ALTA SCUOLA POLITECNICA

XVII cycle

AIS4SIA

Artificial Intelligent System for Sustainable Innovative Agriculture

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EXECUTIVE SUMMARY

Climate change has been identified as an emergency by public opinion only in recent years, but it is now clear to everyone that it will deeply affect every aspect of life on the planet. The increase of the average global temperature and of the frequency and strength of extreme meteorological events, including droughts, is a trend that will characterize the upcoming years. The effect of the new developing environmental conditions will be evident on many human activities, including agriculture. For instance, we are already witnessing a shift in latitude of the optimal conditions for most kinds of crops, including vines, which are considered a valuable source of profit. Despite the resistance of vines to drought and water stress, the higher temperatures and excessive droughts of the last years have caused abrupt alterations of the regular seasonal cycles, and have anticipated harvests, thus representing a huge problem and an economic risk for all kind of farming companies.

Society is responding to the faced challenges through technological advancement, such as the blossom of AI-powered solutions for problems in almost all fields of research and industry. In agriculture, AI algorithms have resulted to be effective in many cases. Empirical indexes, such as the Crop Stress Water Index (CWSI), a tailored numerical quantity representing an indicator of the plant water status, have been developed for the evaluation of the water stress of plants, and the data coming from monitoring such indexes can represent an essential resource to better understand the ongoing changes and evaluate the conditions of the crops. Some solutions for the monitoring of the vine water stress are available, but their adoption is still at an early stage and the technology is not yet refined. From our analysis it curiously emerges that no water resource optimization system, via active and adaptive crop monitoring, is available on the market at affordable prices. Hence, the goal of our proposal is to bridge this gap.

Our solution consists of a system that collects data about the status of vines, and then analyzes them to provide information about the water stress of the plants, parameter that can be exploited to estimate and predict the trends of productivity of the grapes and the wine. Two main parts form the system: a sensing module that collects field data, and a computing engine that elaborates them. The sensing module is made of a series of fixed sensors

that measure pressure, air temperature, air humidity, ultraviolet (UV) radiation, infrared (IR) radiation, and ambient light. An autonomous drone equipped with different kinds of cameras, including a camera used for navigation purposes and a thermal camera, detects instead the canopy temperatures of the leaves of the plants, which is an essential parameter for the computation of the CWSI. The collected data are transmitted to and stored in a server where ML algorithms fuse the information coming from all sensors.

The core feature of our system is the analysis of the field data: studies correlate the water stress (that can be monitored through the CSWI) during each period of the year with the ideal plant and grape growth for each specific grapevine. Therefore, the proposed solution increases the awareness of one of the main parameters affecting production quality and quantity, while also enabling a wise water management, and boosting plants care. Furthermore, with a similar processing, also an historical analysis can be performed to gain insight into peculiarities of the studied wine region, which will turn into an extremely useful information in the long run.

The system will provide value as a data monitoring tool able to inform the farmers on the almost real-time hydration condition of the field with great level of geographic detail. Indeed, the system will be capable of collecting local data representing the current water stress of each location within the crop, informing the farmer on the real time condition of the field. Thus, the farmer will be able to take the necessary steps to address the dehydration of the field with greater accuracy. Thanks to the high precision resolution data collected on the field, it will be possible to irrigate only the areas of the vineyard in real need of water, thus reducing the water waste. This is particularly relevant considering the climatic emergency the world is facing, that is leading to a steep increase of both the number and intensity of droughts. In this context, water management will be a critical issue in the nearby future. The availability of water will indeed decrease, forcing governments to impose restriction on its use and increasing its cost, as it has already been suggested during the last summer drought periods. Therefore, the farmers that will be able to minimize water waste will have a strategic advantage on the others. Moreover, the system will decrease the industry water usage, reducing the impact on society and representing a great benefit for the local community. Farmers and wine producers will be able to have a controlled product in terms of both quality and quantity, as they will optimize the water use to uniform the water stress among the field. In this sense the system will increase the resilience of the vines with respect to climate change.

To conclude, the system well fits the current state of society responding to one of the most urgent challenges: climate change. The proposed solution increases the resilience of the economic system to climate change increasing the farmer's capacity to control and optimize the water usage in their fields. Moreover, the elasticity of the proposed sensing system and of the software suite allows for an adaptive and always evolving solution. The system could successively be developed to fit the needs of other kinds of crops, thus expanding the market for the system. This will increase the impact of such system on the agriculture industry.

1. INTRODUCTION

1.1 RESEARCH PROBLEM FRAMING

Nowadays the issue of the climate change is becoming more and more relevant for the agricultural sector and its most catastrophic manifestations are causing huge losses in crops' productivity. A possibility to effectively react to such extreme events and adapt to a constantly changing scenario is offered by Artificial Intelligence and, more in general, by the Agri-Tech technologies. Unfortunately, such solutions are diffusing only in large-scale production industries whereas in smaller realities they have not been spreading yet due to the lack of technological expertise, aptitude to innovate and the size of the initial investments.

The goal of this project is to study and develop a solution specifically for these small realities that is capable to monitor the health of a crop field in an automatic and non-invasive way which does not need neither a high economical effort nor advanced technological skills to be applied. In particular, as case study, we focus on vineyard since, nowadays in Italy, they are usually structured as small-medium size companies, forming a fragmented economical context very attached to traditional techniques and with a very low technological diffusion. Such realities are now beginning to face the issues of climate change and, due to their peculiar characteristics, are more fragile towards its consequences.

Our objective is to facilitate the adoption of Agri-Tech technologies in such small realities with the aim to increase their resilience towards future environmental scenarios and, at the same time, favor the integration of the traditional knowhow of elder generations of farmers with the technological expertise of younger ones.

1.2 FOCAL POINTS

For the specificity of the context that the project is addressing, five focal points guiding the implementation of the solution have been identified.

1. **Non-invasiveness:** The solution should alter and impact the environment the minimum in order to maintain the delicate biological equilibirium in vinyard and not to affect the quality of the production. Moreover, its application should not obstruct and subtract time to the regular agricultural operations in the vineyard.

2. **Automation:** The solution should be automatic, in the sense that it must be able to work by itself with little or no direct human control and be able to autonomously manage many inputs offered by the environment.

3. **Data-driven:** The solution must provide a data-driven interface that offers an instrument to predict the state of health of the crop field based on environmental data collected over it. The processing of the data should be fast in order to offer an analysis almost in real time with high frequency rates.

4. **Cheapness:** The adoption of the solution should be feasible for small companies with small capitals and not large possibilities to invest and dedicate part of their economic resources to a monitoring activity whose benefits are in long term time scale and not immediately quantifiable.

5. **Ease of use:** The application of the solution must be feasible for employees with little to no technical knowledge, require few basic instructions, and feature an intuitive interface. Moreover, it should resist to physical stresses due to the irregular conformation of vineyards and the presence of natural obstacles and meteorological phenomena.

1.3 DESIGN STATEMENT

The AIS4SIA system collects data about the status of the vines and provides insightful information about the water stress of the plants that can be exploited to estimate and predict the yield trend of the vineyard for the upcoming harvest season.

The system is constituted by two main parts: the sensing modules collect information about the vines and the vineyard status, while a server analyzes the collected data, computes the Crop Water Stress Index (CWSI), and generates maps that can be used to monitor the current status of the vineyard in detail, as well as to make prediction about the future development of the grapes and the plants.

The sensing subsystem is composed of a series of fixed sensors along the rows of the vineyard. The fixed sensors measure: pressure, air temperature, air humidity, ultraviolet (UV) radiation, infrared (IR) radiation, and ambient light. An autonomous drone equipped with different kinds of cameras, including a camera used for navigation purposes and a thermal camera, detects instead the canopy temperatures of the leaves of the plants, which is an essential parameter for the computation of the CWSI. The collected data are transmitted to and stored in a server where ML algorithms fuse the information coming from all sensors.

The core feature of our system is the analysis of the on-field data: studies correlates the water stress (that can be monitored through the CWS) during each period fo the year with the ideal plant and grape growth for each specific grapevine. As a consequence, the proposed solution increases awareness of one of the main parameters affecting production quality and quantity, while also enabling a wise water management, and boosting plants care. Lastly, the elasticity of the proposed sensing system and of the software suite allows for an adaptive and always evolving solution.

1.4 THESIS STRUCTURE

In Chapter 2, an analysis of the economic and social context related to the consequences of climate change for agricultural sector and specifically for vineyards is carried out. An analysis of the stakeholders and of their willingness to adopt innovative solutions provides a more in-depth insight of such peculiar sector and the specification of their needs and relations allows to define the first guidelines and requirements of the project that are summed up in the design statement.

In Chapter 3, a theoretical and technical background on vineyards is offered, with a focus on the biology of the plants as well as the morphological characteristics and cultivation techniques that are currently used in crop fields. Moreover, a precise introduction on the weather modifications predicted by climatic models and their consequences on agriculture are presented both on regional and continental scale. In addition, the principal vegetation indexes, that can be used to monitor the plant's health, are presented. In conclusion, the key concerns related to climate change problem have been extrapolated from interviews with some Italian wine producers together with a schematic overview of some Agri-Tech companies and their technologies.

Chapter 4 precisely defines how the Crop Water Stress Index (CWSI), the vegetation index selected to monitor the health of the plants, can be obtained from data measured on field. A regression analysis correlating the CWSI computed from satellite data and the productivity of a vineyard in the corresponding location confirms the intuition of the goodness of the CWSI for health monitoring. In the last part the technical design, requirements to extract the CWSI on field are defined and the difficulties that this task implies are introduced. Finally, a hybrid solution mixing fixed and movable sensors is presented as the best compromise in terms of the focal points of the projects together with a cost analysis.

Chapter 5 describes the first step towards the development of the project envisioned in the design statement. In fact, to concretely assess key design concepts and to validate the correctness of data collection and elaboration, a first sensing module tailored to focus on core functionalities has been built. Therefore, the implementation of the CWSI measurement both in terms of software and hardware, the functioning of the Graphic User Interface, the peculiarities of the sensors, the mounting and the data collection, processing and saving that characterize this first prototype are here discussed. Then, the on-field measurement session in the vineyard of Azienda Agricola Balladore Pallieri in Calosso (Asti, Italy) to test the module and understand its critical points is presented. Subsequently, the detailed data elaboration to compute the CWSI and visualize it over the crop field is shown, overcoming measurement issues and offering a concrete perspective on the potentiality of the proposal.

Chapter 6 analyses the solutions in terms of commercial sustainability and elaborates an early business model focusing on the creation of value through the conception of a data monitoring system that can be integrated into other Agri-Tech solutions like intelligent irrigation, as it is discussed in Chapter 7 about the future developments too.

2.
USERS' DEFINITION

Before discussing the design, the project is here contextualized to highlight the rising issues that will need to be dealt with in the next years. Then, the main aims and requirements are set through the stakeholder analysis.

2.1 CONTEXT

No matter how far in the future, no matter where on planet Earth, climate change will impact our lives. Our environment is already showing alterations due to a disturbance of its fragile dynamic equilibrium. As will be stated later in a deeper dive into the topic, distortion of seasonal cycles, extreme meteorological events, droughts and early frost are just a few of the effects of this evident change. Many sectors and human activities would be obliged to face the challenges spilling over from this scenario. Agriculture is not excluded and is indeed one of the most-involved fields.

In light of this consideration, other topics arise with even more strength and concern (Ciscar J.C et al, 2018). Food security and sustainable development are just examples. United Nations Sustainable Development Goals (SDGs) admonish and encourage us as well. Thus, in the spirit of that very encouragement, funds and opportunities are provided to the ones willing to address the problem and fight for a better future. Not only the European green Deal and Next Generation EU in Europe but also the growing market in Smart Agriculture (from USD 6.5 billion in 2018 to USD 20 billion by 2027, according to Navod Neranjan Thilakarathne, 2020) are a taste of this renovated effort for green solutions. Nevertheless, as it can be easily understood, climate change in the agricultural sector is not a straightforward problem to be solved. Indeed, if on one hand a lot of investments are coming to this field, on the other hand an army of enterprises are appearing on the market. The need of a well-designed product and/or service is the basis to stand out against the competition and to actually propose an efficient solution able to merge economic and green sustainability.

Another key aspect that should be taken into consideration for the success of one's proposal concerns the peculiarities of the agricultural sector. As the analysis in the following sections will highlight, the main actors in this context are farmers or realities usually not

Figure XX. View on the Langhe and Monferrato landscape, UNESCO World Heritage.

inclined to change, attached to traditions, and with low margins to dedicate to innovative solutions. In other words, the resistance to adoption by the stakeholders is an issue to be faced.

The term Agriculture, though, embraces a vast sea of scenarios and concepts. It is enough to think about all the possible varieties of crops and related needs. Nonetheless, some species are more vulnerable to the consequences of climate change. Therefore, this kind of plants should be carefully regarded and stronger efforts to limit their exposure and penalization should be devoted. Vines are one of those.

Furthermore, vineyards present another attractiveness for an investor: they are valuable crops. Indeed, wine market represents a solid sector and a paradigmatic shared character of different cultures , for instance the revenues related to this field in Italy in 2021 exceeded 12 billion euros (*record nel fatturato* - Tosi, Lorenzo).

Even though from the vast problem of climate change the specific world of vineyards has been chosen, it is worth underlining that a range of topics still opens. In detail, a list of possible issues is related to vine and its agricultural practice such as harvest protection from extreme meteorological events, optimality condition for plant health or production, fungi and mold prevention, area and production processes for certifications' compliance, cost reduction or resource optimization. In this variety of opportunities and challenges, the team has opted for focusing on the resource optimization in the vineyards: both the primary resources (mainly water) and the plant as a resource itself, which has to face a strongly changing climate with a production expectation never decreasing.

In detail, the water stress of the vine and water management are addressed. The delivered system, thought both as a product (sensors and additional hardware) and as a service (data collection, analysis and high-level information end-user provision), is foreseen to improve plant's health, productivity and product quality as well as to avoid water waste.

On top of these premises, one should always bear in mind that, in order to effectively translate the idea into a successful working solution, constraints imposed by stakeholders must be considered. Therefore, as quickly sketched before and deeply investigated later, this fact suggests specific traits that should be taken into account in the design process. In proper words, the solution must be adaptive, scalable, non-invasive with respect to the landscape and the production system, compatible with the existing practice and realities, and affordable. It is paramount that the cost and the effective quality of the proposed solution are economically convenient for farmers; what is more, the solution should be proposed as a functioning product in a short period of time, since climate conditions are changing rapidly, and this may cause shifts or deep modifications in the market analysis first carried out.

It is now time to properly dive into the subject of users' requirements, from the analysis of the stakeholders to the definition of their needs and requirements.

2.2 STAKEHOLDER ANALYSIS

The success of the project, as anticipated before, lies in the right balance between the incoming changes, trends and innovations, the reality nowadays, the cultural boundaries and the actors involved. The actors involved deserve the utmost attention because they directly benefit from our project and should appreciate and recognize the value that could be added to their business.

Considering a stakeholder as "an entity with a stake (interest) in the subject activity" (Keith McGrath, 2017), we have subdivided all the stakeholders involved in our project into three levels, depending on how much they are involved in and touched by our system.

In the following picture, the net of relationships between the main stakeholders of AIS4SIA is represented, in order to also visualize the degree of the connections between the project and the actor. Who is connected straight forward to AIS4SIA just by an arrow are the direct stakeholders; the second level one has at least an intermediary. The third level perceive the effect of the system, but they are not directly involved in it.

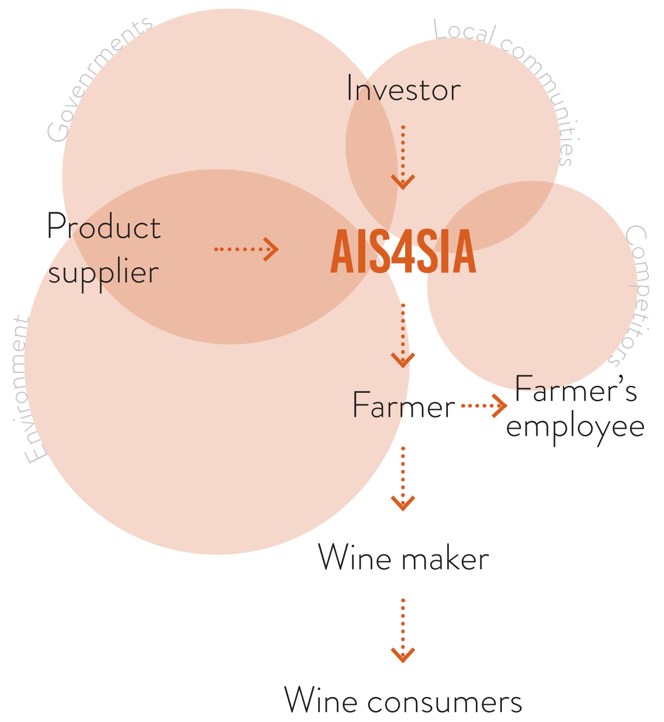


Figure XX. Map of the relation between the stakeholders

Direct stakeholders

The direct stakeholders for AIS4SIA are also the users to whom we turn the project itself, from different points of view: who is interested in the product-service itself and has to use it daily, who understands its potential and sees in it an opportunity to invest in it and who is involved in the making and in the realization of it. Respectively they are the wine farmers, the investors and the product suppliers.

They are the most important stakeholders to be effectively caught by our project and, for this reason, it is fundamental to understand their perspective and issues. Overall, they are the ones that should first recognize the values, the innovation and the benefit brought by the adoption of a product-system like AIS4SIA. Nevertheless, there are critical issues that must be considered, such as a possible skepticism, a resistance to adoption from the side of the wine farmers and an eventual sudden cut-off of investments.

And lastly, but significantly important, in this historical period way more than in any other, a possible difficulty is to find custom components (in limited time and low cost). This is a crucial issue related to the supplier and the supply chain, suffering at the moment of scarcity of resources and delays, most of all in the sector of electronics. Therefore, an oculate and wise choice of the components, as well as a simple design in assembling, are necessary and the supplier are very important stakeholders to take into account.

Indirect stakeholders

The indirect stakeholders are the ones who come in contact with our project, but just via the direct stakeholders. They perceive the wave of the AIS4SIA application's effect, but they do not experience it in a direct way or with a straightforward impact on their daily lives. We are talking about the farmer employee, the wine consumers and the wine makers.

Respectively, they are the people that usually take care of the vineyards, who have to interact or co-exist with the system (during the routine procedure or the main intervention in the vineyards); the final user of the raw product we are talking of, who could feel and appreciate a different quality of the product or just a variation in the price of it. Furthermore, the final consumer could choose to support and to buy a wine made by grapes cultivated according to particular procedures or with peculiar arrangements. And then the wine makers, who have to work with the grapes and deal with their properties, trying to obtain the best wine out of them. They are focused on the quality but also on the quantity of the harvest and they could as well experience the effects of an agricultural method integrated with a system like AIS4SIA.

The potential issues with these actors are again a case of distrust towards innovation applied to their primary supply (maybe a change in quality) from the side of wine makers, the resistance by the wine consumers to accept innovation in the food production chain; and a refusal to work in such integrated systems from the farmer employee.

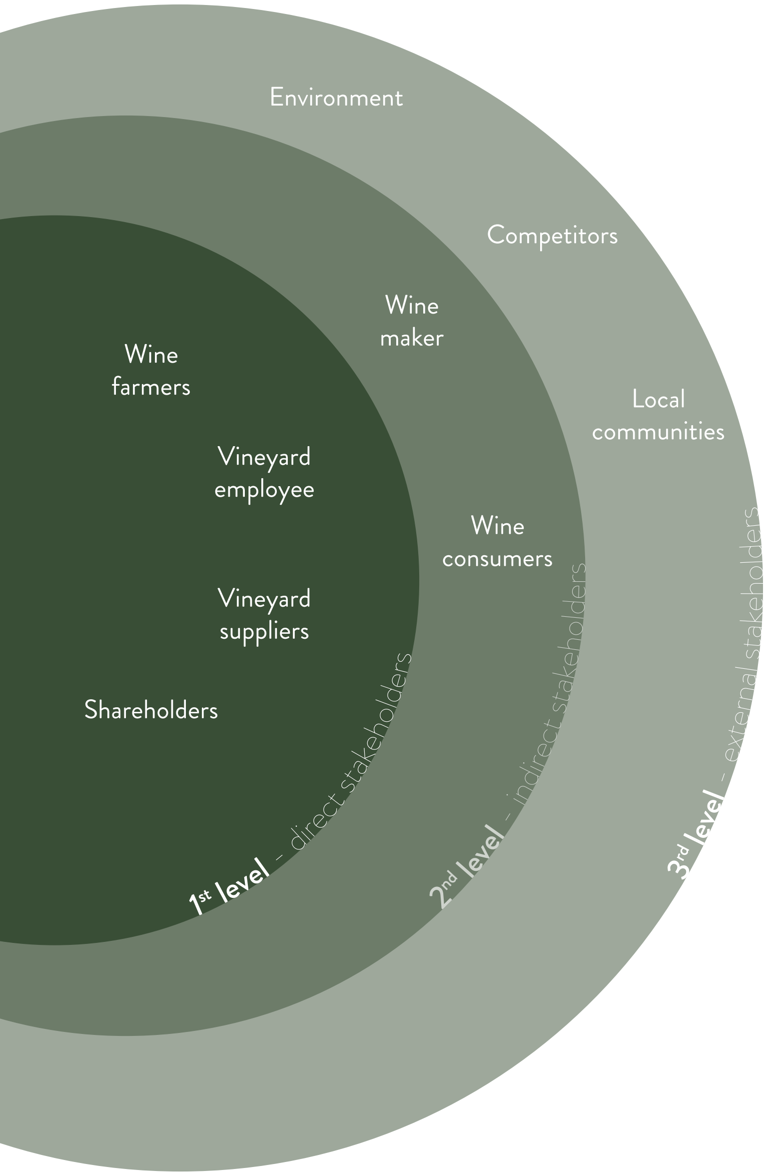


Figure XX. Direct, indirect and external stakeholders on the three levels

External stakeholders

As other stakeholders, in addition to the direct and indirect ones, we have the external stakeholders, on whom our product impacts, even though they are not strictly connected in the basic functioning principles and actions. They are the actors in the surrounding of the AIS4SIA field of application and range, yet cardinal elements to be considered.

One above all is the environment, the first and main reason why AIS4SIA is being developed and would like to spread in the agriculture sector. It should be here that the positive effect of this system shows up, giving back something instead of taking too much from our resources.

There are the local communities, another source of richness for the culture, the people and the economy too, because they have the power of boosting or limiting whatever happens in their territory. To respect, to listen to, to give them better perspective is what our system should do, without imposing and invading, but respecting and protecting the territories.

They could oppose resistance in integrating this system on their territories if scared by a landscape transformation.

More specifically on the side of the workers, there are the labor associations, who have not to be scared by AIS4SIA as a bad enemy on the horizon who could replace some vineyards workers' tasks, metaphorically "stealing" the job to someone. Yet, they should see the AIS4SIA product-system as a mean to open new roles and job positions indeed, (the managing of data and studies on crops, but the maintenance of it too).

There is, then, the market, with the competitors, who already propose something similar and probably are going to develop their projects even more in order to optimize them and expand in the market, rather than to be superseded. It is always a point from which to take inspiration for a better product and for useful developments.

