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A geospatial decision support system for supporting quality viticulture at the landscape scale

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ABSTRACT

The world of viticulture connected to wine making has become a very important activity in many inland areas permitting both the generation of important income and the sustaining of agriculture systems.

Recent progress in both crop modeling and Decision Support Systems (DSS) applied to viticulture promises important changes that combine both high quality production and environmental sustainability. However, most of this progress is only addressed at the farm level and does not challenge the viticulture landscape, which is a key issue when facing DOC, DOCG areas, wine growers' cooperatives and consortiums and strategic viticulture planning.

Thus, this paper aims to demonstrate that a new type of DSS, which is developed on a Geospatial Cyberinfrastructure (GCI) platform, may provide an important web-based operational tool for high quality viticulture as it connects farm and landscape levels better.

The GCI platform supports acquisition, management, processing of both static and dynamic data (e.g. pedological, daily climatic, and vineyard distribution), data visualization, and on-the-fly computer applications in order to perform simulation modeling (e.g. grapevine water stress, evaluation of ecosystem services, etc.). These are all potentially accessible via the Web.

This is possible thanks to the implementation of a set of modeling clusters that is strongly rooted in soil-plant-atmosphere and physically based simulation modeling.

The DSS tool, applied to an area of 20,000 ha in Southern Italy, is designed to address viticulture planning and management by providing operational support for farmers, farmer associations and decision makers involved in the viticulture landscape.

Output of the system includes viticulture planning and management scenario analysis, maps and evaluation of potential and current plant water stress.

The tool will also be demonstrated through a short selection of practical case studies.

1. Introduction

1.1. High quality viticulture towards high quality wine

All around the world, viticulture connected to wine making has today become a very important activity for both generating income and trade (OIV, 2016a) and sustaining agriculture.

This is due to consumers, who have a very important role in high quality viticulture since they increasingly associate the quality of wines with the quality of their geographical origin and the sustainability of production (Warner, 2007). Addressing this viticulture-terroir relationship can be a rather difficult task since vineyard and grape production is highly affected by many problems such as new or recruiting plant diseases (e.g. Kiss et al., 2016; OIV, 2016b). Nevertheless, in response to consumer concerns for the environment, an increasing number of studies have been published since the 90s with the aim of both reducing the environmental impact of viticulture and improving its efficiency (Hill et al., 1999; Rivera-Ferre et al., 2013).

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In this respect, progress in modelling and in its implementation in the Decision Support Systems (DSS) applied to viticulture promises to bring important changes to the combining of high quality production and environmental sustainability.

To be more precise, crop models applied to viticulture are typically classified as either empirical/statistical or dynamic (Costa et al., 2015; Moriondo et al., 2015).

Empirical models – which exploit the statistical relationship between environmental parameters- are computationally simple (e.g. regressions), and often intuitive and widely accepted. These include those models based on climate data (e.g. Santos et al., 2011; Fraga et al., 2014), those based on remotely sensed indices (e.g. Rodriguez et al., 2004; Gouveia et al., 2009; Cunha et al., 2010) which aim to identify phenology phases (e.g. Winkler et al., 1975; Parker et al., 2011) and also, most importantly, those which address risks from insects and plant diseases (Calonnec et al., 2008; Caffarra et al., 2012).

These models, although highly used (Costa et al., 2015), have various weak points (e.g. Shin et al., 2010) such as the high level of calibration required (when applied to a new environment) and, most importantly, they do not address the non-linear relationships between plant and environmental factors. For instance, they have difficulty in addressing water resource management, which is a key dynamic issue in viticulture, and in modelling crop-soil water balance and crop yield. In fact, growth and development of grapevines, grape yield and quality build-up are known to be closely related to water constraints (Gómez-del-Campo et al., 2002; Gu et al., 2004).

Dynamic models, on the other hand, attempt to solve these non-linear relationships and allow greater generalization of crop growth processes and, consequently, a better adaptation to new environments and an overall much better performance. Generally, dynamic models simulate plant growth development on a daily basis and consider site features at specific locations. Moreover, they need cropping parameters, climate data, soil data and farm management data. Highly specialized dynamic models have been used in viticulture to simulate the seasonal dynamics of vineyard water availability (e.g. Lebon et al., 2003), nitrogen dynamics (VineLogic, Nendel and Kersebaum, 2004; Walker et al., 2005), salinity (SWAP, Ben-Asher et al., 2006), carbon balance (Poni et al., 2006), the timing of vine phenological phases (Godwin et al., 2002) and expected grape quality, yield and phenology under climate change (SWAP, Bonfante et al., 2015; Fraga et al., 2016).

Thus, starting from these specialized models, new more integrated modelling approaches have been developed to address holistic vineyard management. These were designed to maintain a high detail modelling of plant growth processes, but within the framework of larger vineyard integrated management. Among the most important of the models is certainly STICS (Brisson et al., 2003), developed at INRA, which was adapted for grapevines and evaluated for many vineyards throughout France, Chile (Garcia De Cortázar, 2006; Valdes-Gomez et al., 2009) and Portugal (Fraga et al., 2015).

In recent years, further development has been achieved by implementing some of these models in truly operational DSS for vine management. Among these are MoDeM_IVM DSS (Cola et al., 2014) and Vite.net (Rossi et al., 2014).

Currently a proper update on these agricultural-based DSS is lacking (Manos et al., 2004) since a good review (ENDURE, 2010) is only provided for the plant protection DSS. In general terms however, all these viticulture-DSS have a similar basic architecture where the farmer enters, via web, some site-specific information (e.g. soil management) for each vineyard decision unit (e.g. Rossi et al., 2014), while other data are obtained automatically (often in real time) by sensors positioned on the farm (e.g. http://www.adviclim.eu/project-2/). All this information is then processed by a server that provides output to the farmer to support his vineyard management (e.g. expected grape quality/quantity, pest management). Several of these systems – built within the framework of research projects – are now marketed as commercial services offered to single farms.

Indeed, these DSS systems have been built, maintained, and evolved at the farm level, where the farm is typically considered an individual point in space or, in the case of very large viticulture farms, "a small set" of individual points.

While fully recognizing the great importance of these farm approaches, it is also important to stress that these systems do not adapt easily to landscape complexity, which has its own space-time variability. Indeed, climate, soils and their properties (as well as many other environmental factors) vary continuously in space.

This evidence becomes a problem when considering that many wine-growing settings in many countries refer to consortium, associations and wine growers' cooperatives, legal bodies devoted to the production of "Quality Wines Produced in Specified Regions" (QWpsr), such as the Italian DOC and DOCG areas. These administrative (and functional) entities typically govern large spatially-continuous territories. In these cases, if the farm DSS approach were applied, it would be necessary to engineer an entire viticulture landscape with sensors to provide input parameters to the "n" farm-based DSS. It is self-evident that this would be very demanding and possibly not the best solution when dealing with large areas (e.g. viticulture district or landscape).

Moreover, it is also clear that today's high-quality viticulture is asked to provide multifunctional results including proper ecosystem services (e.g. Brunori et al., 2016) and even support for wine tourism (e.g. Sánchez, 2010). However, this multifunctionality needs to be developed into a coherent landscape framework rather than at an isolated farm level.

This landscape argument gains further importance when we consider strategic viticulture planning (Costa et al., 2015) and then long term scenario (e.g. climate change) where the landscape level becomes a prerequisite.

