Apple	*Oliver et al. (2013)* *Šimanský et al. (2023)* *Wolf and Boyer (2003)*
As	°	*Terrain function as described in Hijmans (2023)*	Vineyard Apple	*Chozom and Nimasow (2021)* *Nesbitt et al. (2018)* *Salata et al. (2022)*
GSR	kWh/m^2	*Raster Solar Radiation (April - October) using ArcGIS Pro 3.2*	Vineyard Apple	*Mania et al. (2021)* *Salata et al. (2022)*

				Torres et al. (2020)
SI	%	*Terrain function as described in Hijmans (2023)*	Vineyard Apple	*Admasu et al. (2022)* *Alsafadi et al. (2020)* *Manandhar et al. (2013)*

One of the criticisms levelled at the conventional land-use suitability analysis is that the underlying assumptions of precise input data are unrealistic. In a complex land-use suitability analysis, it is difficult to provide the accurate numerical information required by conventional methods based on Boolean algebra. Fuzzy set theory (Zedeh, 1989) and logic can address issues related to vagueness, imprecision, and ambiguity in land-use suitability procedures (Badr et al., 2018). Fuzzy logic allows the representation of the data distribution according to a user-imposed 'optimum' mid-point and spread value for different model/fuzzy membership types, which yields a more realistic output compared to Boolean methods. This becomes especially useful when dealing with problems in which the source of fuzziness is the absence of sharply defined criteria (Zimmermann, 2001). The spread value defines the width and character of the transition zone and directs the distribution of the data over a range of association from 0 (not a member) to 1 (definitely a member) (Malczewski, 2004). In the model, different proposed membership functions were used to represent distinct ways in which changes in factor values were thought to influence suitability.

To define the best fit value for each individual indicator in relation to crop suitability, a combination of three criteria were utilized. Firstly, expert criteria played a critical role in defining optimal and inadequate levels, which has been reported to be a valuable source for the model (de Vos et al., 2013). This achievement was made possible through collaboration with a dedicated team of crop specialist researchers, technicians, and farmers. Their combined years of experience in vineyards and apple orchards were invaluable to the success of this project. Secondly, a review of journal articles and other published data (Admasu et al., 2022; Badr et al., 2018; Beyene et al., 2022; Cardell et al., 2019; Chozom and Nimasow, 2021; del Río et al., 2021; Fraga et al., 2014; Jones et al., 2005; Kim and Shim, 2018; Lone et al., 2023; Nesbitt et al., 2018; Ramos et al., 2008; Tonietto and Carbonneau, 2004) provided information to compare the values proposed by expert groups. Thirdly, using actual agricultural plots (DUN, 2022; SIGPAC, 2022), the value of each indicator was extracted and summarized to visualize how they behave in an already-cultivated area.

An analysis of land suitability requires the consideration of several criteria for specific land use. The Analytic Hierarchy Process (AHP) method (Saaty, 1987; Saaty, 2008) is a well-known multi-criteria technique that has been incorporated into GIS-based suitability procedures (Alsafadi et al., 2020; Rahman and Saha, 2008; Stefanova and Arnaudova, 2020). It calculates the required weighting factors with the help of a pair-wise matrix where all identified relevant criteria are compared against each other with reproducible preference factors. It then aggregates the weights of the criterion map layers. The pair-wise comparison method employs an underlying semantic scale with values from 1 to 9 (with 9 representing absolute importance and 1 absolute triviality) to rate the relative importance of two elements of the hierarchy (Saaty, 1987; Saaty, 2008). The procedure greatly reduces the conceptual complexity of a problem since only two components are considered at any given time. This allowed for an independent evaluation of the contribution of each criterion, thereby simplifying the decision-making associated with the cultivation of economic vineyards and apple orchards. This comparison between indicators was performed using the expert criteria proposed by the researchers and technicians. Although this method is reliant upon the judgement of experts to determine site suitability, errors related to judging the relative importance of factors on site suitability analysis can be both detected and corrected (Banai-Kashani, 1989).

A pair-wise comparison matrix is first constructed only between the three main groups to categorize the importance between them. In a second step, each of the indicators is individually compared to the others of the same main group. This provides the relative importance of each indicator inside its group. To obtain the final weight, each indicators' relative value is multiplied by its main group weight.

The weights taken from the pair-wise matrix should be consistent. The AHP provides information about the compatibility preferences between those weights as an indicator of the degree of consistency. A Consistency Ratio (CR) of 0.10 or less indicates a reasonable level of consistency (Saaty, 1987).

To classify suitability in this study, seven classes were defined, from less to more suitable, based on the result of the AHP. Although the suitability classification system is inspired by the FAO framework (FAO, 1976, 2007), it does not include any cost analysis and it was established to improve the interpretation of the results. Consequently, the system varies in the classes proposed but it better suits the needs of the analysis and the representation of the results, working on a sliding-scale in which criterion values range from 0 (totally unsuitable) to 1 (very highly suitable). Consequently, the interpretation of the classification of each pixel is highly criterion dependent. The seven suitability classes in ascending order are: minimal (0 – 0.3), very low (0.3 – 0.4), low (0.4 – 0.5), moderate (0.5 – 0.6), good (0.6 – 0.7), very good (0.7 – 0.8), and high (0.8 – 1).

To finally compare the suitability of each crop with fire priority areas the results were compared to the ones of IA2.3. This aimed to create the best fuel treatment layout in the rural area within the Wild-land Urban Interface (WUI) to protect it against wildfires, considering economic, social and ecological constraints (e.g. through budget and treatment costs, and preserving habitat cohesion and natural corridors based on species distribution maps, in case they are available). It was achieved by an integrated system that predicts fire occurrence (using machine learning to predict ignition probabilities over the landscape), which was used to run multiple simulations of fire spread using the stochastic fire spread simulator called “Cell2Fire” adapted to the Catalan fuel types, that couples in a smooth way with several decision-making models to find the best fuel breaks allocation targeting to protect the WUI.

The socio-economic analysis was performed in two steps. Firstly, by visiting all the willing farmers to interview them with a series of questions regarding their activity and how it has been developed since the beginning. Secondly, by reviewing all the limiting factors that one may encounter while trying to start this new activity (e.g., cutting trees to create an agricultural plot or implementation of an irrigation system).

4.3.1 Validation

Although values for each indicator in existing vineyards and apple orchards were extracted for a better understanding of how they behave in the existing context, the location of those plantations were not used to directly evaluate the general performance of the land assessment system. This was due to consider that evaluated orchards may not be in highly suitable plots. In mountainous areas, farmers willing to establish vineyards or apple orchards are usually conditioned by socio-economic factors and often do not have the possibility to survey and select highly climatically adequate plots. This situation has been noted by other authors while assessing crop suitability using models (Estes et al., 2013; Heumann et al., 2011; Mosedale et al., 2016). In our specific case, this condition was accentuated given the novelty of these type of crops in mountainous areas (most farmers commenced this activity less than 15 years ago and, in a lot of cases, these crops do not represent the primary economic activity). In addition, surveys conducted among farmers in the region showed that landowners planted directly on their property (without conducting an exhaustive adequation study) and land tenants planted where they could find available and affordable plots.

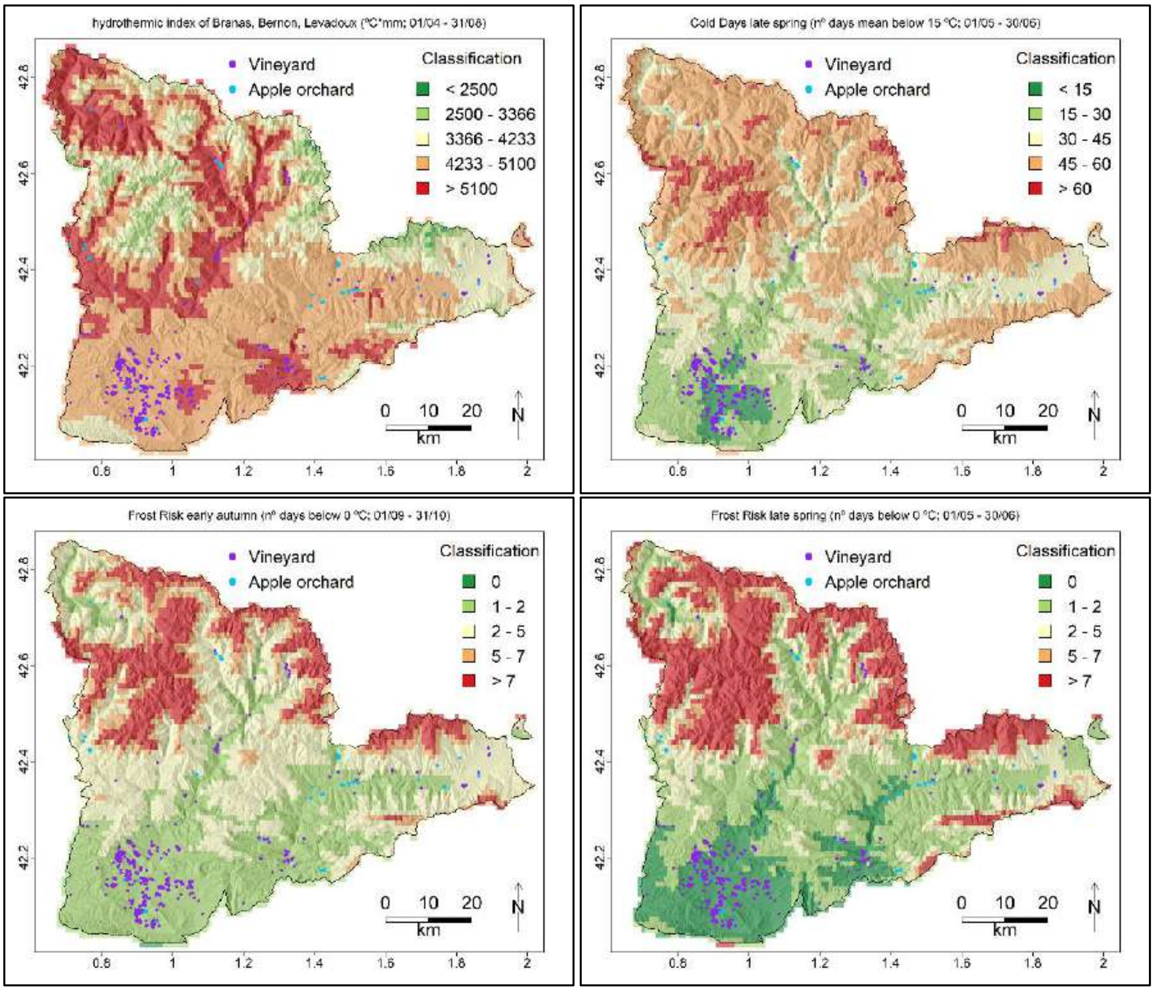
This was also considered an important factor when selecting the suitability assessment approach used in this study against other multi-criteria analysis like machine-learning algorithms. MaxEnt (Philips et al., 2004), for example, is a widely used model. Moreover, it has been applied to crop suitability area delimitation (Estes et al., 2013; Tourne et al., 2019) and specifically for vineyards (del Río et al., 2021) and apple (Xu et al., 2023). Although its demonstrated applicability in assessing suitability, in our case, the available data did not provide a good baseline for applying machine-learning methods due to the factors explained above.