At the end, we cannot consider our system as independent from the governments, which always contribute and influence these projects by the side of regulations, prohibitions but also fundings and supporting measures and benefits.

STAKEHOLDERS		WILLINGNESS TO ADOPT	RESISTANCE TO ADOPT	STRATEGICAL ROLE
Direct	Winefarmers	Both small and big companies could benefit from the reduction of waste of chemicals and water, and from the overall improvement of the efficiency of the crops. Moreover, the system is going to study the trend of the crops related to climate, helping to reduce the impact of extreme events (mainly droughts).	Big companies could be already competitive with traditional systems. Small companies may be more conservative and could be more affected by possible failure of the system.	Main consumer
	Investors	They could see the innovative, yet necessary nowadays, approach of the system, being among the first supporters of this unavoidable evolution.	High initial investments (and long perspective of returns/effects); cheaper, easier or faster to be introduced alternatives on the market.	Financial supporters
	Product suppliers	Cutting-edge system and possibility of growth following the new incoming trends.	Costs for upgrading the technologies or the manufacturing processes.	Operative contributors
Indirect	Winemaker	Higher quality and possibly less expensive primary products.	Distrust towards new technologies substituting traditional processes (worried with respect to the final customer's choices).	Principal source of income out of customers
	Farmer employees	Higher productivity, less repetitive actions, higher time efficiency.	Less human work force need, possible loss of jobs.	They could make the whole system work more efficiently
	Wine consumers	Higher quality of the wine or, at least, from a more sustainable and respectful agricolture.	Distrust towards new technologies substituting traditional processes.	Final source of income for wine makers
External	Local communities	Local economy gains visibility due to new technology exploitation and possible external investors and/or cooperations.	Distrust towards the system's effectiveness and new technologies substituting traditional processes. Loss of local work force (and expertise too).	Who stand for the traditions and the local know-how
	Competitors	Keep up with the innovation of the competitors. Higher efficiency, lower expenses.	Distrust towards new technologies substituting traditional processes, promoting themselves in opposition.	Triggers for progress/ growth
	Environment	Higher efficiency of crop maintenance translates in lower impacts to the environment and positive effect on future generations.	Incorporation of an anthropic system in a natural landscape, material and resource depletion.	It dictates our capabilities and potential developments
	Labor associations	New task and potential new roles/jobs.	Distrust towards new technologies substituting traditional procedure/job places.	Who defend the workers' rights

Figure XX. Tab of the stakeholders, related with the willingness and the resistance to adoption.

2.3 NEEDS

From the analysis of the stakeholders, their needs arise and they are crucial to be considered, in order to set coherent requirements, directly derived from the needs themselves. If the project does not meet the needs of the stakeholders, at least the most important ones, it risks not to be appreciated or understood and, consequently, to fail because of the lack of support.

The list of emerged needs converges in three macro-areas that the project should take into consideration simultaneously, in order to be successful: the quality of the final result, the impact on the environment and the feasibility of the entire system.

In table **XX** the same needs, shared between more than one stakeholder, are highlighted in bold, since they have a particular relevance and lead to the definition of the requirements' categories.

STAKEHOLDERS		NEEDS	RELATIONS	REQUIREMENTS
Direct	Winefarmers	**High profitable volume of production**		
		Minimize losses		
		Resources optimization		
		Preservation of the grapes' quality		
		Organolectical properties of wine grape		
		Affordable system to be implemented		Commercial feasibility
	Investors	**High profitable volume of production**		
		Cost-effective system		
	Product suppliers	Standard components		
		Cost-effective system		
Indirect	Wine makers	**Preservation of the grapes' quality**		
		Organolectical properties of wine grape		
	Farmer employees	Ease up craftwork in agricultural processes		Product quality
	Wine consumers	Informed choice of goods (Traceability and/or Certificates, Labels)		
External	Local communities	Preservation of the territory and the landscape		
	Competitors	Differentiation of the offer		Environmental sustainability
	Environment	**Resources optimization**		
	Labor associations	Job opportunities granted		

Table XX. The Stakeholders in relation with their needs and the consequent project requirements.

2.4 REQUIREMENTS

There are different ways to sort needs and requirements belonging to various stakeholders. Hereafter, the categorization of requirements is based on a topic-wise approach rather than a single stakeholder-wise one. In one way or another, it is important to underline that the requirements are the design specifications through which one can measure the fulfilment of the identified stakeholders' needs. Therefore, it is a key step in the idea-development process in order to achieve a solid and clear final design concept.

From the analysis of the actors potentially involved or impacted by AIS4SIA project and the definition of their corresponding needs, three macro areas can be extracted and exploited for the determination of the design specifications of the envisioned solution.

Commercial feasibility

"Affordability" is one of the keywords that stands out from the previous considerations: a crucial aspect in order to reduce the resistance to adoption by the direct stakeholders such as farmers. To realize the affordability of the final solution, firstly, the system must rely on inexpensive components. In other words, standard off-the-shelf components should be preferred to avoid dependence on one single supplier and to limit the costs related to customized components. The measurement of this requirement can be performed controlling the price of the final product.

Other strategies related to this concept consist in showing a positive cost-benefit analysis for the customers. Another precious aspect that should be leveraged for encouraging the adoption should be the easiness of use. Thus, the possibility of offering an automated product, the integrability on already existing structures of the vineyard and an easy-to-understand product concept represents efforts towards this direction. Once again, to have a concrete metric able to compare the fulfilment of this requirement with respect to other competitors, workforce hours and money spent on labor or material for the installation and maintenance of the system could represent good indicators.

Product quality

Another strong need in the field of wine production is the compliance with given standards, both in the process and quality of the raw material, grapes. Therefore, for farmers whose production is focused on leveraging certification and quality specifications, a system able to assess the status of the plants can be interesting.

Furthermore, also stakeholders that do not fall under this category - such as farmers mainly interested in the production volume - can still hold an interest in the possibility of increasing production or controlling future alcohol percentages that follows from a proper action on the plants according to the parameters highlighted by the proposed system. In any case, the metrics that can be adopted to check the efficacy of the system can be the average grape dimension, color index, polyphenols, total acidity, anthocyanins and potential alcohol.

Environmental sustainability

Finally, other actors that are impacted by the proposed solution, such as farmers, wine makers and consumers, could show a preference towards a green sustainability. Hence, not only to live up to these expectations but also to be coherent with the ultimate goal of this project: mitigate the impact of climate change. Requirements that directly translate from this need are then an endurance and lifecycle of the system, maximization of the parts that can be dismantled in the end-of-life stage and reduction and optimization of the water usage. The former specification is well aligned with the affordability requirement too.

A robust system reduces the costs linked to maintenance and replacement. In order to measure these aspects, possible metrics could be represented by money spent on maintenance, relative number of reusable components (e.g., sensors and Raspberry Pi) and liters of saved water with respect to pre-adoption user case scenario.

Small and large companies: different expectations

A last brief comment is worth to highlight a contrast, that has just been sketched during the analysis, between two types of stakeholders: small and large companies. In fact, the former would tend to stick to traditional agricultural methods and to be quality focused, while the latter are usually more open to innovation and with a focus more on profit. Hence, also their expectations are different. In general, it can be summarized that, in order to meet the favor of these different stakeholders, the market strategy should emphasize reduction of costs and increase in productivity for large companies and the stability on the quality of the product that the system can provide, for small companies. This implies that the design specifications should be able to support both perspectives, that is, the proposed solution should provide the end-user with the needed information to envisage both user-case scenarios.

3.
STATE OF THE ART

The purpose of the initial research on crops and vineyards is to better understand the object of our study in order to create a design that fits the current situation. In particular, basic notions about vine morphology, life cycle and cultivation techniques are presented, since they have been considered during the development of the solution. Most of the information are taken from the *Encyclopaedic Dictionary*.

3.1 OVERVIEW ON CROPS AND VINEYRDARS

Morphology of the plant

Vitis vinifera is a deciduous, lianiform plant belonging to the Vitaceae family. Those species cannot support themselves, but must climb on supports, which in nature are trunks of other species, while in cultivation are the systems of poles and wires.

Once fertilisation has taken place, the fruit of the vine - the grape - originates. Each berry is attached to the stalk by a pedicel inside which vascular bundles pass, carrying water and nutrients for the fruit to grow. The plant produces on one-year branches, called shoots, each bearing 2-3 bunches of grapes.

According to the Encyclopaedic Dictionary, it is possible to briefly describe the growth phases of the berry as follows:

- Flowering: the hibernating buds, left on the branches of the plant after winter pruning, open.

- Setting (June): the stalk begins to grow to its final size and the ovary begins to take on a spherical shape and swell.

- Veraison (late July-August): the berry increases in volume substantially and becomes mushy and translucent, and it begins the formation of the pigments that will give rise to the colour of the berries.

- Ripening (September/October): the most important stage for grape clusters, as the berries double their volume, increase their weight and form definitively. Sugars also accumulate, dyes and various aromas are formed, and the grape seeds ripen.

The phases of growth of the grapes can vary considerably depending on the environmental conditions such as microclimate, temperature, age of the vineyard, parasites, droughts, rains, humidity and wind.

Annual cycle

The annual cycle of vines manifests itself in different phenological phases that are the result of the vine's genetic characteristics interacting with environmental conditions and cultivation practices. It can be divided into two sub-cycles: vegetative sub-cycle and the reproductive sub-cycle, with the formation of fruit and seeds (Marenghi, 2007).

A crucial phase of the vegetative sub-cycle is sprouting, that consists of the enlargement of the buds and the subsequent emergence of the shoot. The phenomenon is controlled by environmental factors (mainly temperature that should be above 10°C), biotic factors (position of buds) and cultivation techniques (planting density and pruning) (Marenghi, 2007).

The conditions that allow good reproductive sub-cycle in terms of flowering, fertilisation and fruit set are several (Marenghi, 2007). Firstly, temperatures must be above 15°C and not above 35°C; there must be good insulation, photosynthetic activity, control of pathogens.

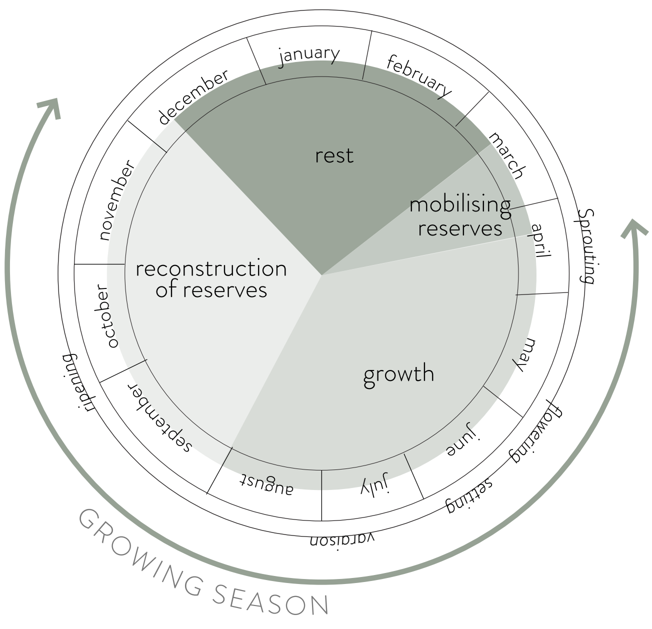


Figure XX. Life cycle of the vineward, image elaborated by the authors, source: Fedele, P., 1933-39. "Grande Dizionario Enciclopedico". UTET (vol 19).

Morphology of the vineyard

In Italy, many forms of vine training are present, such as spurred cordon and guyot. They both generally feature the distance of 2.5-3 meters between rows and 80-120 cm between plants along the row.

Pruning is the set of practices aimed at controlling the development of the green organs to balance them for quality purposes and to contribute to build an optimal microclimate around the plant.

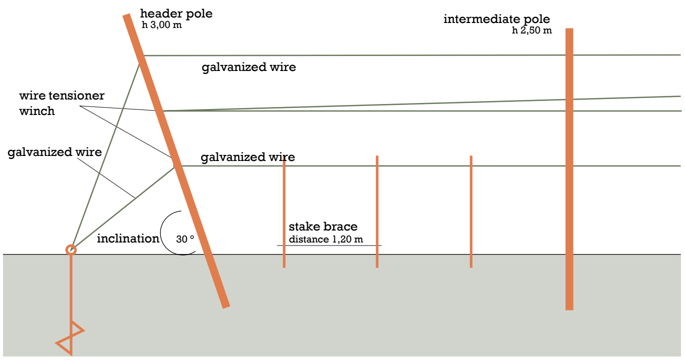


Figure XX. Scheme of the most used structure for growing vines.

Life cycle

The vine is a perennial plant with a life cycle of around 40 years. Up to the age of three years, the plant is young and not productive and reaches a constant production from the fifth/sixth that is maintained up to the twenty-fifth year of life, when it is no longer able to satisfy the winegrower's needs quantitatively and qualitatively. The life cycle of the vine can be explained by the figure X.

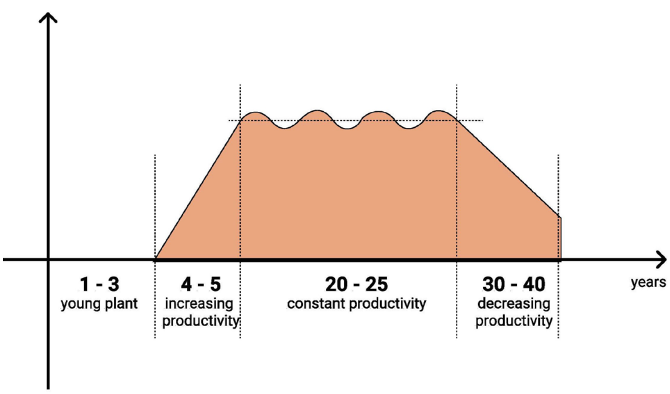


Figure XX. Life cycle of the vine, image elaborated by the authors, source: Fedele, P., 1933-39. "Grande Dizionario Enciclopedico". UTET (vol 19).

Microclimate

According to the optimal condition required, several aspects must be taken into consideration to control plant's health, as follows.

Temperatures
At budding, temperatures below -3 °C are definitely harmful, while just before flowering, drops in temperature of up to 2.5 °C can jeopardise the harvest and cause damage to the plant.
In particular, for the various phases of the vegetative cycle, the optimal ranges of temperatures are:

- Sprouting: 8 to 12 °C.
- Flowering: 17 to 22 °C.
- Until veraison: 22 to 25 °C.
- From veraison to ripening: 22 to 28 °C
- Harvest: 17 to 23 °C.

A high temperature excursion between night and day that guarantees the best results in terms of a quality product due to the higher concentration of aromatic substances in the skin of the grapes that it causes.

Humidity and rain
The vine, in terms of water requirements, is much less sensitive than it is to heat and light. However, too high humidity causes an excessive dilution of substances in the grapes and the presence of parasites in the crop. On the contrary, drought may require emergency irrigation, even though the vine is rather resistant to water shortages. The phases of the vegetative period determine a variation in the vine's water requirements. They are highest during the grape development phase (8 to 120 mm of rain), intermediate during the ripening phase (50 to 100 mm) and lowest at harvest time (0-5 mm).

Wind
Breezes are generally favorable because they limit the activity of certain parasites and regulate the level of humidity in the air, preventing dangerous mold during the flowering period.

Soil
Not all soil types are suitable for growing vines, and different types of vines require soils with different characteristics. The same vine gives grapes with different characteristics when grown in soils with different geological characteristics in terms of water parameters and mineral salts.

3.2 CLIMATE CHANGE

Vineyards And Climate Change – Europe

Climate change is defined as any change in the state of the climate that persists for an extended period of time, and is considered by the vast majority of the scientific community as one of the great environmental concerns facing mankind in the 21st century (Droulia et al., 2021). A steady increase in temperature, as the main measurable effect of climate change, is expected to continue to increase globally and major changes are likely to occur in the global hydrological and energy cycles, resulting in an increase of radiation and of the frequency and severity of extreme weather events. Given its expected important impacts on different sectors of human activity (e.g., agriculture, forestry, energy consumption, tourism), global climate change poses a substantial political, economic and social challenge (Droulia et al., 2021).

Among human activities, agriculture is likely to be particularly exposed to climate change risk since the weather conditions prevailing during the crops' life cycles are the major abiotic factors for their growth, determining, therefore, the quantity and quality of agricultural production and ultimately the economic sustainability (Droulia et al., 2021).

In particular, this phenomenon will lead to an acceleration of the crop cycle, earlier ripening, decreased biomass accumulation, reduced yields; heat and drought stress translate in quality loss (Stagnari et al., 2016).

Europe emerges as an especially responsive area to the temperature rise induced by climate change, especially during the warm season. In particular, Southern Europe wine regions can suffer: higher temperature and water deficit cause progressively unsuitability; therefore, grapevine growing areas northward expansion up to 55 degree North (Droulia et al., 2021).

Agriculture And Climate Change – Italy

Focusing on our country, the Mediterranean region is considered one of the 'hot spot' of climate change, with a warming exceeding the global average increase by 20% and a reduction in precipitation in contrast to the general increase in the hydrological cycle in temperate zones between 30° N and 46° N latitude (Spano et al., 2020) .

In Italy, the analysis of climate data measured by the main national and regional observation networks has allowed us to observe an increase of more than 1.1°C in the average annual temperature over the period 1981-2010 compared to the 30-year period 1971-2000. The last few years, however, have been characterised by rather high temperature increases. (Spano et al., 2020).

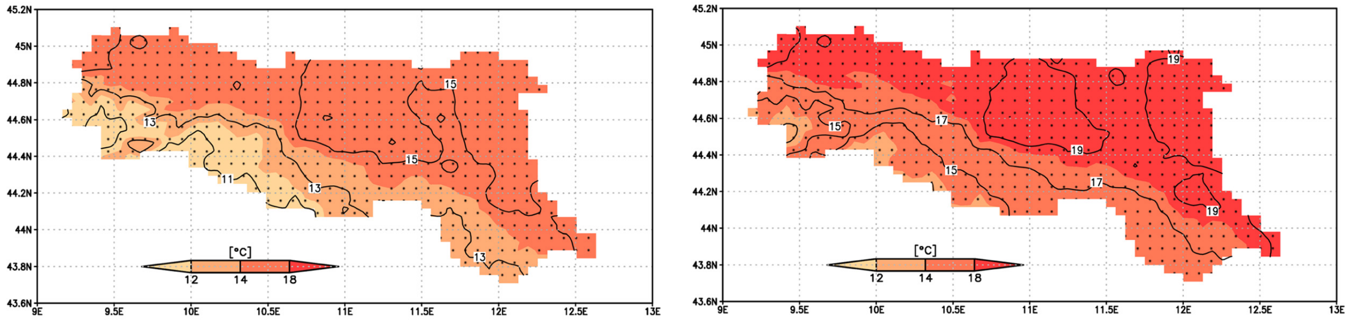
Some aspects that have been found are the greater susceptibility of spring-summer cycle crops with respect of autumn-winter cycle ones; and, accounting to the higher temperatures and heat and water stresses, CO_2 increased concentration. It is expected -25% for irrigated corn; - 50% for wheat (especially in Sicilia, Sardegna e Puglia) and a possible increment in central and northern Italy (up to +25%) (Spano et al., 2020).

In general, CO_2 increased concentration could negatively effect nutritional quality. Furthermore, extreme events such as drought and higher temperature can heighten evapotranspiration. Therefore, water stress requires smart hydric resource management and likely higher cost for irrigated crops.

Projections indicate viticulture will remain suitable, although its sustainability will decrease by showing shortened vegetative cycle, advanced phenology, and lower yields, because of enhanced warming and drying conditions. A possibility is the northward expansion or towards a higher altitude.

Furthermore, heat and water stress could imply quality loss with an organoleptic degradation and non-optimal sugar concentration.

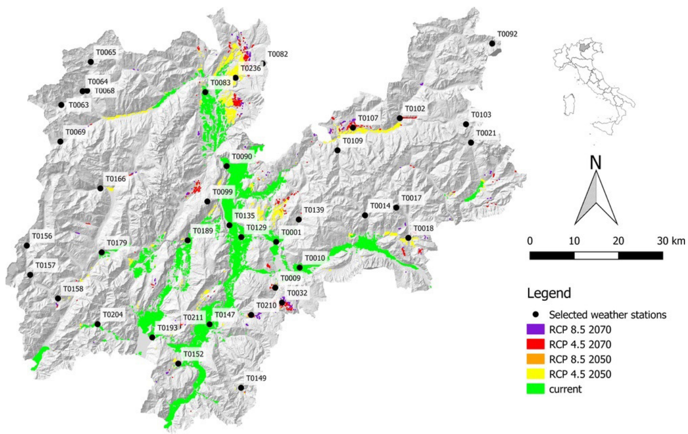
By showing some analysis of the source of some Italian regions, more applicable aspects are considered. It was shown that in Emilia-Romagna, there is a daily mean temperature increment and drier conditions during growing seasons (up to +1.5°C). Sugar concentration increased in Sangiovese grapes. By 2040, DOP zones are still suitable for the production of high-quality grapes, for later ripening varieties as Sangiovese, while high-quality white grape varieties are questionable (Chardonnay).



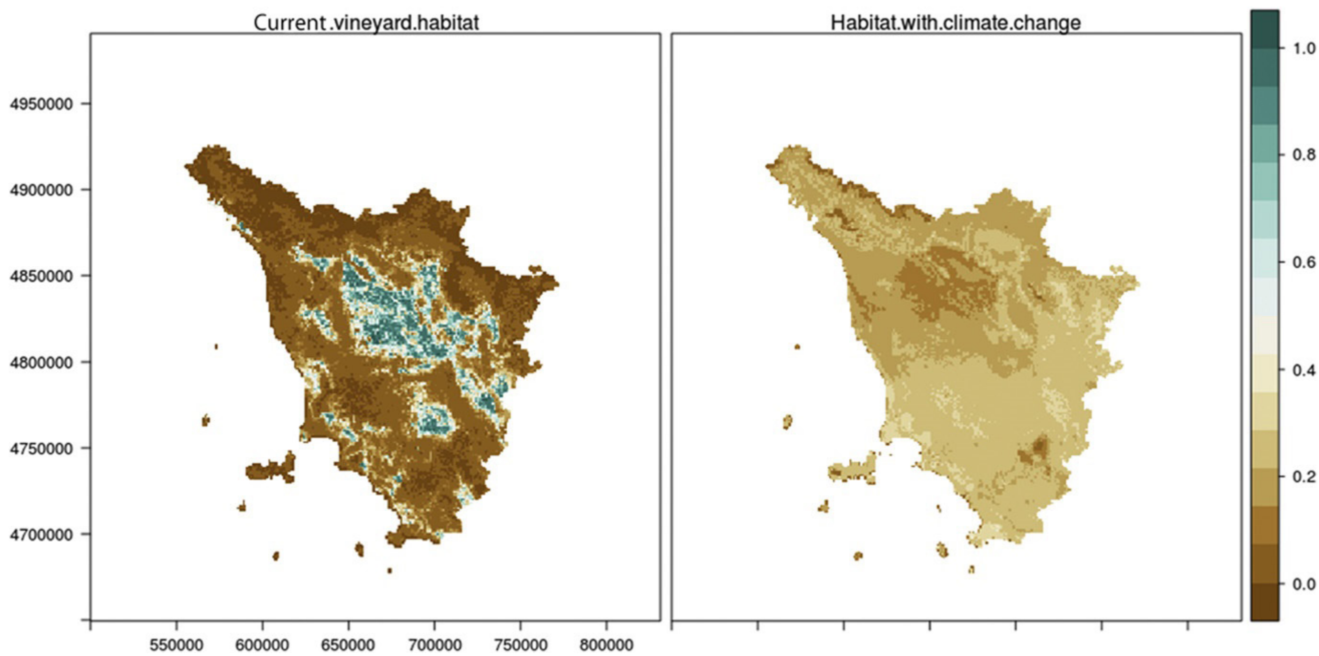
Average seasonal temperature in Emilia-Romagna under RCP 8.5 scenario for the period: left 2011-2040; right 2071-2100. (teslic et al.)