Therefore we here claim that when dealing with viticulture planning and management there is somehow a disconnection between the large significant advances in research achieved at farm level and the research progress made at landscape level, such as those dealing with terroir analysis (Bonfante et al., 2011; Bramley et al., 2011; Priori et al., 2013).

Therefore, it seems evident that it is important to better connect and/or combine farm and landscape levels if we are seeking sustainable and high-quality viticulture planning and management. We also believe that this must be done through the development of operational DSS tools for end-users and stakeholders, which address the complexity of the physical landscape in the viticulture framework.

1.2. Aims

Considering the above framework, the general aim of this paper is to demonstrate that a new type of DSS developed on a Geospatial Cyberinfrastructure (GCI) platform can provide a valuable web-based operational tool to manage high quality viticulture at the landscape level, but with a demonstration of potential deliveries at the farm level (e.g. Cadastral ID). The platform has also been designed to encourage use by the multiuser community (from farmers, to wine associations and public bodies).

Here, we shall describe a viticulture Web tool developed within the framework of the SOILCONSWEB EU project (Terribile et al., 2015). The tool, named *GeoVit* and applied to an area of 20,000 ha in the South of Italy, is designed to address sustainable viticulture planning and management by providing operational support for farmers, farmer associations and decision makers involved in addressing viticulture at the landscape level. The global description of the SOILCONSWEB multidisciplinary infrastructure is given in Terribile et al. (2015), while here insights, specific implementations and results concerning the tool for viticulture application are reported. The tool will also be demonstrated, through a short selection of applicative case studies.

2. Materials and methods

2.1. The study site

The viticulture tool reported here is a component of a more general multipurpose Geospatial Decision Support System (S-DSS) named SOILCONSWEB, currently in use (www.landconsulting-web.eu) and fully active within the administrative boundaries of Valle Telesina (South Italy, Benevento) (Fig. 1).

The study area has a very complex landscape with great soil, land use and climate spatial variability. It extends over about 20,000 ha and encompasses 13 municipalities. The territory is suitable for the production of high quality wines and olive oil. Valle Telesina is part of the larger basin of the Calore river, which crosses the whole area in a West-East direction. The area includes 60 Soil Typological Units including Silandic, Melanic, Mollic, Eutrosilic, Vitric Andosols, Haplic and Vertic Calcisols, Vertic Leptic Cambisol, Haplic Regosol, Vitric Phaeozem, Vitric Luvisol, Calcic Kastanozem, Vitric Kastanozem and Fluvic Cambisol (IUSS Working Group WRB, 2014). Soil types are spatially aggregated into 47 Soil Mapping Units.

2.2. The geospatial cyber-infrastructure

Through SOILCONSWEB, users are able to interact with digital maps and geospatial data directly via web in real, or quasi-real, time. SOILCONSWEB belongs to the family of Geospatial Cyber-Infrastructures (GCI), which have the use of free open-source geospatial libraries and programs. GCI platforms (Yang et al., 2010) can support acquisition, storage, management and integration of both static (e.g. pedology, geology) and dynamic data (e.g. daily climate, vineyard distribution), data visualization, and on-the-fly computer applications (such as those enabling simulation modelling for the determination of vine water stress), all potentially accessible via the Web.

Details of the functionalities and methodological issues are provided in Terribile et al., 2015. Basically, SOILCONSWEB has a 3-tier structure in which data management, data processing for the applications and data presentation are separate processes. The data management tier consists of a database in which the data are stored and retrieved in such a way as to keep information neutral and independent of application servers. The processing tier controls the application's functionality by performing detailed processing data, and the presentation tier is used for displaying the information that comes from the processing services. This client-server communication is based on AJAX (Asynchronous Java Script and XML) technology and most of the data are transferred in JSON format. Graphs and maps are presented in the user interface by using YAHOO Charts as a part of the ExtJS library.

A scheme of the platform functionalities, which can be accessed by the dashboard, is summarized in Fig. 2. In short, there is a flow of data (e.g. from geo-database) that allows different server functions (e.g. models) to operate and produce several services, which are accessible to users through the dashboard.

2.3. Dataset

The dataset connected to the GCI viticulture Web tool includes geo-referenced data and metadata from different sources (Table 1). The main types of data include: (i) thematic maps (with related databases) in the form of a polygon or grid data as soil and geological maps, land use maps, viticultural zoning maps, bioclimatic and biodiversity index maps; (ii) data from specific field survey activities (e.g. soil hydrology, chemical and physical properties), (iii) dynamic data produced by simulation modeling (e.g. soil water balances). Before being integrated into the database, all of the spatial data, namely vector and raster layers, were checked for anomalies and subjected to up-scaling procedures where required (i.e. lower resolution data for specific application). Land use maps that had different code classes (e.g. Touring 1954 and a new survey by the SOILCONSWEB project) were harmonized in order to be comparable and applicable within a tool for land use change analysis over time.

Point data, such as those from soil sampling campaigns, and derived data were firstly checked for anomalies (i.e. spatial coordinates, missing data, outliers, etc.) and then loaded onto the geospatial database, which allows location queries (run in SQL).

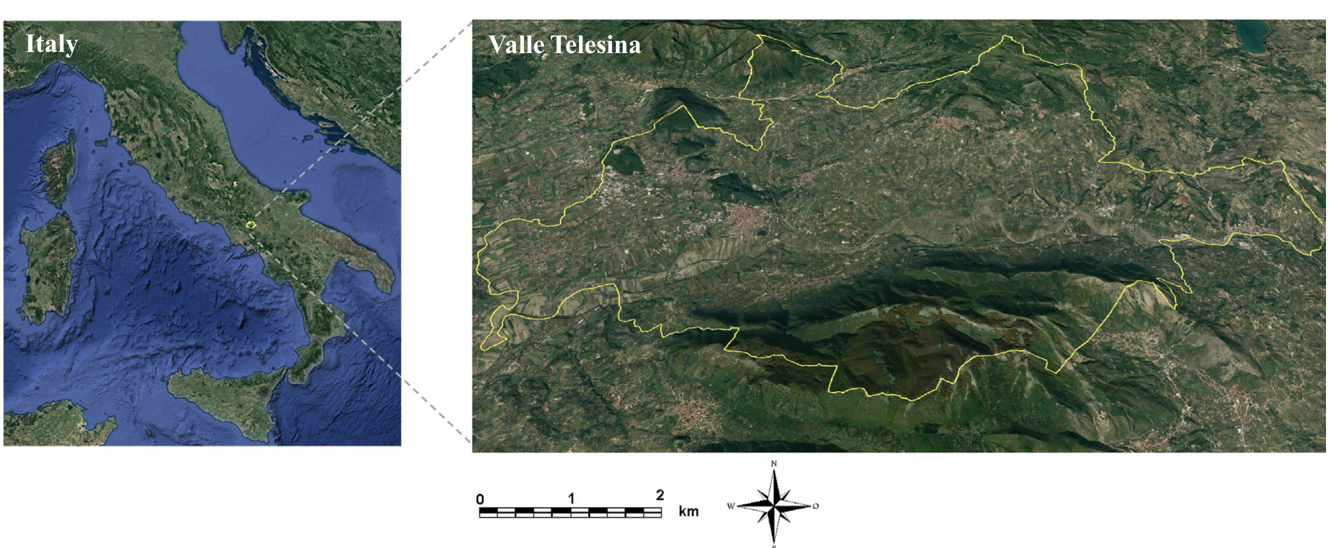

Fig. 1. The study site located in "Valle Telesina" (South Italy, Benevento).

