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Valuation of Climate Services for Viticulturists: Tackling fungal diseases

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ABSTRACT

Viticulturists developing adaptation strategies to mitigate the impact of climate change, which affects a grapevine's physiology and wine typicity, can benefit from climate services. Climate services translate physically based variables, such as temperature and precipitation, into actionable, decision relevant bioclimatic indicators, such as Spring Rain, Heat Stress Days, and Warm Spell Duration. These bioclimatic indicators enable the mitigation of fungal diseases, specifically downy and powdery mildew, as well as sunburn. Accurate seasonal forecasts of these bioclimatic indicators can help farmers with viticulture, labor, and stock management, as well as improve the yield and value of wine-quality grapes. Seasonal forecasts of these indicators are available on the MED-GOLD project's dashboard. This study determines an annual service fee to access these forecasts on the dashboard. The annual fee accounts for the seasonal forecast accuracy over part of the Douro wine region of Portugal, as well as the potential savings and losses of micro (⩽1 ha) holding grape growers. The revenue generated from this climate service fee exceeds the cost of dashboard maintenance by nearly 10 times, even with a fee which is less than half of the potential savings of the micro holding farmer.

1. Practical Implications

Seasonal forecasts and climate projections have the potential to help farmers anticipate upcoming needs and devise plans for a more resilient, sustainable, and efficient future (Buontempo et al., 2020; Born et al., 2021; Wiréhn, 2024; Vaughan et al., 2019). Traditionally, these forecasts and projections included only essential climate variables, such as temperature and precipitation. The forecasts and projections did not include relevant bioclimatic variables, such as Spring Rain, Heat Stress Days, and Warm Spell Duration, which are needed to make agricultural decisions. This problem was compounded by the fact seasonal forecasts and climate projections are not easily accessible - both in terms of understanding and use for farmers.

To tackle these problems, the European Union funded the MED-GOLD project (https://www.med-gold.eu/) through its Horizon 2020 research and innovation programme. The MED-GOLD project ran from December 2017 until May 2022. As part of the MED-GOLD project, a simple-to-understand and easy-to-use dashboard (https://dashboard.med-gold.eu/) was created. The MED-GOLD Dashboard covers three time periods: the historical climate (1979–2020), seasonal climate forecasts (1993–2021), and long-term climate projections (2031–2060; 2071–2100) (Dell'Aquila et al., 2023). The MED-GOLD Dashboard provides essential climate variables, as well as bioclimatic indicators, for three key agricultural sectors of the Mediterranean, namely grapes, olives, and durum wheat. For each sector, an industrial partner was found to co-design, co-develop, test, and assess the added value of the MED-GOLD proof-of-concept agricultural climate service.

In the grape sector, the industrial partner was SOGRAPE Vinhos (Dell'Aquila et al., 2023), the largest wine company of Portugal. They manage over 1,600 ha of vineyards and produce wines across 5 countries and 3 continents. Fungal diseases and sunburn cause considerable losses in grape yield (20–30 %) and value (20 %) in the single harvest each year (Graça, 2021). Through the co-development of process with SOGRAPE Vinhos (Chou et al., 2023; First feedback report from users on

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wine pilot service development, 2023; Dell'Aquila et al., 2023), seasonal forecasts of Spring Rain, Heat Stress Days, and Warm Spell Duration, with a minimum accuracy of 70 % compared to observations, were identified as being helpful for explaining incidences of fungal diseases and sunburn, while improving viticulture, labor and stock management for grape growers in the Douro Valley (Northern Portugal).

In this work, we have determined an appropriate annual fee to access the seasonal forecast of these three bioclimatic indicators on the MED-GOLD dashboard. To determine the fee, we first calculated the seasonal forecast performance of these three indicators over the Douro Valley wine region. The seasonal forecast performance accounts for the hit-rate, false-alarm rate, and accuracy of the European Centre for Medium Range Weather Forecasts (ECMWF) seasonal forecasts version 5 data (Stockdale et al., 2018; Johnson et al., 2019), known as SEAS5, compared to the ECMWF reanalysis version 5, known as ERA5, of historical weather and climate data Hersbach et al. (2020); Bell et al. (2021). The second component of determining the annual fee, includes a cost-benefit analysis identifying the potential savings and losses of a micro holding grape grower. Micro holding grape growers make up the vast majority of grape growers in Douro Valley wine region, making their perspective essential when determining a climate service fee. Combining the results of both analyses, a range of "access fees" was proposed according to the accuracy of the seasonal forecast.

The results showed the SEAS5 seasonal forecasts of the three bioclimatic indicators starting in March to be 54–60 % accurate, compared to the ERA5 reanalysis, for hotter- and/or wetter-than-normal conditions over the Douro region. These forecast accuracies are statistically better than assuming the upcoming season will be "normal", although lower than preferred. Nonetheless, this climate service adds value to the traditional agri-food system.

If the seasonal forecast accuracy is 100 %, incorporating it into the decision making process could save farmers more than 10 % of annual harvest earnings in an average year and more than 15 % in a hotter- and/or wetter-than-normal year. Potential losses due to false alarms, however, must be accounted for.

We propose an annual climate service fee of €20/year to access the seasonal forecasts, over the Douro region, starting in March. This fee was determined by considering: (i) the financial loss due to fungal diseases and sunburn,; (ii) the maximum potential savings of a seasonal forecast in terms of labor and fungicide; and (iii) the 50 % accuracy of the seasonal forecasts starting in March.

In addition, we have shown that the potential revenue that could be generated from the MED-GOLD dashboard seasonal forecast alone, by charging the (minimal) access fee, is almost 10 times the annual maintenance cost of the dashboard. Thus, the revenue could cover adaptive and preventive maintenance activities to improve the MED-GOLD dashboard according to user feedback.

Lastly, the approach developed in this work, to determine the MED-GOLD Dashboard access fee, showed how improvements to the seasonal forecast accuracy directly impact the value of the climate service. The approach we used to identify the value of the climate service tackling fungal disease and sunburn can be applied to other MED-GOLD sector products and climate services. For example, those related to the olive or wheat sectors or future climate projections.

2. Introduction

2.1. MED-GOLD project

The MED-GOLD project was a proof-of-concept agricultural climate service which focused on three staples of the Mediterranean food system: grapes, olives, and durum wheat. Scientific and industrial experts partnered together to demonstrate the added-value of co-designing and co-developing information-driven responses to climate changes. A comprehensive description of the co-development of the MED-GOLD pilot climate service for the grape/wine sector is described in Dell'Aquila et al. (2023).