In Piemonte, the temperatures are expected to increase (in 2080, 2-3°C) and rainfall to decrease (in 2080, -76-77%) during May and June. In future scenarios, costs for disease management will also increase.

In Tuscany, the increase in temperature and decrease in rainfall lead to an increase in the potentially suitable area, but a shorter growing cycle. This leads to a reduction in the final product yield, particularly in areas subject to quality cultivation regulations. For this reason, quality wine areas are moving to higher altitudes. Indeed, in Trentino, climate change could lead to a better ripening and health status of the vineyards.



Landscape suitability projection in the Trentino region (Eccel et al.)



Suitability of the Tuscan territory to viticulture in the current situation and with climate change projections (Bernetti et al.)

Climate changes analysis

In order to describe the climate that we can expect for the future of a given geographical area, it is necessary to start from the knowledge of how climate changes affect the main atmospheric variables - such as temperature, precipitation, wind - both in terms of average values and in terms of extreme values, linked to extraordinary events (Spano et al., 2020).

Expected changes, as just defined, are generally evaluated as the difference between the simulated trend for the future period of interest and the simulated trend over a reference period (current or past).

Climate projections are obtained through the use of high-resolution climate models EURO-CORDEX and refer to four different concentration scenarios for greenhouse gases, aerosols and chemically active gases, which are referred to as RCPs (Representative Concentration Pathways). (Spano et al., 2020).

In particular, the IPCC scenarios mainly adopted for high-resolution climate simulations are the following:

- RCP8.5 (commonly associated with the expression 'Business-as-usual', or 'No mitigation') - growth of emissions at current rates. This scenario assumes, by 2100, atmospheric concentrations of CO2 tripling or quadrupling (840-1120 ppm) compared to pre-industrial levels (280 ppm).

- RCP2.6 ('Aggressive Mitigation') - emissions halved by 2050. This scenario assumes aggressive' mitigation strategies whereby GHG emissions approach zero in approximately 60 years from now.

According to this scenario, it is unlikely to exceed a 2°C increase in the average global temperature compared to pre-industrial levels.

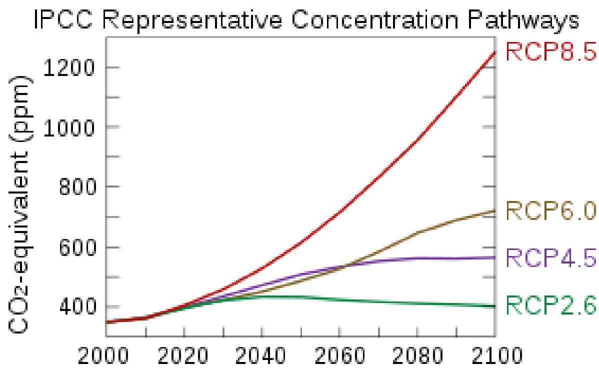
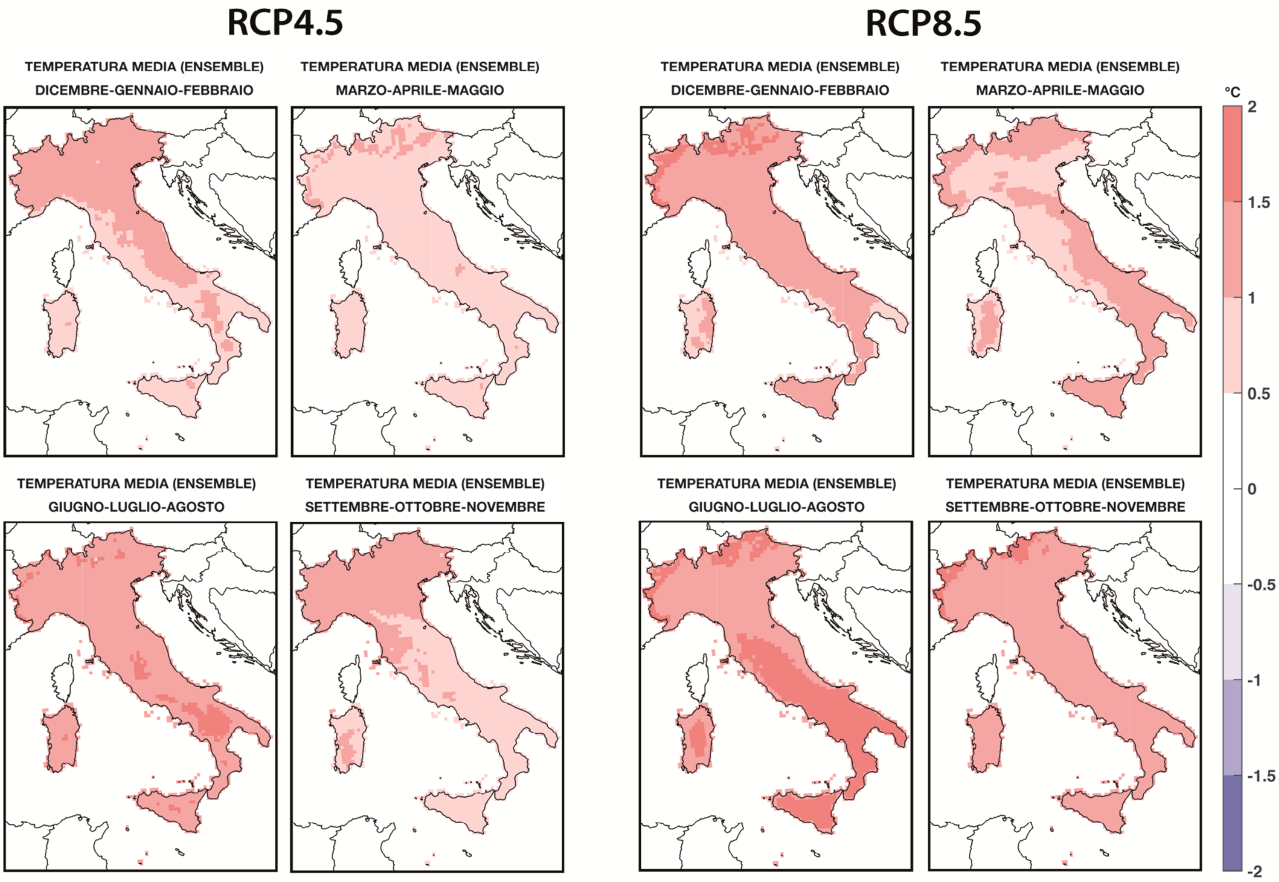


Figure XX: All forcing agents' atmospheric CO2-equivalent concentrations (in parts-per-million-by-volume (ppmv)) according to the four RCPs used by the fifth IPCC Assessment Report to make predictions

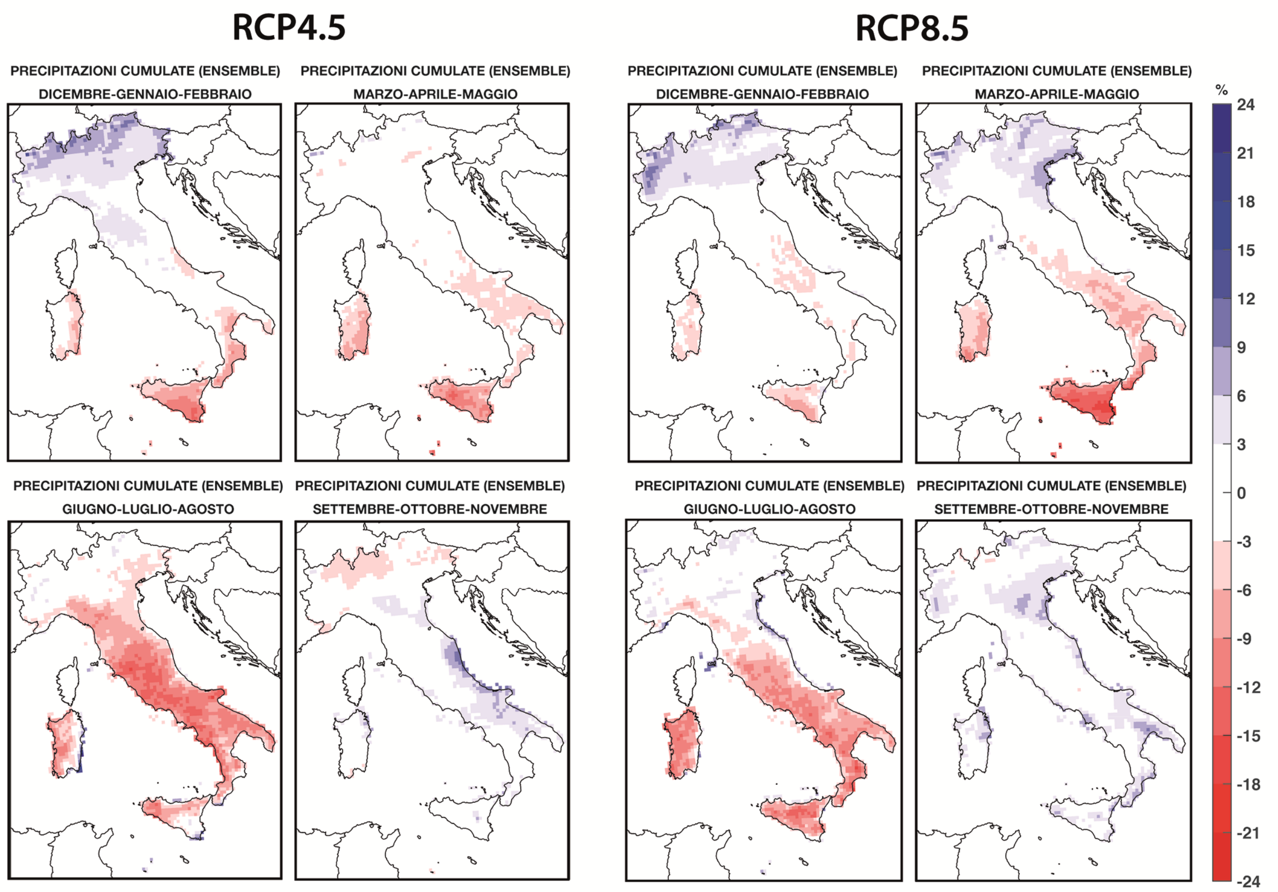
Temperature
Analysing the geographical distribution, the models used agree in simulating a temperature increase over the reference period. In the scenarios showing the largest temperature increases (RCP4.5 and RCP8.5), these are distributed almost evenly over the entire territory in the period 2021-2050 (**Fig**), although some differences are appreciable especially in spring and summer (Spano et al., 2020).

Precipitation
The variations in terms of annual precipitation are interesting to understand how much Italy, from the point of view of climate change, needs policies and strategies that are differentiated according to the area, but also models and tools that are capable of capturing the complexity of the territory and local atmospheric dynamics. If the trend just analysed for the average temperature shows a clear sign of growth for all the different scenarios, the variation in annual precipitation over the coming decades indicates low differences over the Italian area

The RCP4.5 scenario shows the greatest variations in winter, with an increase in precipitation over the Alps and a decrease over Sicily and parts of Apulia and Sardinia, and during the summer season with a general decrease in precipitation over central and southern Italy. The RCP8.5 scenario indicates a more widespread increase that affects northern Italy, except in summer where no major changes are reported. The RCP8.5 scenario also reports low variations over central central Italy and a decrease in southern Italy especially during the summer season (Spano et al., 2020).



Two-meter seasonal-scale temperature change maps over Italy from the EURO-CORDEX ensemble according to the RCP4.5 and RCP8.5 scenarios for the period 2021-2050 compared to the reference period 1981-2010



Seasonal maps of precipitation variation over Italy from the EURO-CORDEX ensemble according to the scenarios RCP4.5 and RCP8.5 for the period 2021-2050 compared to the reference period 1981-2010

Repercussions in Italy

To sum up, climate scenarios predicting higher temperature, less precipitations will result for the agricultural sector in:
- Greater susceptibility of spring-summer cycle crops
- Higher water stress for crops
- Negative variations of productivity of certain crops
- Higher cost for irrigation

Some Northern Italy regions could be positively affected by the average increase of temperatures, whereas the decrease of precipitation will negatively affect all the regions, especially in the South.

Vineyards and climate change in Italy

Enhanced warming and drying conditions determine water stress and overheating, possibly causing:
- shortened vegetative cycle;
- advanced phenology;
- lower productivity;
- higher irrigation costs;
- quality loss (organoleptic degradation and non-optimal sugar concentration);
- northward migration of cultures or towards higher altitude;
- loss of suitable areas for high quality grape varieties cultivation;
- higher exposure to certain diseases (peronospora viticola);
- higher production and final product costs.

3.3 INTERVIEWS: STAKEHOLDERS AND EXPERTS

Stakeholders

In order to know what the wine sector is experiencing right now with climate change, that affects not only the range of temperatures that can be reached in a certain area but also how there is no more smooth transition between cold and frost and heat waves and droughts, it is fundamental to directly hear the opinions of different vineyard owners from different regions of Italy to understand what the conditions of their crops are.

Apart from the common susceptibility against extreme weather events, i.e. hailstorms and spring frosts, that can erase the whole crop, some issues that arose in our interviews brought our focus on the detailed monitoring of the crop's status and on the water problem.

Azienda Agricola Biava (Scanzorosciate, Bergamo)

The Azienda Agricola Biava, in the Moscato di Scanzo area, pointed out that not only are they susceptible to hailstorms, but the problem with the current climate is that the normal cycle of seasons is completely lost: the cold winter months were useful to guarantee a period of hibernation for the plants to restore their function whereas in spring and summer they would grow as temperatures progressively went up. Now that the winter season is milder, there is no quiescence period and the plants are under constant stress causing them to be in worse health when the spring and summer come, therefore limiting their capability to respond to adverse weather conditions.

So a good direction would be that of monitoring the microclimate (i.e., temperature, humidity, light and wind) throughout the crop to have a better and deeper understanding of the condition of each plant, to understand which areas are in fact more or less stressed. These climate variables determine not only overall health of the plant but they are also responsible for fungi and moulds development (no breeze and high humidity), sugar scarcity (inadequate irradiation), incorrect maturation due to too high or too low temperature. A system that monitors such variables could offer a precious insight into the overall condition of the plants.

Azienda Agricola Ricudda (Castellina in Chianti, Siena)

A representative from Azienda Agricola Ricudda, in the Chianti area, also mentioned that something they are looking for is a way to deal with fungi and mould that are caused by wrong ventilation and high humidity. Right now a possible tool that can be used against microorganism attack is ozonated water, a way to kill pathogens without deploying harmful chemicals around the crop. A possible deploying system of such treatment would mean catch the diseases early on, in a greener way.

Again, monitoring the different areas of the crop in terms of the plant condition would mean being able to find the areas that are in a crucial situation and the area on which we have to focus more on, intervening with water, fertilizer and in general following more closely the situation.

Azienda Agricola Balladore Pallieri (Calosso, Asti)

Azienda Agricola Balladore Pallieri is one of the members of the Antica Cantina di Calosso, a small collective winemaker in Piemonte (Italy). It was officially born in 1904 and the main wines produced are Moscato d'Asti, Barbera d'Asti and Calosso DOC.

Since forty years the Azienda Agricola Balladore Pallieri is followed by an agronomist, who manages and controls the production trends of the vineyards year by year in order to guarantee the final quality of the product and the right amount of production expected by their farm. According to him, their crops have not suffered from extreme events correlated to climate change in the last 40 years. Moreover, since there is a record of it, the farm has had a constant and abundant production characterized by regular drops of productivity every four years due to the biological cycle of the vine.

Antica Cantina di Calosso, being part of DOCG consortium, has an upper limit of production per hectare, making it unwise to invest into a technique that would increase productivity. For this reason they report that it could be interesting to find a way to improve quality and sugar content through water stress control (see section 3.4).

Moreover, as is the case for most vineyards in Italy, they have no irrigation system installed and no connection to the local aqueduct. This is why they say it would be interesting for them to monitor the condition in their crops, section by section, to know whether there are some areas that would benefit for localized and drip irrigation to balance the increased water stress in such areas not wasting too much aqueduct water at the same time.

Paolo Carnevali: agronomist and precision viticulture specialist

Paolo Carnevali, the specialist we had the chance to interview, works on the water resource optimization and pointed out that analysing the variability of resource requirement within the same crop could be the next step in precision viticulture. A further interesting route would be improving the way the results are presented to the vineyard owners.

He confirmed that data monitoring in the crops is actually something that is already implemented in the form of stationary weather stations, but it could be implemented with the use of moving sensors and data collected from satellites if the resolution is already good.

Most of all, in order to connect such data to the production of a certain crop one would need to have a thorough understanding of the plant's metabolisms, how it converts water from the soil into nutrients and so on: a good way to by-pass this is to exploit vegetation indexes that are linked to the plant response to a certain climate condition rather than monitoring the climate variables that cause such condition.

This is also a promising route in order to create a system that could adapt also to other species of fruit plants, not only on vines.

3.4 PRECISION AGRICULTURE AND VEGETATION INDICES

Precision agriculture is a broad term to describe the implementation of a data driven approach to agricultural problems that entails data collection and analysis with the aim to provide a blueprint through which inform the decision making about possible intervention on the field (Singh et al. 2020).

In the broad field of agriculture, precision agriculture is being implemented by means of remote sensors and unmanned vehicles in a lot of different crops as case studies (Weiss et al., 2020), whose specific aim is to find which parameters are best to monitor for each crop and which ones give the most valuable information. As was already highlighted in section 3.3, it is difficult to monitor directly the physiological function of a plant, be it a cereal or a vine, and for this reason, a database of vegetation indices for remote sensing has been created (Index Database).

Such indexes are mathematical formulas based on climatic data that can be successfully recovered from satellite or in situ measurements through specific sensors and they correlate such values to specific areas of the plant's health and condition.

Normalized Difference Vegetation Index (NDVI)

One of the most studied indexes is the NDVI which can give useful qualitative information on vegetation status and quantitative evaluation of vegetation parameters (Leaf Area Index (LAI), biomass, chlorophyll concentration, plant productivity, fractional vegetation cover and plant stress). (Huang et al, 2021).

NDVI is one of the simpler indexes that can be evaluated straight from satellite images because of the way it was defined by J.W. Rouse Jr et al (1974):

$$\mathrm{NDVI} = \frac{(\rho_{\mathrm{NIR}} - \rho_R)}{\rho_{\mathrm{NIR}}} + \rho_R$$

where
ρ_{nir} = density of Near Infra-Red (NIR)reflectance
ρ_r = density of Red (R) reflectance

The NDVI takes into account the densities of NIR reflectance and R reflectance: the balance of these two values over a vegetated area yields the vegetation index of the area itself (Xue et al. 2017). Studies have shown that through this simple calculation (satellites such as Landsat can provide the reflectance already divided into this sub-bands) it is possible to discriminate dense forest, non-forest and agricultural felds and to determine evergreen forest versus seasonal forest types (Huang et al., 2021).

NDVI has been thoroughly studied to help precision viticulture systems understand the actual status of the vines, it is in fact possible to show the correlation between this index and biomass (Stamatiadis et al., 2009), leaf area (Junges et al., 2019), and soil type (Hubbard et al., 2021).

NDVI is a normalized index and takes values between 0 and 1 and can be correlated to the plant's health as shown in the figure XX.

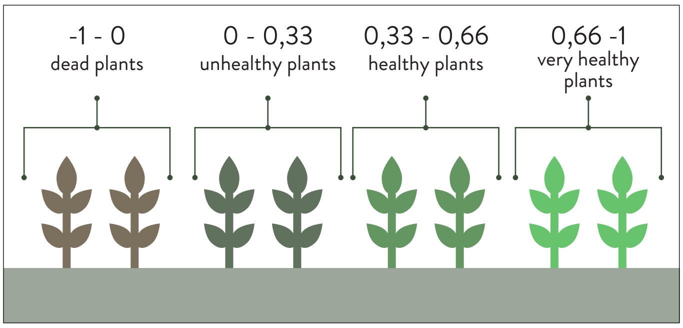


Figure XX. NDVI correspondence to plant's status (Fletcher et al., 2021).

Studies have also shown how it is possible to investigate a correlation between the average NDVI over a crop and the grape yield of that crop (Arab et al., 2021).

Crop Water Stress Index (CWSI) and leaf water potential (LWP)

Another interesting index to be investigated is the Crop Water Stress Index (CWSI), specifically related to the water status of the plant, which is crucial especially as climate change induces increase drought periods, changing the ecosystem especially at medium latitudes as already pointed out in section 3.2.

Water in vineyards is a key parameter since it determines the crop's yield both in terms of quantity and in terms of quality and maturation of the grapes. Especially in vineyards for wine production the water intake and the degree of sun irradiation determines the organoleptic properties that therefore determine the wine's quality.

Moreover, water management in vineyards is even more interesting given that in most cases, traditionally, no irrigation system are taken into consideration, since up until now the climatic conditions were enough to ensure enough water intake for the crops.

As the climate changes though, close monitoring of water status of the crop could result in the successful identification of those areas within a crop that are beginning to suffer from the increasing drying of soil, raising red flags where critical conditions are met.

This way, by knowing the different conditions within the same crop, it could be enough to proceed and implement a simple drip irrigation system that provides water to the areas in need without wasting such a crucial resource over a broader area.

It is important to underline, as is also discussed in section 3.3, that water stress monitoring from data collected through sensors, actually provides information about the plant's response to ground humidity and water availability in soil by-passing the study of plant's physiology and metabolism. A simple investigation on ground humidity is not enough to find which plants are suffering more since each plant behaves differently according to a large number of biological parameters and conditions that have to be met: by focussing on the response of the plant itself, we are able to visualize the actual situation instead of the possible causes.

CWSI has already been studied in literature and correlated to the leaf water potential: where lower ground water availability is measured, the plants' response is to lower their LWP (Bellvert et al. 2015, Belfiore et al., 2019).

Leaf water potential (LWP) is a quantity that represents the potential energy of water through the plant's vessels and essentially guides the water and nutrient movement inside the plant itself: high stress (CWSI = 1) is related to stomatal closure, therefore no movement of liquids whatsoever (it is essentially a way of roots to communicate to the leaves that the soil is drying and the water availability is low) (Gimenez et al. 2013, Bartell et al. 2021). Direct measurement LWP can be carried out by means of a pressurized chamber (Scholander's chamber) (Boyer 1967) that covers the leaf under investigation and provides with the value of LWP in MPa (the amount of pressure required to move the water inside it). Such measurements are, however, rather complex to implement in an autonomous system that would have to measure the water status over a large area.

The evaluation of CWSI based on remote sensing of climatic variables is therefore more efficient that direct measurement of LWP: it is quicker, it can be implemented in an autonomous system, and it requires less direct contact with the plants themselves.