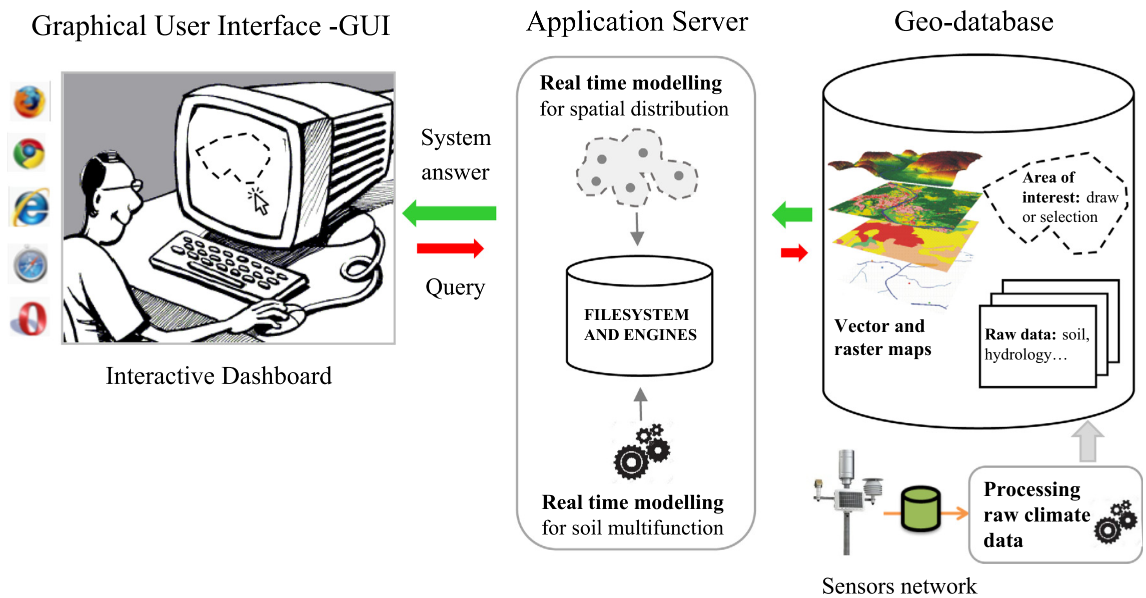

Fig. 2. Geospatial Cyber-Infrastructure operating mode. The flow of data feeds different server functions, which in turn produce a set of services that can be accessed by the dashboard.

2.4. Models: basic methodological issues

The *GeoVit* tool aims to support viticulture planning and management on the landscape scale. To perform this task, the tool requires the implementation of several models whose complexity had to be in accordance with the type of issues to be faced. Therefore, in some cases, these models can be simple, such as in the case of algebraic functions based on empirical data (e.g. thermal sum), or, in other cases, they may be complex, for instance when they have to face mechanical processes (e.g. physically based water movement). Sometimes models may also be implemented with a modular scheme (e.g. modelling cluster) in which the output of one model might represent the input for a second.

Generally, the models were selected on the basis of the following methodological criteria: coherence with available databases, easily interchangeable routines and easy implementation of new routines, priority of physically-based engines, potential for extensive validation and compliancy with the Open Geospatial Consortium specifications.

There are a few important modules to be reported here that are fundamental for the *GeoVit* application described in this work: (i) a module that uses some parts of the original SWAP model (Kroes et al., 2009) for Linux to perform simulations on water balance in the soil-plant-atmosphere continuum; (ii) an engine for both the automatic processing of climate data and the production of digital climate maps; and (iii) additional modules.

(i) SWAP is an agro-hydrologic model that is widely applied in different fields of interest including viticulture, as has already been done in the Telesina valley by Bonfante et al. (2011, 2017) and Palladino et al. (2013), who also calibrated and validated the model. It requires high computational capacity – via Richard's equation – to solve the water balance; it is fully integrated into our system, running on the basis of soil and climate input data stored in the geodatabase.

(ii) WeatherProg (Langella, 2014; Langella et al., 2016) was developed as a core engine of the geospatial cyber-infrastructure with the aim of automatically calculating digital maps about required agrometeorological variables (e.g. rain and air temperature) on both hourly and daily bases. The program starts by downloading raw data measured by sensors distributed inside and outside the study domain. Data are preliminary checked for missing and anomalous data, which are, in turn, automatically infilled by interpolated data after a datum-customized stepwise multilinear regression analysis is performed (regression imputation task). According to the time step and to the amount and geospatial density of the available sensors, digital climatic maps can be produced by means of different methods such as deterministic (i.e. inverse distance weighted), statistical (i.e. geostatistics) or knowledge-based (i.e. based on a PRISM-like model, Daly et al., 1997) methods.

(iii) Other digital terrain analysis procedures were carried out to compute, among other things, potential solar radiation and the geomorphic classification. The calculation of the potential annual radiation map (J m^{-2}) was performed on the base of the digital elevation model (20 × 20 m) by using SAGA Version 3.0.0 (System for Automated Geoscientific Analyses http://www.saga-gis.org), in which the estimation of potential radiation at the earth surface is based on the extraterrestrial radiation (Wilson and Gallant, 2000; Böhner and Antonić, 2009). The geomorphic zoning (preliminary to viticulture zoning) was calculated by means of heuristic fuzzy logic combined with expert knowledge in order to classify about 10 terrain derivatives using 15 output landform classes (MacMillan et al., 2000).

3. Results

Here we describe the *GeoVit* Viticulture Planning and Management support tool, using Valle Telesina (South of Italy) as a case study.

3.1. The dashboard and the basic functions

Fig. 3 shows the general outline of the dashboard developed for the *GeoVit* tool. Its design is the result of much interaction with expert end-users/stakeholders (e.g. Winemakers association ASSOENOLOGI-Campania, Regione Campania viticulture sector,

Table 1
Main databases employed in SOILCONSWEB-GCI for the *GeoVit* tool: description of data type and examples of their use/importance in modeling.

Theme	Data: category and description			Data used in GeoVit tool		
	Source database and (spatial/time) resolution	Type of file	Data	Parameters (obtained by dataset)	Applied model	Example of model outputs
Administrative units	Municipalities	Polygon	Administrative boundaries	Area of municipality	Clipping spatial data from database	Environmental data within administr. boundaries
Legal restriction to land use	e.g. Natura 2000; Hydrogeology restriction	Polygon	Legal boundaries	Limit and type of restriction	Presence/absence of restriction	Surfaces under restriction
DEM	20×20 (contour level); 5×5 (resampled LIDAR)	Grid	Elevation pixel based	Spatial coordinates, elevation, aspect, slope	Clipping spatial data from database; zonal statistics	Geomorphological data within the AOI
Geology	Geological map/1:100,000 Geomorphological map/ 1:50,000	Polygon	Geological units Geomorphological units	Data description of geological and geomorphological units	Clipping spatial data from database	Geomorphological data within the AOI
	Hydrogeology map/ 1:250,000		Hydrogeology units	Lower boundary settings for modeling	SPA modeling	Water balance, soil water content, etc.
Soil and climate	Soil mapping databases/ 1:50,000	Polygon	Main soil morphological, chemical, physical parameters	Soil organic matter content, texture data, soil depth, classification and physical parameters	Clipping spatial data from database; zonal statistics; process based SPA modeling (calculation of water balances and derived indices)	Soil data within the AOI; Water balance: soil water content/ storage, soil water stress index, etc.
	Raw data from weather stations network; 1 station per 2000 ha	Point	Past and daily checked data on rainfall, temperature, rel. humidity, etc.	Cum. rainfall, max/min/ average temperature, cum. evapotranspiration, daily data		
Bioclimate	Raw data from weather stations network; 1 station per 2000 ha	Grid	Past and daily checked data on rainfall, temperature, rel. humidity, etc.	Cum. rainfall, max/min/ average temperature, daily data	Empirical models for the calculation of bioclimatic indices; zonal statistics	Surfaces classified according to bioclimatic indexes
Land use	Land use map/1:50,000 (1954 Touring, 2001 Campania region, 2011 new survey from SOILCONSWEB project)	Polygon	Land use classification on several spatial scales	Land use mapping units	Comparison between matrices of data	Land use changes over time, evaluat. of traditional (oldest) vineyards
Zoning	Map of viticulture zoning	Polygon	Landscape classified according to viticulture zoning	Mapping units (zones)	Clipping spatial data from database	Environm. data and parameters relating to viticulture within the AOI
Biodiversity	Spatial variability of land use; soil quality biodiversity	Polygon/ Grid	Landscape classified according to different land use and soil biodiversity	Mapping units and zones according to indices of: Shannon, QBS, New Landscape Biodiversity (NLBI)	Clipping spatial data from database	Surfaces classified according to landscape and soil biodiversity