The agricultural climate service for the wine sector was co-developed with SOGRAPE Vinhos, the largest producing wine company in Portugal. SOGRAPE's participation as a co-designer in this pilot climate service acts as a catalyst, accelerating the engagement within the wine sector. Having a single dedicated "champion user" in the co-production of the climate service tool was particularly important in the Douro wine region (Fig. 1) due to the distribution of grape growers. From the Douro wine region's holding size distribution, shown in Fig. 2, it can be seen that ⩾60 % of grape growers have micro holdings (⩽1 ha). With only one grape harvest per year, the income generated by the harvest on a micro holding is merely supplementary income for the grape grower. Often times, these grape growers can not commit the time needed for the entire process of climate service co-production, which includes repeated interviews, testing and iterating products/services, etc., in addition to their regular jobs. SOGRAPE has the knowledge, resources, and personnel to dedicate to the co-production process with its own full-time Research & Development team. They participate in research projects and disseminate results to grape-growers and the wider wine sector; including the ∼ 1,000 grape growers who sell their products to SOGRAPE (Graça, 2021) in the Douro wine region.

2.2. Douro Wine Region

The Douro wine region is a mountainous region in Northern Portugal (Fig. 3) with a very steep terrain. Tiered terraces have been etched along its steep slopes. The rocky, schistous soil of the Douro region is dry and poor in nutrients, but has excellent heat retaining properties. With terraces offering different variations in altitude, exposures to sun and wind, soil fertility, and atmospheric humidity, the Douro region is a host to a variety of grape types. The six principal red and white grape varieties include, Tinta Amarela, Tinta Barroca, Tinto Cão, Tinta Roriz, Touriga Nacional, Touriga Francesa, Gouveio, Arinto, Malvasia Fina, Rabigato, Viosinho, and Códega.

2.3. Fungal Diseases and sunburn

Some grape varieties, such as Touriga Francesa, which account for approximately 25 % of all grapevines in the Douro wine region (Vinhos e Aguardentes de Portugal, 2020), have tight grape bunches. This makes them more susceptible to fungal diseases, particularly when warm and moist conditions persist and air can not circulate in the grape bunches (Graça, 2021).

Atmospheric humidity in the Douro wine region, in particular after rain in the spring, can drive risk of infection by Plasmopara viticola (downy mildew) (Fig. 4a) (Graça, 2021). When downy mildew emerges during critical phenological stages, such as at blossom or at fruit set, grapes are damaged, ultimately reducing yield. Downy mildew can be avoided by the procurement and application of protection products, such as copper-based formulations. Determining when protection products should be applied relies on daily monitoring of temperature, rainfall, and vegetation conditions. For example, the period after budbreak, when daily average temperature exceeds 10°C and shoots are at least 10 cm long, a rainfall event of 10 mm over 2 days prompts visual inspections for fungal disease development (Graça, 2021). Fungal development in susceptible areas has, historically, appeared one week after the rain event. After a visual verification of fungal development and protection products have been applied, atmospheric humidity conditions must be monitored as ensuing rainfall events may provoke secondary infections. Should this occur, protection products must be reapplied. Protection products may be applied multiple times throughout the growing season (Graça, 2021). Downy mildew protection products, however, have expiration dates over which they lose activity. Their short shelf life means any quantity not used during the growing season should not be carried over.

When high atmospheric humidity conditions are combined with

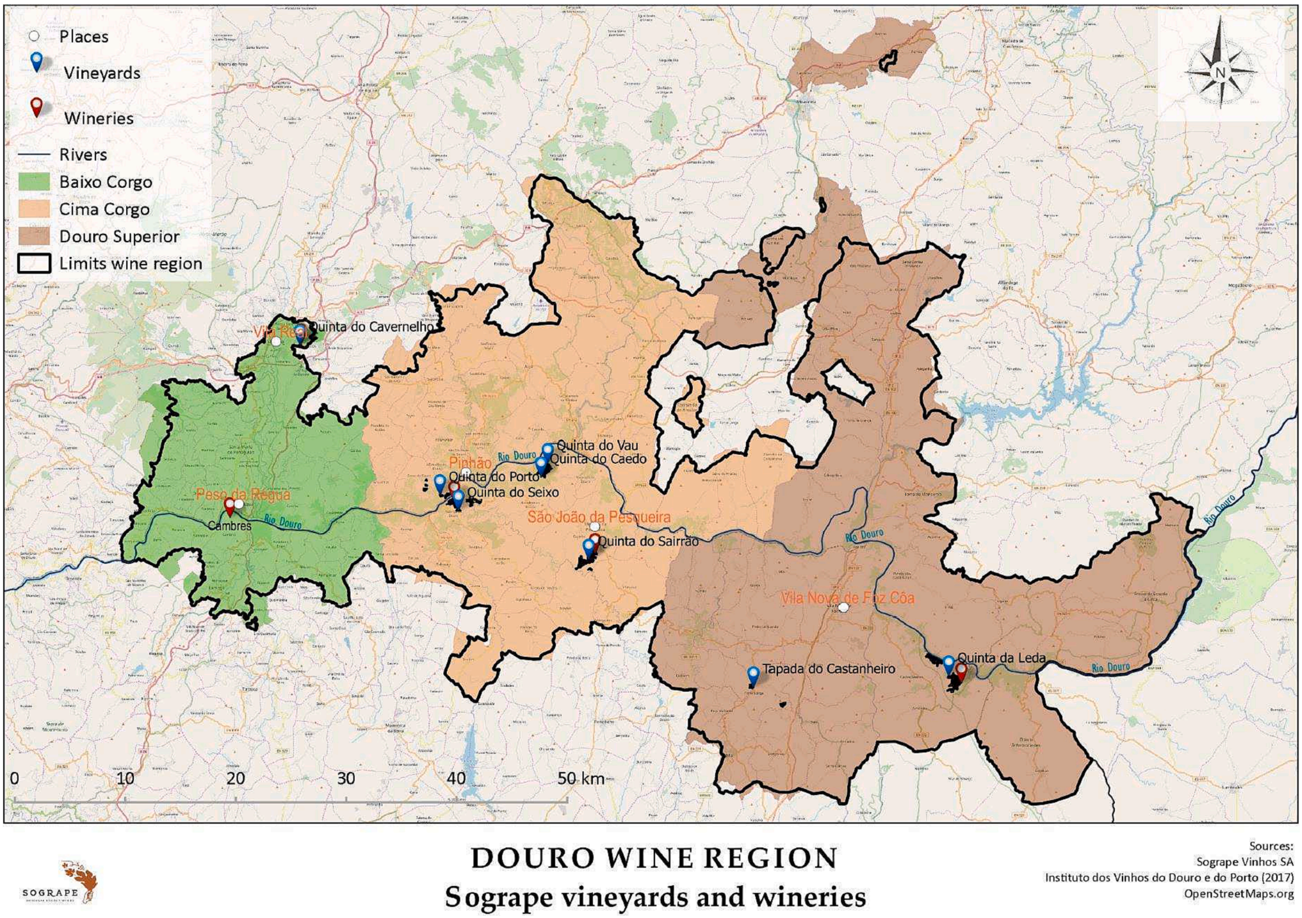

Fig. 1. The Douro Wine Region in Northern Portugal. Image Credit: SOGRAPE (Graça, 2021).