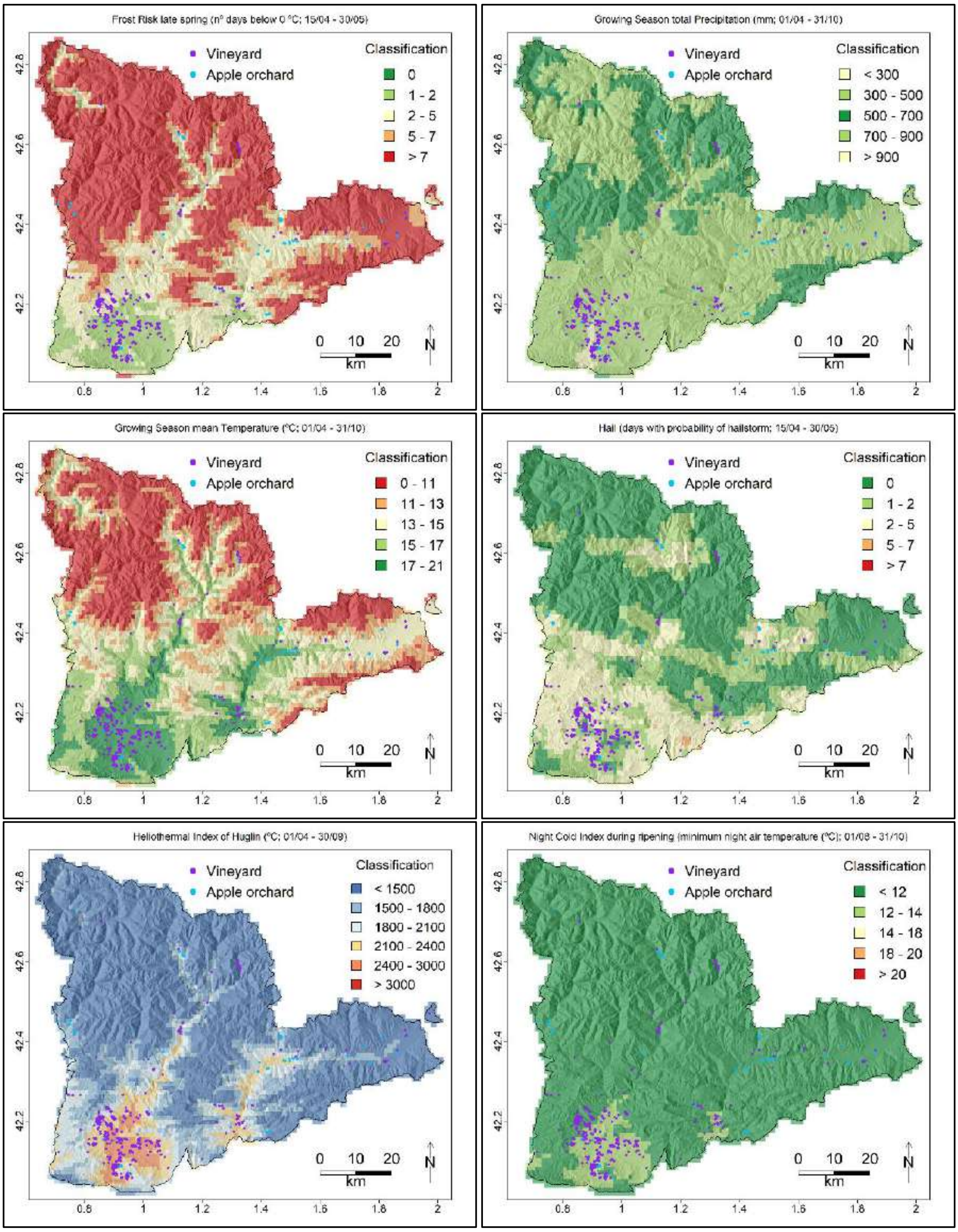
4.4 Results

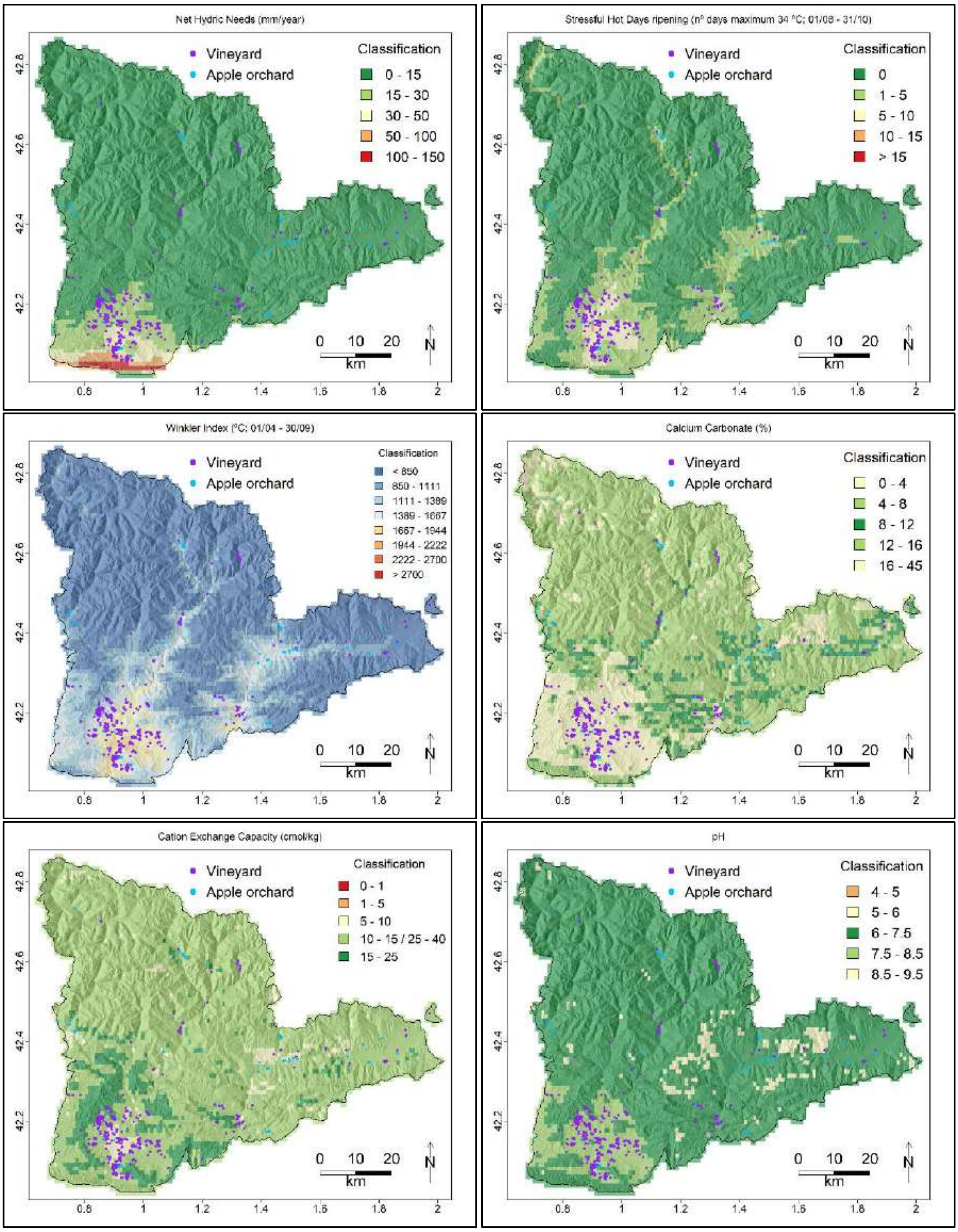
4.4.1 Indicators plots

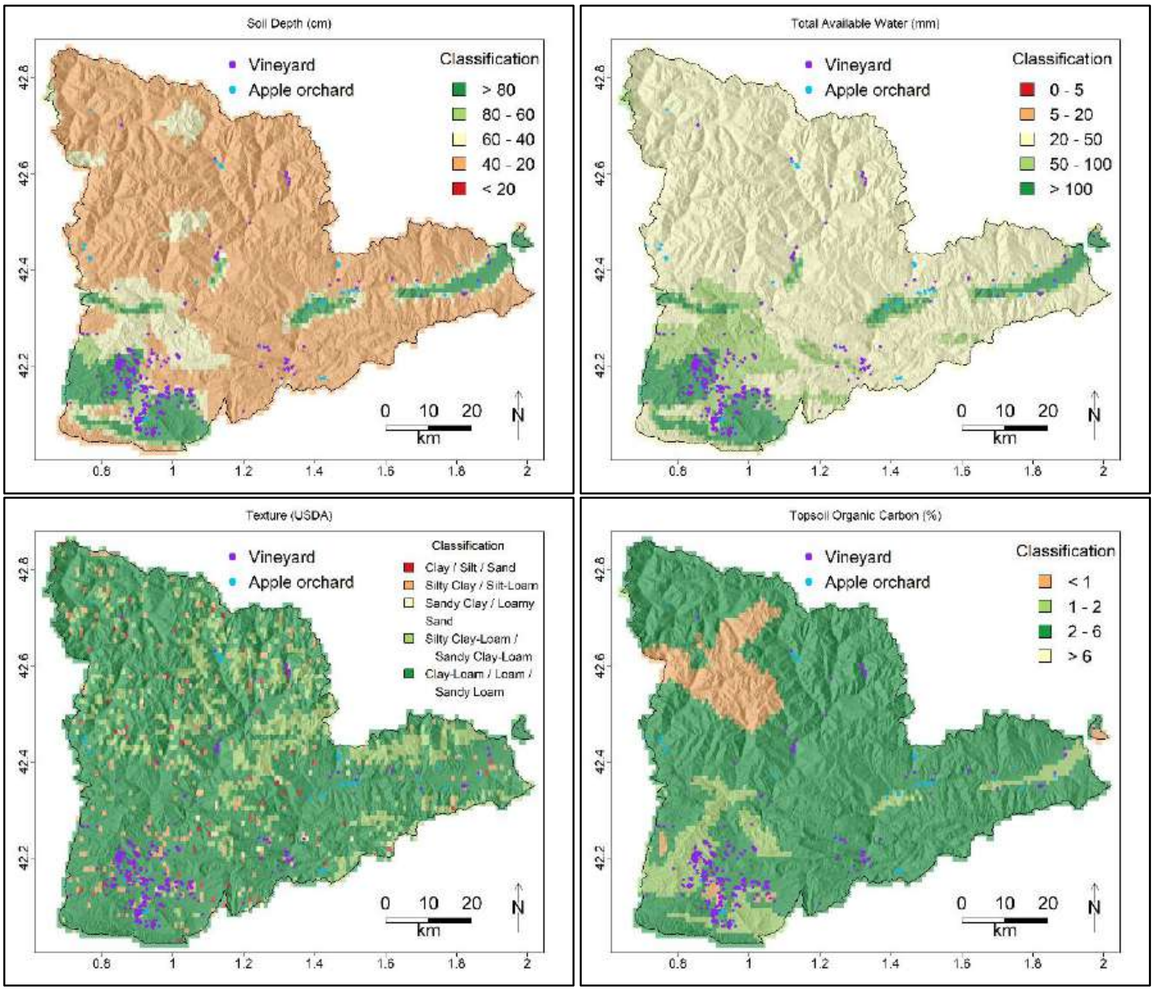
The primary factor driving suitability in mountainous areas is the changing climate conditions due to altitude and exposure, influenced by orography. These variations result in a wide range of climates, complex slopes, and aspects, which are critical for ensuring consistent yields and high quality. A notable difference is observed between conditions in valleys and those on mountain slopes, with valleys and sunny hillsides characterized by more moderate temperatures and fewer frost days, this last condition being critical for annual yield. Generally, the whole area tends to experience conditions favourable for mildew development. Soil indicators reveal a diverse range of properties influenced by topography, parent material, and climate, particularly in a piggyback foreland basin where high CaCO3 content hinders grapevine and apple production. Other areas show more favourable conditions for these crops, with varied pH, TOC, SD, TAW, and CEC values contributing to soil suitability. Slope and solar radiation are also crucial, with south- and southeast-facing slopes providing optimal conditions for crop cultivation. However, steep slopes can pose challenges for mechanization and increase erosion risk. Orientation differences in valleys, such as the unique east-west orientation of the Cerdanya valley, also impact solar radiation absorption, making it more advantageous compared to other valleys.

As a starting point, the plots for each indicator with its raw data are presented for a better understanding of its spatial distribution along the study area.




Frost Risk late spring (n° days below 0 °C; 15/04 - 30/05)
Vineyard
Apple orchard
Classification
0
1 - 2
2 - 5
5 - 7
> 7
Growing Season total Precipitation (mm; 01/04 - 31/10)
Vineyard
Apple orchard
Classification
< 300
300 - 500
500 - 700
700 - 900
> 900
Growing Season mean Temperature (°C; 01/04 - 31/10)
Vineyard
Apple orchard
Classification
0 - 11
11 - 13
13 - 15
15 - 17
17 - 21
Hail (days with probability of hailstorm; 15/04 - 30/05)
Vineyard
Apple orchard
Classification
0
1 - 2
2 - 5
5 - 7
> 7
Heliothermal Index of Huglin (°C; 01/04 - 30/09)
Vineyard
Apple orchard
Classification
< 1500
1500 - 1800
1800 - 2100
2100 - 2400
2400 - 3000
> 3000
Night Cold Index during ripening (minimum night air temperature (°C); 01/08 - 31/10)
Vineyard
Apple orchard
Classification
< 12
12 - 14
14 - 18
18 - 20
> 20
0 10 20
km
N


Net Hydric Needs (mm/year)
Vineyard
Apple orchard
Classification
0 - 15
15 - 30
30 - 50
50 - 100
100 - 150
Stressful Hot Days ripening (nº days maximum 34 ºC; 01/08 - 31/10)
0
1 - 5
5 - 10
10 - 15
> 15
Winkler Index (ºC; 01/04 - 30/09)
< 850
850 - 1111
1111 - 1389
1389 - 1667
1667 - 1944
1944 - 2222
2222 - 2700
> 2700
Calcium Carbonate (%)
0 - 4
4 - 8
8 - 12
12 - 16
16 - 45
Cation Exchange Capacity (cmol/kg)
0 - 1
1 - 5
5 - 10
10 - 15 / 25 - 40
15 - 25
pH
4 - 5
5 - 6
6 - 7.5
7.5 - 8.5
8.5 - 9.5
0 10 20
km
N


Soil Depth (cm)
Vineyard
Apple orchard
Classification
> 80
80 - 60
60 - 40
40 - 20
< 20
Total Available Water (mm)
Vineyard
Apple orchard
Classification
0 - 5
5 - 20
20 - 50
50 - 100
> 100
Texture (USDA)
Vineyard
Apple orchard
Classification
Clay / Silt / Sand
Silty Clay / Silt-Loam
Sandy Clay / Loamy Sand
Silty Clay-Loam / Sandy Clay-Loam
Clay-Loam / Loam / Sandy Loam
Topsoil Organic Carbon (%)
Vineyard
Apple orchard
Classification
< 1
1 - 2
2 - 6
> 6
0 10 20
km
N

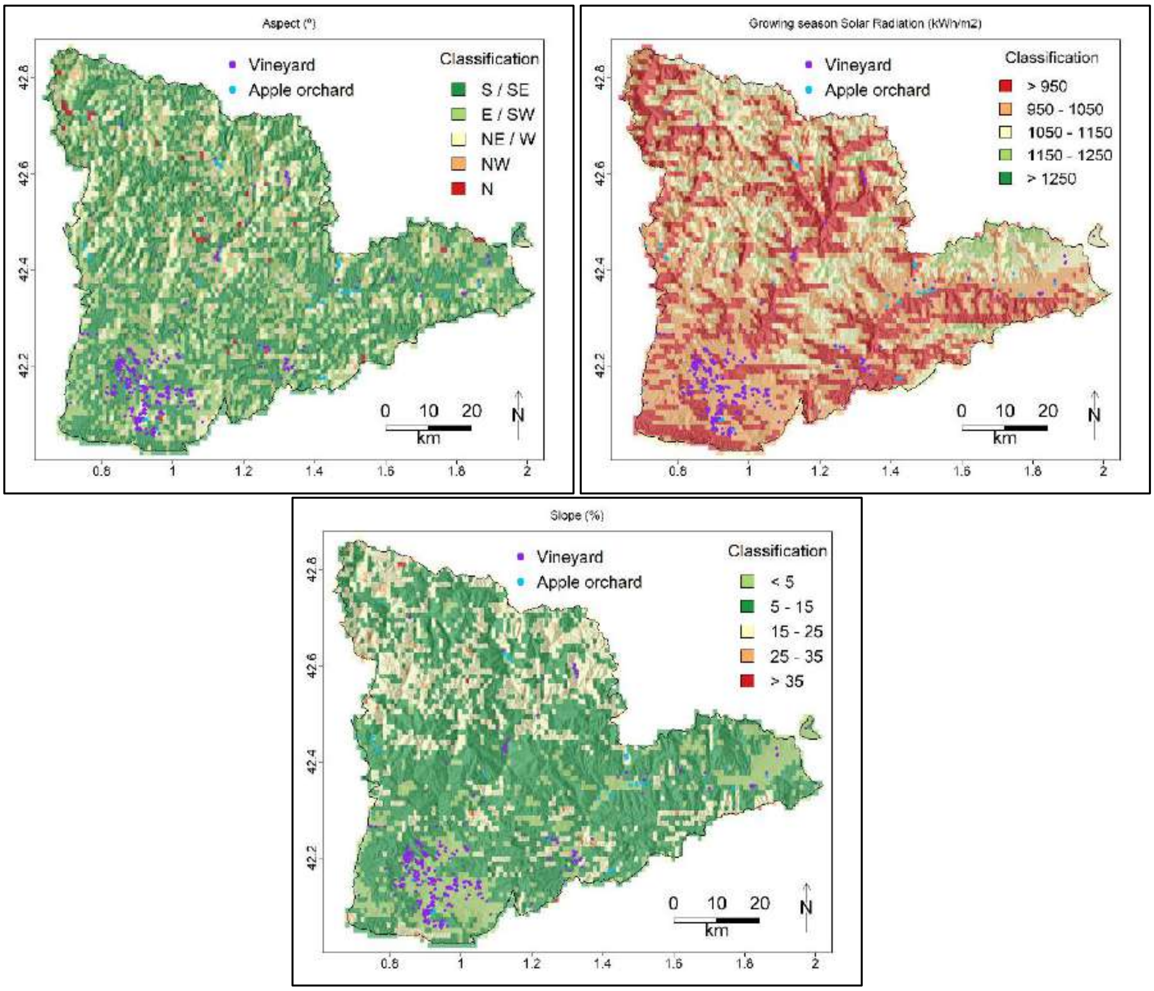


Figure 39. Indicators plots with raw data.

4.4.2 Fuzzy membership

Firstly, fuzzy membership functions are presented for each indicator. Due to the complexity of ranging suitability in a continuous scale, different functions were used depending on the behavior of each indicator towards crop suitability.

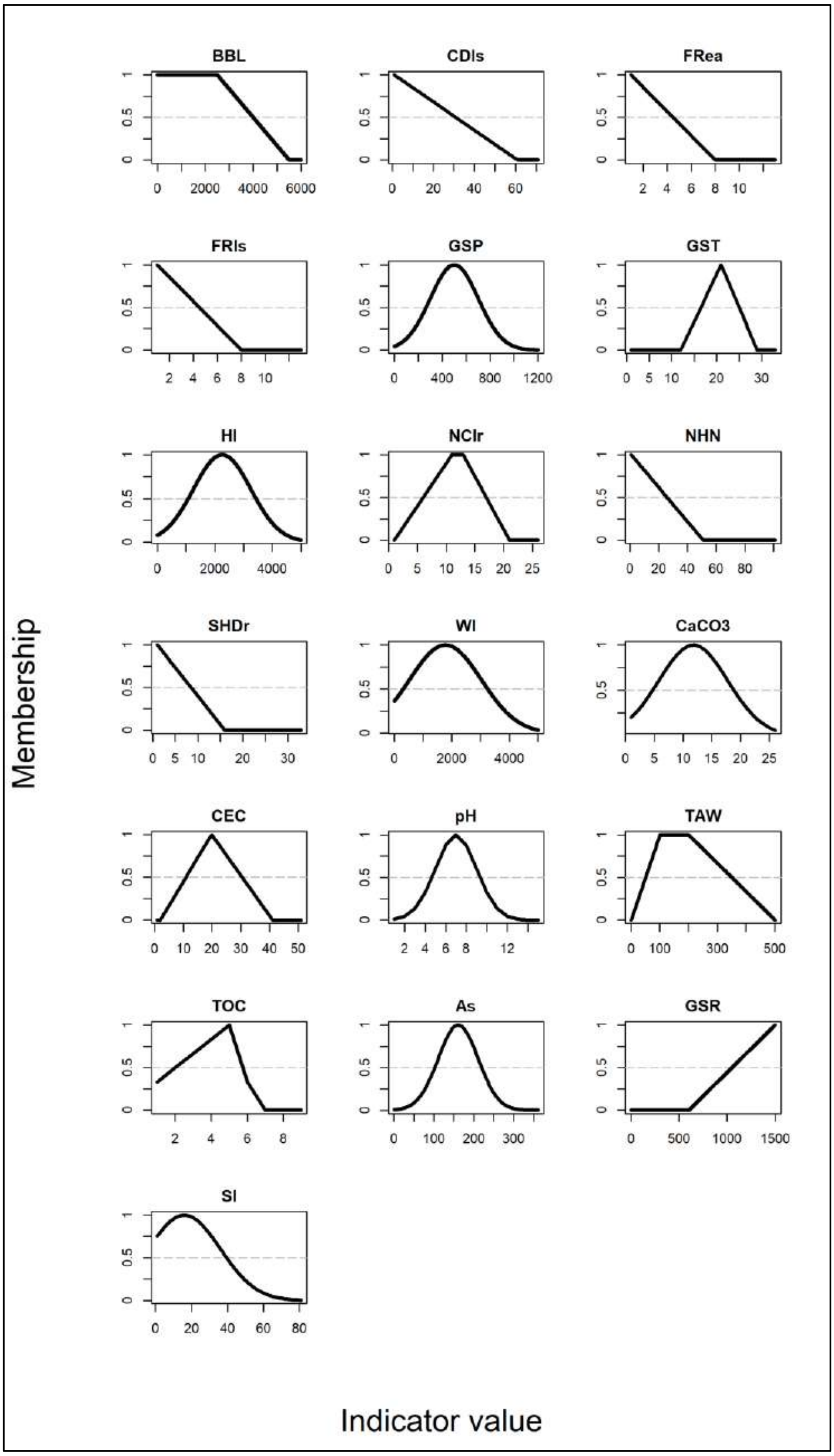


Figure 40. Fuzzy membership functions for each vineyard indicator.