The CWSI can be, in fact, be redefined as a formula depending on simple climatic variables (see section 4.1) and it has been demonstrated that LWP and CWSI show a strong correlation, making it reasonable to measure the CWSI to infer the LWP of the plant. Such correlation has been found by evaluating both the CWSI with remote sensors and the LWP with the pressure chamber (Deloire et al., 2020; Bellvert et al. 2015; Belfiore et al., 2019). On average, the critical conditions of LWP, less than -1 MPa (Deloire et al., 2020) coincides with a CWSI of at least 0.5 (Bellvert et al. 2015, Belfiore et al., 2019). General conditions of the vines under different water stress conditions are reported in the figure **xx** (of course, values are subjected to variation depending on the vine variety).

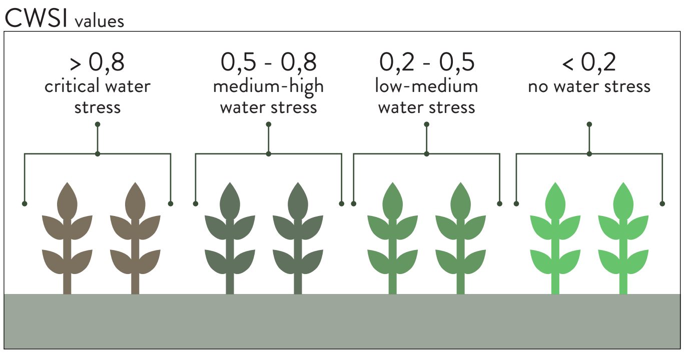


Figure XX. Range of LWP according to Deloire et al. 2020.

Moreover, this relation depends on the variety of plant, and even if we focus on vines, it depends on the cultivar, the specific variety of vine: studies show that, for instance, the Moscato variety shows higher susceptibility to changes in atmospheric and climatic variables making it the ideal case study to understand the variability of CWSI within a single crop. (Bellvert et al. 2015, Belfiore et al., 2019).

Different varieties show a different response to the same leaf water potential because of the difference in the structure and physiology of the plant itself. The same LWP can correspond to a different level of CWSI because of early onset stomatal closure in varieties that are more susceptible (such varieties are labelled as isohydric, as Moscato (Belfiore et al. 2019). This is again another reason why it is more efficient to analyse the response of the plants through water stress indexes rather than just monitoring ground humidity and water availability: different plants react in a different way to the same water conditions.

This of course means that monitoring the CWSI is a good way to monitor every kind of plant's water stress, making a remote sensing system useful for every crop, not limited to wine.

Moreover, CWSI has been found to be one of the most accurate indexes to differentiate between different water statuses (Belfiore et al. 2019), and less sensitive to the area of the canopy that was investigated, making it less susceptible to changes due to operational variables.

Optimal conditions

Whereas the CWSI – LWP correlation is clear from literature, studies are still in progress to determine the actual correlation between CWSI and all those agricultural parameters that were studied in relation to NDVI such as crop's yield, leaf area index.

The ideal LWP (and therefore the CWSI values) vary from crop to crop and from season to season depending on the water requirement of the plant. While it is clear that a lower LWP leading to stomatal closure and therefore to lower photosynthesis, leads to a decreased production and quality, it is also true that a certain amount of water stress could be beneficial to grapes, especially those that are destined to the wine production, since it highly affects the organoleptic properties of the final product (table grapes, for instance should satisfy aesthetic requirements as well, the larger the grape the better, so higher amount of water is generally favoured).

This is the reason why a controlled water stress approach through drip irrigation (Fereres et al 2007) is sometimes preferred, always taking into account that it could lower productivity and damage the quality altogether if not perfectly deployed. Excessive water stress is of course the cause of insufficient maturation and increase of the bitterness of the product due to the lower content of sugars and polyphenols (Fereres et al 2007, Chaves et al. 2010). This is another reason why a continuous monitoring of water stress and check of the quality of the vines can be beneficial in the future of precision viticulture.

3.5 BENCHMARKING AND COMPETITORS

Some companies are already in the early stages of production, so we analysed their strengths and weaknesses (shown in TABLE XX) to better understand where our project should focus.

Our main focus is to provide an efficient monitoring of the health of the crop: it is important for us to provide a full system from the sensing movable unit, to the data analysis code.

Furthermore, the output maps that show the crop's stress should be easy to read, showing clearly the areas that are at a critical level and that should be checked more closely.

Another added value that we can provide is the high flexibility of our system, that can be tailored to the needs of the specific crop in terms of number of fixed stations and frequency of data collection.

The tailoring to the crop goes further: with access to the production data of recent years, we can run a regression analysis using satellite data, to show the relation between the CWSI and the production of the crop, understanding in which season it is crucial to intervene on the stress status.

Once this initial testing is done (both with satellite images and with our local sensors), the continuous monitoring of the health of the crop will provide an active feedback loop to show if the critical areas are indeed improving their stress status after the farmer's intervention.

COMPANY	TECHNOLOGY	STRENGTH	WEAKNESS
SMARTISLAND[1]	A company that offers a product that controls and monitors the water stress of the plant.	The service provides both hardware, software and sensors.	The service does not provide maps about vineyard field's stress conditions.
SAVEGRAPE[2]	The technology is a modular system that is applicable to all the vineyards and controls both irrigation and fertilization.	The strength point of this technology is the flexibility and fast data transmission.	The sensors are spread all around the vineyards, it is not a compact design.
GRAPE [3]	Agri-analytics company that develops cloud based sofware solution integrated with wireless sensors. It offers advanced adaptive irrigation software service (irrigation maps).	Water and energy cost saving services. Soil sensors provided, aerial imagery hydraulic and crop models.	the company solely tackles the irrigation optimization problem.
AGROBIT[4]	It's a smartphone application that gives informations about the plant.	It can be implemented with remote sensing technology .	The app design does not seem user friendly.
AGRICOLUS[5]	it's a system with sensors that maps the field and uses sensors in order to support decisions.	it uses forecasting models in order to forecast information.	It uses only satellite imagery that are not very precise.
DRONEBEE[6]	It's a system that offers different features: both satellite and drone imagery, sofware, plan countering, forecasting models.	in comparison with the other companies, it is a complete technology that takes into account a lot of different aspects.	it is only for analysis, it has not an automatic respond to the issues that can be faced.

Table XX. Summarizing table of the main competitors on the market nowadays.

1 https://smartisland.it/
2 https://www.auroras.eu
3 https://cropx.com/
4 https://www.agrobit.ag/
5 https://www.agricolus.com/
6 https://www.dronebee.it/

4.
DESIGN

After having outlined the parameters of the microclimate that determine the plant's health, in this section we focus on how such values can be monitored in the most efficient way according to literature on precision agriculture. Then we present how such knowledge and technologies can be translated into our project, presenting our design proposal and choices.

4.1 CONCEPT GENERATION AND DEFINITION

CWSI index

The Crop Water Stress Index, or CWSI, is chosen as key vegetation index in this work as it is strongly related to the water status of the crop: a close monitoring of such status is especially important when considering the climatic trend we are living at medium latitudes that ensures that in the next years, water will become more and more scarce.

Thoroughly monitoring the variability of water status within a single crop could represent a strong advantage for agriculture since it can point out which areas are indeed suffering from water shortage and which ones are more water stress resistant. These information can also be exploited to inform decision about irrigation systems, whether they are fundamental or not, whether some areas have to be monitored more closely, and most of all, with continuous data monitoring the actual effectiveness of irrigation can be seen.

Our partners at Azienda Agricola Balladore Pallieri expressed interest in this solution given that, in their case, they do not have any kind of spread irrigation system because they would deem it a waste of potable water coming from the aqueduct, whereas if they better understood the condition of small portions of their crops, they could consider installing micro-irrigation systems to address specific critical zones in their crops leading to an improved water and resource management.

Moreover, by monitoring irradiation and water stress some indication about wine quality can be inferred.

CWSI is an indication of the overall health of the plant and it can also be that by monitoring the evolution of this index we can in some way predict the productivity of the yearly harvest. This hypothesis is investigated through a preliminary data analysis cross referencing the wine production of Azienda Agricola Balladore Pallieri and the CWSI of their crops over the last 20 years, which is dealt with in the next paragraph.

CWSI time series and correlation with production

To investigate the possible correlation between the water status of the crop and the yearly production of the same crop, the first step is to gather all the input meteorological data about the region around the crop needed to evaluate the CWSI over the crop itself.

CWSI is defined by Jackson (1982) as:

$$\text{CWSI} = 1 - \frac{\text{ET}}{\text{PET}}$$

where ET and PET are measures of evapotranspiration potential, closely linked to the water potential in the plant.

A way to calculate this index based on meteorological data is proposed by Anda (2009) and it is as follows.

$$CWSI = \frac{\gamma\left(1+\frac{r_c}{r_a}\right)-\gamma^*}{\Delta+\gamma\left(1+\frac{r_c}{r_a}\right)}\ ;\ \gamma^* = 0{,}66\ hPa/K$$

$$\frac{r_c}{r_a} = \frac{\frac{\gamma r_a R_n}{\rho c_P} - \frac{(T_C - T_A)}{\Delta+\gamma} - \left(p_{v,sat}(T_C) - p_v\right)}{\gamma\left[(T_C - T_A) - \frac{r_a R_n}{\rho c_P}\right]}$$

where

- γ : psychrometric constant
- r_c, r_a : canopy and aerodynamic resistances
- Δ : slope of saturated vapour pressure-temperature relation
- $p_{v,sat}$: saturated vapour pressure
- p_v : vapour pressure
- c_P : heat capacity of air
- ρ : air density
- R_n : net solar radiation
- T_C : canopy temperature
- T_A : air temperature

This formula can be then expanded to show the explicit dependence on meteorological inputs, which ultimately are air temperature (T_a), canopy temperature (T_c), dew temperature (T_d), surface net solar radiation (R_n), wind speed (u), surface pressure (p).

In the following, the formulas found in literature (Anda, 2009) to link the CWSI to the input data are reported with their unit of measure.

$$\Delta = \frac{dp_{v,sat}}{dT} = \frac{6{,}108 \cdot 17{,}271 \cdot 237{,}3}{(T_A+273{,}3)^2} * exp\left(\frac{17{,}271 \cdot T_A}{T_A+273{,}3}\right)\ ;\ [T_A\ ] = °C$$

$$\gamma({}^{hPa}/_K) = \frac{(c_P)_{air} \cdot p(hPa)}{\lambda_v \cdot MW_{ratio}}\ ;\ MW_{ratio} = 0{,}622$$

$$r_a = \frac{4{,}72\left[ln\left(\frac{z-d}{z_0}\right)\right]^2}{1+0{,}54u};\ [r_a] = \frac{s}{m}$$

where
u : wind speed at 2 meters height [m/s]
z : reference height (2m);
z_0 = 0,13 * l;
d = 0,63 * l;
l : plant height (1,5m) (Jackson et al, 1988).

The available wind speed in Copernicus is taken at 10m height so to refer it back to the 2m, this formula proposed by FAO is used. (Valle Junior et al. 2021)

$$u_{2m} = \frac{4{,}87 * u_{h=10m}}{ln(67{,}8h - 5{,}42)};\ [u_{2m}] = \frac{m}{s}$$

The RH value (between 0 and 1) is linked to the dew temperature and air temperature by (Moran et al., 2010):

$$RH = exp\left(\frac{17.271 * T_D}{T_D+237{,}7} - \frac{17{,}271 * T_A}{T_A+237{,}7}\right), [T_A\ , T_D] = °C$$

The saturated vapour pressure is given by (Moran et al., 2010):

$$p_{v,sat} = 6.108 * exp\left(\frac{17{,}271 * T_A}{T_A+237{,}3}\right), [p_{v,sat}] = hPa\ ;\ [T_A\ ] = °C$$

Actual vapour pressure (Moran et al., 2010):

$$p_v = p_{v,sat} \cdot RH$$

Air density (Moran et al., 2010):

$$\rho = \frac{p_{AS}}{R_{AS} \cdot T_A} + \frac{p_v}{R_v \cdot T_A}\ with\ R_{AS} = 287{,}058 \frac{J}{kg \cdot K}$$

$$R_v = 461{,}495 \frac{J}{kg \cdot K}; [T_A\ ] = K$$

Specific heat capacity (Moran et al., 2010):

$$C_P = C_{P,AS} + \varkappa \cdot C_{P,H_2O};$$

where $C_{P,AS} = 1006 \frac{J}{K \cdot k_{gas}}\ and\ c_{P,H_2O} = 1860$

$$\varkappa = MW_{ratio} \frac{p_v}{p_{tot} - p_v}$$

Data source

The input meteorological data were all taken from the European Database Copernicus, which provides time series with hourly precision over specific regions of the earth, apart from the canopy temperature, which was downloaded directly from Landsat Satellites through Google Earth Engine as the Land Surface Temperature parameter.

Whereas Copernicus offers hourly data, every day, Landsat Satellite only detect the data over a specific route once every 15 days, so we filtered the Copernicus data only for the days where we could also have the LST and we downloaded the data referring to 11am local time since that is the time where Landsat takes its own images. This was done to ensure the best compatibility of the data coming from two different sources.

It is important that the two datasets are detected at the same time since the CWSI depends closely on the difference between the air temperature (from Copernicus) and canopy temperature (Landsat LST) and it can be taken as index only if independent of the time of detection.

To increase the number of LST data we cross referenced the information coming from Landsat 7 and 8 satellites which together provide a measurement per week. It is important to highlight that these measurements are scarce and are also subjected to variability due to atmospheric conditions. For instance, if unfortunately the passage of Landsat over a certain area coincides with a cloudy day, it cannot detect any surface temperature thereby decreasing the already small number of data at our disposal.

With these information we plot the CWSI over the crop in our case study with a resolution of 30m, coming from the LST resolution given by Landsat satellites, for every day that is covered by both Landsat Satellite and Copernicus, as depicted in the figure **XX.**

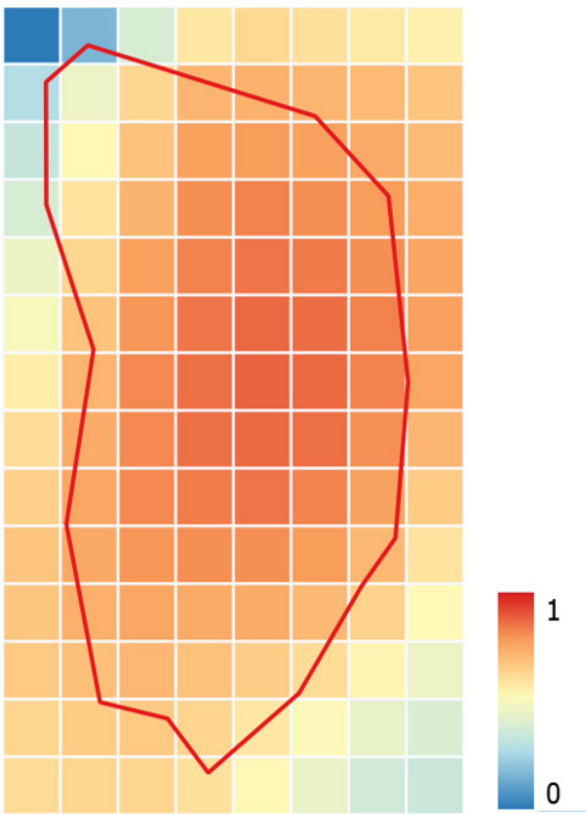


Figure XX. CWSI map evaluated through atmospheric data coming from Landsat 8 and Copernicus database (14 july 2018); 30x30m resolution.

Data analysis – Regression Model

In this section it is inspected the possibility to use the indication of the plants' water stress during the year provided by CWSI to predict the productivity of a crop field. Indeed, the existence of a correlation among these two quantities combined with a precision monitoring of the CWSI could allow the farmers to infer the final productivity of the field some months before the the harvest. Moreover, the knowledge of the CWSI distribution in the crop filed could allow to anticipate the production in the single zones so that ad hoc intervention through intelligent systems could be designed in order to recover the target productivity.

The main difficulty lies in the fact that the yearly production p(t) is available only at the end of the crop lifecycle when the harvest is collected, whereas the CWSI evolves during the year. As a consequence, finding a way to properly represent this relation is not immediate. Moreover, the available dataset is very limited in terms of production, since Azienda agricola Balladore Pallieri provided the production data from 2010 to 2021.

To compute the regression model, we take the average value of CWSI for each month (average over the four passages of Landsat 7 and 8) and then we extract an average spring value *CWSIspring(t)* (from March to June) and an average summer value *CWSIsummer(t)* (from July to September). In this way, we try to find the relation between the productivity and the water stress in the early stages (spring) and in the last stages (summer) of the vineyard lifecycle.

$$p(t) = f\left(CWSI_{Spring}(t), CWSI_{Summer}(t)\right)$$

t = 2010, ... 2021

Due to the extreme scarcity of data that do not allow to obtain robust and reliable results adopting complex and highly parametrized model, we fit the data with the Linear Regression model [Johnson et. al., 2002]:

$$p(t) = \beta_0 + \beta_1 CWSI_{Spring}(t) + \beta_2 CWSI_{Summer}(t) + \varepsilon, \varepsilon \sim N(0, \sigma^2)$$

In particular, we fit the data with the Least Trimmed Squares Robust Regression, [Rousseeuw et al, 1887], [Pison et.al., 2002], a robust technique that automatically detects and excludes the outlier in the dataset providing the best fitting, setting the percentage of outlier data to exclude at 5%. The model, fitted with R package ltsReg [RDocumentation, 2022] shows that both the regressors are negatively correlated with the production, confirming the intuition that higher stress indexes are associated with lower productivity of the crop field. Only the summer CWSI is statistically significant to explain the productivity. Indeed, as reported in the table, the high p-value the winter CWSI does not allow to consider it as influential.

	Estimate	Std. Error	t-statistics	p-value
β_0	1352.7	244.0	5.543	0.000866
β_1	-357.7	361.1	-0.990	0.354958
β_2	-1075.7	566.3	-1.899	0.099285

So, we exclude the spring CWSI and refit the model with the summer CWSI only.

$$p(t) = \beta_0 + \beta_1 CWSI_{Summer}(t) + \varepsilon, \varepsilon \sim N(0, \sigma^2)$$

In this case, the regressor is statistically significant, as reported in the table, (p-value < 0.05), meaning that it needs to be included in the regression model.

	Estimate	Std. Error	t-statistics	p-value
β_0	1264.3	291.2	4.342	0.00187
β_1	-1280.1	506.1	-2.529	0.03228

The fitted model provides an R2 of 0.416, meaning that the summer CSWI only is able to explain more that 40% of the total variability of the production. Considering the extreme variability and high number of internal and external factors that are embedded in the productivity of a crop field, we think that this result is quite satisfactory, confirming that the CWSI during the last stages of the vineyard lifecycle is a good proxy.

Figure xx displays the plot of the fitted yearly production versus the Summer CWSI can be visualized with the associated 95% confidence interval, showing that it is possible to identify a negative trend in the Production with respect to the Summer CWSI selectively excluding few observations with the above mentioned robust procedure.

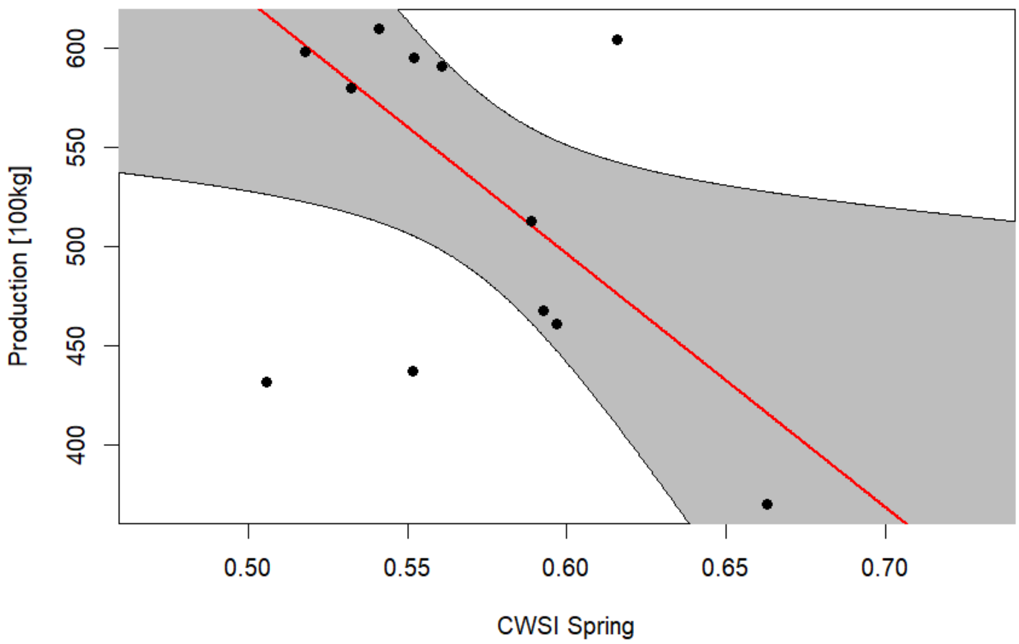


Figure XX: regression model

4.2 DESIGN DEVELOPMENT

Method

Deciding the method for the design development is the first step for the design process. First, the current competitors' solutions available on the market are analysed, as well as the latest trends and prototypes of the most recent scientific papers. This is useful to understand the possible weaknesses of the competitors' products and include such issues in our stakeholder's analysis. After considering the stakeholders' needs, a list of requirements is made. This helps to clarify the required features of the product and the possible critical choices in the design process. Lastly, some design proposals for the product are shown and compared.

State of the Art: Industry and Academy

Many companies sell sensors that can be used to monitor plants health, and there are companies that sell full-integrated sensing kits that are designed specifically for the purpose of monitoring plants' state and growth. Fewer companies offer such products as part of a complex IoT system with integration in cloud or local platforms for the management and control of smart systems (IoT Platform): in this case they also offer software for the extraction and analysis of data, and an autonomous human-supervised control of the response on the field in some cases. Even fewer firms offer an integration of satellite image analysis in such systems. The kits and sensors offered can either be fixed on the ground, on a support or be contained in a case that hosts several sensors. Another kind of solution consists of mobile robots, both aerial and ground vehicles, bringing the sensors around.

Given the interest in automation of productive process and the new possibilities offered by AI in terms of robotic perception, navigation and motion planning, the robotic community has been producing many solutions to these and many related problems (Cerrato et al., 2021). Drones and rovers can make use of Computer Vision to navigate the vineyard and collect a lot of information about plants by just looking at the images. In addition to this, they can also use standard sensing systems, thus increasing a lot the quality of the information they provide. Thanks to their autonomous motion planning intelligence, they can be deployed in a short time for even a short session of measurements.

Technical Requirements

The system to be designed must satisfy the following requirements:
1. ability to measure:
- air humidity;
- air temperature;
- canopy temperature;
- solar radiation (infrared and ultraviolet bands);
- atmospheric pressure;
- wind speed;

2. ability to measure the mentioned variables with enough granularity (ideally, the system should be able to provide a value for each plant in the vineyard);
3. ability to monitor the behavior of this variable along time, on both a daily and a yearly basis, thus requiring multiple measurements along the day and constants measuring capabilities all year long;
4. ability to send the measurements to a local server which analyzes the data and provides information.