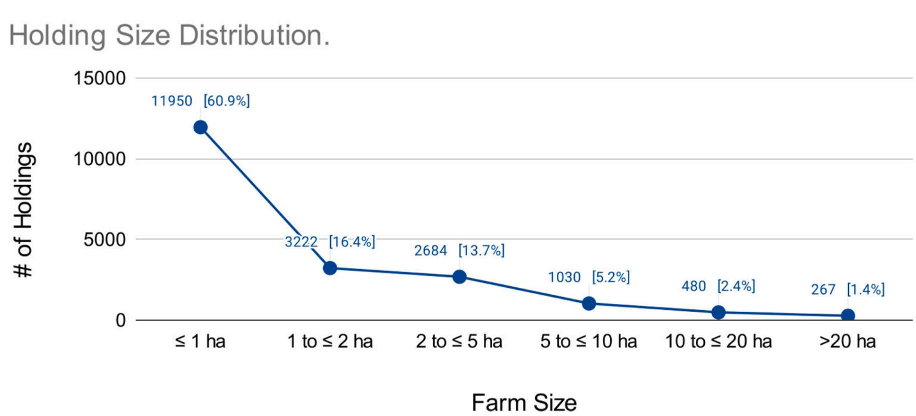

Fig. 2. Distribution of holdings according to Farm Size in the Douro wine region. Percentage of total distribution shown in square brackets. **Data Source:** Instituto dos Vinhos do Douro do Porto, I.P. (2020) (Caracterização et al., 2020).

mild-warm temperatures, sheltered conditions can be created around the bunch zones, especially in high-vigor grapevines. These unaerated bunches may be infected by Erysiphe necator (powdery mildew) (Fig. 4b) (Graça, 2021). Should an infection of powdery mildew occur during the veraison stage of grape bunch development, the result is a loss of grapes quality. Powdery mildew can be avoided through manual trimming and leaf thinning by laborers, known as active canopy management. These exposed grape bunches, however, are susceptible to sunburn as a result of direct solar radiation exposure (Fig. 4c) when temperatures exceed 35°C (Graça, 2021). This is particularly problematic during heatwaves. In addition, when temperatures exceed 35°C, the grapevine undergoes heat stress. The plant closes its stomata and photosynthesis no longer occurs. As the plant uses more water to cool its tissues, it can lead to a disruption in flowering or berry and leaf dehydration, and sunburn. Both sunburn and powdery mildew lead to a decrease in crop quality and value, but active canopy management can prevent the risk of either occurring.

With a single harvest per year, the yield and value of an entire production of wine quality grapes can be significantly reduced, or even lost, due to weather phenomena and viticulture mismanagement. In the Douro region, SOGRAPE found downy mildew typically caused a yield loss of 30 %, whereas sunburn caused a yield loss of 20 %, and powdery

Fig. 3. Mountainous and rocky terrain of the Douro Wine Region. **Photo Credit:** SOGRAPE (Graça, 2021).

(a) Plasmopara viticola, known as Downy Mildew. (b) Erysiphe necator, known as Powdery Mildew. (c) Sunburn.

Fig. 4. Examples of (a) Plasmopara viticola, (b) Erysiphe necator, and (c) sunburn. **Photo Credit:** SOGRAPE (Graça, 2023).

mildew caused a value loss of 20 %. These values are the same for all holdings, regardless of size (Graça, 2021).

2.4. Bioclimatic Indicators

Through several workshops, interviews, and focus group discussions with different levels of management, directors, and executives covering SOGRAPE's decision chain in productive and procurement operations the following bioclimatic indicators were identified as being useful for explaining the incidence of fungal diseases and sunburn in grape bunches Chou et al. (2023); First feedback report from users on wine pilot service development (2023); Terrado et al. (2023); Dell'Aquila et al. (2023).

These bioclimatic indicators, for the Northern Hemisphere, are defined as:

1. Spring total precipitation (SprR), the total accumulated rainfall from April 21st to June 21st. This indicator is associated with vigorous undervine growth which increases atmospheric humidity and restricts airflow, contributing to fungal disease risk Dell'Aquila et al. (2023); AWRI (2023).
2. Heat Stress Days (SU35), the total count of days which the daily maximum temperature exceeded 35°C between 1st April and 31st October Chou et al. (2023). This indicator is associated with the number of days photosynthesis of the plant is limited. After veraison, it can affect the sugar, polyphenol, and aroma precursor concentrations in berries, thereby affecting grape and wine quality Chou et al. (2023).
3. Warm Spell Duration Index (WSDI), total count of days which the daily maximum temperature exceeded the 90th percentile for at least 6 consecutive days between 1st April and 31st October Chou et al. (2023). This indicator is associated with dehydration, flowering disruption, and scalding of berries and leaves Chou et al. (2023).

2.5. Climate Service

The workshops, interviews, and discussions also helped determine that the mitigation of fungal diseases and sunburn in grape bunches impacts several operational areas including: viticulture, labor, and stock management Chou et al. (2023); First feedback report from users on wine pilot service development (2023); Terrado et al. (2023); Dell'Aquila et al. (2023). These areas can benefit from a climate service that helps forecast fungal infection risk and sunburn. Seasonal forecasts of

SprR, SU35, and WSDI, with a minimum accuracy of 70 % compared to observations, were presented in a format which was easy to interpret, understand, and use would suit this purpose Fontes et al. (2016); Chou et al. (2023); First feedback report from users on wine pilot service development (2023); Terrado et al. (2023); Dell'Aquila et al. (2023).

An effective climate service providing forecasts with longer lead times allows viticulture management to improve the timing of vineyard operations such as pruning and canopy management, as well as planning fungal disease treatments. Similarly, labor management benefits from improved identification and anticipation of high-demand labor periods for the application of protective treatments and canopy management. Stock management benefits from a climate service that offers adequate anticipation of seasonal climate trends which allows for the early procurement of downy mildew protection products at a lower cost. Additionally, chemical waste can be reduced when the correct amount of downy mildew protection products are purchased.

A climate service that provides accurate seasonal forecasts allows for the timely procurement of fungicide product and hiring of labor to tackle downy and powdery mildew, as well as sunburn, can reduce losses in grape yield and value. For many viticulturists, a key question is *"How much is a climate service worth?"*

Previous work regarding the climatic service market or the valuation of climate service benefits for adaptation Vaughan et al. (2019), such as in Vogel et al. (2017) and Cortekar et al. (2020), or in improved water management Delpiazzo et al. (2023), have not addressed the issue of access fees. The approach developed in this work to determine an annual climate service access fee, in particular where the fee is linked to the performance of the forecast, is novel.