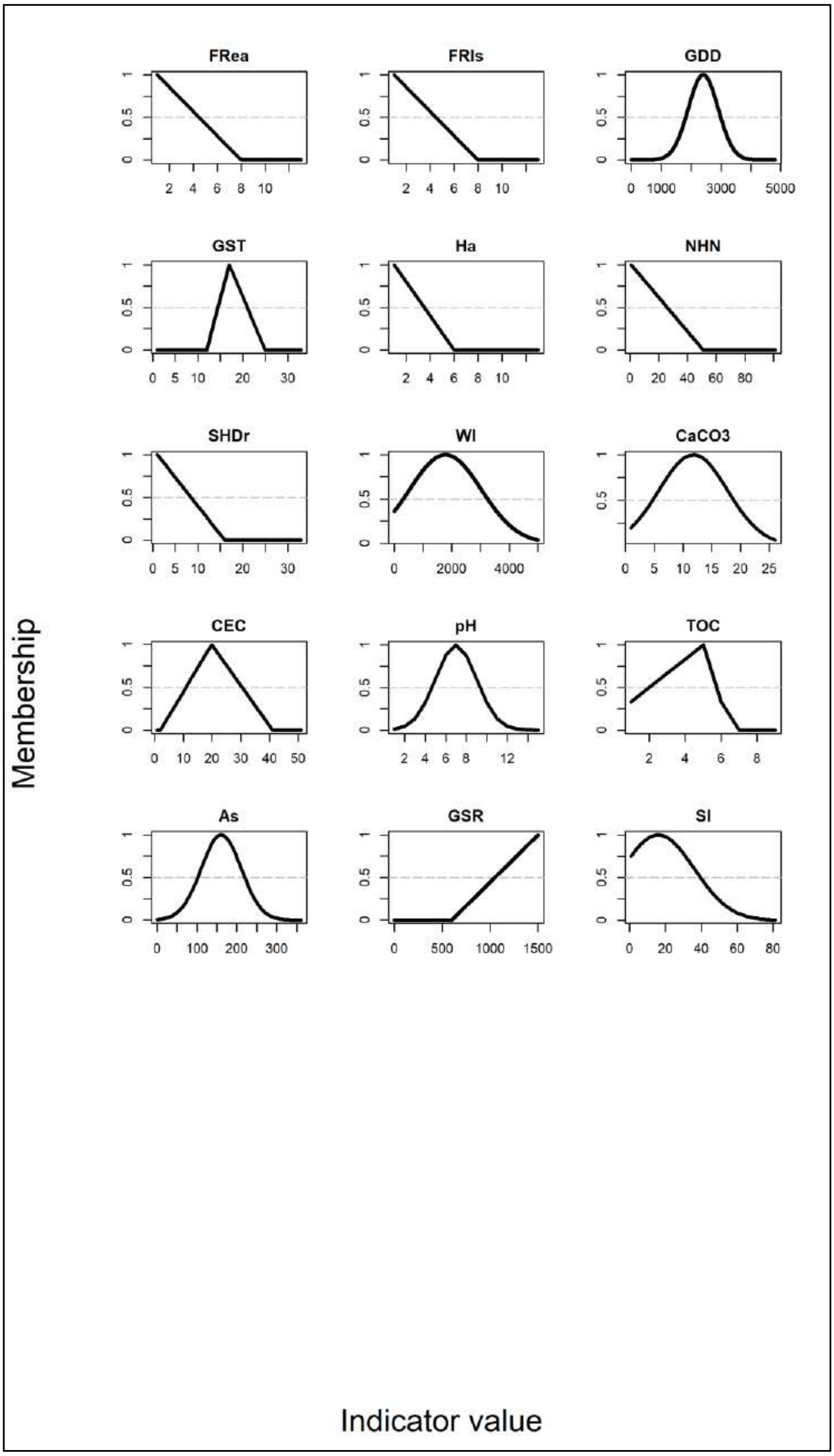


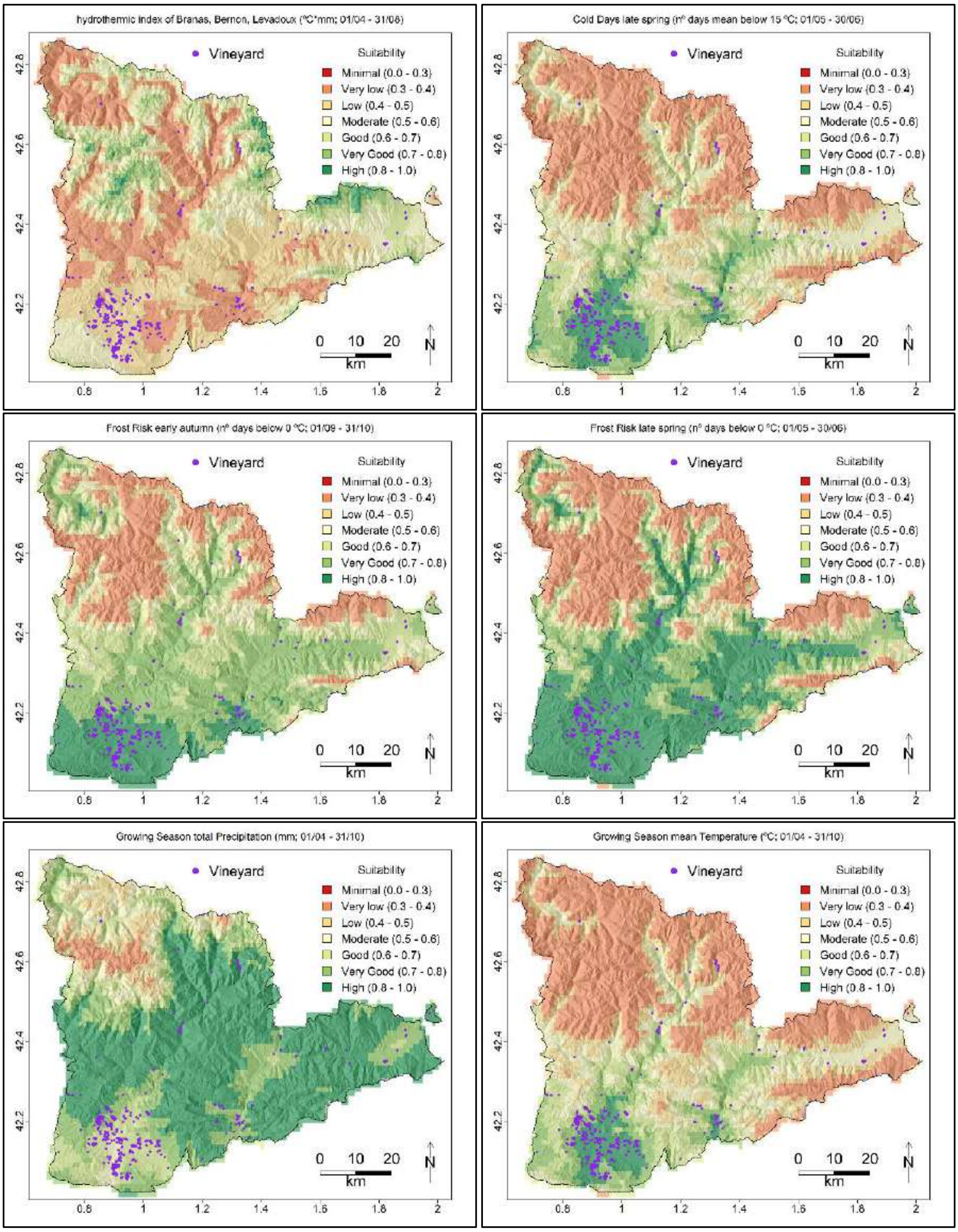
Figure 41. Fuzzy membership functions for each apple orchard indicator.

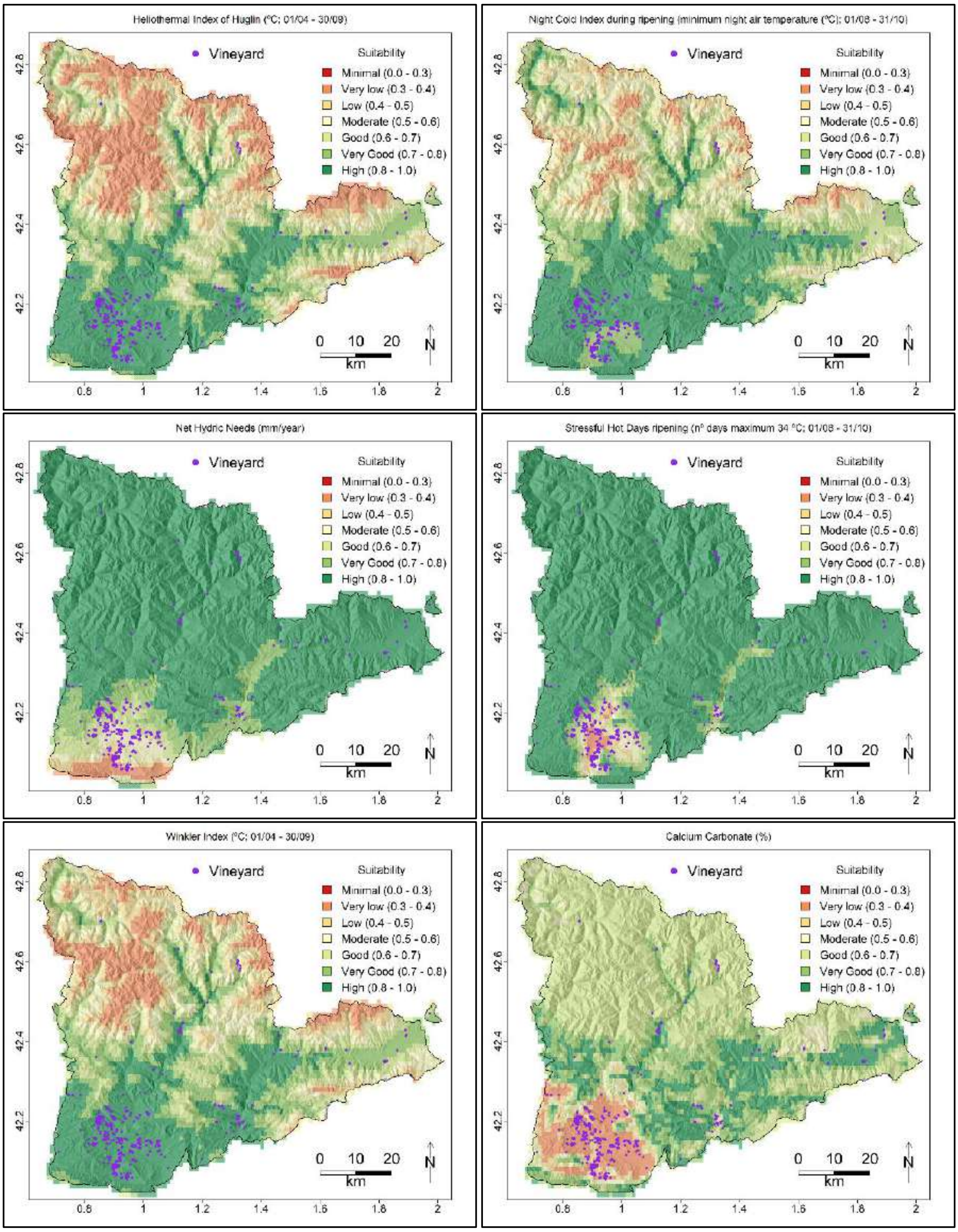
For categorical indicators fuzzy membership functions were not possible to use. They were reclassified using a table instead.

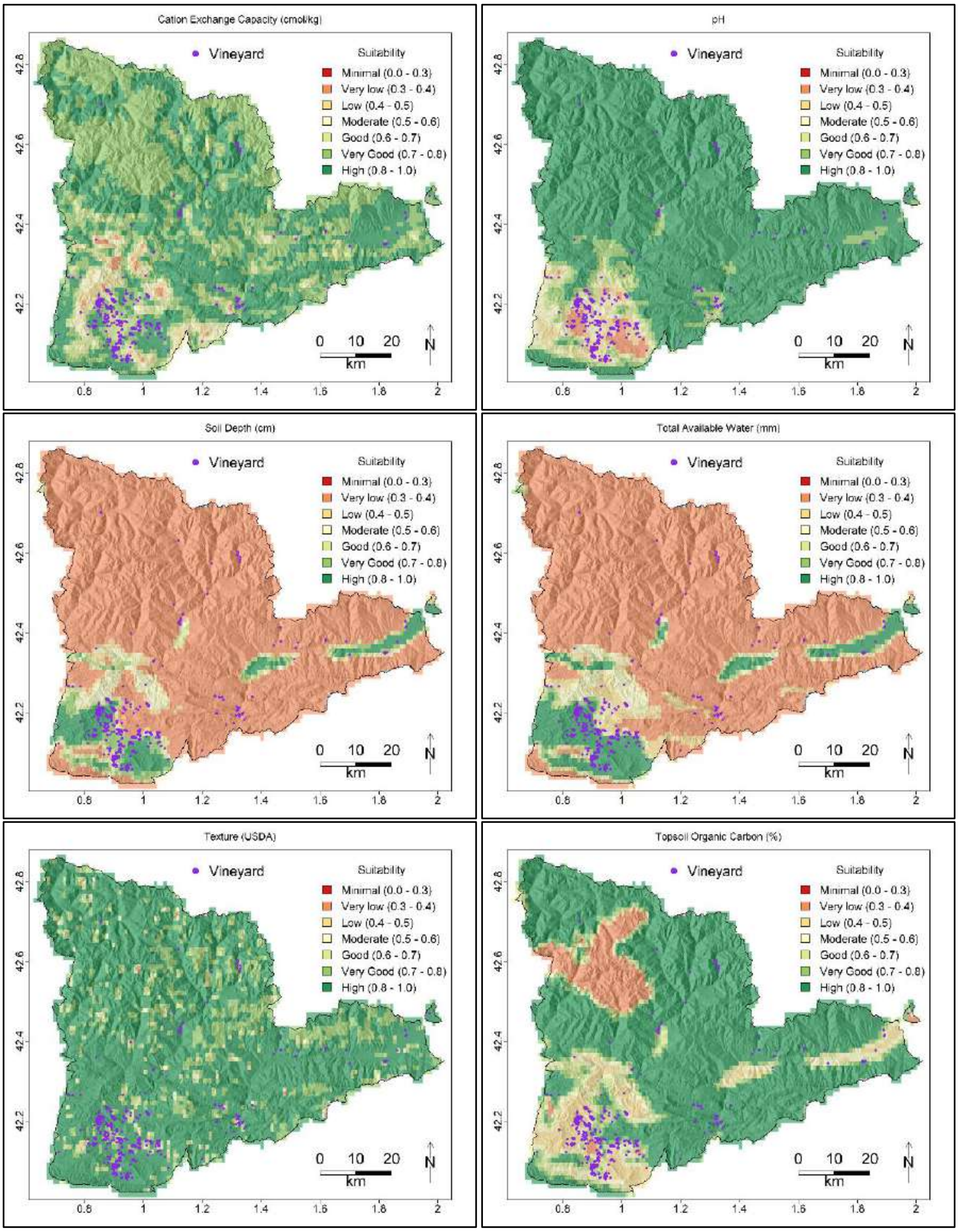
Table 54. Reclassification table for categorical indicators.

Indicator	Value	Membership
SD (cm)	> 80	1
SD (cm)	80 – 60	0.8
SD (cm)	60 – 40	0.6
SD (cm)	40 – 20	0.4
SD (cm)	< 20	0.2
Te	Sandy Loam / Clay-Loam / Loam	1
Te	Sandy Clay-Loam / Silty Clay-Loam	0.8
Te	Loamy Sand / Sandy Clay	0.6
Te	Silty Clay / Silt-Loam	0.4
Te	Clay / Silt / Sand	0.2

Secondly, suitability maps derived from applying the fuzzy membership function to each indicator are presented. Those represent how each indicator spatially behaves towards vineyards or apple orchards.


hydrothermic index of Branas, Bernon, Levadoux (°C*mm; 01/04 - 31/08)
Vineyard
Suitability
Minimal (0.0 - 0.3)
Very low (0.3 - 0.4)
Low (0.4 - 0.5)
Moderate (0.5 - 0.6)
Good (0.6 - 0.7)
Very Good (0.7 - 0.8)
High (0.8 - 1.0)
0 10 20
km
N
Cold Days late spring (n° days mean below 15 °C; 01/05 - 30/06)
Vineyard
Suitability
Minimal (0.0 - 0.3)
Very low (0.3 - 0.4)
Low (0.4 - 0.5)
Moderate (0.5 - 0.6)
Good (0.6 - 0.7)
Very Good (0.7 - 0.8)
High (0.8 - 1.0)
0 10 20
km
N
Frost Risk early autumn (n° days below 0 °C; 01/09 - 31/10)
Vineyard
Suitability
Minimal (0.0 - 0.3)
Very low (0.3 - 0.4)
Low (0.4 - 0.5)
Moderate (0.5 - 0.6)
Good (0.6 - 0.7)
Very Good (0.7 - 0.8)
High (0.8 - 1.0)
0 10 20
km
N
Frost Risk late spring (n° days below 0 °C; 01/05 - 30/06)
Vineyard
Suitability
Minimal (0.0 - 0.3)
Very low (0.3 - 0.4)
Low (0.4 - 0.5)
Moderate (0.5 - 0.6)
Good (0.6 - 0.7)
Very Good (0.7 - 0.8)
High (0.8 - 1.0)
0 10 20
km
N
Growing Season total Precipitation (mm; 01/04 - 31/10)
Vineyard
Suitability
Minimal (0.0 - 0.3)
Very low (0.3 - 0.4)
Low (0.4 - 0.5)
Moderate (0.5 - 0.6)
Good (0.6 - 0.7)
Very Good (0.7 - 0.8)
High (0.8 - 1.0)
0 10 20
km
N
Growing Season mean Temperature (°C; 01/04 - 31/10)
Vineyard
Suitability
Minimal (0.0 - 0.3)
Very low (0.3 - 0.4)
Low (0.4 - 0.5)
Moderate (0.5 - 0.6)
Good (0.6 - 0.7)
Very Good (0.7 - 0.8)
High (0.8 - 1.0)
0 10 20
km
N


Heliothermal Index of Huglin (ºC; 01/04 - 30/09)
Night Cold Index during ripening (minimum night air temperature (ºC); 01/08 - 31/10)
Net Hydric Needs (mm/year)
Stressful Hot Days ripening (nº days maximum 34 ºC; 01/08 - 31/10)
Winkler Index (ºC; 01/04 - 30/09)
Calcium Carbonate (%)
Vineyard
Suitability
Minimal (0.0 - 0.3)
Very low (0.3 - 0.4)
Low (0.4 - 0.5)
Moderate (0.5 - 0.6)
Good (0.6 - 0.7)
Very Good (0.7 - 0.8)
High (0.8 - 1.0)
0 10 20
km
N