It is worth noting that some requirements are not that strict once considered in the context and for the purpose that data are collected: first, the variability of these variables over time and space differs a lot among them, and for some of them an averaged value (on space and/or time) is enough; secondly, the data are needed for the computation of the CWSI index and not all of them have the same weight in the formula. For instance, wind speed can vary a lot over time and space (wind is rarely constant in speed and direction over time and space), but the average value of wind speed is enough for the computation of the CWSI: therefore, the wind speed average over a span of time of approximately one hour and a large geographic area, as a large portion of a vineyard, is enough for our monitoring purposes. Similarly, air humidity does not have a great weight in the computation of the CWSI index, meaning that a small error in the measurement of this variable does not dramatically affect the final value of the index. On the other hand, solar radiation has a large impact on the final value of CWSI, but its distribution in space does not vary almost at all, therefore a single measurement for a wide area is generally enough for our purposes. However, loosening these requirements should always be considered with reference to the specific geographic and climate features of the vineyard object of study: for example, a field on a plain would probably not show a great variability in the measured variables either, while a vineyard on a hill would see quite different values of solar radiation, wind, humidity, and temperature in its different geographic parts.

Challenges

The challenges of designing an autonomous system for the monitoring of such variables are mainly related to the 'autonomous' aspect of such system. Many solutions are based on mobile robots, either rovers or drones, that can navigate the vineyard and can collect data when and where they need. The problems associated with this kind of solution regard the difficulties of designing a good navigation system that can move the robot along the rows and through the field in a GPS-denied environment, and the cost of designing a robust robot that can navigate a vineyard without problems, i.e. without getting stuck in the uneven terrain. The solutions for both these problems are the main concern of the robotic community, with some researchers specifically addressing these issues for agriculture applications.

Other solutions based on static sensors avoid all these problems, but they lack in flexibility and they are generally more invasive, as they require the presence of additional objects in the vineyards, in most cases with a dense distributions of the sensors along the rows. Even if the costs of these sensors can be lower, the number of sensors to be installed is greater than the number of sensors required to be installed on a swarm of robots that navigate the vineyard, therefore making the two solutions comparable from an economic perspective.

Design proposals and comparison

Given the current analysis performed so far, three system designs were explored and analysed, but only one is presented here. The first two consist of a complete static system and a complete mobile one. The third one, which is the only one presented here, consists of a hybrid solution of the two that aims at taking the best of each of the first two. The hybrid system is shown in Table **xx** and presents an extremely conservative economic quote, given the current market prices of the needed components.

The solutions are compared reflecting the following metrics:
- cost;
- invasiveness;
- adaptability of the solution and speed of deployment for everyday usage;
- technical feasibility of having all mobile sensors;
- technology readiness.

Before comparing the different designs, an explanation of why a metric is included will be given.

Cost is an essential metric, as expensive products and solutions are less likely to be adopted, especially if the investment return is not obvious or not assured: research work can be done in this sense to show the effectiveness of the system and thus reduce the risk related to the return of the investment.

Invasiveness is another important factor: the agriculture activity still requires a lot of manual and human work, and the deployed system cannot obstruct the movement of workers and machines.

Flexibility of the solution is crucial and its importance can be explained with an example: if a specific area of the field or even a specific plant require a focused monitoring, a mobile system can provide that without any change to the system; on the other hand, a static system cannot address such need, or must be modified to do it. Speed of deployment is another important parameter, but in this sense all design possibilities explored offer a good performance.

As for the sensors mobility, it is hard to find a commercial mobile platform that hosts so many different sensors: it is theoretically possible to install such diverse modules all on the same vehicle (either drone or rover), but inconvenient to adopt such a solution, as it requires high design complexity and does not lead to any significant improvement in data collection, cost optimization, or improved efficiency of the system. However, rovers can surely be a better choice over drones in this sense, as they are better suited to host a large number of modules and sensor without requiring a high level of design optimization as flying platforms would.

Lastly, Technology Readiness Level (TRL) is an important factor, as it indicates if a technology is ready and already commercially available, or it still requires development and investments for its commercialization.

Table **xx** sums up the economic quote for the hybrid solution.

The hybrid solution is based on a series of fixed sensing stations (weather stations and pyranometer) spread across the field, and a swarm of drones that navigate the vineyard with a thermal camera mounted on them. The sensors and the drone communicate with a server that can either be local or on cloud. The whole system is managed through an IoT Platform. The fixed sensors are relatively cheap and many sensors can be deployed and used across the vineyard. Installing them on a mobile platform (rover or drone) would increase the complexity and the cost of the system. The thermal camera, on the other hand, is an expensive component, and it is hard to use it attached to a fixed structure but still be able to use it on multiple plants and direct it to specific leaves of the plants. Therefore, using a mobile platform for this purpose is the most logical choice. The choice between the rover and the drone is straightforward at this point: considering that commercial models of drones and rovers suitable for agriculture have approximately the same cost, there is a wider range of choice for drones, and drone technology for vision, navigation, and image acquisition is especially developed and cutting edge. Moreover, the drone is not invasive with respect to the rows of the vineyard as it mostly flies over the plants and not among them.

Notes on the design choices

The design quote is extremely conservative and is based on the commercial cost of components sold by reliable and well-known companies whose products are available in Italy. The camera modules of the drone models found have technical characteristics higher than the required ones for our purposes.

The N./hectare column has been defined based on personal experience and logical deduction and with a conservative mindset. For instance, the planned number of commercial weather station per hectare is overestimated, even for the most uneven territory. The value of one pyrometer each 4 hectares should be a good estimate, given that the irradiation on plants is quite uniform on plants. The number of drones required per hectare is the figure that mostly weights on the final cost per hectare of the hybrid solution. Also in this case, the estimate is quite conservative. Considering the current flight autonomy of commercial drones of small and medium size, a single drone should be able to cover an hectare multiple times per day, considering as task to take a picture of a leaf for each of the plant in the assigned area of the vineyard. However, the second drone per hectare that is indicated in the table accounts for the possibility of malfunctioning of the drones and the time required for repair, and for the intensification of the task in case of special monitoring periods.

Model	Environmental variables & Function	Cost	N./hectare	Cost per hectare
Commercial weather station with solar panel	Wind speed, pressure, humidity, air temperature, soil temeprature and moisture	100.00 €	10.00	1,000.00 €
Pyranometer	Solar radiation	50.00 €	0.25	12.50 €
Drone with integrated thermal camera	Canopy temperature	10,000.00 €	0.50	5,000.00 €
RF and wireless communication system for local network		700.00 €	1.00	700.00 €
Server		1,000.00 €		
	MINIMUM TOTAL COST	11,850.00 €	**TOTAL COST PER HECTARE**	7,712.50 €

Table XX:

5.
PROTOTYPE AND DATA ELABORATION

In this chapter, the design choices and the technical implementation of the first prototype, are illustrated. Such prototype is just a first step towards the realization of the whole system, a useful step to determine the key design concepts and to confirm the validity of the data collection and elaboration codes and formulas.

The data collection session in Azienda Agricola Balladore Pallieri in which the prototype was tested is then described in terms of a priori strategic choices and a posteriori data elaboration and output maps creation. All the information is finally translated into the steps that link the prototype to the design outlined in section 4.2.

5.1 SOFTWARE DESIGN

In this section, the software core that governs the logic of the prototype is addressed and explained. Without diving into the line of codes, the goal is to emphasize the reasons that lead to the implemented design choices. In particular, the mechanism that controls the hardware, the user interface that allows human-prototype interaction and the saving routine that returns the desired output will be investigated. The code has been developed in Python and relies on external libraries.

The first step consisted of determining whether to build the prototype to be completely automatic or still dependent on human decision-making. In order to test the validity and correctness of the developed solution in an easier way, the latter and simpler implementation has been opted for. A stand-alone automatic system is envisioned in further and more advanced stage of the project. This choice leads also to a simpler debug phase and more flexibility in the data collection since the user can acquire a better understanding of the underlying process.

The graphical user interface (GUI) then was a natural consequence of the aforementioned decision. Thus, a user-friendly window has been created so to allow the interaction with the processing board. The code dedicated to this purpose was mainly derived from an open access package tailored to GUI creation, namely PySimpleGUI. In detail, classes for the creation of buttons and acquisition of user input were exploited with the purpose of controlling the reading of the peripherals and integration of external information (manually specification as text input of quantity such as wind speed, e.g.), respectively. A special button, "Save", is dedicated to the calling of line of codes in charge of handling the saving procedure of data on the local storage, an external 64 GB SSD memory mounted on the Raspberry Pi. The final appearance of the GUI for this project is reported in the following figure.

Figure xx: Appearence of the Graphical User Interface implemented for the prototype.

Two extra windows ("Themes" and "Logs") are designed in order to allow the user to choose the graphic theme and to see the logs generated during the execution of the program.

For what concerns the management of the peripherals, the reader must be aware that six sensors were interfaced with the Raspberry Pi board:
1. DHT22 (Temperature and Humidity sensor);
2. MLX90614 - GY906 (Surface Temperature sensor);
3. BME280 (Pressure, Temperature and Humidity sensor);
4. TSL2591 (Ambient Light and InfraRed intensity sensor);
5. LTR390 (Ultraviolet intensity sensor);
6. GY-NEO6MV2 NEO-6M GPS (Global Positioning System).

It must be underlined that sensors 2, 3, 4 and 5 communicate with the board via I2C protocol, a shared bus protocol handled by the open-source library "smbus". The set-up and control of these sensors have been instead based on open-source files that can be found online (\ref{https://www.waveshare.com/wiki/Environment_Sensor_HAT}).

On the other hand, DHT22 uses a serial bus to send data to the board. All the main operations such as the set-up of the sensors and the reading of its data registers are managed with a high-level approach: the library "adafruit-circuitpython-dht" has been exploited and the relative functions called hiding the low-level module control.

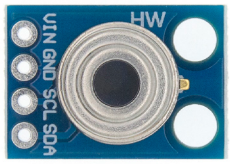
Lastly, the GPS module shares data with the Raspberry Pi via serial bus (port /dev/ttyAMA0) according to NMEA 0183 protocol. The latter is software implemented thanks to "pynmea2" open-source library. In general, upon clicking of the button, a call to the specific portion of the code entitled to handle the data collection for the required quantity is performed, involving the corresponding sensors. In order to have a system more robust to measurement noise, an average of more measurements has been taken whenever that was possible.

In detail, the air temperature is the result of the average of DHT22's and BME280's output. The same fact applies to the humidity measurement. It must be underlined that BME280 sensor undergoes an initial

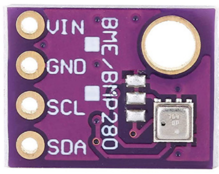
SENSORS:

1. DHT22 (Temperature and Humidity sensor);

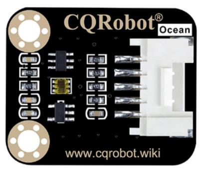
2. MLX90614 - GY906 (Surface Temperature sensor);



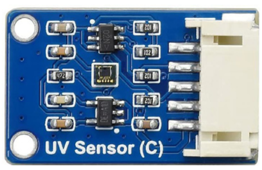
3. BME280 (Pressure, Temperature and Humidity sensor);



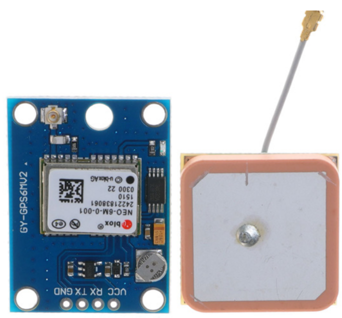
4. TSL2591 (Ambient Light and InfraRed intensity sensor);



5. LTR390 (Ultraviolet intensity sensor);



6. GY-NEO6MV2 NEO-6M GPS (Global Positioning System).



phase of calibration of parameters whenever the entire system is turned on. A similar approach is adopted also for canopy temperature measurements. The returned quantity is nothing but the average of ten measurements acquired each 0.2 seconds. This implies that the data will be available after two seconds under the assumption that the majority of time the camera is pointing at the desired object.

The last remark concerns the GPS module. The software has been designed in order to check at least 150 data strings coming from the localization system. Whenever a valid NMEA 0183 localization string is found, this information is returned and associated to the collected data. Notice that the higher the number of checked strings, the higher the probability of finding a valid one, but the slower the system. It must be then considered that the GPS module usually requires some time (up to five minutes) before correctly synchronizing with the satellite and providing a valid data string. Furthermore, the signal acquisition can sometimes fail in indoor or valley-like environments even though these should not be the cases of the designed user-case scenario envisioned in this project.

Once all the desired data are collected, the saving routine can be called. Upon clicking on the button "Save", the code takes advantage of the python module csv to dump data into the local storage as CSV format files. It must be highlighted that, firstly, the header row of the csv file can not be chosen by the user (i.e., the entries fields, which parameters are supposed to be measured, are established in advance). Secondly, the data are collected in a specific python data structure: a dictionary. Every data acquisition round creates a dictionary that will constitute a row in the csv file. After having stored the information, the dictionary is reset to null values and waits to be refilled with new measurements.

A last technical note is the following: the GPS latitude and longitude coordinates are acquired during the saving procedure before the dumping of the dictionary in the user's file and not during the other quantities acquisition. This implementation choice has been made so to lower the computational burden. In fact, the idea is that, if something were to go wrong during the measurements' phase, one could just repeat the data collection without repeating the acquisition of the location coordinates.

Another design choice that can be worth underlining is that no telecommunication system is adopted for the data storage. This stems from the consideration that, in the first place, a local storage presents an easier management. Secondly, a communication link is not always available. Indeed, one could rely on proprietary technology (such as NarrowBand – Internet of Things, NB-IoT), but this scenario implies fees. Or one could opt for an open software communication protocol (such as LoRaWAN, Long Range Wide Area Network), that still requires an initial investment on the proprietary hardware. In a future stage of the project, these scenarios can be considered as valid option in order to set up a cloud service for the end users.

Notice that this possible future implementation constitutes a first step towards a complete automatization of the system. Other key aspects needed to envision the latter scenario include a data collection routine managed via software without the presence of the end user. In other words, no more graphic user interface with buttons and inputs but an automatic data collection based on timing, distances or predefined GPS coordinates. Furthermore, also the wind speed should be integrated in this autonomous system and, therefore, another hardware design and dedicated line of codes should be considered.

5.2 HARDWARE DESIGN

The realized prototype is a simplified version of the product aimed to be sold. The idea behind that is to test the software designed and to truly understand if the project works or needs some modifications.

For the prototype, a Raspberry Pi 4 Model B is used.

The Raspberry Pi 4 Model B is the latest version of the low-cost Raspberry Pi computer. Those kinds of computers are on the market since 2012 and are widely spread as they allow several uses in the technological field, having just one card. They mount an operating system called Raspberry Pi OS. In addition, raspberry devices are quite cheap and very small, sold with no case.

They are powered with an external battery and commended through a touch display and a keyboard, so to be movable. A scheme to illustrate how the raspberry works **(Fig. xx).**

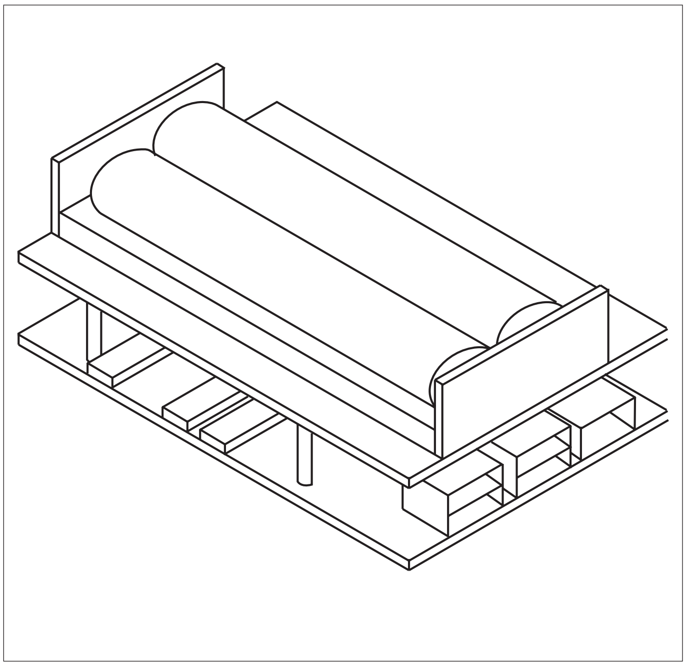


Figure XX: simplified sketch of the raspberry and its battery system

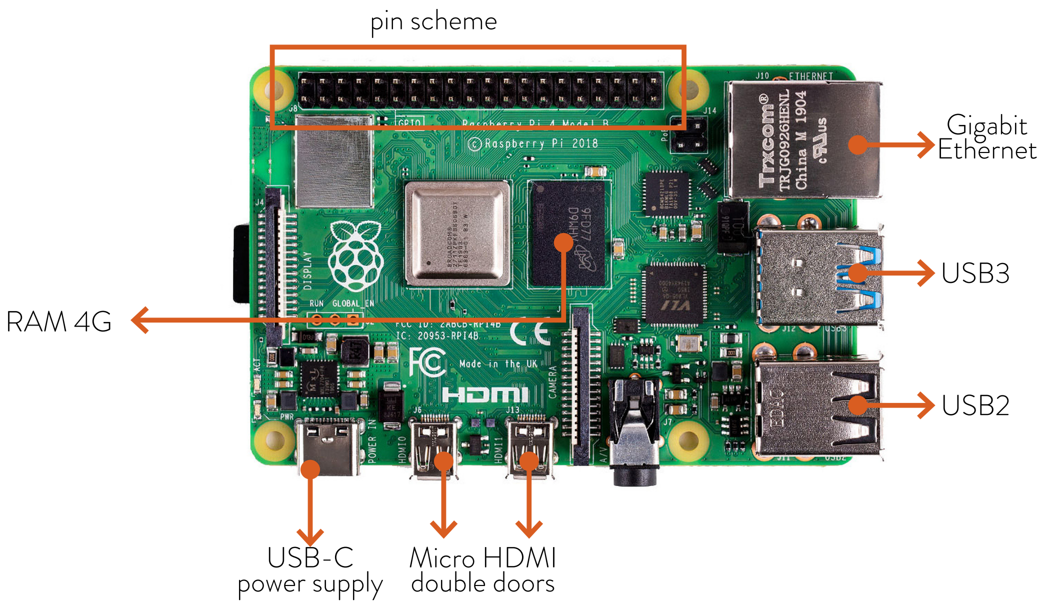


Figure XX: the raspberry and its components

The data that need to be surveyed are:
- Relative Humidity
- Air Temperature
- Surface Temperature
- Pressure
- Solar radiation (InfraRed intensity - Ultraviolet intensity)
- Position
- Wind speed

Therefore, the Raspberry pi 4 is used as the main brain of the system, to which the following sensors are connected:

1. DHT22 (Temperature and Humidity sensor);
   The AZDelivery DHT22 AM2302 sensor allows temperature and humidity to be measured digitally, providing highly accurate data. Its compact size and high-quality materials make it very durable. The versatility of the DHT22 sensor, which can support both 3.3V and 5V voltages, makes it perfectly compatible with Raspberry Pi. Precision: humidity ±2-5% UR; temperature < ± 0,5 C.

2. MLX90614 - GY906 (Surface Temperature sensor);
   GY-906 MLX90614 is a non-contact Infrared Temperature Sensor Module MLX90614ESF IIC I2C for Arduino. This sensor comes with a breakout board with all of the components needed for operation and two types of pins, unsoldered. It has a small size, 10k Pull up resistors for the I2C interface with optional solder jumpers. The measurement resolution is of 0.02 degrees. One of the main requirements is a high accuracy (0.5°C) over a wide temperature range and high accuracy calibration. This sensor is welded onto the Raspberry.

3. BME280 (Pressure, Temperature and Humidity sensor);
   The BME280 pressure sensor is a very precise module that allows detailed measurement of air pressure and is ideal for determining temperature, weather conditions and altitude. Via an I2C connection, it gives access to enough weather data to make good forecasts. It has a small size (3.6 x 3.8 x 0.93 mm), has low power consumption (1.8 to 3.6 V). To allow its use, the sensor has been welded. The pressure precision is ±1hPa, the humidity precision is ±3% and the temperature one is ±1.0°C.

4. TSL2591 (Ambient Light and InfraRed intensity sensor);
   The sensor can measure infrared light and human visible light, Built-in ADC, can directly output light intensity through I2C interface, which is not easy to be interfered by noise. The sensitivity of the sensor is as high as 188μLux, dynamic range is as wide as 600M:1. Thanks to the built-in infrared photodiode, it can measure more accurately even in an environment with large infrared noise interference. The onboard level conversion circuit is compatible with 3.3V/5V working level.

5. LTR390 (Ultraviolet intensity sensor); The sensor LTR390-UV-01 is used for measuring ultraviolet rays and visible light. The ADC is embedded, direct light intensity value output via I2C bus. It is compatible with 3.3V/5V operating voltages.

6. GY-NEO6MV2 NEO-6M GPS (Global Positioning System). The module has a ceramic antenna, a data backup battery, and LED signal indicator. The default baud rate is 9600. and the accuracy is 2,5 meters. This sensor is welded onto the Raspberry.

Each of the sensor is crucial in the acquisition of the data that need to be then elaborated for the definition of the CWIS. Because of the number of sensors, the Raspberry has been connected with two breadboards.