2.6. Valuation of Climate Service

This work determined an acceptable annual fee to access the seasonal forecasts of SprR, SU35, and WSDI on the MED-GOLD Dashboard (described in Section 3.1). An annual fee for seasonal forecast accuracies of 50 %, 70 %, and 90 % was calculated at the request of SOGRAPE (Graça, 2021). The overall forecast accuracy depends on the hit-rate, false-alarm rate, missed forecasts, and correct rejections (described in Section 4.1). The performance of the seasonal forecast is integral for determining the climate service's "value" because it is directly linked to the hiring of labor, product procurement expenditures, and potential savings for the grape growers.

The existing market for the MED-GOLD Dashboard amongst viticulturists in the Douro wine region is driven by micro holding grape growers. Their profit/loss margins will govern the maximum cost of the climate service. Micro holding grape growers indirectly reflect purchasing power and influence purchasing choices. The cost of the climate service must not exceed the potential loss by fungal infection or sunburn, nor significantly reduce profit margins of the grape grower. To determine a valuation of the MED-GOLD Dashboard, it is essential to understand the potential financial gains and losses of a micro holding grape grower due to fungal disease and sunburn. This will be presented in Section 4.2. In this work, the valuation of climate service was based on: (i) the performance of the seasonal forecasts of SprR, SU35, and WSDI on the MED-GOLD Dashboard (Martins et al., 2021; Dunn et al., 2020); (ii) the cost of inaction of fungal disease; and (iii) the potential savings due to actionable climate knowledge. The aim was to propose a reasonable fee for a climate service tackling fungal diseases and sunburn.

2.7. Technical Considerations & Business Sustainability

In addition, this work determined if the existing market in the Douro wine region, with the proposed fee, can sustain the minimum annual IT infrastructure cost of about €12,000, which was determined during the MED-GOLD project's prototype development.

The MED-GOLD Dashboard and the MED-GOLD ICT (Information and Communication Technologies) platforms it relies upon were designed around a Public Cloud-based infrastructure, namely Amazon Web Services (AWS). The main reason for this fundamental architectural choice resided in one of the defining features of Cloud computing: elasticity. While traditional "on-premises" IT infrastructures usually require large capital expenses in order to acquire, configure, build, and maintain a physical data center, publicly available Cloud platforms allow users to dynamically create, manage, and destroy needed IT resources in an elastic way, only generating operating costs when those resources (e.g.: storage, computing units) are actively used. This way, a Cloud-based application, such as the MED-GOLD Dashboard, can still be viable for small-scale scenarios, and, when designed according to best practices, can easily be scaled up as the need arises. For a more detailed description of the technical considerations about the deployment of the MED-GOLD ICT platform and the Dashboard application, please refer to Caboni et al. (2021).

The expected cost of €12,000 included both the MED-GOLD Dashboard web application's infrastructure itself and the entire data processing pipelines it relies upon: source data fetching from the European Union's Earth Observation Programme Copernicus Climate Change Service (C3S) (https://cds.climate.copernicus.eu/) Climate Data Store (CDS), validation and normalization of scripts, indicators calculations, and storage. It is important to note that this cost should be considered as the bare minimum to sustain the recurring cost of the basic Cloud-based IT infrastructure and wouldn't allow for any enterprise-level maintenance or application-level improvements.

3. Materials and Methods

3.1. MED-GOLD Dashboard

The MED-GOLD Dashboard is user-focused web-based application designed and created to visualise and disseminate relevant climate information for three Mediterranean agricultural sectors. For a comprehensive review of the MED-GOLD Dashboard for the grape and wine sector, please refer to Dell'Aquila et al. (2023). There is also a MED-GOLD dashboard user guide entitled "Deliverable 3.5 A handy easy-to-use manual for stakeholders Wine practitioners of the climate service tool. PART II: the grape/ wine sector." available at https://www.med-gold.eu/documents-deliverables/.

The MED-GOLD dashboard presents climate information provided by the CDS Buontempo et al. (2020); Copernicus Climate Change Service (2021). The CDS provides access to numerous quality checked climate data sets including the ECMWF ERA5 reanalysis of historical weather and climate data Hersbach et al. (2020); Bell et al. (2021), which we used to verify the ECMWF SEAS5 seasonal forecasts of atmospheric and oceanic conditions (Stockdale et al., 2018; Johnson et al., 2019). SEAS5 consists of a 51-member ensemble initialised every month on the first day of the month and integrated for 7 months (Johnson et al., 2019). SEAS5 has a spatial resolution of 0.25 degrees. On the MED-GOLD Dashboard, the SEAS5 was used to compute SprR, SU35 and WSDI starting at different months (March to June) Doblas-Reyes et al. (2013) Calí Quaglia et al. (2022) Giuntoli et al. (2022). For a comprehensive description of all CDS products used in the MED-GOLD Dashboard, please refer to the project "Deliverable 7.2 Data Management Plan" available at https://www.med-gold.eu/documents-deliverables/.

The MED-GOLD dashboard presents the climate information for each of the three time periods (historical climate, seasonal forecasts, and long-term projections) in their own sections. In each of these sections, the climate information is classified into the following three categories: Climate variables (e.g. precipitation); Bioclimatic indicators (e.g. Spring Rain); and Wine Risk Indicators (e.g. Sanitary and Heat Risk). The dashboard is a visualization focused web-based application that also allows users to browse, view, and download climate data. Relevant parameters can be selected one-by-one according to preferred time range, geographic location, scenario type/forecast starting month, climate indicator, etc. The indicators are available in several different formats and visualizations, allowing for easy, quick, and seamless integration into critical decision-making. Users can access and interact with relevant climate information without any programming knowledge or the need to manage large climate data files. The main functionalities of the dashboard were based on specific needs highlighted by SOGRAPE.

The study considers only one component of the MED-GOLD dashboard - namely, seasonal forecasts of three bioclimatic indicators.

3.1.1. MED-GOLD Dashboard: Seasonal forecasts

The seasonal forecasts of each bioclimatic index on the MED-GOLD Dashboard is presented in terciles. The terciles indicate: above normal, normal, or below normal, where 'normal' is defined as the range between the 33rd and 66th percentile over the 1993–2020 period from the bioclimatic index derived from the ECWMF ERA5 reanalysis of global weather and climate Hersbach et al. (2020) Bell et al. (2021). 'Above-normal' is defined as greater than the 66th percentile and 'Below-normal' is defined as less than the 33rd percentile (Deliverable3.2, 2023; Deliverable3.3, 2021). The values which lie above the upper tercile or below the lower tercile are commonly considered as anomalies in climate science (ECMWF, 2021; Deliverable3.5, 2023). The presentation of the indicators as above/below normal is a result of the dashboard's co-development process, taking into account user feedback, allowing for a more diverse range of users of climate information ranging from beginners to advanced First feedback report from users on wine pilot service development (2023); Dell'Aquila et al. (2023).