Cation Exchange Capacity (cmol/kg)
pH
Soil Depth (cm)
Total Available Water (mm)
Texture (USDA)
Topsoil Organic Carbon (%)
Vineyard
Suitability
Minimal (0.0 - 0.3)
Very low (0.3 - 0.4)
Low (0.4 - 0.5)
Moderate (0.5 - 0.6)
Good (0.6 - 0.7)
Very Good (0.7 - 0.8)
High (0.8 - 1.0)
0 10 20
km
N

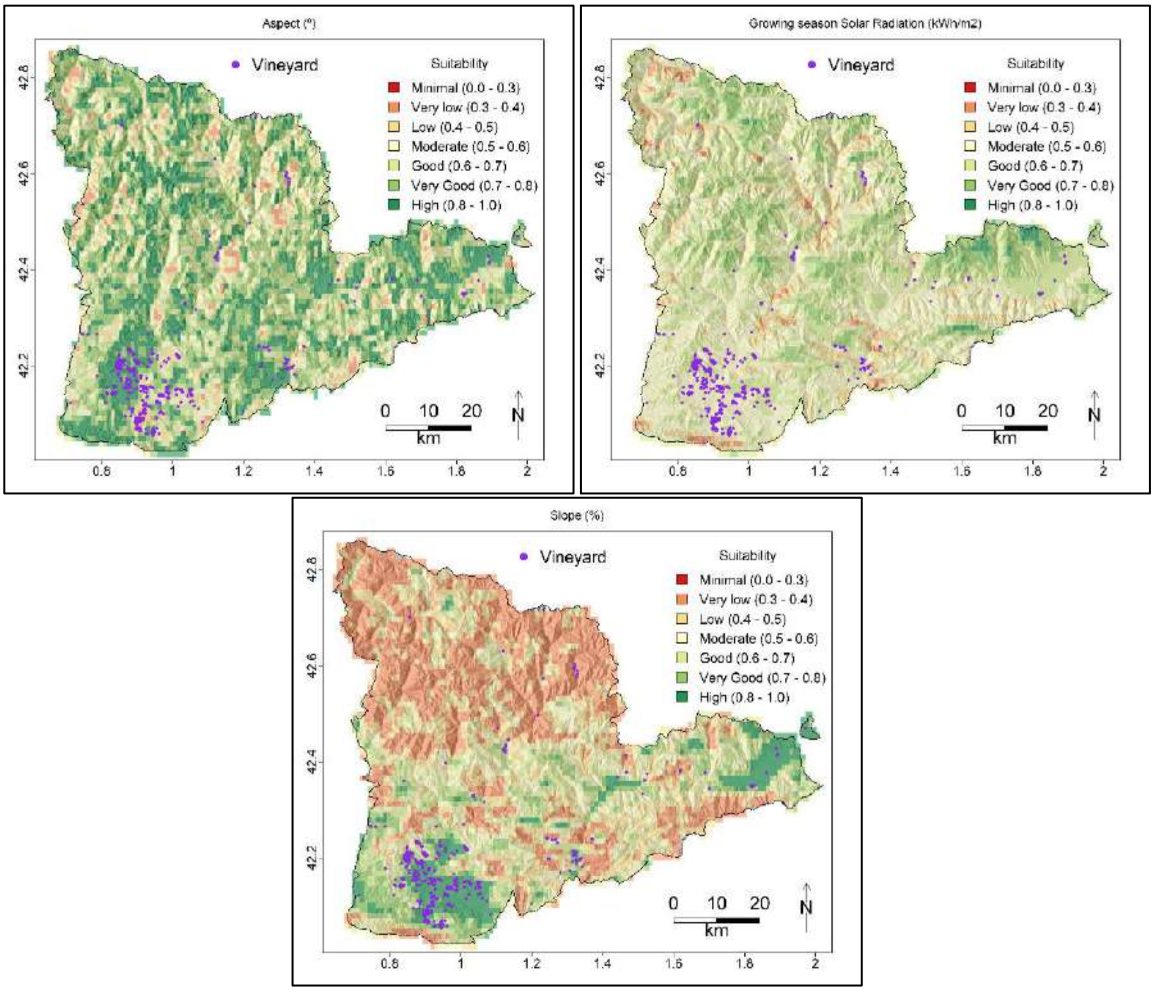
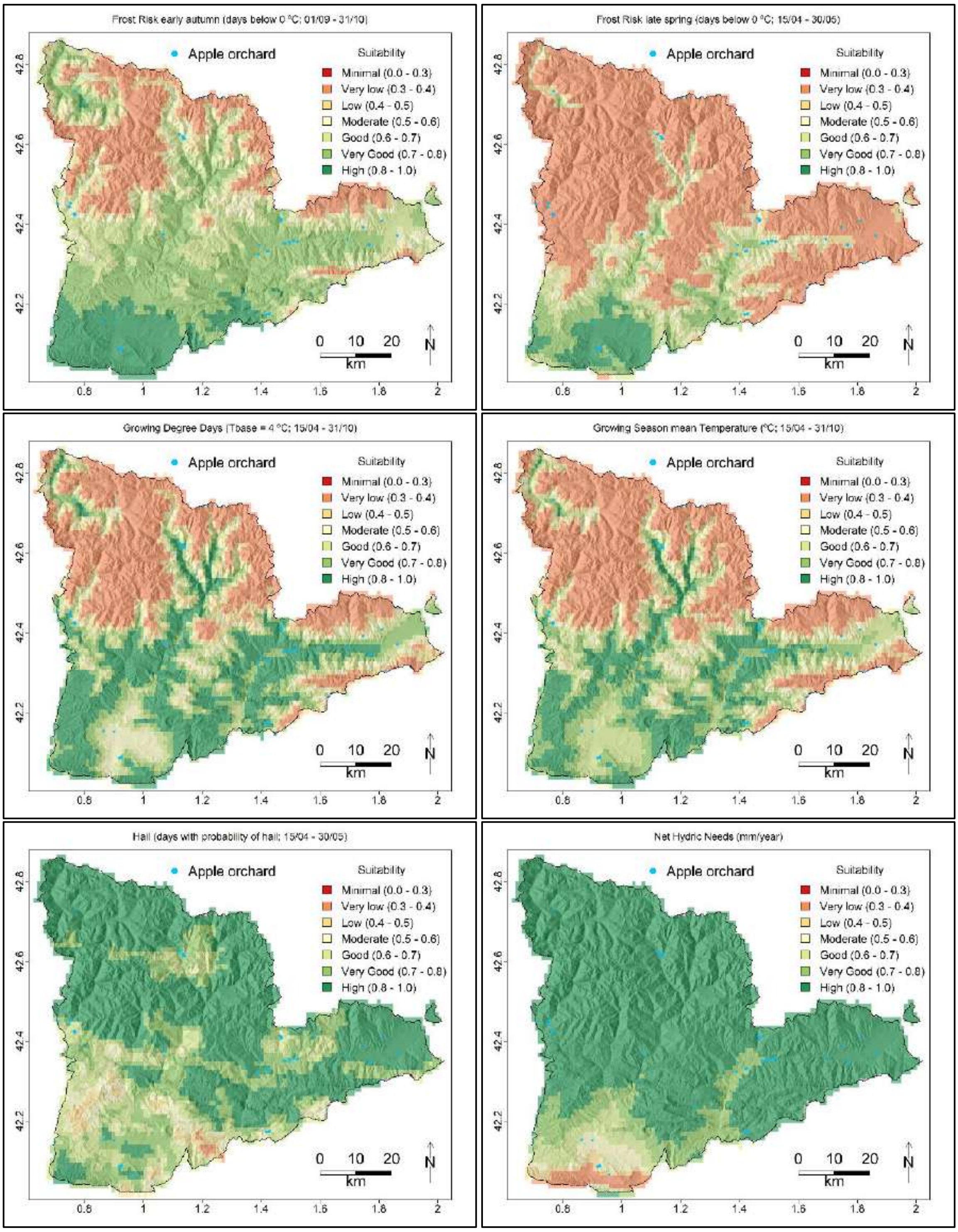
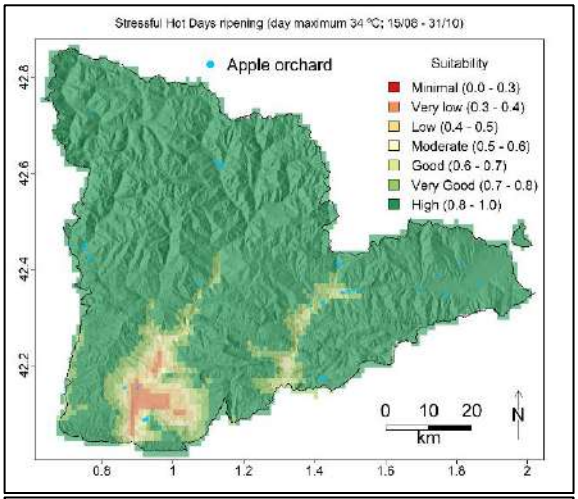
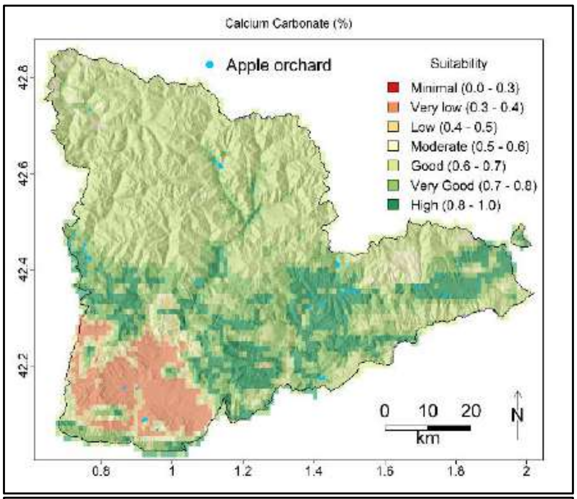
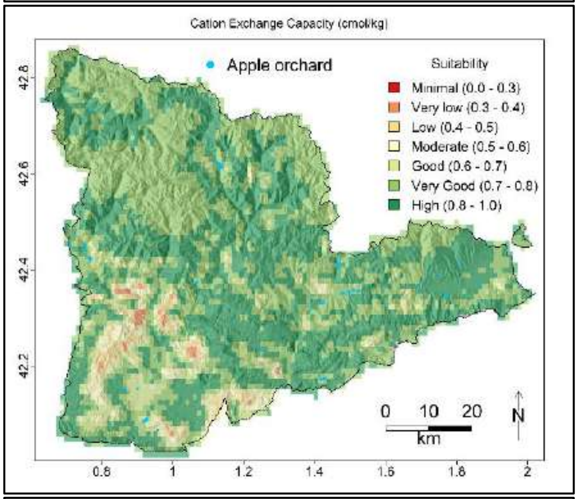


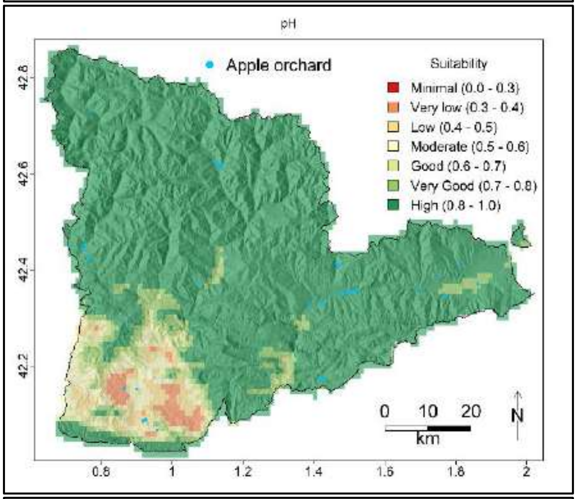
Figure 42. Vineyard suitability for each indicator after applying the fuzzy membership function to its raw values.

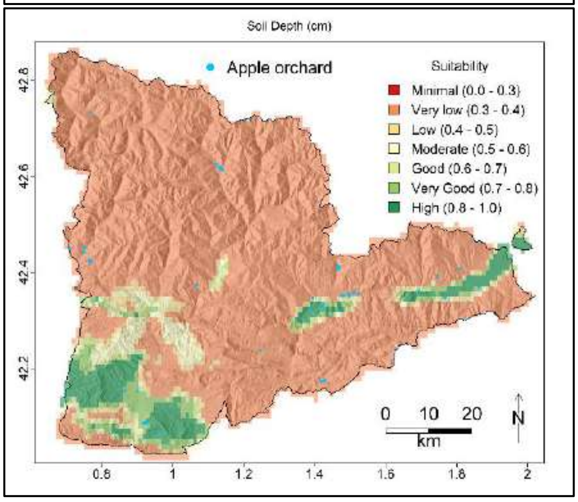

Frost Risk early autumn (days below 0 °C; 01/09 - 31/10)
Frost Risk late spring (days below 0 °C; 15/04 - 30/05)
Growing Degree Days (Tbase = 4 °C; 15/04 - 31/10)
Growing Season mean Temperature (°C; 15/04 - 31/10)
Hail (days with probability of hail; 15/04 - 30/05)
Net Hydric Needs (mm/year)
Apple orchard
Suitability
Minimal (0.0 - 0.3)
Very low (0.3 - 0.4)
Low (0.4 - 0.5)
Moderate (0.5 - 0.6)
Good (0.6 - 0.7)
Very Good (0.7 - 0.8)
High (0.8 - 1.0)
0 10 20
km
N
42.2
42.4
42.6
42.8
0.8
1
1.2
1.4
1.6
1.8
2

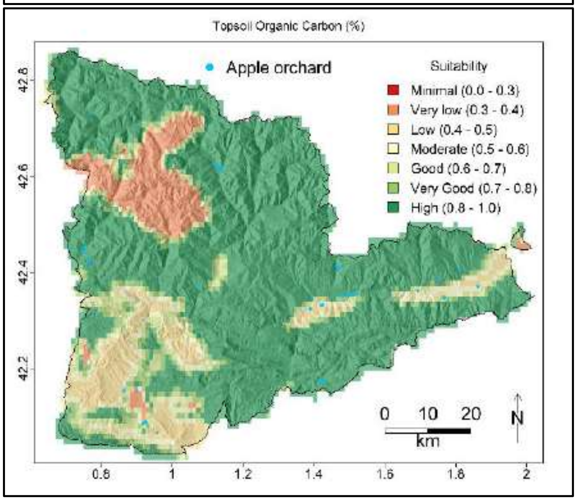

Stressful Hot Days ripening (day maximum 34 °C; 15/08 - 31/10)
Apple orchard
Suitability
Minimal (0.0 - 0.3)
Very low (0.3 - 0.4)
Low (0.4 - 0.5)
Moderate (0.5 - 0.6)
Good (0.6 - 0.7)
Very Good (0.7 - 0.8)
High (0.8 - 1.0)
0 10 20
km
N


Calcium Carbonate (%)
Apple orchard
Suitability
Minimal (0.0 - 0.3)
Very low (0.3 - 0.4)
Low (0.4 - 0.5)
Moderate (0.5 - 0.6)
Good (0.6 - 0.7)
Very Good (0.7 - 0.8)
High (0.8 - 1.0)
0 10 20
km
N


Cation Exchange Capacity (cmol/kg)
Apple orchard
Suitability
Minimal (0.0 - 0.3)
Very low (0.3 - 0.4)
Low (0.4 - 0.5)
Moderate (0.5 - 0.6)
Good (0.6 - 0.7)
Very Good (0.7 - 0.8)
High (0.8 - 1.0)
0 10 20
km
N


pH
Apple orchard
Suitability
Minimal (0.0 - 0.3)
Very low (0.3 - 0.4)
Low (0.4 - 0.5)
Moderate (0.5 - 0.6)
Good (0.6 - 0.7)
Very Good (0.7 - 0.8)
High (0.8 - 1.0)
0 10 20
km
N


Soil Depth (cm)
Apple orchard
Suitability
Minimal (0.0 - 0.3)
Very low (0.3 - 0.4)
Low (0.4 - 0.5)
Moderate (0.5 - 0.6)
Good (0.6 - 0.7)
Very Good (0.7 - 0.8)
High (0.8 - 1.0)
0 10 20
km
N


Topsoil Organic Carbon (%)
Apple orchard
Suitability
Minimal (0.0 - 0.3)
Very low (0.3 - 0.4)
Low (0.4 - 0.5)
Moderate (0.5 - 0.6)
Good (0.6 - 0.7)
Very Good (0.7 - 0.8)
High (0.8 - 1.0)
0 10 20
km
N

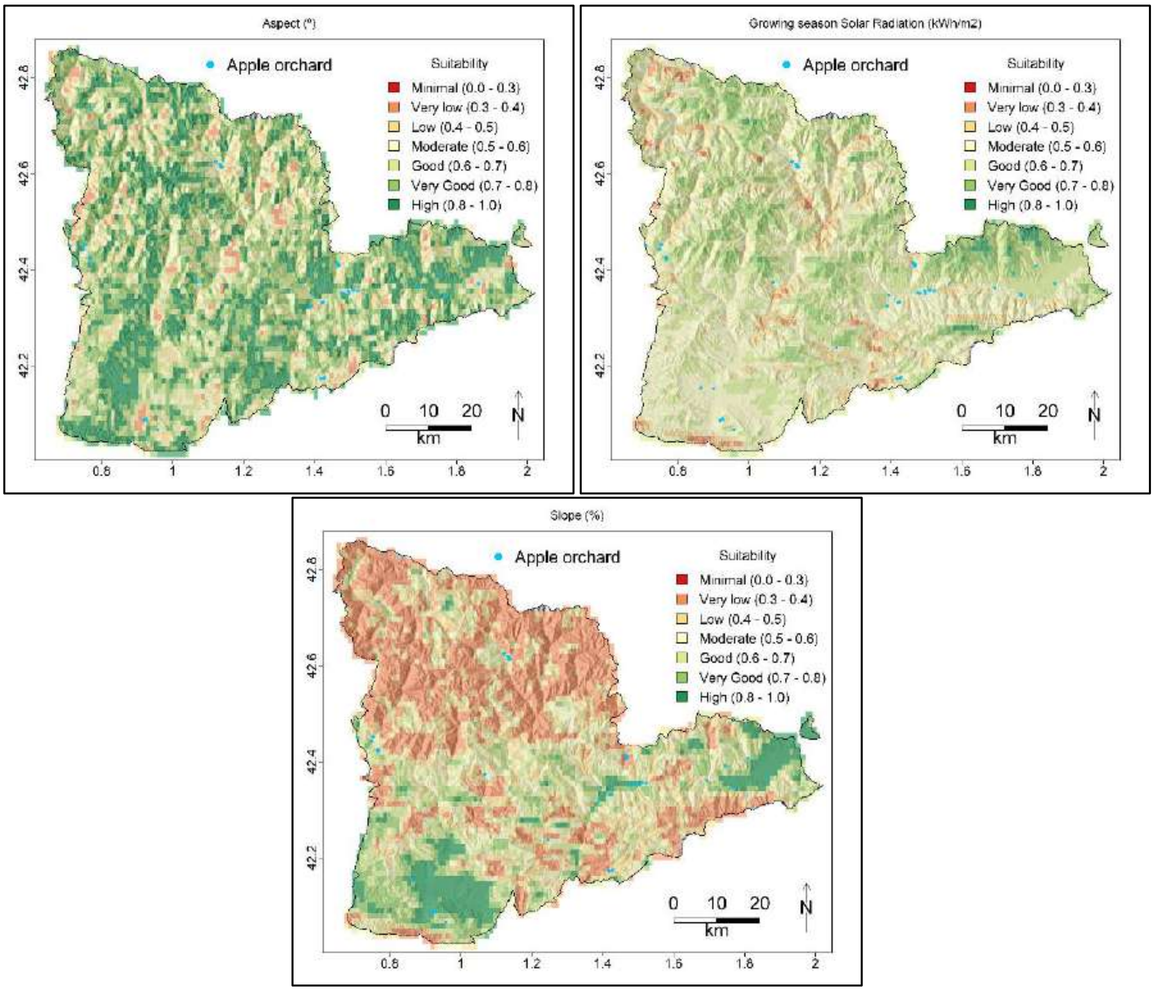


Figure 43. Apple orchard suitability for each indicator after applying the fuzzy membership function to its raw values.