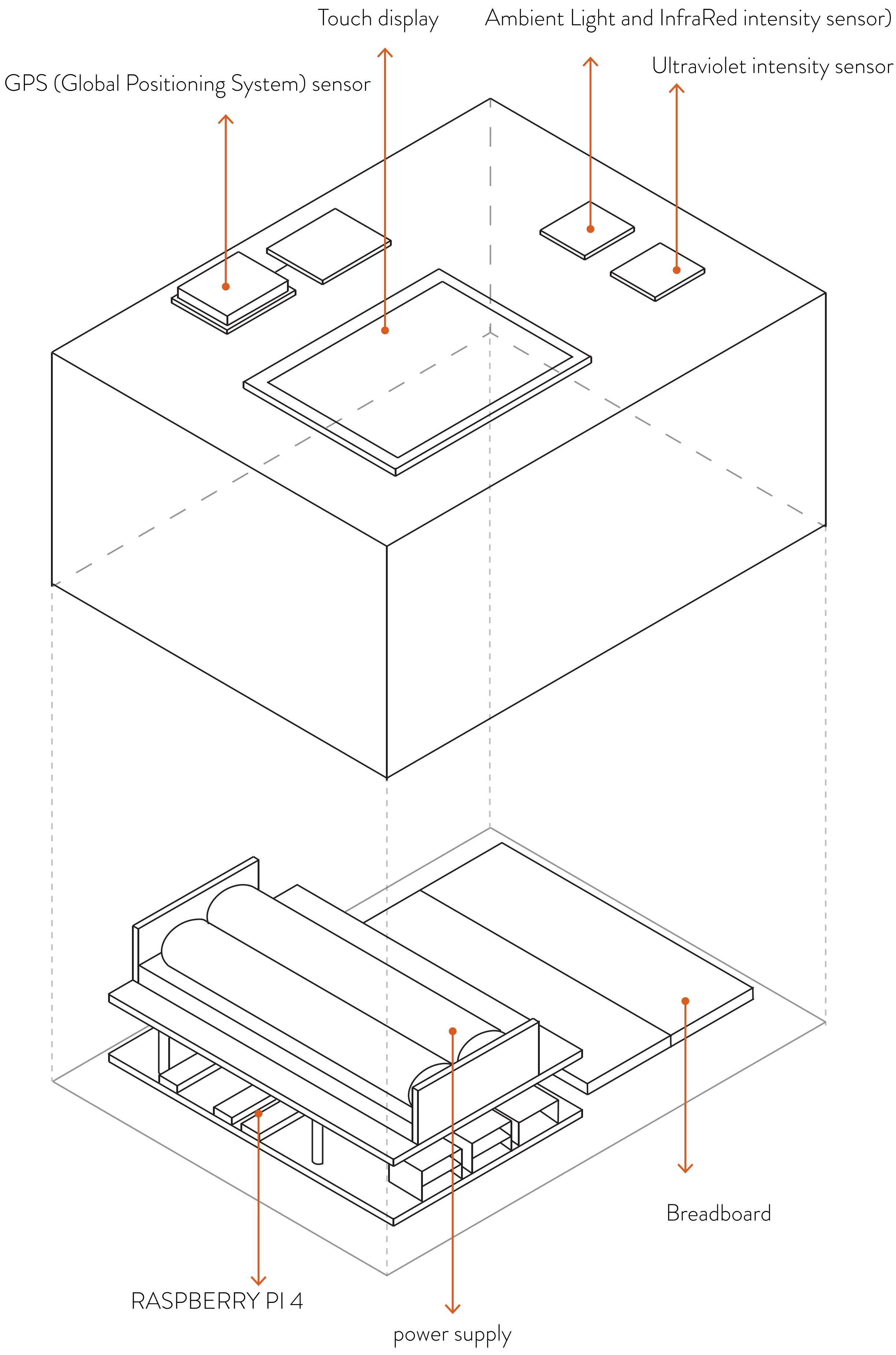
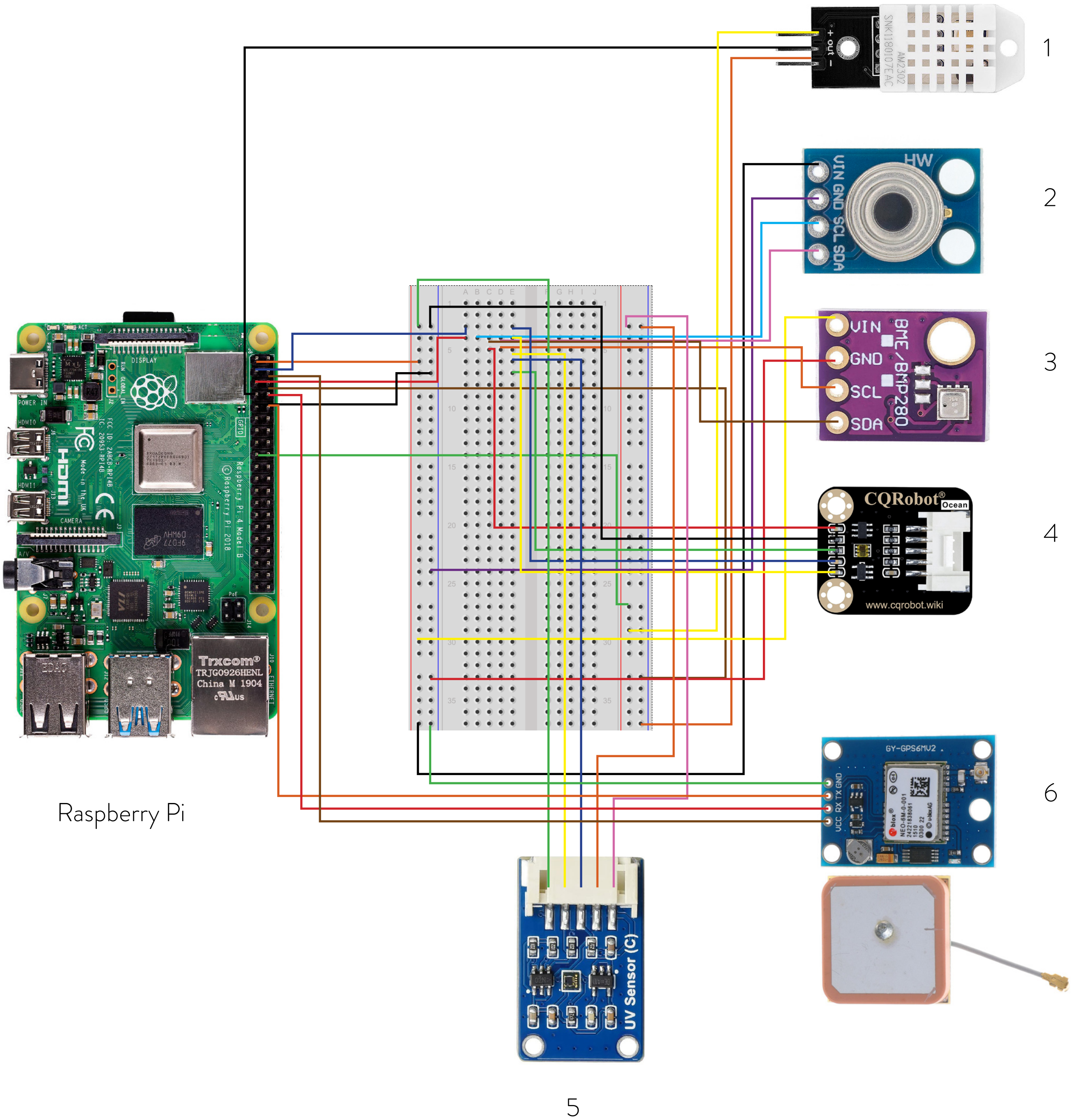


Figure XX: simplified sketch of the raspberry box with the different components



Sensors:

1 - DHT22 (Temperature and Humidity sensor);
2- MLX90614 - GY906 (Surface Temperature sensor);
3- BME280 (Pressure, Temperature and Humidity sensor);
4- TSL2591 (Ambient Light and InfraRed intensity sensor);
5- LTR390 (Ultraviolet intensity sensor);
6- GY-NEO6MV2 NEO-6M GPS (Global Positioning System).

Figure XX:simplified circuit diagram connecting the raspberry with the different sensors

5.3 ON SITE MEASUREMENTS

Azienda Agricola Balladore Pallieri

The on-field testing of the prototype was carried out in Azienda Agricola Balladore Pallieri (see Section 3.3), a representative of our direct stakeholders and of the reality in which the system could be applied.

Calosso is located on a hill, surrounded by the territories of Langhe and Monferrato and the great part of its business as a municipality turns around wine production, with two third of its area as agricultural land devoted to vineyards. Thanks to their positioning, they take advantage of a mild climate and they do not suffer of droughts or massive and strong hailstorms during the year.

For this reason, this area is the perfect candidate to monitor the change in productivity. Indeed, the effect of extreme events can be ruled out, concentrating on the modifications of climatic conditions due to climate change determining a constant increase of temperatures and change of seasonal cycles.

Context and goals of the session

The primary objective of the on-field session was to check the validity of the software and hardware of the prototype, simulating the collection of the data as it should happen in the final system. Through this simulation the aim was to investigate if the initial design constraints and requirements were realistic and applicable to our case study, Azienda Agricola Balladore Pallieri.

Moreover, together with the practical take aways, it was an opportunity to experience first-hand the real condition of vineyards, their organization and how the farmers work in that context.

The test was carried out in late spring (04.06.2022) to investigate the status of mature vines and the weather conditions were good, ensuring a more reliable measurement of irradiation.

Figure XX. Castle of Calosso, the San Martino church and some fields of the Azienda Agricola Balladore Pallieri.

Instruments

To carry out a complete simulation of the final system, the Raspberry Pi was used in combination with:

- an anemometer (BT-100-WM, accuracy of 0.3-30 m/s, +/- 5% reading), fundamental to detect the wind speed since it cannot be done through a miniature size sensor mounted on the Raspberry Pi.

- a moisture meter (HH2 DELTA-T DEVICES, accuracy of 0.3-30 m/s, +/- 5% reading), used for a comparison between CWSI and ground humidity data.

- a GPS (Garmin e-Trex 3 portable 5, accuracy of 5-10 mt, within 15 mt 95% reading), to navigate the crop and reach the waypoints where the data collection would take place.

All the devices were powered by external batteries.

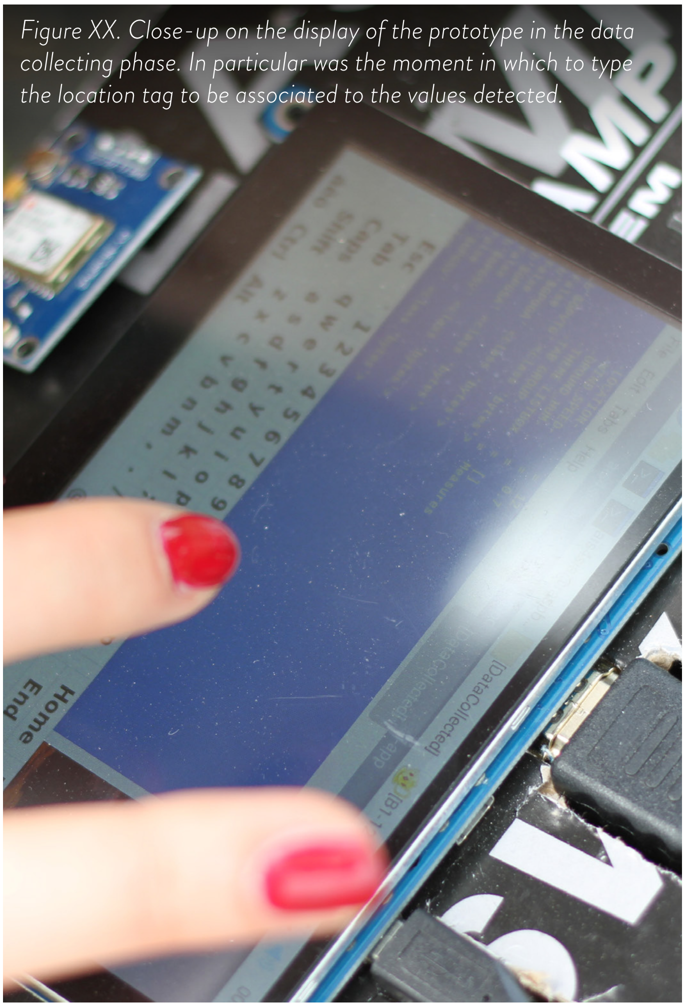


Figure XX. Close-up on the display of the prototype in the data collecting phase. In particular was the moment in which to type the location tag to be associated to the values detected.

Figure XX. Intruments used for data collection, from the top the anemometer, the moisture meter and the GPS

Data collection session

Before physically going with the team to Calosso, it was necessary to design a strategy for the data collection.

Three areas of interest spread in almost an hectar were identified based on:
- the images from the satellite, from which it was possible to infer the driest areas;
- the different situation between uphill and downhill, to check for different water drainage in the soil;
- the possibility to investigate how strong the variation on a small scale are by choosing areas that are side by side.

Area A and C are close together and uphill, whereas area B is downhill on the north-eastern corner of the field as shown in Figure XX; an extra zone of 18 points near the B area (zone D), was added while on site to investigate how much the data differ from plant to plant.

The combination of these areas made it possible to collect data in homogeneous situations (in A and C), testing how capable the AIS4SIA system is of spotting light differences, but also to see if a stronger change in condition (with area B) would show on the output data.

In each area, precise waypoints were chosen to have a measurement roughly every 10m, creating a network of 6x7, 6x8, 5x7 locations respectively for area A, B and C. Each location was named with the letter of the sector and an increasing number, organized to follow a snakelike path along the grid. At each point, all parameters were simultaneously collected through the Raspberry Pi and additional external sensors.

The software is able to acquire automatically the leaf temperature, the pressure, the IR and the UV. Windspeed, ground humidity are inserted manually, together with the name of the waypoint to as a double check in case of GPS malfunctioning.

In this way, we only had to refer the name of the position to the correct pixel on the satellite map to create the first iteration of the geospatially referred CWSI heatmap shown in Fig XX.

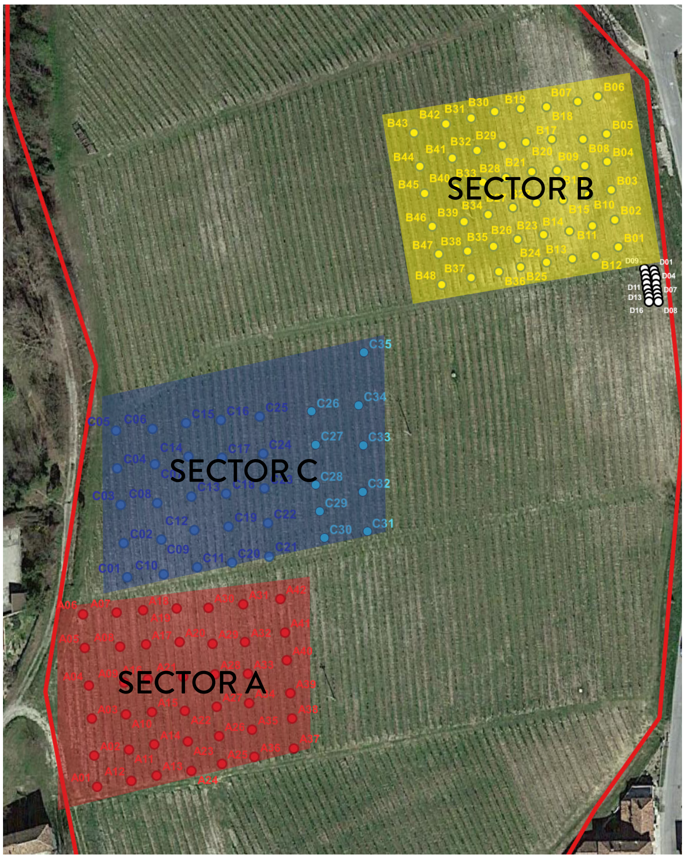


Figure XX. Detail of the leaf temperature measurement with the thermocamera.

Figure XX. Bird view of the selected field of Azienda Agricola Balladore Pallieri, with the A, B, C and D areas defined by the respective waypoints.

Figure XX. View of the vines and the field were the AIS4SIA team carried out the study on 4th June in Calosso (AT).

Figure XX. Pictures of the on field survey of 4th June at the Azienda Agricola Balladore Pallieri and of the meeting with Alessandro and Vittorio Balladore Pallieri.

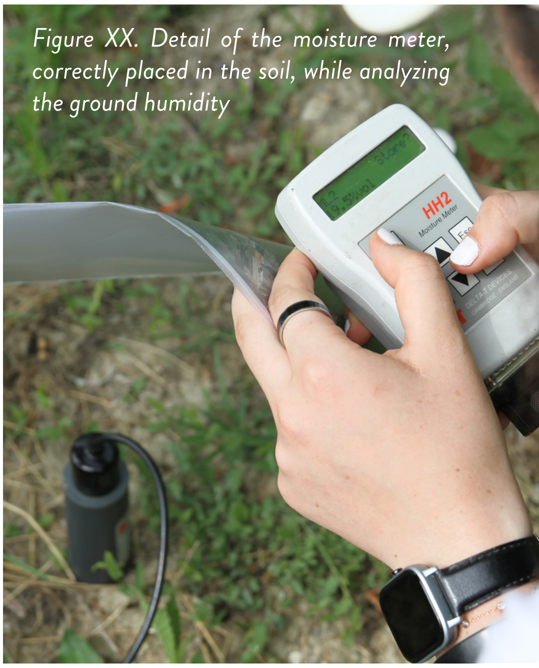


Figure XX. Detail of the moisture meter, correctly placed in the soil, while analyzing the ground humidity

Figure XX. Detail of data collection from the anemometer and annotation of the values

Figure XX. Data collection procedures for each waypoint: once arrived in the exact waypoint, simultaneously the wind speed and the gound humidity were collected with the external instruments, and all the other parameters from the prototype.

5.4 DATA ELABORATION

Raw data collection

In the on-site session, the data was collected in a csv file in the form of a table where the detections were related to the GPS coordinates where they were detected.

This csv file with the collected values was then imported in Rstudio where all further calculation and elaboration were carried out based on a code we developed. The output of the code is then a .geotiff file that returns the value of the CWSI as well as the coordinates where the input values were collected: such file is then exported and elaborated in QGIS to produce the geo-referred maps of our measurements.

To create a raster file to compare with the satellite measurements carried out in the preliminary phase, each point is converted into UTM coordinates and referred to the corresponding 10x10m pixel in the grid; if two data are taken in the same pixel, the average is considered. This resolution was chosen to investigate the variability within a single satellite measure which could provide at most a 30x30 m resolution.

One further experiment was done by measuring the CWSI plant by plant (and it was then referred to a 1m resolution grid) to see how the variability changes also within our 10x10m pixel.

Once the field data are referred to their corresponding pixel, the CWSI is evaluated starting from the collected values, through the formulas mentioned in 4.1, corrected as follows.

Instead of evaluating the relative humidity (RH) from the dew temperature (Td), the sensors directly detect the RH, simplifying the formula. The wind speed, which was available at a 10m height and then corrected to the 2m value, is directly measured at 2 metres.

Another addition to the previously mentioned formulas is the initial calculation of Rn starting from the value of the UV-vis and IR power densities that the sensors detect:

$$R_n = UV_{rad} * (1 - r) + \; IR_{rad} - \; \xi_s * \; \sigma_B \; * \; T_c{}^4$$

where

$r = 0{,}19$ is the albedo,

$\xi_s = 0{,}98$ is the soil emissivity,

$\sigma_B = 5{,}67 * 10^{-8} \frac{W}{K * m^2}$ is the Stefan-Boltzmann constant,

T_c is the canopy temperature measured through the thermal camera sensor

Adjustments

During the data collection the IR sensor went in overflow causing it to display the wrong value for the long radiation.

To bypass this issue we used the data collected by the other sensors to evaluate the IR intensity, by means of Stefan-Boltzmann's law.

$$IR = \xi_a * \; \sigma_B \; * \; T_a{}^4$$

where

$\sigma_B = 5{,}67 * 10^{-8} \frac{W}{K * m^2}$

T_a is the air temperature detected,

ξ is the air emissivity evaluated starting from the vapour pressure (P_V) in the following formula, as indicated in literature (Silva et al., 2019).

$$\xi = 0.52 + 0.065 \sqrt{P_v}, \quad con \; [P_v] = \; hPa$$

Furthermore, we found that the air temperature sensor overheats easily and this causes it to overestimate the value of the temperature and overall it gives an unreliable output: where all the other environmental values increase during the day following a linear trend, it shows unrealistic oscillations.

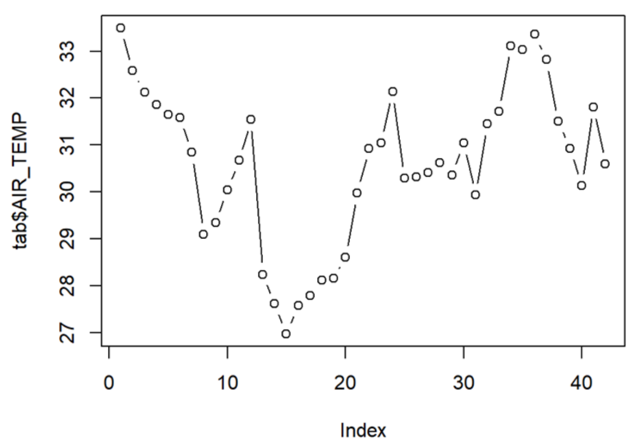


Figure XX. Air temperature trend collected in zone A.

To overcome this, we took the air temperature values referred to the hour of the day of interest from a nearby meteorological station controlled by the RAM (Rete Agrometeorologica del Piemonte).

Following these adjustments we were able to create the first iteration of the 10m resolved grid in the selected zones:

In addition to the previously determined zones, we added a small area **(FIG XX)** where we measured the CWSI each meter, collecting roughly one measurement per plant. This gave us the insight into the high variability the crop is subjected to, since even these values show very different intensities.

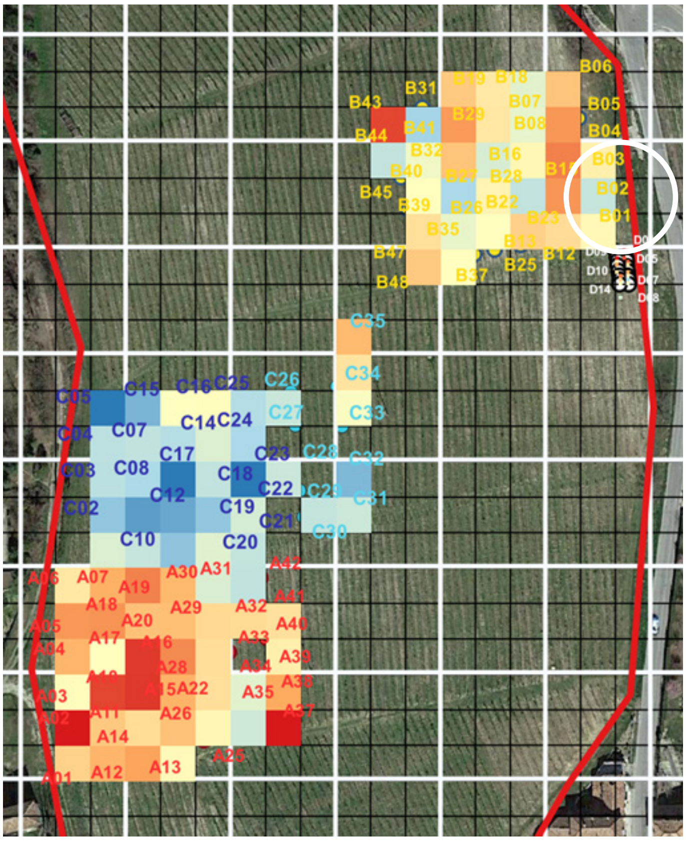


Figure XX: first data elaboration output: CWSI map across the different zones A, B, C and D.

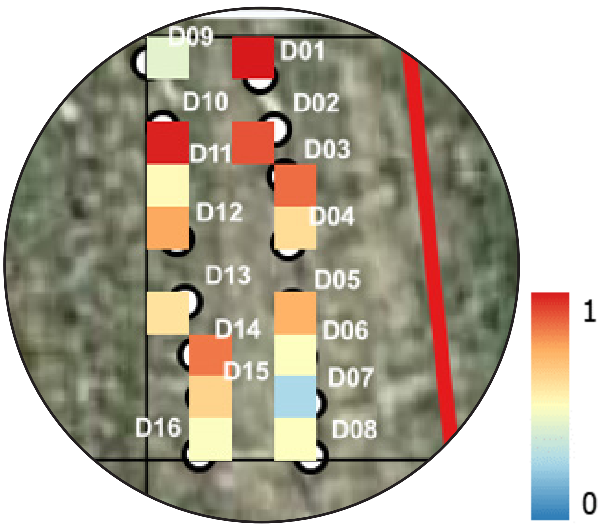


Figure XX: zoom in of the area in which measurements are taken each meter.