In this study, we have only considered conditions under which grape growers would benefit from fungicide and sunburn prevention, namely hotter- and/or wetter-than-normal conditions, as recommended by SOGRAPE. As such, we analyzed and reported the performance of the three bioclimatic indicators when above-normal conditions were forecasted in SEAS5 compared to ERA5 reanalysis. This study should not be confused with a comprehensive evaluation of the bioclimatic indicator performance seasonal forecast, which would also investigate the causes of deteriorating performances. For an advanced analysis of the seasonal forecasts of the bioclimatic indicators for the wine sector please refer to Chou et al. (2023).

3.2. Performance metrics of Bioclimatic Indicators

The performance of SEAS5 seasonal forecasts of above-normal conditions, from 1993–2020, for each of the three indicators (SprR, SU35 and WSDI) was calculated for the region over the SOGRAPE company vineyards located in the Douro wine region (lon 7° 0' 59" W, lat 41° 1' 20" N). The SEAS5 resolution of 0.25 degrees translates to approximately 21 km by 21 km over this grid box, which covers approximately 441 km^2. The bioclimatic indicators are homogeneous over the grid-box.

The performance of each of the three indicators is based on the hit-rate, false-alarm-rate, and accuracy of the SEAS5 seasonal forecasts compared to the ERA5 reanalysis Mason et al. (2003). The definitions of hit-rate, false-alarm-rate, and accuracy used are as follows (Eqn. (1)–(3)):

$$H = a/(a+c) \tag{1}$$

$$F = b/(b+d) \tag{2}$$

$$A = (a+d)/(a+b+c+d) \tag{3}$$

Where:

- a denotes a Hit. It is the number of times an event was correctly forecasted and occurred.
- b denotes a False-Alarm. It is the number of times an event was forecasted but did not occur.
- c denotes a Miss. It is the number of times an event occurred but it was not forecasted.
- d denotes a Correct-Rejection. It is the number of times an event was not forecasted and did not occur.

The MED-GOLD dashboard provides seasonal forecasts of SprR, SU35 and WSDI starting at different months (March to June) Doblas-Reyes et al. (2013) Calí Quaglia et al. (2022) Giuntoli et al. (2022). The earlier an accurate forecast can be made the better is for the climate service users. For each index, and for each starting month, the three performance metrics (hit-rate, false-alarm-rate ans accuracy) are calculated. The performance of the bioclimatic indicators over the Douro valley gives a complete picture of the quality product the MED-GOLD project provides the grape growers and helps determine the value of the climate service.

For grape growers using seasonal forecasts for planning purposes, both 'false alarms' and 'missed alarms' are problematic. In the case of a false alarm, the seasonal forecast recommends that grape growers purchase product and hire labour to deal with a hotter- and/or wetter- than-normal summer, an investment that is not needed in the end. The grape growers' money would be lost when a False-alarm occurs. In the case of a missed forecast of a hotter- and/or wetter-than-normal summer, no actionable climate knowledge is gained from the seasonal forecast. The grower does not lose additional money through pre-purchase of unnecessary goods and services on the basis of the forecast suggestion. Their expenses, as well as losses in yield and value, in the season, would be the same as without a climate service.

This work determined the value of the actionable climate knowledge that can be gained from seasonal forecasts by considering the amount of money that could be saved by using the climate service, as well as the impact of missed and false alarms. In other words, we conducted an ecosystem service to find the right value of the climate service.

3.3. Ecosystem Services valuation approach

Ecosystem Services (Burkhard et al., 2018) constitute a socio-ecological approach to analyze the relationship among ecosystems, economics, and social systems trying to measure and quantify the economic impact due to ecosystem changes. According to the Common International Classification of Ecosystem Services (CICES v.5.1 (Haines-Young and Potschin-Young, 2018)) classification, in agricultural fields, ecosystem services related to fungal diseases are included in regulating services: to control, prevent, and reduce the number of fungal disease event.

To find the correct value of a climate service for viticulturists tackling fungal disease and sunburn in the Douro wine region, we took two ecosystem service approaches: 'Market Value' and 'Standard Output'. The approaches are described below. The market value approach is included to provide farmers in the Douro region a relatable analysis, while the standard output approach allows for a generalization of this study to other farmers in the European market.

3.3.1. Market Value

The Market Value approach took into account the average yield, yield loss, and price of good quality grapes, over a six year period from 2014 to 2019, from a >20 ha property in the Douro wine region (Graça, 2021). These values were provided by SOGRAPE and assumed to be representative for the region. The value of €3,136/ha was set as the economic value of ecosystem services based on an average yield of 3,200 kg/ha with an average price of €0.98/kg for a good quality yield of wine grapes (Graça, 2021). We used these values to estimate cost of inaction against fungal diseases and sunburn by vineyard area.

3.3.2. Standard Output

In addition to the market value approach, we also present a valuation based on the European Union's standard output. The Standard Output (SO) of an agricultural crop is defined as the average monetary value of the agricultural output at farm-gate price, in €/ha (Glossary, 2023). The

European Standard Output values are released by EuroStat every few years, which represents the 5-year average of an agricultural product (crop or livestock)(Glossary, 2023). According to Eurostat SO 2013 (EuroStat, 2021) the Standard Output of "Vineyards - Quality Wine" is €2,610/ha for the Norte region of Portugal where the Douro wine region sits. This value was used in the following calculations of inaction. The standard output is used as a classification of agricultural holdings by type of farming and by economic size across Europe (Glossary, 2023). This value was determined by using the average prices from 2011 to 2015 and applied to the 2016 Farm structure survey data (EuroStat, 2021). The standard output includes sales, redeployment, self-consumption and changes in the stock of products, without the costs of transport and marketing, except for those products for which the price for packaging is also included. The standard output does not include direct payments, Value Added Tax (VAT) or taxes on products (European Commission Regulation 1242/2008, European Commission Regulation 1166/2000).

3.4. Farm Personas

The valuation of a climate service which forecasts infections risk, allowing for better hiring practices and the deployment of preventative measures, was performed for 3 personas: the 'Reactive Farmer', the 'Prepared Farmer', and the 'Pro-active Farmer'. The 'Reactive Farmer' makes spontaneous decisions according to present conditions; and is most similar to the 'real world' grape grower who must react in terms of purchasing fungicide and hiring labor as the situation unfolds. The Reactive Farmer is most susceptible to abrupt increases in costs. The 'Prepared Farmer' uses industry knowledge and experience to prepare for infections and procures some fungicide products ahead of time at a lower cost. This persona has the ability to absorb some loss if labor or products are not needed. Lastly, the 'Pro-active Farmer' bases their decision to procure fungicide or hire labor entirely on the seasonal forecast. They assume the seasonal forecast is correct all the time (a.k.a. a 100 % accuracy).

A cost-benefit evaluation was performed for each of these personas for differing seasonal forecast accuracies of the bioclimatic indicators. Tables 1.