Some indicators showed a high suitability for both crops (~ 75 %), such as SHDr, pH, NHN, CEC, and TOC. In addition, Te showed a high suitability for vineyards and Ha for apple orchards. On the other hand, there were a few indicators with a more restrictive distribution. Slope, for example, negatively weighted between ~50 – 75 % of the territory. A similar pattern can be seen for TAW, GST, BBL, CDIs, and GSR. For grapevine, FRIs exhibited a more even suitability distribution; however, for apple, FRIs exhibited very low values overall (~70 % of the area with less than 0.3). This change was due to the temporal window of the indicator, i.e., it was earlier for apple than grapevine, which involved a higher probability of frost days. SD and TAW, although not having values between 0 – 0.2, most of them didn't exceed the 0.5 threshold (occupying these values 85 – 70 % of the whole study area).

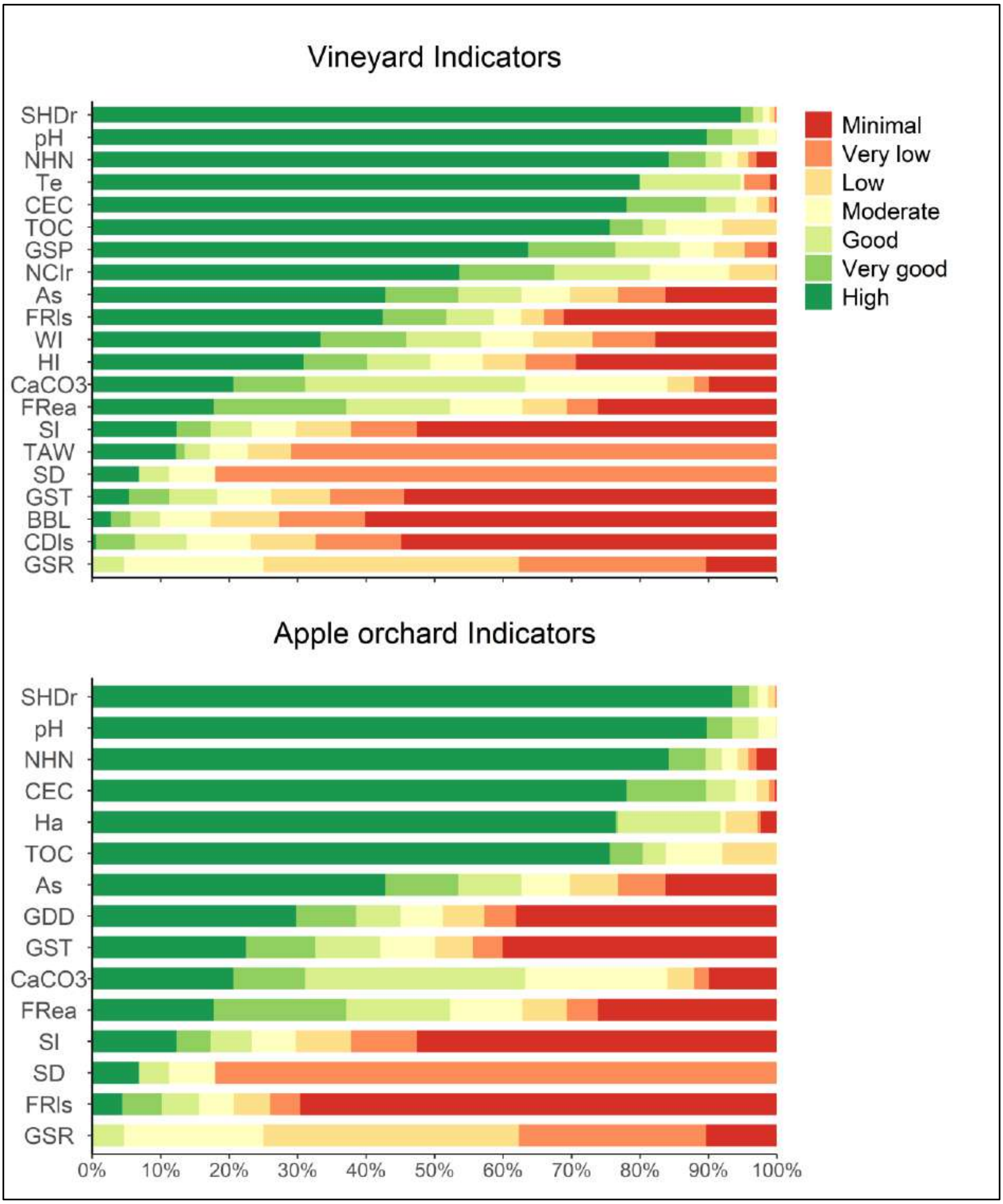


Figure 44. Summary of surface percentage covered by each suitability class.

4.4.3 Analytic Hierarchy Process

The resulting pairwise matrixes are presented below.

Table 55. Pairwise matrixes for vineyards. In descending order: main groups, climate, soil, topography.

Main group	Climate	Soil	Topography
Climate	1,00	5,00	3,00
Soil	0,20	1,00	0,33
Topography	0,33	3,00	1,00

Indicator	BBL	CDIs	FRea	FRIs	GSP	GST	HI	NClr	NHN	SHDr	WI
BBL	1,00	0,25	0,25	0,14	0,20	0,20	0,20	0,25	0,13	0,20	0,20
CDIs	4,00	1,00	0,50	0,20	0,25	0,25	0,25	1,00	0,20	0,50	0,25
FRea	4,00	2,00	1,00	0,15	2,00	2,00	2,00	2,00	0,20	3,00	2,00
FRIs	7,14	5,00	6,67	1,00	5,00	5,00	5,00	6,00	1,00	2,00	5,00
GSP	5,00	4,00	0,50	0,20	1,00	1,00	1,00	3,00	0,17	5,00	1,00
GST	5,00	4,00	0,50	0,20	1,00	1,00	1,00	3,00	0,17	5,00	1,00
HI	5,00	4,00	0,50	0,20	1,00	1,00	1,00	3,00	0,14	5,00	1,00
NClr	4,00	1,00	0,50	0,17	0,33	0,33	0,33	1,00	0,25	1,00	0,33
NHN	7,69	5,00	5,00	1,00	5,88	5,88	7,14	4,00	1,00	5,00	7,00
SHDr	5,00	2,00	0,33	0,50	0,20	0,20	0,20	1,00	0,20	1,00	0,20
WI	5,00	4,00	0,50	0,20	1,00	1,00	1,00	3,03	0,14	5,00	1,00

Indicator	CaCO3	CEC	pH	SD	TAW	Te	TOC
CaCO3	1,00	1,00	1,00	0,10	0,20	0,33	6,00
CEC	1,00	1,00	1,00	0,10	0,20	0,33	6,00
SD	1,00	1,00	1,00	0,10	0,20	0,33	6,00
pH	10,00	10,00	10,00	1,00	2,00	2,00	9,00
TAW	5,00	5,00	5,00	0,50	1,00	1,00	8,00
Te	3,03	3,03	3,03	0,50	1,00	1,00	7,00
TOC	0,17	0,17	0,17	0,11	0,13	0,14	1,00

Indicator	As	GSR	SI
As	1,00	0,50	3,50
GSR	2,00	1,00	3,45
SI	0,29	0,29	1,00

Table 56. Pairwise matrixes for apple orchards. In descending order: main groups, climate, soil, topography.

Main group	Climate	Soil	Topography
Climate	1,00	7,50	3,00
Soil	0,13	1,00	1,00
Topography	0,33	1,00	1,00

Indicator	FRea	FRls	GDD	GST	Ha	NHN	SHDr
FRea	1,00	0,13	1,00	1,00	0,11	0,25	1,00
FRls	8,00	1,00	8,00	9,00	1,00	5,00	7,00
GDD	1,00	0,13	1,00	1,00	0,11	0,33	0,25
GST	1,00	0,11	1,00	1,00	0,11	0,33	0,25
Ha	9,00	1,00	9,00	9,00	1,00	6,00	8,00
NHN	4,00	0,20	3,00	3,00	0,17	1,00	5,00
SHDr	1,00	0,14	4,00	4,00	0,13	0,20	1,00

Indicator	CaCO3	CEC	pH	SD	TOC
CaCO3	1,00	0,14	1,00	0,14	2,00
CEC	7,00	1,00	7,00	0,50	8,00
pH	1,00	0,14	1,00	0,14	2,00
SD	7,14	2,00	7,00	1,00	4,00
TOC	0,50	0,13	0,50	0,25	1,00

Indicator	As	RH	Sl
As	1,00	1,00	0,20
GSR	1,00	1,00	0,20
Sl	5,00	5,00	1,00

The Consistency Index was correct for all comparison matrices with values equal or below 0.10

Table 57. Consistency Index (CI Saaty (1987)) for each crop. Main group was composed by climate, soil and topography.

Group	CI (vineyard)	CI (apple orchard)
Main group	0.032	0.080
Climate	0.099	0.071
Soil	0.060	0.066
Topography	0.048	0.058

For vineyards, a comparison between the main groups showed the importance of climate (~ 63 %) over topography (~ 26 %), with soil coming last (~ 11 %). Relative weights are rated inside each of the main groups, and a scalation to obtain the final weight for the comparison was needed. This process was achieved by multiplying the main indicator weight to which the indicator belongs by the relative weight of that indicator. If all were considered to have equivalent weights in assessing crop suitability, the value would be ~ 5 %. For climate, NHN (~ 16 %) and FRIs (~ 15 %) were considered the most important indicators to assess environmental suitability. The least weighted were BBL, CD, NCIr, and SHDr, all with values below 3 %. The rest of the climate indicators were weighted at around 5 %. Soil indicators obtained a very low final weight due to the low main group value (~ 11 %), which greatly influences how determinant this group was in the analysis. Only pH was close to 5 % and the rest were 2 % or less. Topography indicators had to over 5 % (GSR ~14 % and As ~ 9 %) and one with a low weight (Sl ~ 3 %).

Table 58. Resulting indicators' weight for each main group (relative weight) and in the final analysis (final weight) for vineyards.

Main group	Main weight	Indicator	Relative weight	Final weight
Climatic	0,633	NHN	0,258	0,163
Climatic	0,633	FRIs	0,236	0,149
Topography	0,260	GSR	0,534	0,139
Topography	0,260	As	0,341	0,089
Climatic	0,633	FRea	0,081	0,051
Climatic	0,633	GSP	0,075	0,048
Climatic	0,633	GST	0,075	0,048
Climatic	0,633	WI	0,075	0,047
Climatic	0,633	HI	0,074	0,047
Soil	0,106	pH	0,407	0,043
Topography	0,260	Sl	0,125	0,033
Climatic	0,633	SHDr	0,043	0,027
Soil	0,106	TAW	0,215	0,023
Climatic	0,633	NCIr	0,035	0,022
Climatic	0,633	CDIs	0,032	0,020
Soil	0,106	Te	0,172	0,018
Climatic	0,633	BBL	0,016	0,010
Soil	0,106	CaCO3	0,061	0,007
Soil	0,106	CEC	0,061	0,007
Soil	0,106	SD	0,061	0,007
Soil	0,106	TOC	0,021	0,002

For apple orchards, the comparison between the main groups also showed the importance of climate (~ 69 %), achieving a value even higher than that of grapevine. In addition, it decreased the difference between soil (~ 13 %) and topography (~ 18 %). In this case, an equal value for all the components of the analysis would be ~ 7 %. Climate indicators highlighted the effect of Ha (~ 25 %) and FRIs (~ 24 %). FRea, GDD, GST, and SHDr were all below 5 % and NHN was the only indicator close to 7 %. Soil values were distributed in two similar groups, with $CaCO_3$, pH, and TOC presenting very low percentage (~ 1 %) and CEC and SD being ~ 5 %. Topography had an equal value for both As and GSR (~ 3 %) and a higher value for Sl (~ 13 %).

Table 59. Resulting indicators' weight for each main group (relative weight) and in the final analysis (relative weight) for apple orchards.

Main group	Main weight	Indicator	Relative weight	Final weight
Climatic	0,690	Ha	0,368	0,254
Climatic	0,690	FRls	0,340	0,235
Topography	0,178	Sl	0,714	0,127
Climatic	0,690	NHN	0,116	0,080
Soil	0,132	SD	0,433	0,057
Soil	0,132	CEC	0,371	0,049
Climatic	0,690	SHDr	0,070	0,048
Climatic	0,690	FRea	0,038	0,026
Topography	0,178	As	0,143	0,025
Topography	0,178	GSR	0,143	0,025
Climatic	0,690	GDD	0,034	0,023
Climatic	0,690	GST	0,033	0,023
Soil	0,132	pH	0,070	0,009
Soil	0,132	CaCO3	0,070	0,009
Soil	0,132	TOC	0,056	0,007

After fuzzification, although many indicators had percentages of more than 75 % of the highest class of adequacy (e.g., SHDr, pH, Te, CEC, and TOC), these had a very low weight in the final analysis in percentage terms, resulting in a contribution to the final result not as significant as other indicators with a higher weight (e. g. NHN, FRls, and As). In this way, the best pixels were highlighted when a combination of the highest values of the most weighing indicators converged in a region of the space. On the contrary, an accumulation of negative values for high weighting indicators involved low suitability pixels. The main group weighting also had a significant impact on how its indicators performed in the final analysis. In the comparison of the main indicator groups, climate emerged as the dominant factor influencing suitability for both grapevine and apple cultivation, followed by topography and then soil.

The suitability evaluation for vineyards and apple orchards resulted in around 1,401 (0.2 %) and 7,704 ha (1.3 %) of highly suitable land, respectively. Following this classification, in descending order, very good suitable plots represented around 168,167 (28.6 %) and 70,530 (12.0 %) ha, respectively; good suitable classes around 176,461 (30.0 %) and 141,052 (24.0 %) ha, respectively; moderate around 93,922 (16.0 %) and 258,360 (43.9 %) ha, respectively; low around 133,620 (22.7 %) and 106,425 (18.1 %) ha, respectively; very low around 14,402 (2.4 %) and 3,902 (0.6 %) ha, respectively; and minimal was not defined in any pixel over the whole area.

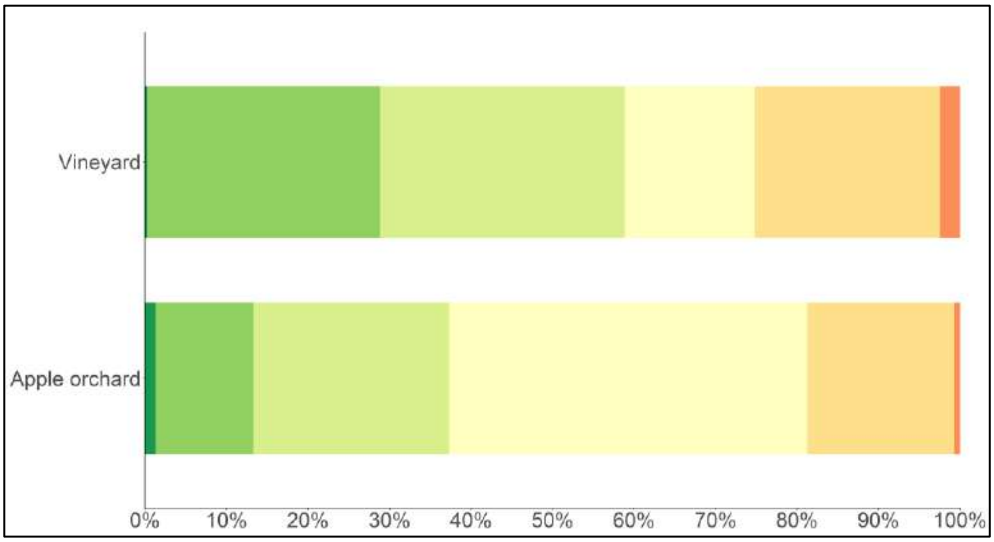


Figure 45 Bar plot summarizing the percentage of cumulative area covered by each suitability class for each crop.