Solopaca and La Guardiense wineries, freelancers and farmers) who required many changes and the incorporation of specific facilities.

Its structure had to include graphical tools, procedures to combine spatial data (analysis and visualization), the production of tables and maps, and easy and intuitive navigation. Basically, the dashboard is made up of five different sections (red boxes in Fig. 3). Moving around the central map display from right to left, there are (i) a user area in which user queries are recorded, (ii) web GIS facilities which enable the user to navigate through spatial data layers, (iii) GIS facilities to build queries, to obtain spatial statistics and other similar requests, (iv) drawing/selection of the area of interest (AOI), and eventually (v) the specific application dashboard of Geospatial viticulture *(GeoVit)* tool.

The last three points are of major interest. To be more specific, point (iii) was required by Regional offices located within the territory. Indeed, many of these local offices do not have access to desktop GIS facilities (possibly due to funding restrictions) and, thanks to this specific module, local experts are able to freely build queries and obtain map services to fulfil their specific needs. An example of this might be the rapid visualization, by querying maps stored in the geo-database, of the oldest vineyards present in the area (e.g. some dating from 1950). Point (iv) is the AOI drawing/-moving tool, through which the user (e.g. winemaker association managers) can delimit the region of interest (e.g. areas eligible for new vineyard planting) where they can run the application they need (there is also the possibility to select specific Cadastral ID numbers). Therefore, the AOI may consist of one or more polygons (these can also be moved within the project area), which might also be re-edited/deleted, stored in a personal space or made public for general use. Once drawn, the AOI represents key data that are stored in a database and linked to the user.

Point (v), the application dashboard, *GeoVit*, is the tool to use in viticulture planning and management. It has many models and routines to answer questions posed by end-users. This application dashboard has its own hierarchical structure (Fig. 3 left side) with three main categories, (chosen on the basis of interaction with stakeholders) to separate the main domain of viticulture interest:

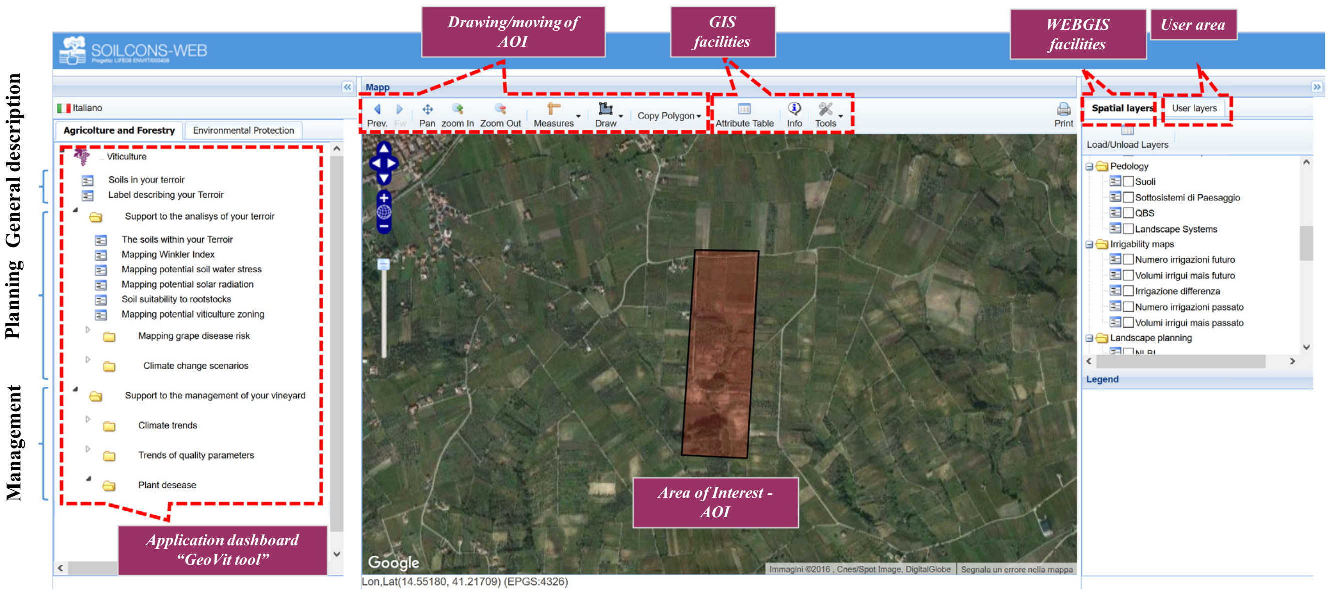

Fig. 3. General outline of the dashboard.

- *General description of the AOI:* it includes applications for the description of the terroir chosen by the end user. Basically, the user selects his farm (i.e. draws the AOI boundaries) and gets a report from the system (real time automatically created .pdf file) describing the main geological, climate, soil and land use features of his/her farm. It is important to underline that this category has been specifically requested by vine growers for marketing needs. They wanted to be able to highlight some local characteristics of physical parameters, such as soil properties, on the wine bottle labels.
- *Planning:* this set of tools is aimed at viticulture planning within the AOI. It includes tools built to produce reports, maps and statistics about a farm's spatial distribution of soils, Amerine and Winkler index (A&W, Amerine and Winkler, 1944), potential water stress, potential solar radiation, soil suitability for the main rootstock, the risk of downy mildew (*Plasmopara viticola*) disease (mapping of Branas index, Branas, 1974). What is more, following the winegrowers' request, a map has been included of a potential zoning, based on fuzzy analysis, to be tested locally by farmers. In addition, a climate change scenario was included based on A&W index maps, produced using forecasting of climate data for the 2021–2050 period (from AGROSCENARI project, www.agroscenari.it; 35 × 35 km resolution grid covering the entire Italian territory). These data have been generated by a statistical downscaling model (Tomozeiu et al., 2014) starting from coupled atmosphere–ocean global climate models (AOGCMs) under emission scenario A1B (ENSEMBLE, der Linden and Mitchell, 2009).
- *Management:* vineyard management application includes using several tools. Basically, it allows us to acquire and process daily climate data and permits real-time visual assessment of the trends of the major climatic parameters (requested by vine growers), trends of the main production parameters, and a model to assess the degree of downy mildew disease attacks.