4. Results

4.1. Performance of the bioclimatic indicators

The performance of the three bioclimatic indicators from SEAS5 seasonal forecasts, starting at different months, was compared to the ERA5 reanalysis over the SOGRAPE company vineyards. The hit-rate, false-alarm-rate, and accuracy of SprR, SU35, and WSDI are presented in Tables 2–4 respectively. The metrics in Tables 2–4 range from 0 to 100 %. A forecast with a hit-rate lower than 33 % is equivalent to the climatological average range (i.e. within the "normal" range) and as such does not provide actionable climate knowledge to the grape grower. The higher the hit-rate, the better. In regards to the false-alarm rate, a good forecast will have low values. For the accuracy metric, the higher the value, the better.

The hit-rate of seasonal forecasts of SprR starting in March and April are only 25 %, however, as the season progressed the performance improved and the hit-rate of the June forecast rose to 63 %. The false-alarm rates also improved as the season progressed, going from a maximum of 33 % to 11 % in June. The overall accuracy of SprR forecasts for wetter-than-normal springs are all well above 33 % and is better than assuming the climatological mean. The accuracy is good in May and June, above 70 %, however, the forecast starting April is only 54 %.

For SU35 the hit-rate for seasonal forecasts were better in March and June compared to April and May. The June forecast had the best hit-rate with 70 %. Comparably, May forecasts only had a hit-rate of 30 %. The false-alarm rate in both March and May were above 40 %, which is high. The overall forecast accuracies of SU35 for warmer-than-normal conditions, for all starting months, were above 46 % and better than assuming the climatological mean. The best performance accuracy was in June with 68 %.

The hit-rates of seasonal forecasts of WSDI, for all starting months, range from 42 % to 58 %. The false-alarm rate from March through May are quite high, with the April forecast reaching a peak of 50 %. Significant improvements are seen in June (14 %). The overall forecast accuracies of WSDI for hotter-than-normal conditions, regardless of starting month are greater than 46 % for the Douro region and can be considered better than assuming the climatological mean.

Of the three bioclimatic indicators, the most accurate was SprR. The accuracy of SU35 and WSDI, overall, were nearly identical. Interestingly, the hit-rates of SU35 and WSDI were better than SprR, however, their false-alarm rates were worse.

For all indicators, the accuracy of the seasonal forecasts for hotter-and/or wetter-than-normal conditions were most accurate when starting in June. The relatively poorer performance in April and May, compared to March and June could be related to seasonal predictability and to large-scale phenomena influencing the local scale meteorology in spring Broennimann (2007); Giuntoli et al. (2022); Calí Quaglia et al. (2022).

It should be iterated that this study simply reports the accuracy of the seasonal forecast over the SOGRAPE vineyards for the purpose of determining the value of the climate service. This study is not a verification analysis of the seasonal forecasts in general, nor have we investigated the causes of deteriorating performances of the bioclimatic indicators, as found in April. This has been done in the following works of Chou et al. (2023); Dell'Aquila et al. (2023); Stockdale et al. (2018); Johnson et al. (2019).

Table 1
Contingency table.

		Forecasted	
		Yes	No
Observed	Yes	(*a*) Hit	(*c*) Miss
	No	(*b*) False	(*d*) Reject

Table 2
Spring Rain (SprR) performance metrics for seasonal forecasts starting at different months. The hit-rate, false-alarm-rate, and accuracy are shown in percentages (%).

	Mar	Apr	May	Jun
Hit-Rate	25	25	38	63
False-alarm Rate	24	33	11	11
Accuracy	60	54	73	81

Table 3
Number of Heat Stress Days (SU35) performance metrics for seasonal forecasts starting at different months. Values are shown in percentages (%).

	Mar	Apr	May	Jun
Hit-Rate	50	40	30	70
False-alarm Rate	44	31	44	33
Accuracy	54	58	46	68

Table 4
Warm Spell Duration Index (WSDI) performance metrics for seasonal forecasts starting at different months. Values are shown in percentages (%).

	Mar	Apr	May	Jun
Hit-Rate	42	42	58	50
False-alarm Rate	36	50	43	14
Accuracy	54	46	58	69

4.2. Valuation of Climate Service

As mentioned, the cost of the climate service must not exceed the potential loss by fungal infection or sunburn, nor significantly reduce profit margins of a micro holding grape grower. As such, we first determined the cost of inaction against fungal disease. Secondly, we determined the maximum potential savings the seasonal forecasts knowledge can provide. Thirdly, the total cost of the climate service was calculated, which accounts for forecast errors. Lastly, we calculate whether the proposed climate fee can sustain the MED-GOLD dashboard.

4.2.1. Cost of inaction against Fungal Disease

In Table 5 the average yield and income for different holding sizes, based on the market value approach, are presented alongside potential cost of inaction due to fungal disease and sunburn. Additionally, the yield loss, according to Eurostat methodology, in terms of standard output prices of good quality grapes was also calculated (Table 6). We only considered the value of quality grapes necessary for wine in this study and have not considered lower quality grapes.

The potential losses presented for the 1 ha holdings range from €627–941 following the market value approach, and €522–783 following the standard output approach. These potential losses are the upper bound of any climate service fee.

4.2.2. Value of actionable knowledge for Fungal Disease and Sunburn

The next step in the approach developed to determine the value of a climate service for fungal mitigation was to calculate the potential savings a seasonal forecast could provide in terms of early procurement of fungicide and labor. For this we considered the costs associated with an average year (Table 7) and a hotter- and/or wetter-than-normal year (Table 8). The values used in the following section for labor costs, the number of sprays of downy mildew protection product, amount of protection product needed, and costs of protection product, were based on those from a holding in the Douro region averaged over a six-year period (Graça, 2021). On average 9.4 kg/ha of downy product was used per spray, which cost €9/kg when procured 6 months ahead of time, or €16/kg when procured 2 weeks ahead of time (Graça, 2021). For each hectare of the holding, the Pro-Active Farmer could save an additional €110 in labor (Graça, 2021) for an accurate seasonal forecast.

In the cost-benefit analysis presented in Tables 7 and 8, we assume the Reactive Farmer has to procure all downy mildew protection product 2 weeks ahead of time at a higher cost. The Prepared Farmer has purchased the quantity need for 2 sprays 6 months in advance at a lower price. They must make any additional purchases of protection product needed in the season at a higher price. The Pro-active Farmer assumes the seasonal forecast has a 100 % accuracy and purchases all protection product 6 months in advance. The savings relative to the Reactive Farmer is presented for both the Prepared and Pro-Active Farmer.