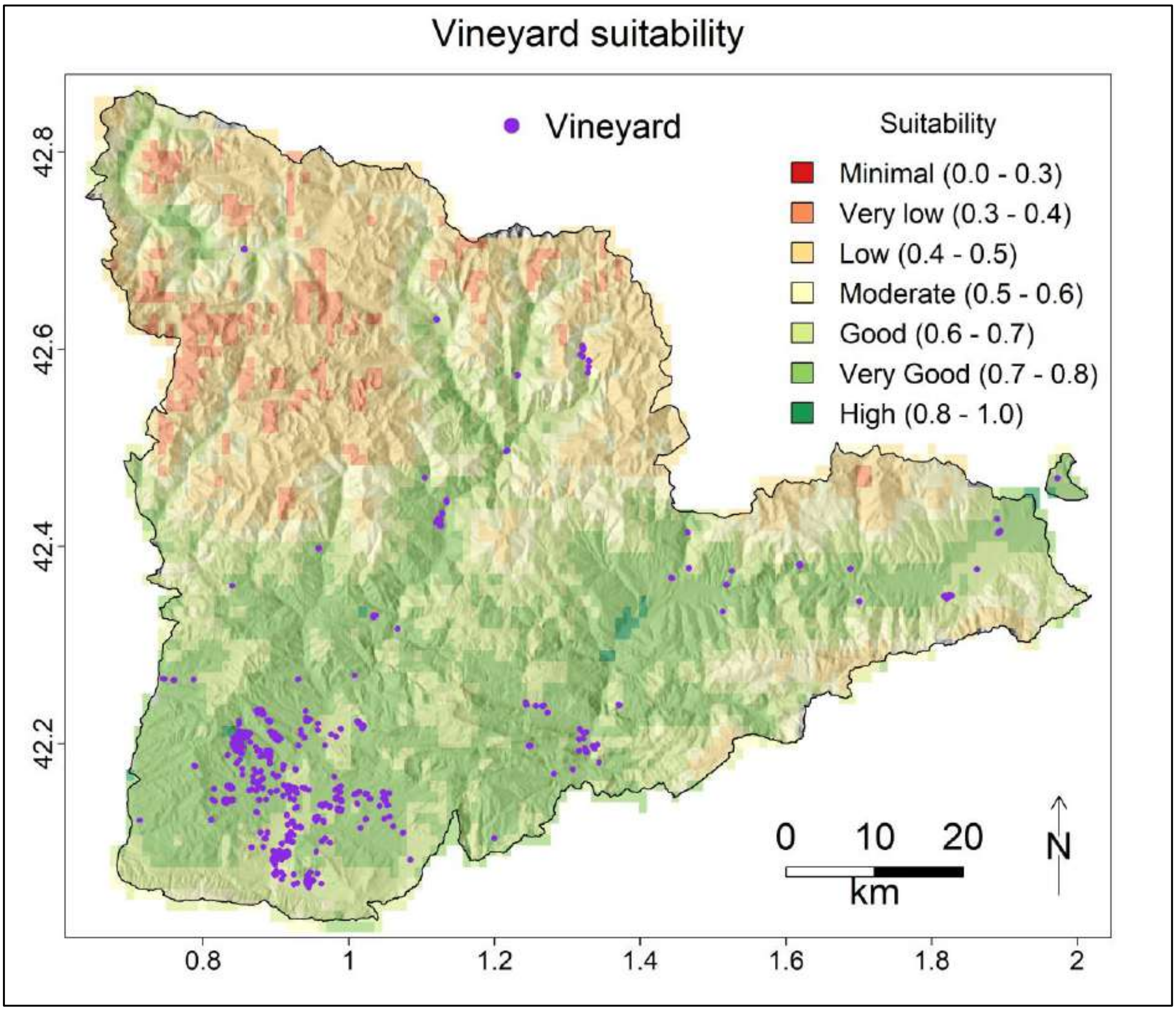


Figure 46. Resulting vineyard suitability map.

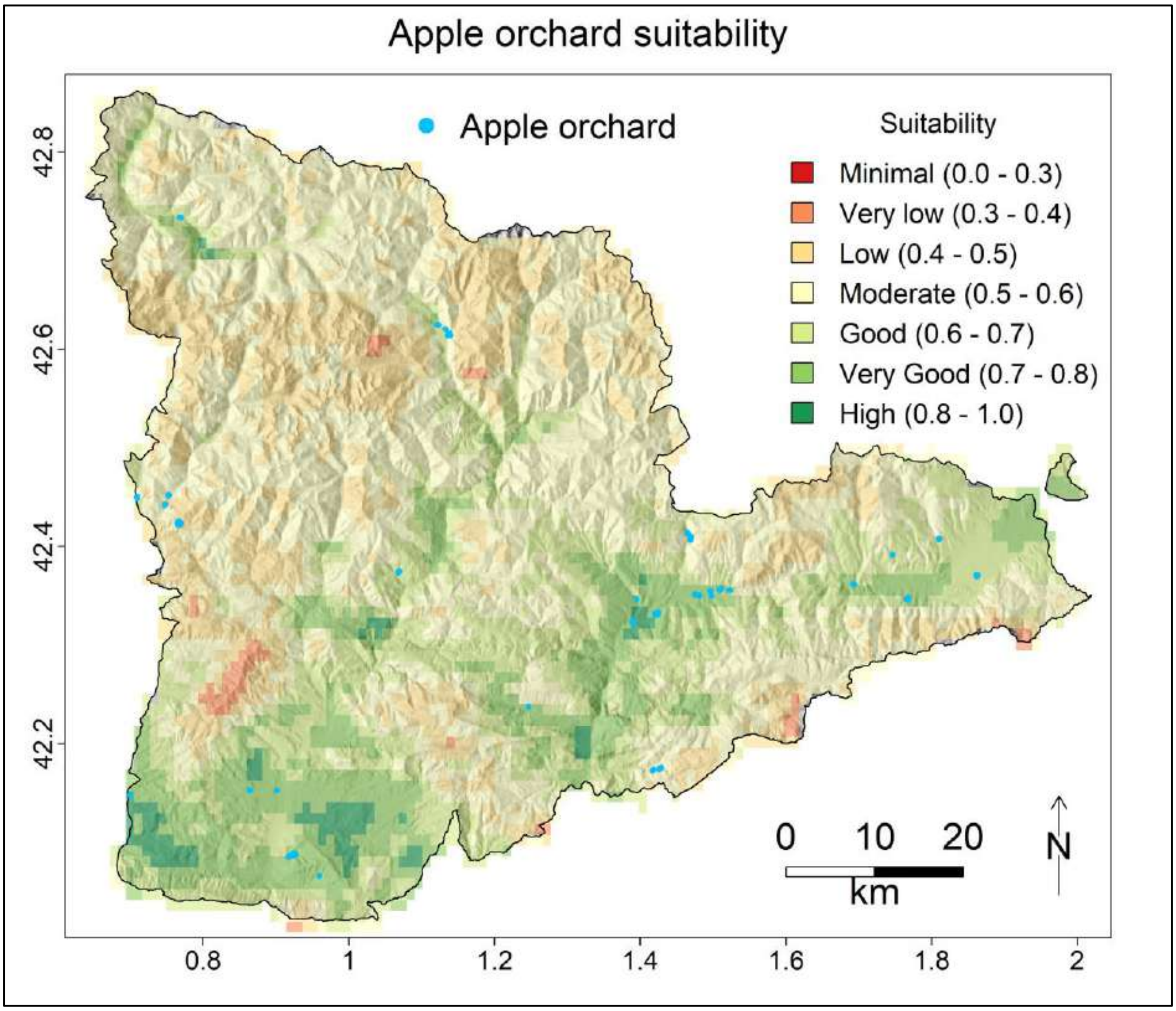


Figure 47. Resulting apple orchard suitability map.

4.4.4 Fire priority zones comparison

Statistics show that overlapping areas compose 10,332 ha of very good or high suitability (0.7 – 1) for vineyards and 4,561 ha for apple orchards. This surface represents 1,84 and 0,81 % respectively of the total area of the study zone.

Table 60. Total area of suitability classes for each crop and area that lies within fire priority zones (in brackets).

Crop	Total area [area inside fire priority zones] (ha)						
	Minimal	Very low	Low	Moderate	Good	Very good	High
Vineyard	0 [0]	14,402 [134]	133,620 [2,298]	93,922 [2,503]	176,461 [9,696]	168,167 [10,321]	1,401 [11]
Apple orchard	0 [0]	3,902 [149]	106,425 [1,683]	258,360 [9,891]	141,052 [8,729]	70,530 [4,362]	7,704 [199]

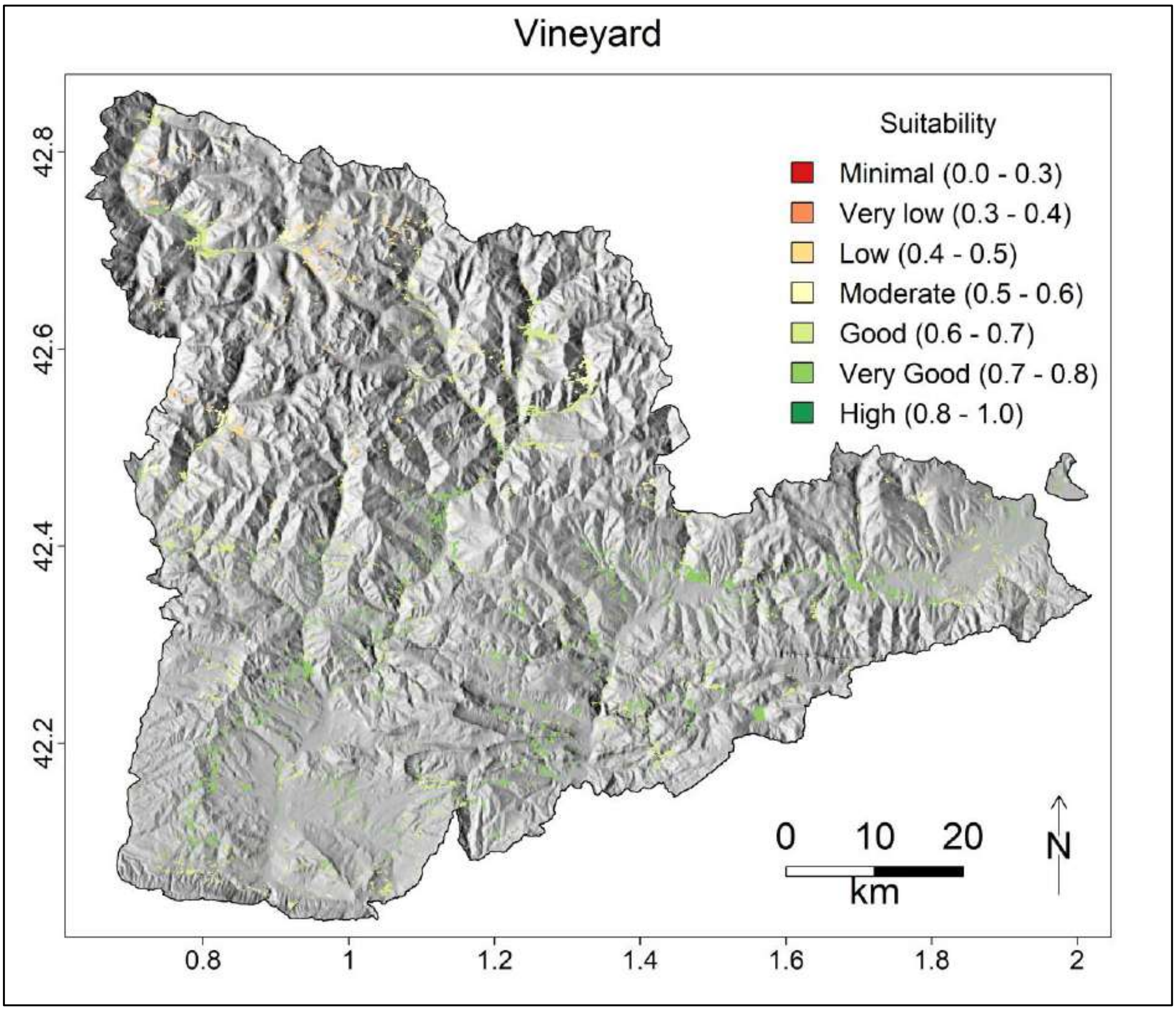


Figure 48. Fire priority zones suitability for vineyards.

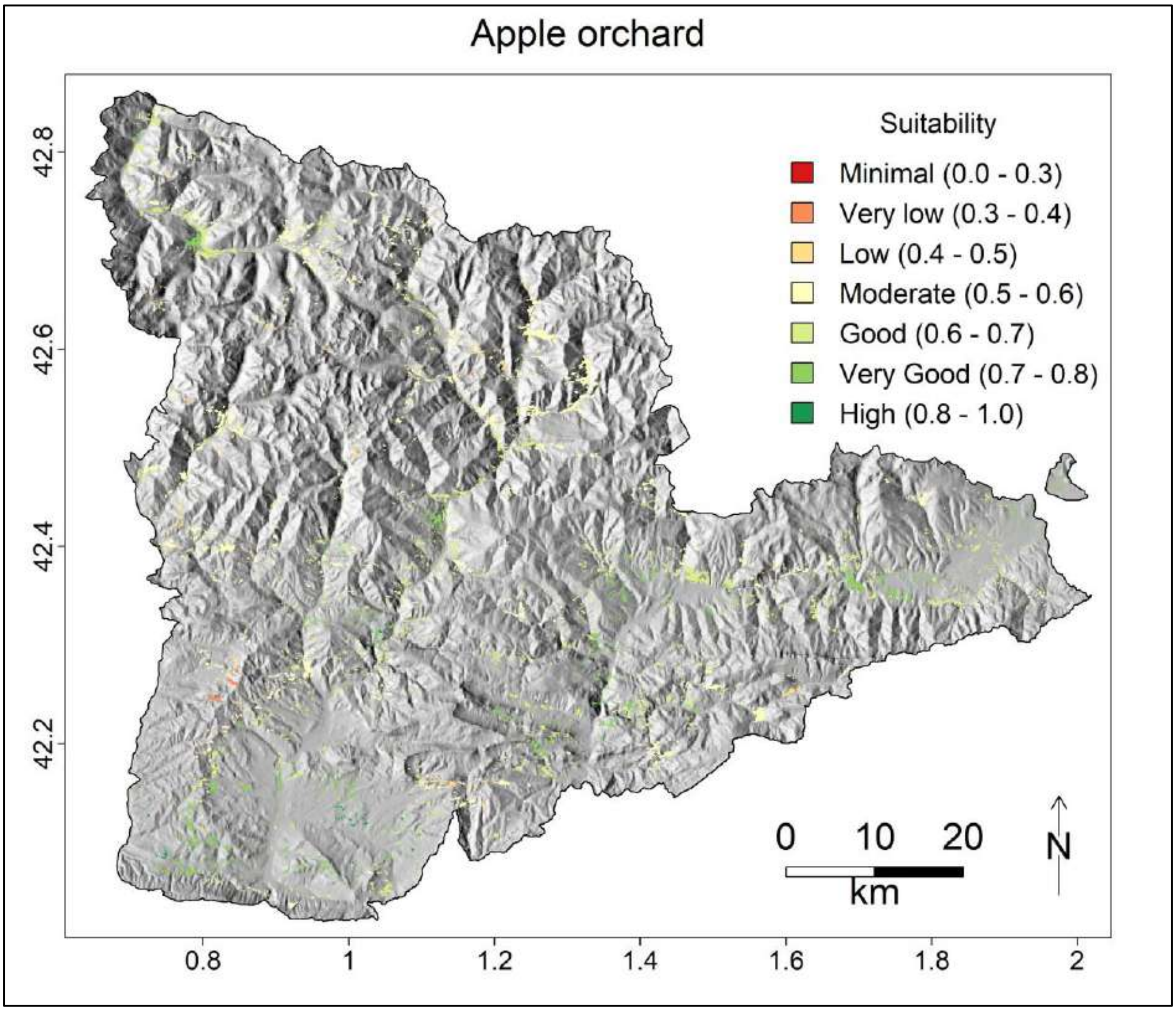


Figure 49. Fire priority zones suitability for apple orchards.

4.4.5 Socio-economic analysis

A further explanation of socio-economic constraints will be presented in the Deliverable 3.3 IA2.2 Brief: Economic efficiency gains from new value chain solutions to stimulate the uptake of fire-preventive measures and reduce losses from wildfires. Herein only a summary of the main factors is presented.

Table 61. Summary of the main limiting factors found during the face-to-face interviews and the review.