As mentioned in section 3.4 (fig XX a pag 34), the values of CWSI can be divided into four classes that differentiate between "no water stress" up to "critical water stress"; to provide the customer with the more direct information possible, these maps have been drawn to show exactly those classes (fig XX).

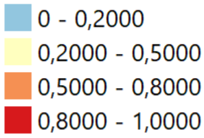


Figure XX. Final CWSI map.

Finally, to test the possibility of carrying out measurements without establishing the position beforehand, we drew the heatmap based on the exact locations instead of referring them to the pre-determined grid (Fig. XX).

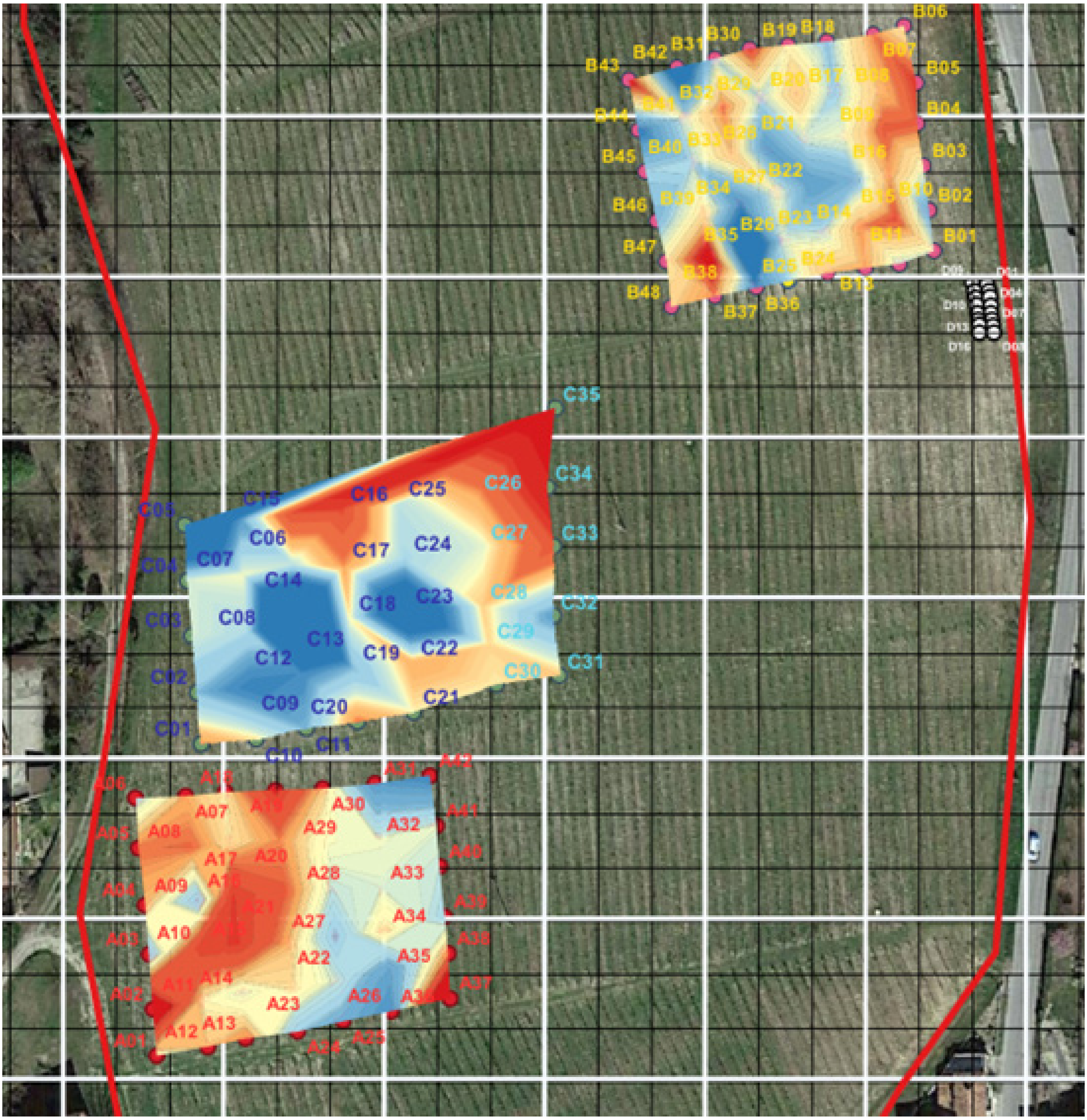


Figure XX. Heatmaps of the CWSI values

Primary data elaboration

As a first correction the wind speed, which was measured point by point with a portable anemometer, was substituted with the mean hourly value based on our measurements. This was done to overcome the intrinsic sensitivity of the instruments to instantaneous variations of the wind speed, such as local gusts and movements, when the actual water stress status of the plant is given by a more general condition. From the raw data elaboration 6 values among the 133 data points fell out of the acceptable range for the CWSI, that should span from 0 to 1.

To find the source of these discrepancies, the data values collected in situ were analysed to find possible outliers and wrong trends as was the case of the air temperature and IR sensor. Figures **XX** show the outliers in the canopy temperature measurements in zone A which did not follow the general linear trend of growth as time went on, and they perfectly correspond to the out-of-range CWSI measures. This data were corrected through interpolation and the following pictures shows that by changing these single values the CWSI is corrected.

In the B zone, instead, there were no unacceptable values of CWSI but we found a clear outlier in the UV radiation data, which was substituted with the average of the other values to return a more realistic value.

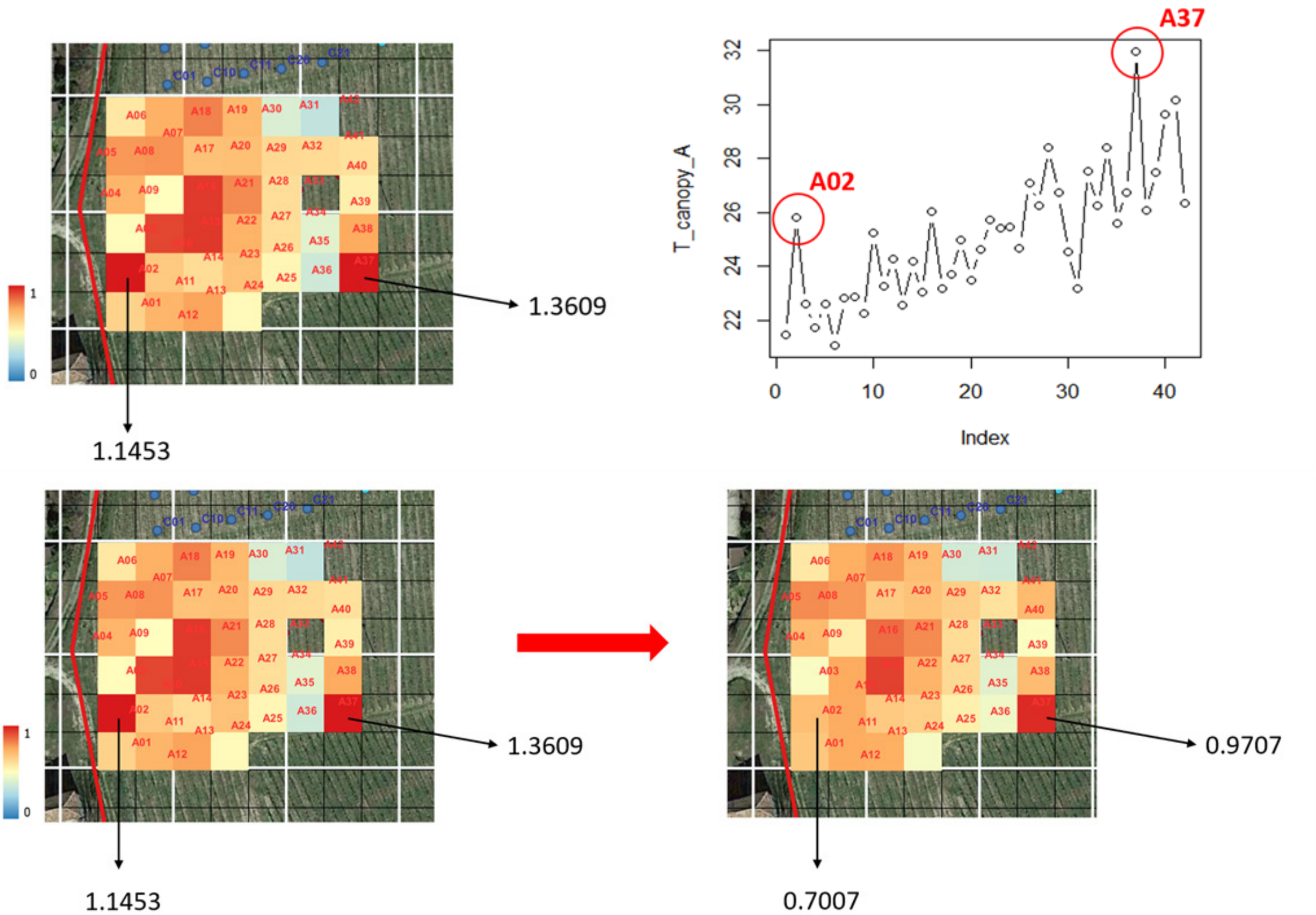


Figure xx: (On the top) CWSI with as-collected data with the unacceptable values, corresponding to the air temperature outliers in the graph on the right.
Figure xx: (On the bottom): correction applied to the map.

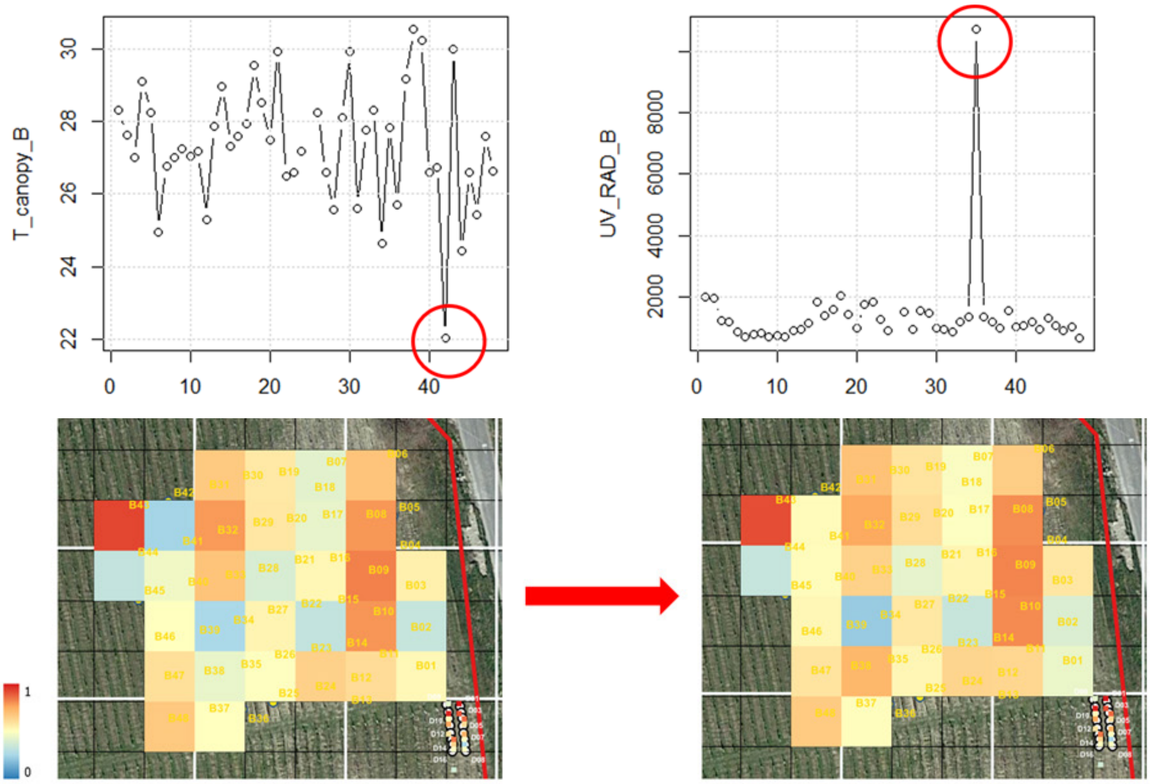


Figure xx: (On the top) outliers in the canopy temperature and UV radiation in zone B.
Figure xx: (On the bott) correction applied to the map.

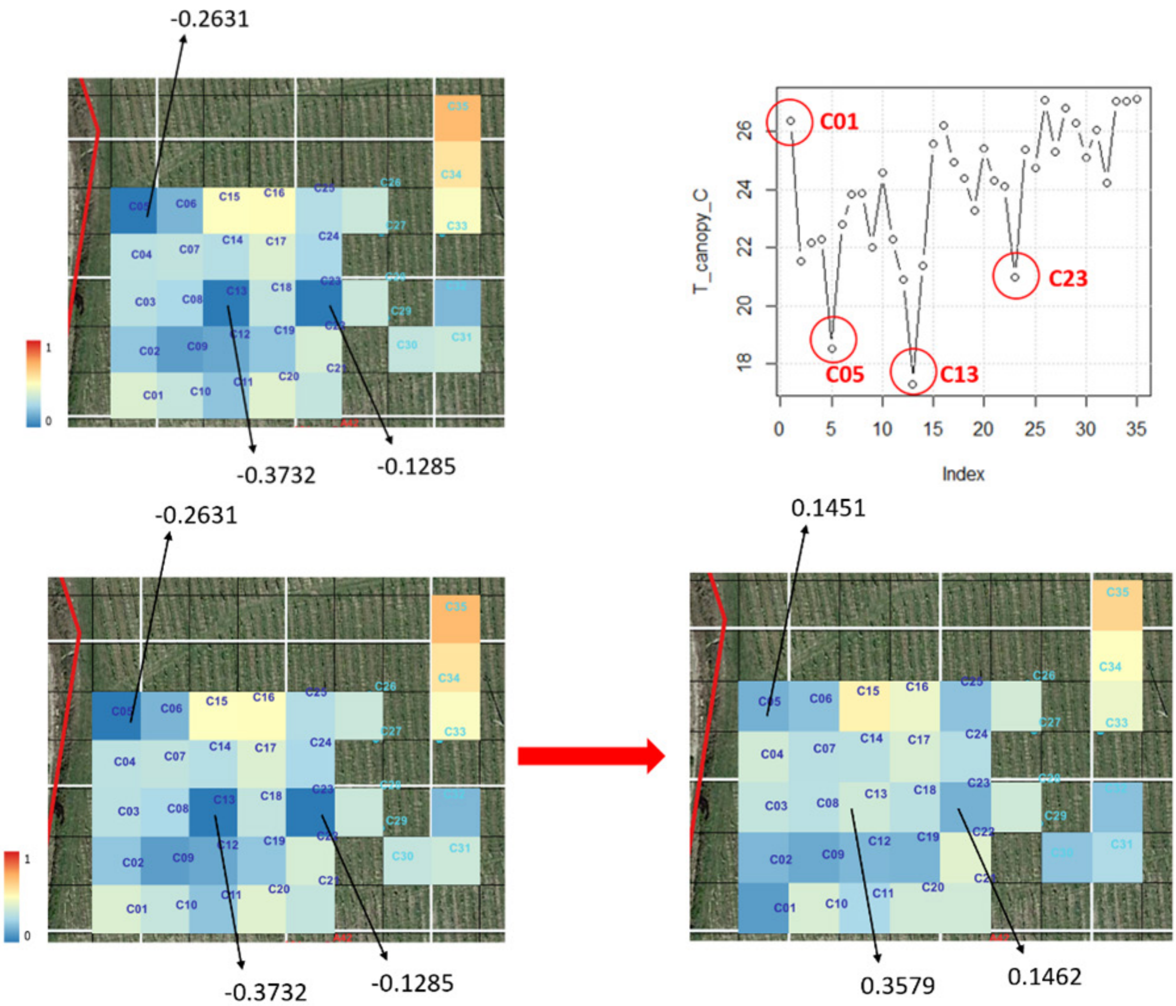


Figure xx: (On the top) CWSI with as-collected data with the unacceptable values, corresponding to the canopy temperature outliers in the graph on the right. Figure xx: (On the bottom) correction applied to the map.

Ground humidity

After this elaboration, we considered the collected data for ground humidity to see if such a simple measurement could give a first indication of the CWSI without using complex formulas and multiple sensors.

These maps show a poor correlation between the two values, since a high value of ground humidity should be related to a less critical water stress status, as is also confirmed by the correlation analysis carried out with R, which showed a correlation coefficient between the two variables of 0.34.

This poor correlation is not surprising since the ground humidity sensor detects the humidity in the first 10-15cm of the soil, whereas fruit trees such as the vine collect their nutrients deeper in soil with their roots, so it is safe to infer that they would be sensible to the entity of the humidity deeper down. Furthermore, as addressed in section 3.4, ground humidity is a variable that precedes the plant's metabolism and as such is not indicative of the plant's condition.

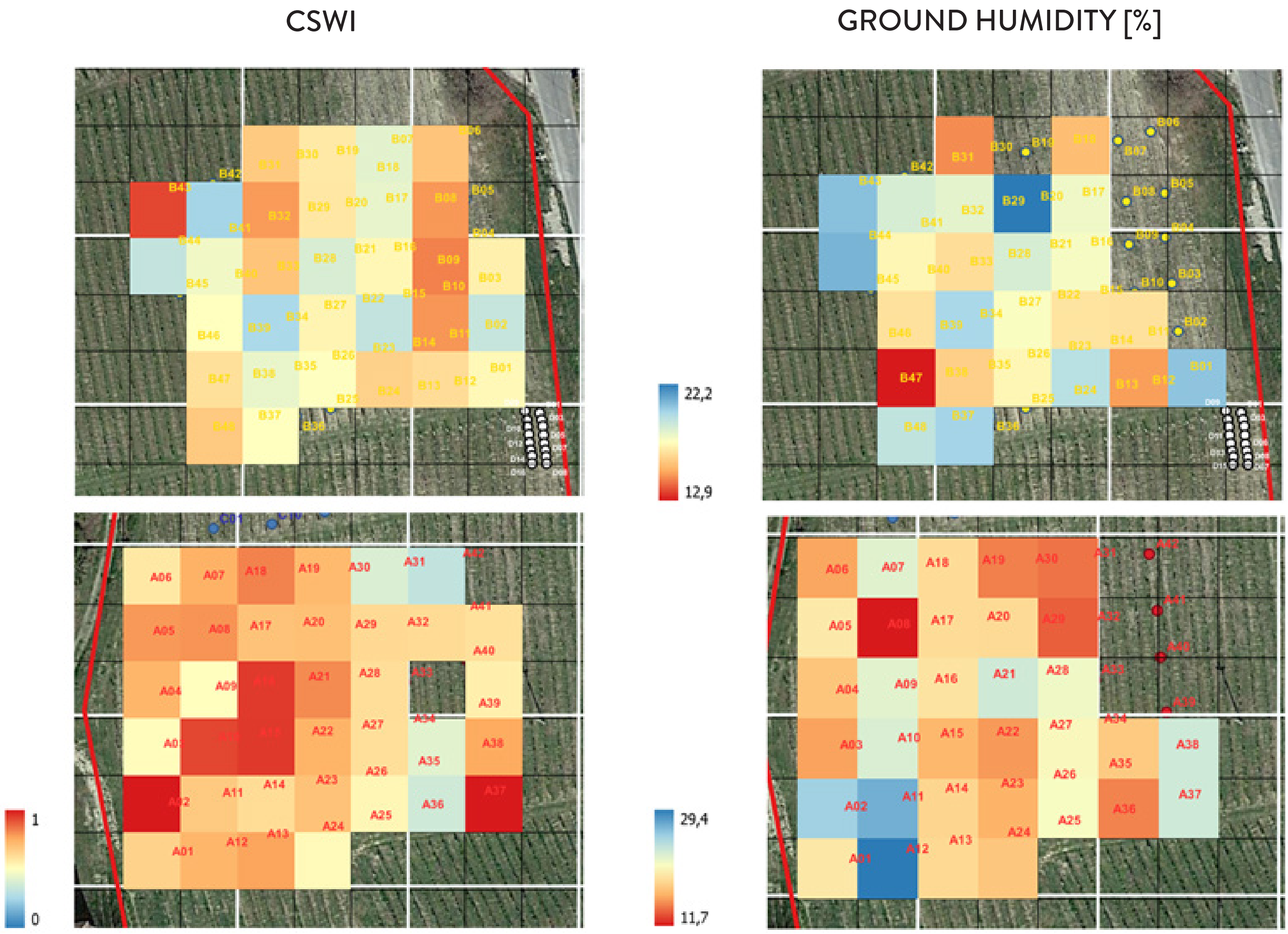


Figure XX: CWSI - ground humidy maps in comparison. Zone B on the top; zone A on the bottom.

Secondary data elaboration

After the first elaboration, a Sensitivity Analysis is carried out on the dataset we collected in situ in order to find which input data had more influence on the final CWSI value using a Global Variance Based Sensitivity Analysis [Sobol, 1993]. This method is mased on the modeling the input-output relation of the system with the following decomposition:

$$Y = f(X_1, \dots, X_d) = f_0 + \sum_{i=1}^{d} f_i(X_i) + \sum_{i<j}^{d} f_{ij}(X_i, X_j) + \cdots + f_{1,\dots,d}(X_1, \dots, X_d)$$

where all the input variables X_1, ..., X_d are modelled as independent an uniformly distributed. Under the hypothesis of orthogonality of the terms, it holds the decomposition of variance of Y as the sum of terms attributable to each input and to the interactions between them:

$$Var[Y] = \sum_{i=1}^{d} V_i + \sum_{i<j}^{d} V_{ij} + \cdots + V_{1\dots d}$$

where:

$$V_i = Var_{X_i}\left[E_{X\sim i}[Y|X_i]\right]$$

$$V_{ij} = Var_{X_{ij}}\left[E_{X\sim ij}[Y|X_i, X_j]\right] - V_i - V_j$$

and so on ($X \sim i$ means all variables but X_i). This allows to introduce the so called Sobol Indices, summing up the contribution of the variables to the variance of the output:

- First Order / Main Effect: $S_i = \frac{V_i}{Var[Y]}$

measuring the effect of X_i alone, without considering its interactions with the other variables.

- Second Order Effect: $S_{ij} = \frac{V_{ij}}{Var[Y]}$

measuring the effect of the interaction between X_i and X_j

- Total Effect: $S_{T_i} = \frac{E_{X\sim i}\left[Var_{X_i}[Y|X_{\sim i}]\right]}{Var(Y)} = 1 - \frac{Var_{X\sim i}\left[E_{X_i}[Y|X_{\sim i}]\right]}{Var(Y)}$

measuring the effect of X_i taking into account its interactions of any order with the other variables.

We compute the Sobol Indices from the collected data using the R package Sensitivity [Cran, 2022], implementing Monte Carlo estimation of Sobol Indices [Martinez, 2011]. **Figure XX s**hows the results.