The results in Table 7 show that a Pro-Active farmer can benefit from a climate service on an 'average' year relative to both the Reactive and Prepared Farmers. For a seasonal forecast with an accuracy of 100 % the Pro-Active farmer could save €373.20, compared to the Reactive farmer, which is more than 10 % of the market value and standard output earned for quality wine grapes on 1 ha. The Pro-Active farmer saves >2.8 times the amount the Prepared farmer saves. Table 8 shows that the Pro-Active farmer aims to gain much more in wet years, through early procurement, if the seasonal forecast is correct. These values show that the Pro-Active farmer could save 16 % of the market value and 19 % of the standard output on a 1 ha farm compared to the Reactive farmer. The Pro-Active farmer saves >3.8 times more than the Prepared farmer saves.

In addition, we computed the savings for a various combinations of prepared and spontaneous downy mildew sprayings (not shown) to determine range of loss/savings due to early procurement of downy mildew products and labor. For 1 ha, assuming 100 % seasonal forecast accuracy, a Pro-active Farmer could save €175 (for 1 spray and labor) to €768 (for 10 sprays and labor) compared to Reactive Farmer in downy mildew product costs. In 2016, 10 sprays were needed; it was the

Table 6
Cost of inaction against fungal diseases for various holding sizes in terms of Eurostat Standard Output 2013 (Euro/ha) for the Norte region of Portugal (EuroStat, 2021).

	1 ha	5 ha	10 ha	160 ha
Vineyards - quality wine	€2,610	€13,050	€26,101	€417,615
Downy Mildew Loss (30% less yield)	€783	€3,915	€7,830	€125,284
Sunburn Loss (20% less yield)	€522	€2,610	€5,220	€83,523
Powdery Mildew Loss (20% value loss)	€522	€2,610	€5,220	€83,523

Table 7
Costs associated with the procurement 4 sprays of downy mildew fungicide, typical of an average year, for a 1 ha holding (Graça, 2021). Savings related to labor included for Pro-Active farmer. Source: SOGRAPE (Graça, 2021).

	# Sprays procured 6 months ahead	# Sprays procured 2 weeks ahead	**Total Costs**	Savings relative to Reactive Farmer
Reactive Farmer	0	4	€601.60	-
Prepared Farmer	2	2	€470.00	€131.60
Pro-Active Farmer (Forecast accuracy 100%)	4	0	€388.40	€373.20

Table 8
Costs associated with the procurement of 6 sprays of downy mildew fungicide, typical of a 'wet' year, for a 1 ha holding (Graça, 2021). Savings related to labor included for Pro-Active farmer. Source: SOGRAPE (Graça, 2021).

	# Sprays procured 6 months ahead	# Sprays procured 2 weeks ahead	**Total Costs**	Savings relative to Reactive Farmer
Reactive Farmer	0	6	€902.40	-
Prepared Farmer	2	4	€770.80	€131.60
Pro-Active Farmer (Forecast accuracy 100%)	6	0	€507.60	€504.80

Table 5
Cost of inaction against fungal diseases for various holding sizes in terms of market value (Graça, 2021). Values rounded to nearest Euro.

	1 ha	5 ha	10 ha	160 ha
Avg. Yield (3,200 kg/ha)	3,200 kg	16,0000 kg	32,000 kg	512,000 kg
Avg. Price for good quality yield (0.98 €/kg)	€3,136	€15,680	€31,360	€501,760
Downy Mildew Loss (30% less yield)	€941	€4,704	€9,408	€150,528
Sunburn Loss (20% less yield)	€627	€3,136	€6,272	€100,352
Powdery Mildew Loss (20% value loss)	€627	€3,136	€6,272	€100,352

Table 9
Costs associated with false-alarm and missed forecasts for labor costs and the procurement of 6 sprays of downy mildew fungicide, typical of a 'wet' year, for a 1 ha holding. Source: SOGRAPE (Graça, 2021).

	# Sprays procured 6 months ahead	# Sprays rightarrow be procured or lost	**Total Costs**	Savings relative to Reactive Farmer
Pro-Active Farmer (Forecast 50% miss)	3	3	€705.00	€197.40
Pro-Active Farmer (Forecast 50% false)	6	-3	€507.60	€−166.40

maximum number of sprays recorded by SOGRAPE (Graça, 2021).

While the savings potential from seasonal forecasts are very attractive, the purpose of Table 9 is to demonstrate the impact of a missed forecast of a hotter- and/or wetter-than-normal year and similarly a false-alarm forecast. When a forecast is missed, the Pro-Active Farmer still saves money relative to the Reactive Farmer. A 'false-alarm' forecasts of a 'wet' year, however, can lead to a loss for the Pro-Active Farmer through wasted protection product and additional labor. The False-alarm rate of seasonal forecasts must be accounted for in the price of the climate service.

4.2.3. Proposed Climate Service Fee

In Table 10 the range of potential savings associated with 1 to 10 sprays are presented for the Pro-Active Farmer compared to the Reactive and Prepared Farmer. This is assuming a seasonal forecast with a 100 % accuracy. Additionally, the average potential savings for 3 to 6 sprays is presented, which is more realistic. This 'averaged potential savings' is what the grape growers aim to gain by using the seasonal forecast of the bioclimatic indicators on the MED-GOLD Dashboard. We used this value to help determine a first estimate of an annual climate service access fee; which we took to be 10 % of the average potential savings for a seasonal forecast with a 100 % accuracy. The choice of 10 % is a very conservative estimate to give us a lower bound of an annual fee. For simplicity, this initial dashboard access fee is scaled linearly by 50 %, 70 %, and 90 % to represent forecast accuracy. This linear relationship can be adjusted if future studies collect and analyse data from more farmers regarding past financial losses due to fungal infection, as well as the financial changes that occur when some farmers incorporate seasonal forecasts into their decision making process.

If using the seasonal forecasts for hotter- and/or wetter-than-normal conditions starting in March, where the accuracy is closer to 50 % rather than 100 % (see Section 4.1), we propose a Climate Service Fee of €20/year. This minimal fee should not act as a barrier for the adoption of the MED-GOLD Dashboard climate service for protection against fungal disease by viticulturists.

While the seasonal forecast accuracy for hotter- and/or wetter-than-normal conditions is best in June, in the context of anticipating hiring labor and the early procurement of fungicides to reduce infection risk, June is too late.

4.2.4. Maintenance and Sustainability of Climate Service for Viticulture

With a proposed Climate Service Fee of approximately €20 per year, which is a low estimate, we determined whether the potential market could sustain the maintenance and sustainability of the MED-GOLD Dashboard. Assuming a market uptake of the Douro holding distributions (Fig. 2), for both 30 % (conservative) and 50 % (realistic, as estimated by SOGRAPE (Graça, 2021)), we show that an annual income of €117,789 and €196,330 can be generated (Table 11).

The calculated annual income far exceeds the expected €12,000/year needed to maintain the MED-GOLD dashboard and accounts for the increased number of dashboard users. This income could cover the costs of continuous monitoring and maintenance of the dashboard's infrastructure; including corrective maintenance (i.e.: technical tasks, including but not limited to correction to an application's source code needed to repair and correct logical and technical defects discovered after the original deployment).