3.2. Models

The above applications are based on a core concept: the possibility of processing data from the AOI. Indeed, there are several processing procedures behind these tools, ranging from simple visualization of thematic maps with the option of running zonal attribute operations to more complex elaborations (e.g. set of differential equations) by applying dynamic simulation models at different spatial scales. The latter are absolutely essential if *GeoVit* has to properly address the functionality of complex systems such as the water balance in the Soil-Plant-Atmosphere continuum (SPAc), which is ruled by processes that vary in time and space.

Hence, in some cases *GeoVit* implementation involved writing new program codes for models or, in some other cases, recompiling and adapting existing program codes to be implemented in our system (see Table 2 for details).

When required, both physically based and empirical models were integrated into a modular scheme (modelling cluster).

In Table 2, a schematic description is given of models implemented for the *GeoVit* functionalities. They can be described according to: i) their functions; ii) activities required for their implementation; iii) required input parameters; iv) main outputs; v) capacity for enabling, or not, the “on the fly” operations. The last point is very important in order to distinguish models running in real time from those whose functionalities are exploited off-line.

Indeed, some models may be used with an off-line procedure and the output produced is uploaded onto the server, ready to be used for other modeling applications or to be directly visualized (e.g. maps and tables). Below are three examples of these off-line procedures:

- The use of bioclimatic indices to be related to yield quality. These are based on empirical relationships about thermal conditions, moisture and solar radiation levels. The following data were preprocessed by using time series of climate data: the indices of A&W, Huglin (Huglin, 1978) and Branas, which is related to the risk of occurrence of downy mildew disease.
- Soil suitability to several grapevine rootstocks (Costantini, 2006). This procedure was applied in a standard GIS environment through a classic land evaluation approach (FAO, 1976, 2007) using soil, landscape and weather parameters.
- Viticultural zoning map included the above layers merged in a GIS environment with several other layers referring to climate, physical and environmental parameters.

A completely different approach is required for ongoing dynamic processes (such as the current climatic season) where

Table 2
Details for modeling implemented in SOILCONSWEB-GCI for the *GeoVit* tool functionalities.

Modeling chain	Application	Main functionalities	Required implementing activity (new codes to be written)	Examples of input parameters	Examples of output in the S-DSS	On the fly operation
General description	(MC1) Basic Terroir data	Collecting environmental data describing the Terroir	Writing new codes: (i) development of the WeatherProg engine; (ii) clip of data and of WeatherProg output (vector, raster and table format) on the base of AOI, and spatial statistics	(i) Raw weather data from sensors at hourly or daily time steps; (ii) raster maps of weather data; (iii) raster, vector and tabled data relating to soil type, elevation, land use, geology, bioclimatic indices, administrative units, etc.	Exportable reports in PDF format containing environmental data relating to Terroir description, including climate data (average values and last acquisition data) and soil profile pictures	Y
Planning	(MC1) Support for the analysis of Terroirs	Mapping main physical and environmental parameters	Writing new codes: clip of data on the base of AOI and basic spatial statistics; Applying: (i) GIS capabilities for calculation of environmental parameters (physical parameters) relating to viticulture; (ii) empirical models for bioclimatic index calculation; (iii) land evaluation approaches and merge functionalities in GIS environments for producing viticulture zoning and soil suitability evaluation	Raster and vector data relating to elevation, aspect, soil, geology, bioclimatic indices, climate data, land suitability to rootstock, viticulture zoning, etc.	Vector and raster maps (provided with dynamic legends appropriate to the AOI dimension) depicting the parameters requested	N
		Mapping indexes relating to plant diseases risk and alternative climate scenarios	Writing new codes: clip of data on the basis of AOI and basic spatial statistics Applying empirical models for bioclimatic indices calculation	Raster and vector data relating to bioclimatic indices (Winkler index, Branas index, etc.)		
Management	(MC2) Climate trends	Depicting through graphs and mapping climate data variation over time (daily time step)	Writing new codes: (i) development of the WeatherProg engine; (ii) collecting "map stacks" of climate data, including last acquisition, on the basis of variable time periods; (iii) adapting and rewriting pre-existing SWAP model codes; (iv) "pick up" of SWAP model input data from the geo-database on the basis of the AOI; vi) clip of data on the basis of AOI and basic spatial statistics	Raster maps of weather data and evapotranspiration process	(i) Graphs depicting climate trends on daily base (temperatures, rain, solar radiation, potential evapotranspiration) referring to required time periods; (ii) raster maps of cumulated values relating to climate parameters (rain, solar radiation)	Y
	(MC3) Trends of quality parameters	Depicting parameter trends relating to quality through graphs (daily time step)	Writing new codes: (i) development of the WeatherProg engine; (ii) collecting "maps stacks" of climate data, including last acquisition, on the base of variable time periods; (iii) adapting and rewriting pre-existing SWAP model codes; (iv) "pick up" of SWAP model input data from the geo-database on the base of the AOI; vi) clip of data on the base of AOI and basic spatial statistics	(i) Raster maps of weather data; (ii) raster, vector and tabled data relating to soil properties	Graphs and exportable values relating to water stress trends on a daily basis (including 5 days forecast), referring to time periods required	Y
	(MC4) Risk of plant disease	Depicting the risk of incurring in plant disease through graphs and mapping	Writing new codes: (i) adapting and rewriting pre-existing model codes; (ii) development of the WeatherProg engine; (iii) collecting "maps stacks" of climate data, including last acquisition, on the basis of variable time periods; (iv) "pick up" of model input data from the geo-database on the basis of the AOI; (v) clip of data on the basis of AOI and basic spatial statistics	(i) Raw weather data from sensors at hourly time steps; (ii) raster maps of weather data;	Graphs and maps relating to the risk of incurring in the diffusion of a plant disease (*Plasmopara viticola*)	N
	(MC5) Rural landscape fragmentation	Interactive fragmentation mapping	Writing new codes: counting pixels within a variable width (radius) moving circular area	Raster data relating to urban settlement diffusion classified in binary images (1: pixels recognized as urban; 0: other pixels)	Raster map of rural landscape fragmentation	Y

off-line procedures cannot be applied and, rather, it is necessary to implement models that operate in real time and allow "on the fly" processing through the web. For instance, this is the case when the user wants to know, for a specific AOI, the potential water stress that can be reached by a vineyard during a given time period.

Basically, soil and climate input data stored in the geo-database are "picked up" by automatic routines, which allow the application of the model throughout the study area. In this context, something that is of crucial importance is the combination of this agro-hydrologic model (SWAP), simulating the water balance in the soil-plant-atmosphere continuum, with the WeatherProg routines, the output data of which represent part of the input climate data for both the functioning of SWAP model and several other applications developed specifically for *GeoVit*.

The combined implementation of SWAP and current climate data in our DSS is rather innovative and important because: (i) currently, viticulture-DSSs are based on relatively simplified hydrologic models (e.g. bucket models), with a coarse schematization of the flow field and several key physical processes (e.g. redistribution and actual transpiration) which play a key role in determining crop water stress balances; (ii) to our knowledge, web-based truly "geospatial" DSS (therefore clipping geospatial data) that deliver "on-the fly" dynamic simulations based on current climate data are not yet available for viticulture.