Infrastructure	Socio-economic	Climatic	Legislative
Fence in many cases is mandatory. Wildlife damage can be really high, both to young plants and to annual yield	Difficult to obtain long-term rents and buy the plot may be unfeasible	Weather phenomena such as late spring frosts or hailstorms require protective measures	Licenses to build wells or create river abstractions could take years and probably be rejected
Access to water is complicated. Usually none of the actual agricultural plots have an irrigation system	Generally, workforce is insufficient, with temporal availability and not specialized	Late spring frosts are particularly critical because they can jeopardise the entire season's yield	Land use change from forest to agricultural plot will most likely have to undergo an environmental assessment
Transit between plots may be long due to the lack or status of the roads.	Lack of a cooperative structure (in the case of vineyards) to sell the product directly or share processing costs	Places with low wind and high humidity may be really prone to plages	High proportion of land (especially those forested) is protected (e.g., Natura 2000), which difficult the land use change process
Slope may hinder mechanized tasks			

We have performed 11 interviews with vineyard owners (from 21 found) and 7 with apple orchard owners (from 15 found). For vineyards, implementation costs round 15,000 € per hectare without considering the cellar, which may greatly vary depending on its size and previous infrastructure availability. For apple orchards, implementation costs round 60,000 € per hectare without considering all the necessary infrastructure to store the apples one harvested. This is due to the existence of a cooperative which groups almost all the farmers in mountainous regions, and this means that farmers do not have this type of infrastructure on their farms. The difference between vineyards and apple orchards mainly comes from all the net structures that are mandatory for apple orchards.

4.5 Readiness level

Regarding the Technology Readiness Level (TRL) indicator, the initial level was TRL 3 (Experimental proof of concept). The development of a new approach to assess suitability in mountainous regions and the application to the study results in TRL 5 (Technology validated in relevant environment).

4.6 References

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5 Design and field test of work systems (Section 3)

5.1 Objective

In Europe, forest works are the most common mean to modify the fuel structure and reduce the biomass load of the forest in order to reduce the risk of wildfires ignition and/or minimize its intensity while facilitating the access to the forest to firefighters crews.

Depending on the approach, forest works may fulfill several synergic silvicultural goals, among which wildfire prevention is just one of the targets. For instance, thinning and pruning may serve to create a less fire-prone forest while selecting future trees for productive purposes and/or increasing accessibility and aesthetic properties of areas with touristic value.

In this sense, mechanical work plays a crucial role due to its relative acceptance from the public opinion (particularly compared to the present view of prescribed fires). A correct equilibrium among all the preventive treatments should be achieved, applying on the landscape the most appropriate on a case-by-case basis (as elaborated in Section 1 of this deliverable). Yet, all of the main treatment options require improvements and adaptations to the local conditions in order to be more effective. Additionally, attention should be paid to their acceptance by the most relevant stakeholders, such as the forest owners, the forest workers that are demanded to perform the tasks and, clearly, the public opinion.

Under this frame, the main objective of this section is to highlight the effectiveness of the preventive silviculture works (fuel reduction) and to maximize the value recovery of removed biomass. This overall goal includes several cascading aspects to be addressed, such as the selection of work systems that reduce fatigue or risk for forest workers (without substituting the manual work, threatening their jobs), the minimization of environmental damages and the capacity to return a forest structure that achieves the demanded silvicultural and aesthetic outputs.

Overall, the mission is to provide a more favorable economic balance of operations, unlock raw material resources currently unexploited addressing the circular economy guidelines and allowing fuel treatments of larger forested areas thanks to its lower net cost per hectare (IA 2.2).

5.2 Methodology

Forest works in general, and more specifically, biomass removal activities are extremely influenced by local conditions. Type of vegetation, climate, topography, pedology type and size of property, presence of local constrains such as inclusion in protected areas, type of organization in charge of the activity, training and physical capacity of the crews are just some of the factors to be considered when seeking for innovative solutions in forest operations.

In order to gather the necessary information in each Living Lab the LL leader was involved in the decision process. The local technicians were requested to identify the target silvicultural treatment addressing a specific local case with high impact on the wildfire management of the territory. Silvicultural details such as the type and general purpose of intervention, the expected result in terms of final stand structure, work limitations (e.g., protected endemic species) etc. were provided. Additionally, the current work systems deployed were described, identifying the benefits -*why we do it in such way*-, the constrains -*why we are forced to keep doing it*- and the limitations or drawbacks, also in a future perspective -*what should be improved*-.

5.2.1 Living Lab Sardinia

In December 2021 the first scouting visit to Sardinia was done in order to identify the possible demo sites and interview the local partners regarding the desired type of innovation to be implemented in their territory. The technicians of FORESTAS, leader of the LL Sardina, had arranged an extensive overview of possible sites, as well as several meetings with site managers to discuss the local requirements.

According to the Grant Agreement (GA) in this LL, besides the demonstration of mechanical treatment, was planned also the post-treatment reduction of vegetation regrowth via controlled grazing on a minimum area of 20 ha (IA 1.4).

The main treatment identified as strategic for the LL was the maintenance and recovery of wildfire preventive infrastructure (fire and fuelbreaks). These are forest fuel interruptions strategically located in areas with high risk of forest fire and/or low accessibility in case of emergency. In general terms these infrastructures are composed by a central viability with a buffer on both sides of variable depth (minimum total recommended width is 30 meters). Originally, these were conceived as firebreaks, where the buffer is completely cleared of vegetation. Nowadays, fuelbreaks or shaded fuelbreaks are preferred, extending the width of the buffer but releasing a sparse vegetation to partially cover the ground. The function of such infrastructures is to facilitate access and intervention of the firefighting teams and reduce the violence of wildfire upon its passage over the infrastructure, creating a strategic breach where focusing the extinction efforts.

The long-term plan for FORESTAS is to convert all firebreaks and common fuelbreaks to shaded fuelbreaks (Figure 50). Additionally, these infrastructures require a periodic maintenance to control the vegetation regrowth in the buffer area. A non-managed fire-fuelbreak could result even more dangerous of the surrounding vegetation under some conditions, facilitating the fast propagation of fire, and thus calls for extensive and well-planned maintenance, with a relevant financial and operative effort for the territorial authority in charge (or private owner).

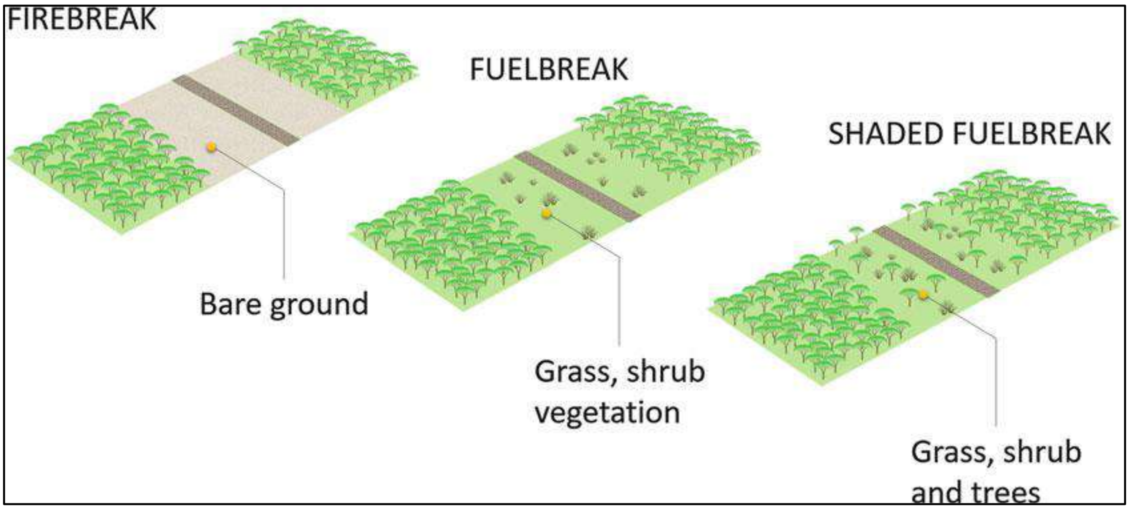

Figure 50. Different fire and fuelbreak concepts compared. Source: Ascoli D. et al. 2018

Following the visit, two sites were selected for the forest demonstrations:

Porto Ferro – this is part of a 7 km long firebreak infrastructure along a coastal pine plantation of Pinus pinea (figure 51). The original purpose of the plantation was to reduce wind damage to the inland crops as well as stabilize the coastal dunes. Currently, it is a relevant touristic hotspot with heavy load of visitors in the summer season. The firebreak is located in a delicate agro-forest environment included in the Natura 2000 protected area "Lago Baraz – Porto Ferro" additionally the area is included in the newly designed "Zona Speciale di Conservazione (ZSC) – Special Area of Conservation" covering the former Area of EU Importance (SIC ITB011155).

The vegetation is composed by an overstory of *Pinus pinea* L. (approximately 70 years old) with a quite complete crown continuity (featuring occasional gaps) and an understory of *Pistacea lentiscus* L. with considerable development, particularly on the verge of the firebreak opening which has been invaded by an exuberant vegetation growth.

Table 62. Summary of the main characteristics of the test area in Porto Ferro (Sassari, Italy).

Location	**Porto Ferro**
Dominant Species	*Pinus pinea* L.
Age	70 years old
Surface	6600 m^2
Type of intervention	Thinning
Tree removal	30%
Shrub removal	30%
Volume removed	43,83 m^3
No. of plants removed	192
Avg. plant diameter	24,72 cm
Average plant height	8,6
Ground slope	0%

Figure 51 Selected firebreak in Porto Ferro, Sassari.

Silvicultural requirements – the firebreak was to be converted in a shaded fuelbreak for a depth of 30 meters from the roadside. Originally the buffer was planned on both sides, involving also the east flank of the infrastructure, characterized by a Eucalyptus mixed spp. plantation established to further protect the agricultural crops from salty winds. In a following stage, it was decided to run the demonstration just on the pine stand, postponing the operations on the eucalyptus. The buffer should result in a gradual increase of vegetation density from the roadside to inward the pine stand. The resulting desired density of trees and shrubs should have guaranteed a 70% cover of the ground to protect soil from erosion, reduce vegetation regrowth and maintain (or enhance) the esthetic value of the site. Protected endemic species (e.g. *Chamaerops humilis* L.) should be not damaged during the operations. Additionally, both due to the protected area restrictions and the impact on citizen's opinion, no visible signs should be left on the ground. This last condition limited both the use of machinery inside the buffer (due to the possibility to leave track marks on the ground) and the extraction of whole trees (since branches would easily dig furrows into the sandy soil).

Due to wildfire risk, all residues should be extracted from the forest and disposed of at the roadside. On site mulching could have been considered, but under the condition to guarantee a minimum transit of machinery inside the buffer (the former forest area).

Value recovery – the local market allowed for a limited use of the timber assortments sourced from the forest works:

- Pine logs could be used for production of high-quality wood chips (produced with debranched logs). Sawmill transformation was not considered due to the quality of trees (mostly short, twisted and with relevant taper) and the absence of a local industry. The idea of using debarked eucalyptus timber for the construction of tourist signs or small beach structures like gazebos was canceled when the eucalyptus buffer was excluded for the demo.
- Pine branches and crowns as well as the removed shrubs had no suitable consumer within a 150 km range, forcing to mulch and leave them at roadside.

Technical and social requirements – FORESTAS is the public entity managing most of public properties in Sardinia (over 200,000 hectares) and responsible for wildfire prevention over the whole Sardinia island. It plays also a role of extensive public employer in the Region Sardinia with the double purpose to guarantee rural employment while providing landscape management. Furthermore, the over 6,000 employees are ageing and steadily less suitable for heavy tasks in forest clearing. As such, FORESTAS is equipped with modern machinery, but prioritizing extremely light or micro-equipment in support of a mostly manual work system. On a wider perspective, the whole forestry sector in the Region has a low financial capacity due to a limited market for forest products and services.

Work system selection – considering the above, the researchers of CNR-IBE opted for solution featuring the following characteristics:

- Light, agile and inexpensive prime mover, allowing fast relocation to different work sites. The solution should be suitable for second-hand machines in terms of hydraulic and electronic demand, providing the possibility to further reduce the acquisition cost.

- Multi-purpose solutions, capable to perform multiple tasks (possibly all the task required by the fuelbreak management) with a unique machine, conceived to support and facilitate manual work rather than substitute it.
- Innovative but accessible and easy-to-use solution.

After a careful analysis of the requirements and the possible available technologies it was decided to use a mini-winch designed to be installed on the upper part of the boom of a micro-excavator (about 4 tons). Winches are extremely common in forest operations, yet small size solutions for excavator booms are relatively new and had been historically used in Scandinavia and Iberia in specific work niches (mostly small-scale forestry).

Figure 52. example of mini-winches installed on light forest machines in ELMIA wood fair, Sweden.

The selected model was a HAFO Sapi Pro (figure 53), a hydraulic winch system that due to its low weight, it can be mounted quickly and easily on various devices; with a 6 mm rope diameter, 50 meters in length, and a pulling capacity of 1450 kg.

Figure 53. HAFO Sapi Pro mini-winch installed on the micro-excavator (left) and detail of the winch on the first section of the boom (right).

This winch, equipped with a remote control, enables the excavator to extract timber up to a distance of 50 meters, exceeding the depth of the fuel break buffer. Additionally, despite the small size and the reduced traction power, the favorable elevate position and winching angle theoretically should allow to extract relatively large logs.

The mini-winch was easily installed on a 10 years old micro-excavator (4 tons). The equipment of the machine was completed with a timber grapple featuring a fixed blade (removable in about 4 minutes) designed to cut and remove shrubs and branches (up to 12 cm diameter). Once removed the blade the grapple can handle logs for concentration, piling, feeding a chipper or loading a truck.

Figure 54. cable extended from the mini-winch for timber extraction (left) and whole configuration including winch and the grapple integrating a wood shear (right)

Experimental design – the original test plan included a comparison of three work systems: 1) the innovative solution combining manual felling and mechanized processing of trees and most of the remaining operations performed by the excavator (timber concentration and piling as well as cutting, extraction and piling of shrubs); 2) the current professional work system based on manual work supported by farm tractor with winch for timber extraction and 3) the current work system of FORESTAS, featuring a completely manual harvest of trees and shrubs followed by manual extraction of biomass with the support of micro machinery (e.g., motorized wheelbarrow). For this purpose, the firebreak was divided in 6 subplots on each side (pine on the western side, eucalyptus on the eastern side). These were in pairs supposed to be treated with each work system, replicated twice.

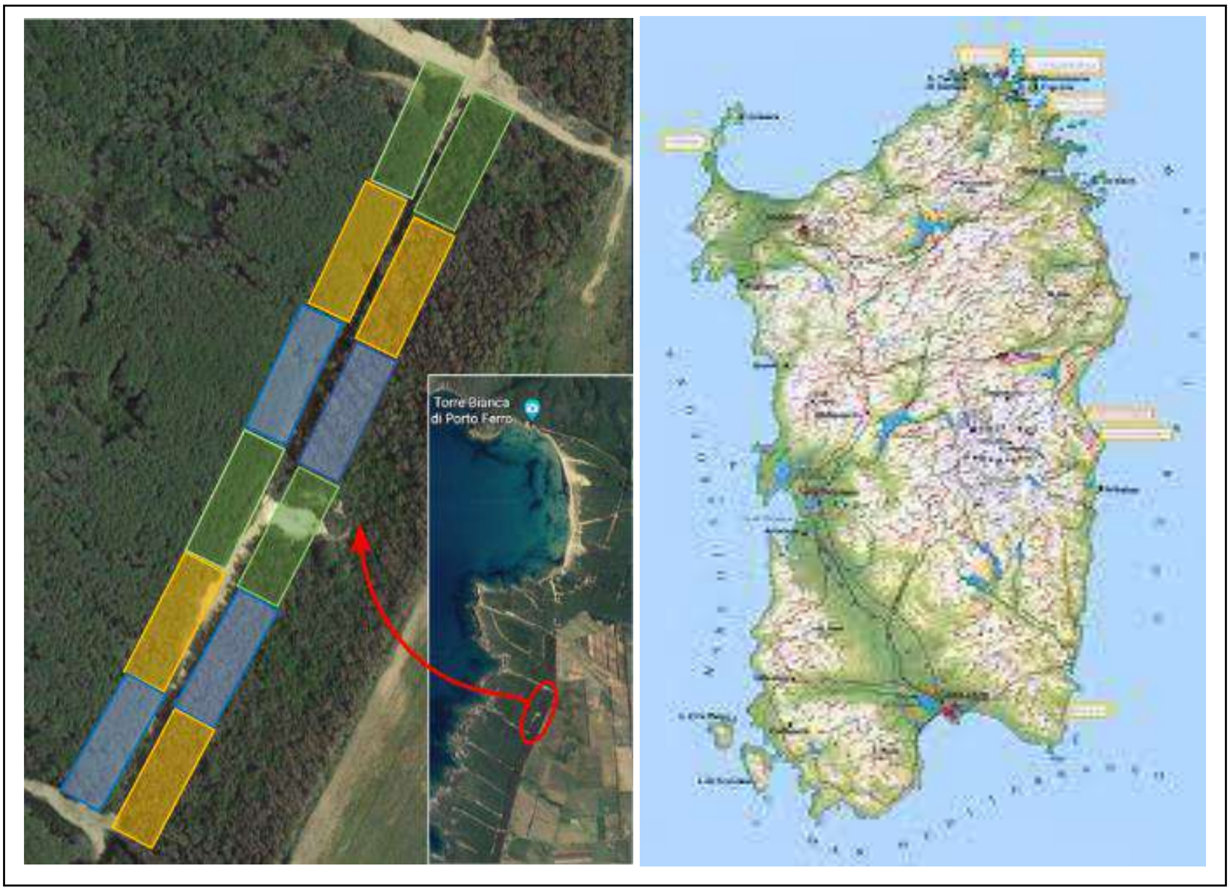

Figure 55. Position of the study area and division of the strip in sub-plots for the comparison of different work systems (colors represent subplots featuring innovative, commercial and non-commercial work systems).