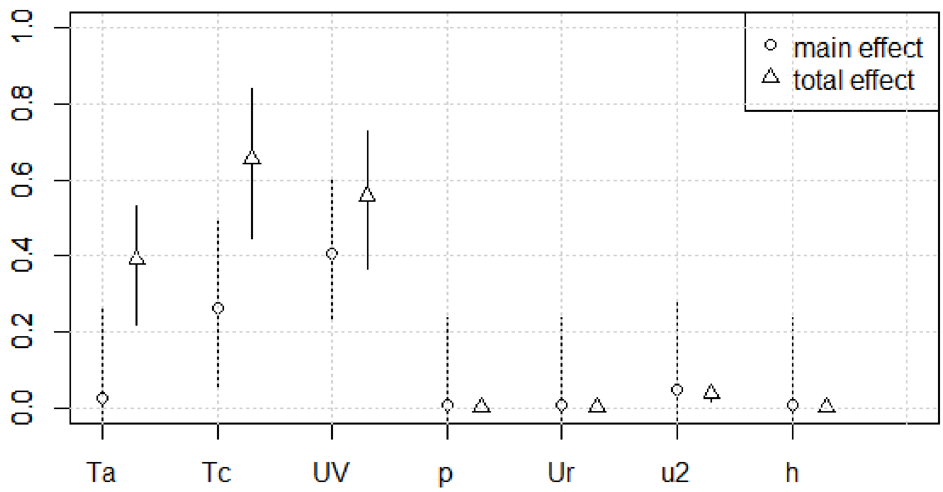


Figure XX: Sensitivity analysis, Sobol indices

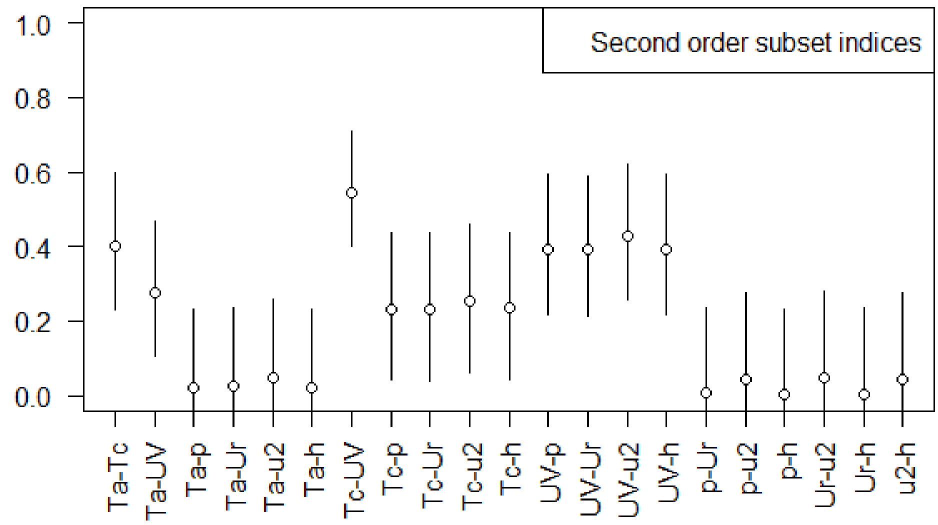


Figure XX: Sensitivity analysis, second order effects

The analysis of Total Effects points out that the most influential parameters are the Air Temperature (Ta), the UV Radiation (UV) and the Canopy Temperature (Tc). Moreover, we observe that the interaction between the variables plays an important role since the sum of Main Effects is below 1 (0.74) and the sum of the Total Effects is highly over 1 (1.64). In particular, from the Second Order Effects we note that Ta, Tc and UV strongly interact one with the other although UV is strongly correlated with the other variables too.

This analysis is useful to choose a path for further implementation of our system, from prototype to market. It clearly shows which input data are more important and so which sensors are the best to invest in to improve their reliability and lower their uncertainty (air and canopy temperature, UV radiation).

Another possible implementation, along with improving the most influential sensors, would be to differentiate between mobile and static sensors, as already discussed in section 4.2. Moving sensors are the ones whose value is specific to the vine we are analysing, so for sure Canopy Temperature; fixed sensors could be the ones that detect a variable that does not change within the field or a specific area, such as radiation which is uniform over such a small area.

In other words, with these considerations, we find where we can simplify the design of the prototype without compromising the validity of the results, and where we have to improve our design to increase reliability.

5.5 FROM THE PROTOTYPE TO FINAL SYSTEM

The in situ testing has been fundamental to highlight some criticalities of this first version of the design as well as the features that can be changed and improved to move forward. The ensuing data elaboration with the sensitivity analysis has helped to discriminate between the climatic variables that could be averaged over a certain area without compromising the reliability of the result and the ones that instead need to be more precise.

All these outputs are the key points onto which the final design choice outlined in section 4.2 is based on: a network of both stationary and moving sensors. This final choice enables us to lessen the payload on the drone, hence improving its battery life, and to decrease the number of single quantities to be detected for each plant, thus decreasing the residence time for each measurement, while keeping the reliability and resolution that are the key features of our system. The fixed sensors would also be less prone to damaging and overheating, reducing maintenance costs.

Possible improvements that arise from the data collection session include investing in a more performing thermal camera that would capture the image of a whole plant and then, through an image vision software in the data elaboration phase, find the canopy temperature. This is interesting because it would overcome the criticality of the positioning of the camera at a short distance away from a leaf while also making sure it does not shadow the area of monitoring compromising the measurement.

Then, to move to full automation, the code could be implemented to find the data points that fall out of the [0,1] CWSI range and automatically correct the values if they are related to outliers in the raw data. Right now, between the detection and the output maps there is an extensive manual data elaboration carried out through a trial-and-error strategy. The procedure is fundamental in the developing stage to make sure that the code is working and that the corrections on the outliers make sense, but it would be a hindrance when the product is used by the customer. The last link that is still not present is the path of the collected data from the system to the computer where the elaboration takes place, which now happens manually through the cloud because the Raspberry Pi is connected to the internet.

The final AIS4SIA system that we propose follows exactly the steps that are explained in this report.

1. An initial preliminary analysis of the crop's recent history is carried out through the correlation between satellite images and the production to check if the regression model works and if it can be tailored to the specific situation. In this way, the customer can clearly see that acting on the CWSI indeed translates into a change in production.

2. The actual system is deployed installing the stationary weather stations in statistically relevant points of the field and acquiring the number of drones needed according to the surface to be monitored.

3. Daily measurements are carried out so that the crop's status monitoring is continuously updated and is easily controlled through the maps showing the geospatial heatmap of CWSI throughout the field.

4. Farmers can focus their attention solely on the red zones where the CWSI value shows critical water stress, possibly inspecting them personally to assess the situation and intervening by giving more water just in those areas.

5. Thanks to the continuous monitoring and precise interventions, in the following days and weeks the farmers can check if those red zones go back into the security range of water stress, taking advantage of the positive feedback loop thus created.

6.
BUSINESS MODEL

The following chapter explains the strategy that will be adopted to enter the market. This strategy is divided into two parts: the first one, product development, explains the necessary steps to conclude the development of the system, while the second, product deployment, illustrates how to actually enter the market.

6.1 VALUE PROPOSITION: DATA MONITORING SYSTEM

The product delivers value as a data monitoring and information-based decision-making tool. The system is therefore based on its capacity of collecting, elaborating, retrieving, and displaying high-granularity site data regarding crops' health state. This data is used by the customers to take informed decision regarding water usage in their land.

Minimizing water waste

The current state of the art is that water is spread uniformly in the fields with no regards to the actual crops' different water needs. Hence, a big amount of water is wasted to wet well-hydrated plants. The monitoring tool inform the farm's personnel on how to better distribute water into the field. The system is indeed capable of capturing the real hydration condition of a crops, thus creating a very informative map of where there is the need of more water distribution.

Resilience to climate change and increasing number of droughts

This information is particularly important considering the climatic context that the world is currently facing. Climate change is indeed setting a wide range of new challenges. In all Southern Europe rising temperature are also followed by an unpreceded number of rough droughts, which are getting both more severe and more frequent. In this particular environmental condition, water management is getting more and more important and will be a crucial issue for the very survival of many fields in the southern part of the region. Water will thus become a rare resource and managing its use will be a key economical aspect for farmer. The AIS4SIA system will provide farmers with a tool to defend themselves against the increasingly challenging environment they are facing. It can indeed be used to cut water waste and make the water stress level homogeneous across the field, irrigating only the needing zones.

Increasing productivity and quality uniformity

As discussed previously, there is some statistical evidence of a relation between the hydration level and the productivity. Hence, by controlling water distribution and the consequent effects on the crops water stress, it is possible to optimize the field's yield.

The data collected in the fields will then expand the dataset used to study the relation between the production and the crop's water stress. This process will allow for a continuous improvement of the regressive model, achieving over time a greater capacity of predicting the crop's production from the data.

6.2 DEVELOPMENT STRATEGY

Phase 1: product development

Before placing the product on the market, a further development phase is needed to address and develop some technical issues. Therefore, the main activities will be:
- developing the prototype;
- collect data with in-site testing;
- set up the commercial contracts with the supplier of the hardware needed for the system.

During this period the AIS4SIA project will be self funded, to avoid the risk of losing some of the managerial control due to the participation of external stakeholders. Considering this strategy, it is crucial to keep an agile process, avoiding waste and stressing flexibility. This means that the three processes need to be carried out as cheaply as possible. This is possible considering that the prototype development has already started and that the component can be purchased quite cheaply. Therefore, the only costs of the overall product development are the ones connected with building the first fully working prototype. The timing for the product development phase should be as short as possible, in order to enter the market as soon as possible. This is crucial to get an advantage respect to future competitors and to limit the lag with the existing one.

Phase 2: product deployment

Customer side

The customers will be mainly large grape producers, as these are the ones mostly interested in optimization tools. Moreover, large producers are more exposed to potential losses compared to small ones as they have bigger investments in the production. Thus, relocating North their crops to avoid droughts, will be more expensive. Supplying some big businesses with the system will be a great showcase for the product, increasing the market trust on it. Thanks to that it will be possible to further penetrate the market with small high-quality wine makers. They will be in the system as they are often linked to their territories as the local regulation on wine making (such as the DOCG denomination in Italy or the Cru denomination in France) often is very strict on the territories in which a certain product can be produced. Therefore, producers cannot relocate their businesses and are very interested in obtaining a tool to fight the changing climate. However, these kinds of producers are often more jealous of their traditions and not so inclined to accept technologies in the vineyard. Therefore, it is better to start with bigger and profit-oriented companies and widening the customer segment only once the market will be established and the climate change will be more evident. Having few bigger customers will also allow us to focus deeply on the relationships with each of them. It will therefore be possible to have a close relationship with the customers, with common face to face visits and close assistance to verify the quality of the service. This approach will boost the market trust towards the AIS4SIA system, thus helping with the following market penetration on smaller businesses. Once the number of the clients will increase, the customer relationship will gradually shift to an online based assistance in order to lower costs. In the first phase, the main channel will be meetings in person to directly assist the client with issues with the use of the system and the interpretation of the data. However, the channel used to deliver the data about the crops water stress will be an application for mobile devices and a client dedicated website for desktops and laptops. Helping clients interpreting the information will facilitate the understanding of the system in the during the early stages of the market penetration process.

Implementation strategy (activities partners and resources)

To make the system work, three main physical resources will be needed: the drones, the distributed sensors and the data storage system. All these three resources will need to be supplied by external contractors. The supply chain will therefore be horizontal to decrease the capital need in the early stage of the product deployment in the market. This strategy allows to link the costs to the unit sold, increasing the variable cost. The key activities in the product development phase, apart from the prototype development, will be contracting with the supplier to ensure the supply chain needed for our product. This is a very important activity as it will allow to control the cost structure of the next phase. During the late stage of the prototyping phase, the team will contact some potential clients to illustrate the capability of the AIS4SIA system to attract them. During the market penetration phase the key activities will mainly be focused on the implementation of the system, which will include: installation of the system, maintenance of both the hardware and the software and technical consulting to better understand the data. All these activities will be performed by the team itself and not outsourced. The production of the drones and of the distributed sensors units will instead be outsourced.

Cost and revenues

In the prototyping stage the costs will be only connected to the acquisition of the parts needed to build the prototype. Outsourcing the construction of the drones and of the distributed sensors will decrease the fixed costs and, thus, the initial capital the project needs. The costs will indeed be due to buying the components of the system. The only fixed costs will be the salary of the team. This will allow linking the costs to the revenues, which is helpful in the starting phase of the market expansion. The revenues will be composed of a one-time payment for the acquisition and installation of the system and of a monthly payment for having the app. This strategy allows to reduce the risk of investing a lot of capital in a manufacturing plant in an early stage of the market development.

Conclusion

The overall process needs to start through a product development phase to further refine the system and design some technological issues that at the moment have not been addressed. This process will be carried out though an agile approach using private funding to avoid distributing managerial power too early. Once the final product has been developed, it will enter the market as a tool to mitigate water waste in grape fields. It will be composed of an application that provide real time data about the local hydration state of the field. The system will be sold with an upfront payment to cover the drone and distributed sensors costs and a monthly payment that will provide the large part of the profit. Moreover, the company will provide assistance and maintenance over time.

7.
CONCLUSIONS

7.1 MAIN FINDINGS OF THE PROJECT

Offering a monitoring system to optimize resource consumption and improve the quality and the quantity of the production of a crop field are the main goals of the solution we offer: a spread and interconnected network of sensors that can inspect almost in real time the conditions of the plants, with high resolution and reliability.

Vineyards are a perfect target of study and application for AIS4SIA system because they need specific conditions for having a rich yet balanced harvest regarding the organoleptic properties of the wine while assuring high levels of productivity. In fact, variations of temperature, solar irradiation, water, and humidity out of the ideal ranges could dramatically impact the final results.

The extensive monitoring is achieved through climatic data detection by means of both fixed and moving sensors, respectively mounted on weather stations and on drones. Such atmospheric data are exploited to evaluate the Crop Water Stress Index (CWSI), assessing the health of different regions of the field. The focus on CWSI is dictated by the current trend of climate change, especially in temperate regions where vine culture is extensively diffused like Northern Italy and France. Here desertification trends are bringing about hotter and drier summers so that, in the following years, it is expected to be fundamental to equip crops with irrigation system balancing the lack of rainfalls and keeping the crop in the optimal condition of Water Stress.

The system provides to the vineyard owner with the added value of precise information about the crop's health variation in time and in space with a resolution and precision much higher than the one a human operator could achieve manually, even the most expert agronomist. Thanks to its ease of use and strict connection to the environment, the solution could have a beneficial impact on the know-how exchange of old and young generations of farmers and technological penetration in this traditional economical sector.

In line with our stakeholders' requirements, AIS4SIA solution is not invasive at all, as it consists of fixed weather stations (already spread in agriculture) and moving drones not requiring the alteration of vineyard structure and that do not obstruct the cultivation operations. Moreover, it is adaptable to a larger IoT network, a requirement that could become crucial in the next years with the digitalization of the agricultural sector.

The features of the system have not only been designed and analyzed from a contextual and theoretical point of view. Indeed, a preliminary analysis through satellite data allowed us to elaborate a first statistical model correlating the water stress index during the year with the final productivity, showing that it is possible to infer useful information from this quantity. Then, a prototype of the solution has been assembled to test its design and effectiveness with an on-field data collection session. On the one hand, with the hands-on experience, the advantages and disadvantages of the design choices have emerged and have offered useful hints to improve the solutions and show new directions of development. On the other hand, the results of the data collection and elaboration have shown the potentialities of the system for the spatial resolution and precision that it achieves, outperforming both human eye and satellite monitoring.

7.2 POSSIBLE IMPLEMENTATIONS

Navigation system

As emerged from our research and the application of it, through the prototype we developed and the study we conducted, the first implementation to be made is the concretization of the navigation system - in terms of codes-, sensors and devices to be implemented on a drone.

Indeed, some issues like the weight of the components, the requirements of the sensors during the data collection session, the atmospheric conditions (weather, temperature, wind, light etc) and the vineyard itself (how the fixed structures are composed, how it is morphologically constituted and geographically distributed, where the fields are located one with respect to the other) have to be highly considered in the design of the support for the on field navigation. Mainly for the reliability of the results, but for the general sustainability of the system itself, which has to be efficient, providing an accurate output from the data collection and in a convenient ratio between the time necessary for doing the operations, the autonomy of the batteries, the space covered and the variable atmospheric conditions. Even though we consider the drone the best choice for the data acquisition method and the agility of the operations, in case AIS4SIA would not remain confined just to the vineyards but would, indeed, expand to fruits crops too, also a rover could be notable. In fact, mainly on flat lands, it would be a cheaper solution and maybe even most efficient, having more margins in terms of weight regarding to the batteries (and so the autonomy but the equipment installed on it too).

Irrigation system

The second logical and natural implementation of the AIS4SIA system is an operative connection with an actuator network that could act upon the findings of the data analysis: that is, the connection with the irrigation system that could deploy water selectively either by improving an already existing drip irrigation network or by using a completely new way to disperse water in the field, such as employing swarms of drones that could represent a new generation rain irrigation system. This last option could represent a highly disruptive technology and could complete the full hybridisation with robotics of a system like AIS4SIA: the same technology detects data and provides a solution according to the output of the data analysis. Improving an already existing and more standard drip technology system – with valves that divide the network into sectors -, instead, could mean the least impact possible on the crop, together with the smallest investment from the farmer. In any case, our product puts data analysis as the core of our project, the main value we can provide is the insight into the crop's actual health and status, in real time. Such system is ready to be integrated in an IoT network of already existing actuators, which is a growing field of research in the context of Smart Agriculture.

Adopt and adapt

It is important to highlight as well that, even though we focused solely on vineyards, it should be clear that our solution can be applied to all kinds of crops with the same goal, provided a good preliminary analysis is carried out. We believe that, even though the AIS4SIA system is optimized in one direction for the moment, different versions of the same basic system – that is, different sensors tailored to the specific crop, different actuating system with which these sensors are linked, etc – can be easily created to suit the needs of the different plants. It would be, of course, necessary to root the project in the requirements settled by the crop and around its lifecycle - as we did for vineyards (see section 4.1) - to adapt the system for other fruit trees or even other kinds of crops such as maize or strawberries. We strongly believe that this represents an interesting possibility and could very well be a necessary development in the field of agriculture for the next years.

7.3 FUTURE PERSPECTIVES

The importance of research and testing in the direction we are going also lies in the intrinsic feedback loop it creates: by ensuring a continuous monitoring that gives us real time information, we can inform the decision of the vineyard owner about the possible intervention on the crop itself and we can actually see in the data collected after that, if that intervention has proven useful or not.

For instance, it is possible that the CWSI map shows a more stressed aera, so the first working hypothesis is to increase the amount of water that reaches those vines, but in the following month no change in the CWSI occurs: it is possible that those plants are stressed for reasons other than lack of water, water is enough but maybe the soil drains too much, or there are some other external agents that are harmful to the plant.

With time and continuous investment, when a wider database has been created by collecting data from different case studies across different regions and along a longer period, we could improve our awareness of the plant's metabolism, in terms of how it reacts to different external conditions and stimuli.

Moreover, further consideration could rise by cross-referencing the data coming from different areas, which could show either strong differences or similarities therefore providing insight into the vine's behaviour. In fact, for each spot where AIS4SIA system is located, a deep and precise picture of the field and of the weather conditions is available; and it is also correlated with the productivity and the historical analysis.

The wide reach of this project could set the basis for another, higher and interconnected ecosystem for more in-depth studies about the delicate correlation between climate and agriculture, extracting maps, indexes, trends to raise flags and signals to keep the pace with the faster changes to nature's planetary equilibrium.

8.
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TECHNICAL DATASHEETS

49. BME280 datasheet

50. BT-100WM datasheet

51. DHT22 datasheet

52. Garmin GPS eTrex® Touch 35 datasheet

53. GY-NEO6MV2 NEO-6M GPS datasheet

54. HH2 datasheet

55. LTR390 datasheet

56. MLX90614 - GY906 datasheet

57. TSL2591 datasheet

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9. APPENDIX

9.1 APPENDIX 1: BUDGET

Supporting document N.	Cost type (1)	Date dd/mm/aa (2)	Type of document (3)	Cost Description (4)	Amount in € (5)	
1	O	06/05/22	Invoice	Raspberry Pi 4 model	214,99	
2	O	06/05/22	Invoice	Pressure and humidity sensor (BME280) - mounted on Raspberry	39,98	
3	O	06/05/22	Invoice	Temperature and humidity sensor (DHT22/AM2302) - mounted on Raspberry	8,49	
4	O	17/05/22	Invoice	Surface temperature sensor (thermal camera, MLX90614) - mounted on Raspberry	47,58	
5	O	07/05/22	Invoice	Ultraviolet radiation sensor (LTR390-UV) - mounted on Raspberry	13,40	
6	O	07/05/22	Invoice	Ambient light sensor (TSL25911FN) - mounted on Raspberry	14,99	
7	O	07/05/22	Invoice	Wind sensor (Btmeter BT)	39,29	
8	O	07/05/22	Invoice	GPS (GPS6MV2) - mounted on Raspberry	9,99	
9	O	07/05/22	Invoice	component	12,99	
10	O	07/05/22	Invoice	Cables (ELEGOO) - Raspberry component	8,48	
11	O	07/05/22	Invoice	component	9,99	
12	O	07/05/22	Invoice	Lever switch (HUAYAO) - Raspberry component	9,99	
13	O	07/05/22	Invoice	Touch display	55,99	
14	O	07/05/22	Invoice	Block plugs (Tnisesm) - Raspberry component	10,99	
15	O	07/05/22	Invoice	Converter (Adafruit MCP 3008) - Raspberry component	59,97	
16	O	07/05/22	Invoice	18650 UPS & Power Management Board - Raspberry component	55,99	
17	O	24/05/22	Invoice	Heatsink - Raspberry component	5,99	
18	O	24/05/22	Invoice	Raspberry Pi 4 model (substitution)	175,99	
19	O	25/06/22	Receipt	Batteries (2x)	50,00	
20	O	26/06/22	Receipt	Batteries (2x)	36,00	
21	O	01/06/22	Invoice	Touch display (substitution)	55,99	
22	O	01/06/22	Invoice	External battery	25,46	
					Total	962,53

Total Budget	1.090,13

9.2 APPENDIX 2: TEAM ACTORS AND ORGANIZATION

The project started with the kick-off during the ASP week in Turin in July 2021. During this session the overall market was explored and the first ideas on the problem statement were defined. In particular, it was chosen to focus on developing a system to protect crops during extreme meteorological events such as hailstorms. The following months were used to discuss this idea, trying to come up with a reasonable solution. Moreover, the team dived into the agricultural sector to better understand the context. During this period the team members worked in parallel, having each a specific issue to research for. Moreover, the team had a call once a week to discuss the findings and to brainstorm about the overall system.

At the end of this period, it was chosen to shift the focus of the project to water management as the research performed indicated that as a better issue. Then, a couple of months were used to better define the scope of the project. To do this the team agreed on meeting each week to brainstorm together. Thanks to this session it was possible to develop a plan on how to complete the project. Considering the plan, the team was divided into two sub team, one working on the data analysis and one working on the hardware of the system.

Once the preliminary analysis was concluded, the team started working on the prototype. To do that, two sub-team were created. One working on the formulas and on the software code needed to extract the CWSI from the raw data collected, and the other working on the building of the prototype, including the software needed to take the measurement in the field.

The prototype was tested during a visit to a farmer, conducted by 4 members of the team. To carry out the missing activities, the team was again divided into two parts. The first sub-team analysed the data collected and created the CWSI visualization maps. The second team started working on writing the final report. Once the first team concluded its task it joined the second one to conclude the report.