Among the main outputs of the SWAP application in our tool, there is the estimation of the crop water stress, expressed by the Crop Water Stress Index (CWSI, see following Eqs. (1) and (2)), which is considered a key field phenomenon in the quality of wine production (Gómez-del-Campo et al., 2002; Gu et al., 2004; Intrigliolo and Castel, 2009; Van Leeuwen et al., 2009; Acevedo-Opazo et al., 2010) because of its key importance in the hormonal balance of the grapevine (Champagnol, 1997). Other important "on the fly" spatial modelling engines have been applied to estimate the potential risk of plant disease (e.g. downy mildew disease). In general, these dynamic models are thought of for users (farmers, association managers, winemakers, technicians) who require monitoring on a landscape scale. Unfortunately, these models have not yet been adequately validated and, so, their detailed description is not reported in this contribution.

Most applications in *GeoVit* apply statistical models for the production of reports (mean, max, min, standard deviation, etc.), and spatial processing routines to calculate climatic parameters within specific AOI (i.e. rain, temperature, potential solar radiation) over time.

If necessary, according to the operation required via web by the users, some of the above models can run together in a sort of modeling cluster (MC). Some details of the most important and necessary (for stakeholders) MC procedures employed in the *GeoVit* tool follow below.

3.2.1. MC1 – reporting viticulture key parameters

This module incorporates the basic procedures used for several applications within the tool. It consists of two main procedures: (i) spatial statistics within the AOI on either/both vector and raster basis; (ii) report making (exportable .pdf file) containing statistics and other information in table format.

The module applies in all cases when the user aims to collect environmental data about his specific AOI. It starts by using PostGis functionalities, enabling to define the analysis of the raster or vector layers stored in the geo-database and interested by the requested specific operation. The production of an automatic PDF-report incorporates data from spatial layers that are important for viticulture. Among these are: landscape features (e.g. digital elevation model, geology and soil maps, land use maps, etc.), climate features (e.g. rain, temperature and solar radiation maps, bioclimatic indices) and physical processing features (e.g. average crop water stress index). The module operates by: (i) "clipping" the layers, using the AOI as the crop area; (ii) calculating pixel based zonal statistics (min, mean, max); (iii) building the .pdf file in tabular fashion by reporting data thanks to the free PDF generator (FPDF). Additional routines are applied in order to insert useful information into the report such as pictures from soil profiles that correspond to soils occurring in the AOI.

3.2.2. MC2 – current climate trend of my viticulture landscape

Obviously daily climate variation is a key issue in viticulture since temperatures and rainfall greatly affect plant metabolism, phenology and plant diseases.

However, it is also equally evident that many farmers do not own any agro-meteorological stations to locally monitor vineyards in a way that is useful for precise viticulture management. Consequently, this module was designed to enable users to freely select both a range of dates and the AOI of their vines. The climatic procedures systematically performed by WeatherProg yield a complete stack of time-varying digital climatic maps for each climatic variable in the geodatabase, which are in turn clipped on-the-fly to run the calculations requested by the end users in real-time. The module outputs consist of the production of graphs and maps relating respectively to climate trends (e.g. rain, temperatures, potential solar radiation, etc.) and accumulated climate data within specific AOIs for a time period (daily based) defined by the user.

More specifically, this module using PostGis functionalities operates by clipping climate maps that use the AOI as a crop area, so it produces pixel-based zonal statistics. This routine is repeated *n*-times, for each daily climate map to be processed, in accordance with the time period considered (i.e. 10 days correspond to 10 maps). The layers are added together and produce the accumulated maps (visualized as images thanks to the Browser-based JavaScript framework OpenLayers), while the data obtained from spatial statistics are used for drawing automatic graphs of climate trends.

3.2.3. MC3 – current trend of potential the Crop Water Stress Index (CWSI) of my viticulture landscape

Due to advances in viticulture research (e.g. Koundouras et al., 2006; Intrigliolo and Castel, 2009; Van Leeuwen et al., 2009; Acevedo-Opazo et al., 2010), winegrowers well know the influence of water stress on fruit ripening, aroma potential, bud differentiation and the overall oenological potential of grapes, but water stress information is rather difficult to obtain. The *GeoVit* "on-the fly" module uses the capability of the SWAP model (recoded for *GeoVit*) to estimate the current CWSI within the user defined AOI. An approach using CWSI in a standard GIS environment has already been adopted on the landscape scale for addressing the link between quality of production and both climate and soil-plant water status (Bonfante et al., 2011) and on the farm scale to identify the functional homogeneous zones (fHz) of vineyard and to evaluate the effects of climate change on grape quality (Bonfante et al., 2015, 2017).

Accordingly, we defined the daily CWSI by the following:

$$CWSI = \left[1 - \frac{T_r}{T_p}\right] \cdot 100 \tag{1}$$

where T_r and T_p are the daily crop real and potential transpiration in *Vitis vinifera*, respectively. The potential evapotranspiration – obtained from the reference evapotranspiration and the crop factor, $ET_p = k_c \cdot ET_{ref}$ (Kroes et al., 2009), – is partitioned into potential evaporation, E_p, and potential transpiration, T_p, according to the geometry and development of the canopy. Specifically,

$$T_p = ET_p - E_p \quad \text{and} \quad E_p = ET_p^{-k_{gr}LAI} \tag{2}$$

where LAI is the leaf area index, and k_{gr} is the product of the extinction coefficients for diffuse k_{df} and direct visible light k_{dir}.

Real transpiration is calculated by SWAP according to the model proposed by Feddes et al. (1978), where root water uptake S is described as a function of the pressure head, h:

$$S(h) = \alpha(h) \cdot S_{max} = \alpha(h) \cdot T_p/|z_r| \tag{3}$$

being z_r (cm) the thickness of the root zone and $\alpha(h)$ a semiempirical function of pressure head h, varying between 0 and 1. The shape of the function $\alpha(h)$ depends on four critical values of h, which are related to crop type and to potential transpiration rates. The real transpiration rate T_r is computed by the integration of S over the root layer.

The sum of daily CWSI within specific periods represents the total accumulated stress:

$$CWSI_{cum} = \frac{\int_{t_1}^{t_2} 1 - \left(\frac{Tr}{Tp}\right) \cdot dt}{t_2 - t_1} \cdot 100 \tag{4}$$

where t_1 and t_2 represent respectively the first and the last day of the period considered for the simulation.

The irrigation can be easily implemented in the SWAP model (Rallo et al., 2012; De Lorenzi et al., 2017) but currently is not provided in the GeoVit tool because in the study area (and many others Italian areas) irrigation is not allowed for many high quality DOC/AOC (controlled designation of origin) wines.

The MC3 modelling cluster is based on the assumption that the AOI considered by the user is currently a vineyard; it operates through the following steps: (i) the user defines the AOI, time period for the simulation and the sprouting date; (ii) the AOI represents the spatial reference for the PostGis processing; thus soil and plant parameters stored in the geo-database are "picked up" and used as data inputs for the model (so soil and plant parameters are statistically representative of the AOI); (iii) climate data input (rain and evapotranspiration) are defined by the selection of the time period, which refers to the "stack" of daily climate maps produced (WeatherProg), while the crop growth parameters in the study area describe the development (in terms of Leaf Area Index and root depth) of a grapevine not subject to nutrient stresses (see Bonfante et al., 2017); (iv) using the above inputs, the models run on a daily basis over the entire chosen period of time; (v) on the basis of model output, the system produces graphs and tables which report the potential CWSI values relating to the time period defined by the user. These data are produced for each soil type within the AOI. A forecasting procedure of the CWSI is also implemented in the MC3. This feature – specifically requested by the local cooperatives – is based on a 5-days climate forecast that produces an estimate of rain and evapotranspiration for step iii).