Study and demo execution – the original test plan needed to be widely modified and adapted to several unexpected issues and changes:

- The partner hosting the test decided not to carry on the works in the strip covered by eucalyptus vegetation, removing this part of activity and the subsequent value recovery based on debarked eucalyptus logs for beach furniture.
- A further change of planning involved the subplots dedicated to the work system 3), which the hosting partner converted in open areas for tourism reception rather than maintaining the original destination.
- A delay in the formal assignment of the forest contractor reduced the available work time for the demo, as forest operations are forbidden in the wildfire season,

Overcoming these changes, the basis of the planned experimental design was maintained.

The analysis conducted highlighted that:

- The innovative work system has a similar cost per hour, but higher productivity, leading to a lower cost per hectare of the silvicultural preventive works.
- The excavator mounted winch featured a productivity comparable to the tractor mounted one in spite of the different traction power (respectively 1.45 t vs 6.5 t); this is because the installation on the boom allowed for adjusting the trajectory of the winched log, avoiding obstacles and reducing ground friction.
- The impacts on the soil and remaining vegetation very similar between the two working systems since skidding was performed using a winch in both cases. However, there was a difference in the exported timber: in skidding with a tractor, the wood became dirtier with soil, causing greater wear on the chainsaw chain during processing, which required more labor (more frequent sharpening). This outcome suggests that, in spite of appearance, the impact on soil is probably lower with the excavator mounted winch: further studies would be needed to confirm this hypothesis.
- The excavator arranged both logs and slash in well organized piles, which reduced the area occupied on the roadside and facilitate the following operations of loading, chipping or mulching on site.

The public demonstration gathered mostly technicians of the local public authorities and university students. The solution arose a considerable interest, particularly for the use of a simple shear-grapple for all the tasks involved and the capacity of the micro-winch to effectively extract large logs despite the reduced traction power.

Date of public demonstration	30th March 2023
Number of attendances	16

Figure 56 attendants of the public demonstration in Porto Ferro.

Monte Grighine – This area is part of more than 1 km length of a pine forest located below a wind farm. It consist of 50 years old forest formations of *Pinus Nigra* and *Pinus radiata* with uneven density due to a past wildfire event (around 25-30 years ago). The shrub layer is featuring *Pistacia lentiscus*, *Rhamnus alaternus*, *Phillyrea latifolia*, *Erica arborea*, *Arbutus unedo*, and, on more acidophilic substrates, *Phillyrea angustifolia*, *Myrtus communis*, and *Quercus suber.*

Figure 57. Structure of the firebreak of Monte Grighine before treatment and subplot preparation (right).

Table 63. Summary of the main characteristics of the test area in Monte Grighine (Oristano, Italy).

Location	**Villaurbana**
Dominant Species	*Pinus Radiata* L., *Pinus nigra* L.
Age	50 years old
Surface	11700 m^2
Type of intervention	Thinning
Tree removal	100%
Shrub removal	100%
Volume removed	39,96 m^3
No. of plants removed	126
Avg. plant diameter	23,0 cm
Average plant height	9,4
Ground slope	15%

Silvicultural requirements – Within a depth of 30 meters the prescriptions required total removal of all tree species, with the exception of the cork oaks (*Quercus suber* L.) whose felling was not allowed. Within the first 5 meters from the road all shrub layer was to be removed (still with the exception of cork oaks). In the buffer ranging from 5 to 30 meters 70% of shrubs should be removed, particularly around cork oak (complete clearing within a radius of 3 meters from each individual, even seedlings). Shrub continuity was to be reduced allowing the retention of taller plants (*Arbutus unedo*) with clear crown separation from the ground. This would provide shadow and ground protection in the resulting strip, dedicated to cattle grazing as a mean of land use and further solution to maintain a low load of fuel. All residues (shrubs and pine slash) were to be removed from the strip and disposed of at roadside to minimize the wildfire risk.

Value recovery – differently than the previous site of Porto Ferro, the demo position was strategically located in terms of possible end users of the biomass by-products sourced by the operations:

- The nearby biomass-fed power plant "Sardinia Bioenergy" allowed to deliver biomass delimbed or whole trees. This was the main destination for pines. The availability of the own sawmill of FORESTAS in the nearby Monte Arci station disclosed the possibility to segregate the best logs for a higher added value destination if a minimum quantity could be gathered (e.g., a full truckload).
- Shrub biomass had an innovative potential use thanks to the preliminary provision contract that FORESTAS signed with the dairy company "Arborea". This industry planned the construction of a biogas plant for the disposal of livestock sludge about 40 km from the demo site. According to the industrial plan, the carbon substrate was to be provided with lignocellulosic biomass of broadleaves shrubs. Any conifer biomass should be avoided as resins may inhibit the microbial activity of the biogas reactor.

Technical and social requirements – Same as in the previous site

Work system selection – given the lower level of constrains of this site from the silvicultural point of view, a different equipment could have been selected. For instance, a larger and more powerful machine could had performed more efficiently the total removal of shrubland from the buffer area. Yet, it was opted to maintain the equipment selected for the more restrictive case of Porto Ferro, and verify its performance in a different work setting. The comparison among sites would provide valuable insights regarding the flexibility of use of the selected solution, and prove that a unique machine could be deployed in delicate and sensitive areas as well as in more resilient sites. A wide range of application increases the potential annual usage of the machine, allowing for a faster return of the investment.

Experimental design – the same experimental design previously described was planned in this site. Considering the higher operative length and the overall area of intervention, the subplots had a larger area.

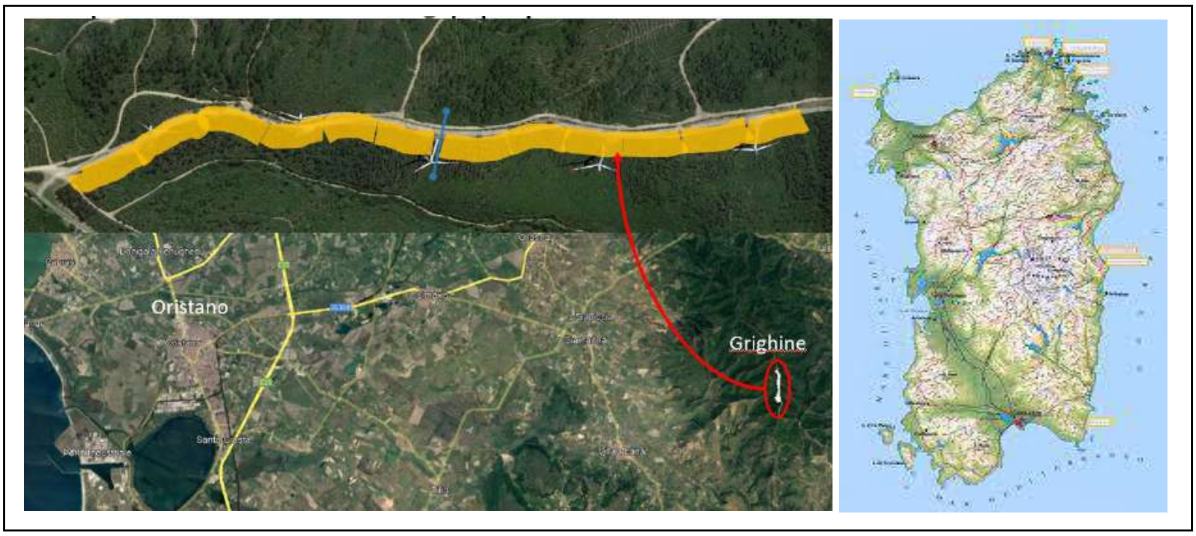

Figure 58. Location of the demo site in Monte Grighine.

Study and demo execution – also in this case the original test plan needed to be widely modified and adapted to several unexpected issues and changes:

- The contracted company lost most of its workforce, and their functions were covered, where possible, by CNR researchers.
- Timber felling was performed by the FORESTAS team rather than by the chainsaw operators of the contracted company (for same reason as above).

Overcoming these changes, the basis of the planned experimental design was maintained.

The innovative and traditional work system compared were the same as previously described, as well as the results and impressions recorded. On the one hand, considering the lower environmental constrains in this area, a larger machine could have been deployed to treat the same area in a lower time. On the other hand, the excavator used may be transported with a common farm tractor equipped with trailer, while larger equipment may require more specialized (and expensive) solutions for relocation among the work sites.

Date of public demonstration	09/05/2023
Number of attendances	18

Figure 59. Attendance to the public demonstration in Monte Grighine.

5.2.2 Living Lab Catalonia

Viladecavalls – This research was conducted in a naturally regenerated *Pinus halepensis* forest after a wildfire, with sporadic holm oak (Quercus ilex) in the dominated level, which exhibited a high accumulation of fuel. The forest is located in Viladecavalls, Catalonia (Spain), and presents an inhomogeneous vegetal cover with a different plant density gradient. The plots for the study were selected as representative of the different stages of trees development. The difference between the stands can be resumed as below:

Plot 1: Dense stand of tall and slender trees with a large quantity of climbing plants. Almost impenetrable by walking. Terrain from moderately steep to almost flat.

Plot 2: Intermediate stand with smaller trees than plot 1, less climbing plants but presence of stones and obstacles. Moderately steep.

Plot 3: Very high density of thin and short trees, no presence of climbing plants but almost impenetrable due to the pines. Moderately steep.

Table 64. Summary of the main characteristics of the stands included in the test area in Viladecavalls (Barcelona, Spain).

Plot	1		2		3
Species	*Pinus halepensis*	*Quercus Ilex*	*Pinus halepensis*	*Quercus Ilex*	*Pinus halepensis*
Density (trees/ha)	1,700	340	4,980	283	9,620
Mean DBH (cm)	16.9	4.5	10.2	4.4	5.9
Basimetric Area (m^2/ha)	42.7	0.6	47.0	0.5	30.7
Mean height (m)	7.16	2.0	6.17	2.9	4.32
Mean square diameter (cm)	17.9	4.6	11.0	4.8	6.4

Silvicultural requirements - The silvicultural treatment involves selective thinning to promote the most promising trees (future trees) and reduce the density of the plots. The main purpose of this study involves implementing measures that enhance the health and resilience of the forest ecosystem while respecting the preferences and concerns of those who own and manage the land. While cost reduction is still relevant, this type of operation aims at modifying the final structure with specific requirements:

- Interruption of any vertical fuel continuity (ladder fuels);
- Minimal treatment intensity and ground cover reduction to avoid grass and understory regrowth, as it would rapidly lead to an increased wildfire risk;
- Maximum cleaning of forest ground, to facilitate accessibility for firefighting and management operations and,
- Increase of future value of the remaining trees.

Value recovery – The local market is relatively active for pine-based products. Above a threshold of 8 cm, assortments as poles, pulpwood and sawnwood are accepted by the market. Yet, in most of the silviculture preventive operations, most of coarse biomass is left on the ground, extracting occasionally just the logs with larger diameter. This is due to the cost of extraction with the current systems, not compensated by the value yielded, and the minimal wildfire risk represented by stems left on the ground. Additionally, *Pinus halepensis* features a typical extremely high density in post-fire regenerated stands, calling for early treatments if the risk of extreme wildfire events should be minimized. Thus, the typical product of preventive silviculture in these stands provides logs with low or very low diameters, which are used just as biomass. This is locally differentiated in industrial feedstock (from whole trees and with low market value) and high-quality fuel (from delimbed trees and with higher price).

Technical and social requirements - This kind of forestry management must be aimed at securing the forest from the risk of wildfire while also satisfying the forest owners. Even though these interventions are funded by the public authority, they are voluntary, and often not carried out to low the value (including aesthetic) of their forests. Therefore, striking a balance between conservation efforts and the interests of forest owners is crucial. Additionally, forest ownership in Catalonia is highly fragmented, particularly in the peri-urban areas which feature the highest level of wildfire risk. This requires the adoption of an agile work system, which can be easily relocated with minimal costs. An added value would be a polyvalent solution performing all the required tasks (e.g., harvesting, hauling, etc.).

Work system selection – The study focused on the performance of a lightweight multifunctional machine to prevent the risk of fires in Mediterranean areas. The main purpose is to compare the cost and productivity of the proposed system with the current preventive silvicultural treatments, which are mainly based on manual labor. To achieve our objectives, we used an innovative combined machine, the Malwa Combi 560C, which serves a dual function: it fells trees acting as a harvester and extract them as a forwarder (Figure 59). This dual function makes forestry work very flexible and minimizes relocation costs thanks to its minimal size. In harvesting function, the machine is equipped with a processor capable of felling and delimb stems ranging from 2 to 42 cm. This harwarder can operate at all the vegetative layers of the pine stands, yielding biomass or delimbed logs for high-quality biomass production.

Figure 60. Malwa Combi 560C in harvester mode (left) and in forwarder mode (right).

Experimental design – Three different plots were selected, representing various stages of development of post-fire regenerated stands, with densities of approximately 1700, 5000, and 9600 trees per hectare, respectively. Each plot posed different challenges due to variations in tree size, density, and the presence of climbing vegetation. Prior to the tests, trees to remain (future trees) were marked in all plots for an easier identification. In common practice, the selection is performed directly by the operator; but in this case, despite being a highly experienced machine operator (over 10 years), the Swedish driver was facing Mediterranean forests and silviculture for first time. Thus, manual marking was considered necessary.

While harvesting, the operator was requested to open limited corridors, as narrow as possible, and fell trees up to the maximum reach of the crane. The same corridors were used later for timber hauling. Logs were piled at roadside for following transportation to the end user.

Study and demo execution – The study analyzed the use of lightweight machinery to reduce wildfire risk in Mediterranean forests, comparing an innovative mechanized system with traditional methods based on manual labor. The main goal is to reduce the amount of biomass available for combustion through preventive thinning operations. By using a combined machine capable of both harvesting and forwarding functions, flexibility is increased, and relocation costs are minimized, making it suitable for areas with small-sized and fragmented forest ownership.

The results demonstrated that mechanization could reduce the cost of preventive silvicultural treatments by up to 75% compared to traditional manual methods involving chainsaws, winches, and other tools. The harvester's productivity varied depending on the plot characteristics, ranging from a maximum of 2.93 m^3 per productive machine hour (PMH15[1]) in the least dense plot to 0.64 m^3/PMH15 in the plot with the smallest trees and highest density. Forwarding productivity showed similar variability, from 6.43 m^3/PMH15 to 2.09 m^3/PMH15, influenced by the volume and size of the felled trees.

One key advantage of the mechanized system was its ability to recover wood that could be sold as biomass, partially offsetting treatment costs and contributing to a more sustainable forest management approach. By reducing the fuel load and interrupting vertical fuel continuity, the mechanized thinning operations also lowered the risk of future wildfires while promoting the growth of the remaining trees and increasing their future value.

Despite the benefits, the economic viability of mechanized thinning was affected by factors such as wood quality and ground slope. In plots with steeper slopes, exceeding 30%, the machinery faced limitations in mobility, making manual labor a more suitable option. Additionally, the study found that while the mechanized system caused minimal

[1] PMH15 refers to a productivity that includes up to 15 minutes of delays.

damage to the remaining trees and soil, manual methods often resulted in more significant impacts, especially due to the pruning and handling of dense stands.

The public demonstration gathered mostly technicians of the local public authorities, high school and university students. The solution showed arose a considerable interest, particularly for the use of an innovative multipurpose machine for dual functions: as a harvester, it felled, processed, and delimbed trees, while in the forwarding mode, it transported the wood to designated areas for further processing.

Date of public demonstration	24th and 28th November 2023
Number of attendances	52 + 24

Figure 61. Attendance to the public demonstration in Viladecavalls.

5.2.3 Conclusions and next steps

A properly selected mechanized work system may drastically reduce the cost of preventive silviculture. Test cases involved two of the most common fuel treatment activities for wildfire prevention: fuelbreak management/creation and forest thinning. Besides the reduction of costs per hectare, a tailored solution for fuel removal reduces fatigue and risks for the operators and makes available a wide range of raw materials for a large set of possible processes. Deliverable 3.3 will report in detail the economic analysis of the tested work systems, contrasting the results of the study with the performance of the current, highlighting the potential to boost territorial management on a larger area (considering the same budget) by introducing proper innovations in form of semi-mechanized or fully mechanized systems.

A last field test and public demonstration (figure 62) is ongoing, to integrate the options of fuelbreak management with a highly mechanized work system. Also in this case the performance of the innovative equipment will be compared with the work system commonly deployed in the area for the same task. In this case the focus was to maximize the speed of operations while minimizing its interaction with other systems. As such, recovery of bioproducts is reduced to just large timber for biomass production. All the remaining residues, composed by branches and crowns of pine trees as well as all bushes, are comminuted on site. Results will be in Deliverable 3.3.

Figure 62. Ongoing test (2024-10-23) with professional light harvester for fuelbreak management. On the left it deploys a combined processor/grapple head, on the right installs a mulcher for direct comminution of residues and bushes.

5.3 Readiness level

As anticipated, the innovation envisaged in this section is not strictly technological, but related to the application of commercial technology in a different work "environment".

Regarding the Technology Readiness Level (TRL) indicator, the initial level was non less than TRL 8 (System complete and qualified). But this qualification was limited to Nordic and Central European forestry, in commercial silviculture of productive conifer stands (*Picea abies* L. and *Pinus sylvestris L.*).

The application to the new context, characterized by a different goal (preventive), different species (*Pinus halepensis* and *nigra*) and specific work procedures was the specific goal of this section of IA 2.2. The demonstrations in forest and the studies carried on proved the suitability of the machines tested for the specific application for wildfire preventive silviculture, resulting in a TRL 9 (actual system proved in operational environment).

5.4 References

Ascoli D. et al. 2018 "Firebreak and Fuelbreak" in Manzello S. (ed.), *Encyclopedia of Wildfires and Wildland-Urban Interface (WUI) Fires, https://doi.org/10.1007/978-3-319-51727-8_70-1*

FIRE-RES