Moreover, the additional income could also be used, through adaptive and preventive maintenance activities, to keep improving the Dashboard according to users' feedback, e.g. by leveraging all eventual new CDS products and databases, increasing climate data resolution, developing and implementing new relevant indicators, etc.

5. Conclusions

The MED-GOLD Horizon 2020 project aimed to demonstrate the added value of climate services for traditional agri-food Mediterranean systems. For the Wine sector, one of the most relevant questions raised in the project was: Where can climate services add value to the decision making process of wine companies and farmers when climate information is conveniently tailored and presented in a user-friendly manner? One of the main outcomes of the project was the MED-GOLD dashboard which provides essential climate variables, as well as bioclimatic indicators, in a simple-to-understand and easy-to-use manner.

The three bioclimatic indicators, SprR, SU35, and WSDI, analyzed in this study have been co-developed to provide actionable climate knowledge to help mitigate fungal diseases; allowing for early procurement of fungicide products and the hiring of labor for canopy management.

In this climate service oriented paper we developed an approach to determine an acceptable annual fee for a micro holding grape growers to access the seasonal forecasts of the three bioclimatic indicators on the MED-GOLD dashboard. To determine the fee, first, we calculated the seasonal forecast hit-rate, false-alarm rate, and accuracy of these three indicators over the Douro Valley wine region. Second, we performed a cost-benefit analysis identifying the potential savings and losses of a micro holding grape grower.

Table 11
Annual income generated based on 30 % and 50 % market uptake of Douro holding distributions (Fig. 2) multiplied by an annual climate service fee of €20.

	Market Uptake of Holding Distributions	
Farm Size	30 % Market Uptake	50 % Market Uptake
⩽1 ha	€71,700	€119,500
>1 to ⩽2 ha	€19,332	€32,220
>2 to ⩽5 ha	€16,104	€26,840
>5 to ⩽10 ha	€6,180	€10,300
>10 to ⩽20 ha	€2,880	€4,800
> 20 ha	€1,602	€2,670
Total Annual Income	€117,798	€196,330

Table 10
Range of potential savings of the Pro-Active Farmer, compared to the Reactive and Prepared Farmers, for a hotter- and/or wetter-than-normal year, for a 1 ha holding.

				Proposed Fee		
	Savings Range 1 to 10 Sprays	Avg. Savings 3 to 6 Sprays	10% of Avg. Savings	90% accuracy	70% accuracy	50% accuracy
Pro-Active Farmer vs. Reactive Farmer	€175–768	€406	€40	€**36**	€**28**	€**20**
Pro-Active Farmer vs. Prepared Farmer	€194–636	€275	€28	€**24**	€**19**	€**15**

The results showed SEAS5 seasonal forecasts of the three bioclimatic indicators, for hotter- and/or wetter-than-normal conditions, starting in March have an accuracy of 54–60 % compared to the ERA5 reanalysis over the Douro region. These forecast accuracies were better than assuming the upcoming season will be similar to the climatic average (a. k.a. "normal"). As such, we can see that this climate service adds value to the traditional agri-food system. Micro holding farmers over can benefit from the actionable climate knowledge as a result of the SEAS5 accuracy.

Of the three indicators, despite having a lower hit-rate, the overall seasonal forecasts of SprR performed better than SU35 and WSDI because it had lower false-alarm rates. The most accurate forecasts are those starting in June, however, correct as they may be, they bring little value to procure better pricing in products or labor.

The results of the cost-benefit analysis showed that the cost of inaction due to fungal diseases and sunburn ranges from €627–941/ha using the Market Value approach and €522–783/ha using the European Commission Standard Output approach. When the seasonal forecasts of the bioclimatic indicators are included in the decision making process, they can save a farmer more than 10 % of the annual income from a harvest for an average year. Similarly, more than 15 % of the annual income from a harvest can be saved in a hotter- and/or wetter-than-normal year. These values represent what could be saved when the seasonal forecast accuracy is 100 %, however, potential losses due to false-alarms (24 %-44 % in March) must be accounted for.

After taking into consideration the financial loss due to fungal diseases and sunburn (Section 4.2.1), the maximum potential savings of a seasonal forecast in terms of early procurement of labor and fungicide (Section 4.2.2), and the accuracy of the seasonal forecast starting in March (Section 4.1) over the Douro region, which is closer to 50 % rather than 100 %, we propose a Climate Service Fee of €20/year.

Based on this analysis, a climate service that correctly forecasts the infections risk:

- 90 % of the time should cost €24–36.
- 70 % of the time should cost €19–28.
- 50 % of the time should cost €15–20.

The approach used to determine the proposed climate service fee can be adjusted as performance of the seasonal forecast improves, in terms of hit-rate, false-alarm rates, and overall accuracy. As the seasonal forecast accuracy improves, so does its value to grape growers. The value to grape growers can increase with further developments or iterations of the MED-GOLD Dashboard. Best practices for climate service may include providing performance metrics (such as hit-rate, false-alarm rate, and accuracy) alongside their products in a transparent manner to instill a user's confidence.

The methodology presented in this paper can be extended to the valuation of other MED-GOLD Dashboard indicators (e.g. sanitary risk), regions (e.g. Italy), and time periods (e.g. climate projections). Elements of the methodology which can be generalized for the purpose of determining a user fee include: (i) evaluating the performance of a prediction; (ii) evaluating the financial impact and potential savings of a decision based on different forecast accuracies; (iii) linking the fee to the performance of the service; and (iv) transparent discussions regarding costs from the perspective of both the application user and software developer regarding maintenance. As such, a similar valuation can be performed for other MED-GOLD products created for the Olive and Durum Wheat industries. The annual income generated by the access fee for the seasonal forecast described in this paper would be only one contribution to the total income generated to maintain the MED-GOLD Dashboard.

Lastly, given the proposed fee, the distribution of holdings, and assumed Market Uptake of farmers of the Douro wine region, we showed the annual income generated can easily cover the maintenance of the MED-GOLD Dashboard. This allows surplus revenue to be used for improving the Dashboard according to users' feedback, as well as developing and implementing new relevant indicators, and leveraging new CDS products and databases.

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CRediT authorship contribution statement

Christine Nam: Methodology, Formal analysis, Writing - original draft, Writing - review & editing. **Laura Teresa Massano:** Methodology, Formal analysis, Writing - original draft, Writing - review & editing. **Antonio Graca:** Conceptualization, Writing - review & editing. **Rossana Cotroneo:** Formal analysis, Writing - original draft, Writing - review & editing. **Alessandro Dell'Aquila:** Conceptualization, Writing - original draft, Writing - review & editing, Project administration, Funding acquisition. **Federico Caboni:** Writing - original draft, Writing - review & editing.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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