3.2.4. MC4 –current potential risk of plant disease of my viticulture landscape

Fungal diseases in viticulture are among the main issues to be tackled during cultivation. Consequently, it should not be a surprise that monitoring vineyard diseases is one of the main requests by viticulture farmers. Indeed, knowing the insurgence of an infection risk is fundamental so as to limit the number of pesticide treatments, which, in turn, allows the user to limit the damage to crop and environment, and, also importantly, the related costs.

In this context, working on the landscape scale, *GeoVit* cannot be compared with the large family of DSS addressing vineyard disease (e.g. Rossi et al., 2014), which are based on on-site sensors (placed in vineyards) recording real time temperatures, moisture, leaf wetness, etc. and, so, capture the very local environmental conditions. Nevertheless, considering that only an extremely limited number of viticulture farms in our large study site (as in many other districts) can afford sensors and technology implementation for dedicated vineyard disease DSS, we had to take a different perspective.

Thus, *GeoVit* employs two different procedures: (i) a "static" geospatial evaluation of "potential downy mildew risk disease" (in the form of a map for a specified time), which has great importance in viticulture planning (especially in organic viticulture); and (ii) a "dynamic" evaluation of the "current potential downy mildew risk disease"; this is useful for the management of individual farms which can assess information about the risk of occurrence of pathological events in advance. At this stage of the *GeoVit* development, this procedure does not consider management variables (e.g. treatments with pesticides, pruning, etc.), thus simulations are based only on environmental conditions.

The modelling (i) procedures employs spatialised time series of climate data to calculate the Branas index on the scale of the entire Valle Telesina area for two different time periods. These are the current year and a climate change scenario for the period 2021–2050. Therefore, it is possible to estimate the future spatial distribution of the Branas index by estimating the spatial occurrence of environmental conditions favourable to downy mildew disease. This could be very useful in planning new vineyards, especially if the goal is to reduce the use of pesticides, such as in organic viticulture.

This model is applied through an off-line procedure and the Branas index map outputs are uploaded onto the server. Thus, the user can visualize the maps here by simply selecting the AOI and the simulation period in which he is interested.

The modelling (ii) procedure aims to provide an insight into the potential of the *GeoVit* approach on the farm scale and show the S-DSS connection between the landscape and the farm levels.

Here, we provide just a brief overview of the implemented dynamic models developed for *GeoVit*, since they are still in their second phase of testing. The MC4 modelling cluster aims to provide information about potential downy mildew disease (*Plasmopara viticola*) in terms of both the risk of infection insurgence and the relative level of intensity. This is achievable within specific AOI, on both the farm and the landscape spatial scales. MC4 implements a downy mildew disease model derived from a simplification of the Rossi et al. (2008, 2010) and Rossi and Caffi (2012) model.

The pest model runs on top of the digital climatic maps produced by WeatherProg at an hourly time step. To be more specific, the module starts with the selection of the AOI, which defines the boundaries of the area to be analysed. The user also selects the time periods to be considered for the simulation, providing the start and the end date (up to 24 hours before). The model runs and produces outputs in real time. These outputs are collected and returned in the form of graphs and maps that represent, respectively, the infections and relative levels of intensity within the AOI.

3.2.5. MC5 – support to organic viticulture landscape

Nowadays organic farming is among the priority issues in European legislation relating to the environment, agriculture and food. This is confirmed by the European Action Plan (http://ec.europa.eu/agriculture/organic/eu-policy/european-action-plan/2004_en) and the Rural Development Programmes 2014–2020 (http://ec.europa.eu/agriculture/external-studies/organic-farming-support_en.htm). In this context, we here attempt to provide a modelling set that can provide useful support for planning in organic viticulture. This includes output from all of the modelling engines already discussed in planning (A&W, radiation, rootstock, etc.), as reported in Table 2.

However, in organic viticulture, it is also important to address many other environmental issues. Therefore, the following models/procedures are made available (they can be navigated starting from *GeoVit*): (i) soil erosion, especially for evaluating the impact of land use change on viticulture, (ii) biodiversity of soil and landscape, (iii) integrity of rural landscape; (iv) visual on-the-fly evaluation of landscape change from the 1950s to the present day.

The soil erosion module applies RUSLE to evaluate (*what-if* modelling), for a specific AOI, the potential impact of erosion after having changed land use to viticulture. The biodiversity module enables the farmer to assess a set of biodiversity indices ranging from those based on soil fauna measurements (QBS, Parisi and Menta, 2008) to those based on land use diversity (Shannon, 1948; New Landscape Biodiversity Index, Pileri and Sartori, 2005). Something of special interest is the model that evaluates how far the rural landscape is affected by the fragmentation brought about by urban structures. This is important because fragmented territories are affected by a series of factors (e.g. loss of biodiversity, presence of busy roads, major air pollution, etc.) that can conflict with a healthy environment and, therefore, be a serious concern in term of organic viticulture. This "on the-fly" module was designed with the aim of providing users with an immediate evaluation of the rural landscape fragmentation (McGarigal et al., 2012; Reddy et al., 2013) within his/her specific AOI. The input data for this analysis are in the form of raster maps that are pre-classified (ArcGIS environment) in binary images (1: pixels recognized as urban; 0: other pixels). The rate of fragmentation at each point (pixel) expresses how much urbanisation there is within a defined circular mobile neighbourhood, the radius extension of which can be selected by the users (from 100 up to 800 m). The higher the value, the greater the rate of rural fragmentation.

All the above models and procedures represent the basis for the numerous *GeoVit* applications reported in Fig. 3. A few of these are explored in the following examples, which refer to a practical use of the system.

4. Case studies

As already stated, requests from viticulture (orientated towards high quality wine) on the landscape scale can be divided into two broad domains from the operational point of view: planning and management.

Planning tools refer to applications that aim at better planning. This is the case when a farmer aims to choose the best grape variety or the best rootstock for his land or, conversely, the best land to grow a specific type of grape on.

On the other hand, the management tool takes a specific type of viticulture (variety, etc.) for granted and supports operational viticulture management. This is the case when a farmer aims to evaluate what a growing season on his farm is it going to be like.

Two overviews of case studies referring to the above applications are reported below; full details are given in Appendix A (supplementary materials). Fig. 4 depicts the various steps the user has to follow to obtain the desired output information.

4.1. Case 1: Terroir description and support to planning

This procedure is employed by end-users (e.g. managers of winemakers association) who are interested in:

(a) acquiring information, which is typically not easily available, relating to the physical and climatic characteristics of a specific terroir, with the aim of providing additional information to consumers by putting such data on the bottle label. This is performed by applying the MC1 routine
(b) having support when replacing one variety with another variety. For instance, when replacing the local *Piedirosso* with *Aglianico* (grape varieties) on a specific farm. Here, by applying the MC1 routine, the user can evaluate whether several key environmental factors (e.g. bioclimatic indices, soil properties, etc.) are suitable for a specific variety.
(c) evaluating whether some key environmental factors might be appropriate for the organic management of vineyards. To be more specific, a user can "explore" a territory (Fig. 5) by evaluating some environmental factors that might facilitate organic vineyard management (less fertilizer, fewer pesticides, high biodiversity, low rural fragmentation by urban settings). Users employ MC5 and obtain the spatial distribution of the following indices: (i) Shannon, (ii) Soil Quality Biodiversity (QBS), (iii) the New Landscape Biodiversity Index (NLBI), exploring landscape and soil biodiversity, (iv) A&W index and (v) Branas index, evaluating the potential risk of downy mildew disease attacks (modelling cluster MC1).

4.2. Case 2: management

This procedure is employed by end-users (e.g. farmers) who aim to optimize the harvesting of grapes for good wine quality. For the sake of brevity, here we limit this evaluation to the crop water stress (closely connected with grape quality).

In issue d), by using MC3, an end-user such as a winemakers association manager can plan the current year's harvest (early September in the study site) by evaluating accumulated crop water stress (e.g. through graphs) of *Aglianico* cultivar on the various viticulture farms belonging to the winemaker association. This also allows identification of the best harvesting time for each farm.

Moreover, strategic viticulture planning can benefit from water stress sensitivity analysis. To be more specific, the MC3 application can be repeated elsewhere in the study area (i.e. Valle Telesina) to obtain several scenario analyses related to the large spatial variability of the environmental factors to be considered over time (e.g. soil properties, climate data). In this context, in Fig. 6, we report results regarding the application of the *GeoVit* tool when using the applicative "Trend of water stress" in 20 different locations, which were identified by randomly moving a singular AOI within the whole study area. These results also highlight the flexibility of the *GeoVit* tool, which is capable of adapting to and representing the physical variability of the environment.

5. Discussion

In this paper we highlighted the importance of geospatial decision system in supporting sustainable viticulture on the landscape scale and incorporating other connected environmental themes.

To be more specific, we have attempted to demonstrate that Geospatial Cyberinfrastructure might be the way ahead for a new approach to viticulture on landscape scale by providing a multi-user, multiscale tool which is applicable over a range of cases from entire districts (13 municipalities) to single farms.

The platform must be considered flexible and open to further implementation; consequently, it is important here to discuss some key points of the approach, some of the lessons learned and some of the problems to be better addressed. Among these, we emphasize the following:

- There is a large variability of users and this greatly affects the assumed usefulness of *GeoVit*. There are cases where territories are mostly managed by elderly viticulture farmers (e.g. the Vitulano cooperative) who are not at all inclined to using computer media. Eventually, it became obvious that only in those cases where there were young, dynamic farmers (e.g., the Guardiense cooperative winery) was the platform appreciated and employed.
- Moreover, and particularly in our case study (as in many other viticulture districts of Italy), there are many farms with difficulties in even maintaining standard climatic stations properly. In

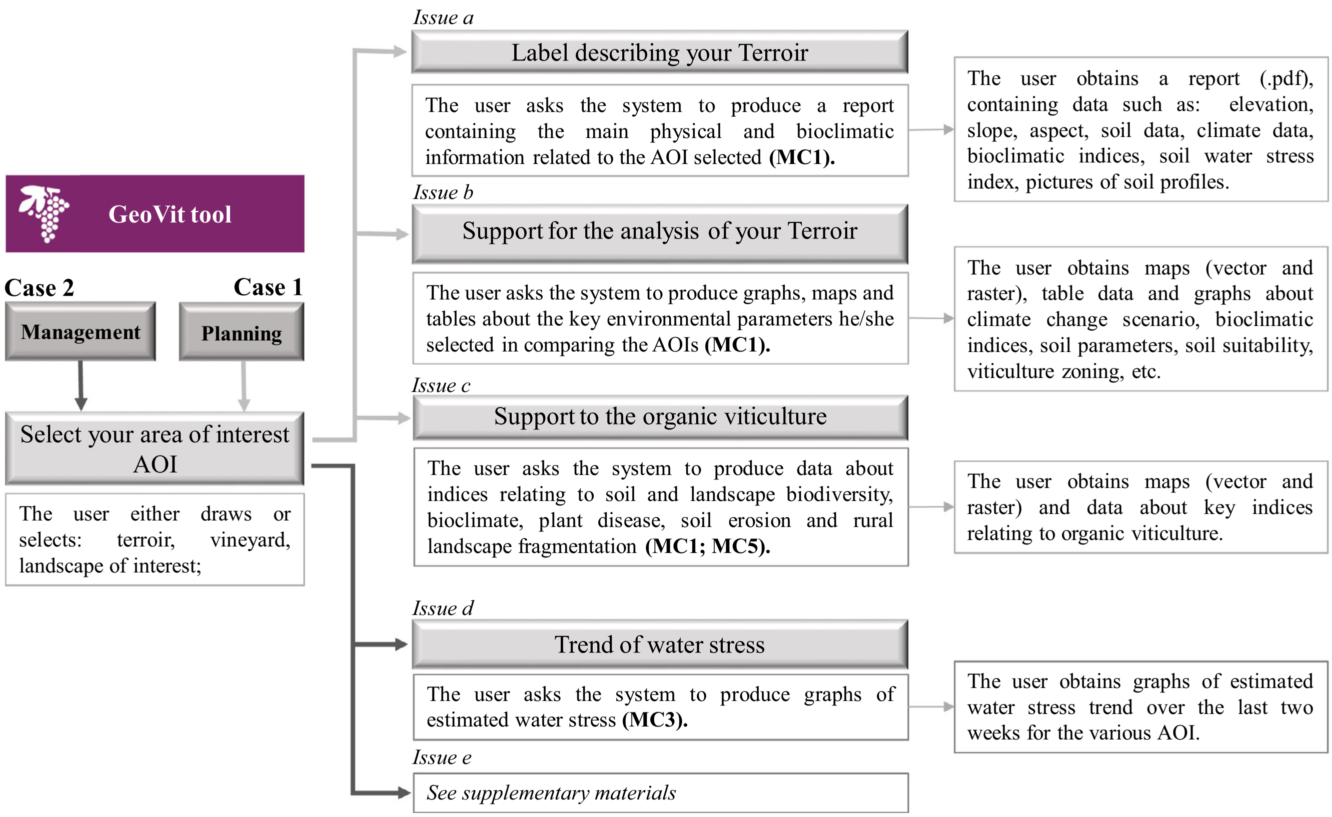

Fig. 4. Flow chart of the *GeoVit* tool. AOI: Area Of Interest; MC: Modelling Cluster.

such a situation, for instance, if a new climatic station is placed on a specific farm (in our case paid for by the local region), its output will deliver data not only for that specific farm, but it will also improve spatial inference of climatic data for many surrounding areas; thus the system has an intrinsic optimization of investment and procedures. Therefore, this open structure towards new data and modeling implementation looking towards the viticulture landscape represents one of the strengths of the system and it does not allow specific comparison between GeoVit and currently available farm-based DSS systems.

- In the *GeoVit* approach, the vineyard plays a central role within an integrated and sustainable framework. Indeed, viticulture is connected to other land uses; for example, a new farmer may highlight whether there were vineyard land use changes on his farm over a desired time-lapse. Thus this enables an understanding of the multi-temporal land use stability (including the 50s) of a vineyard in a given AOI, also considering the landscape surrounding the AOI.
- The *GeoVit* (or similar system) is capable of producing real time, site-specific environmental data. This may also help marketing. Indeed, farmers believe that obtaining landscape features information for a specific AOI and publicizing them on the wine label may influence wine consumers' choices and, thus, the price of the wine. This implementation, even though specifically requested by the local wine sector, has only been used to a very limited extent. This shows the importance of having "follow-up" activities to communicate the potentialities of *GeoVit* better.
- The *GeoVit* integrated and multilevel approach is of special interest since it partly implements the much spoken of and poorly executed theme of strategic viticulture planning where it is important to identify possible strategic lines (quality) to be pursued (varietal choices, optimizing treatments, etc.) by territories.
- With a view to organic viticulture, the system is particularly highly performing and opens-up new opportunities for this specific sector. For example, it is possible to identify areas that are particularly suited to organic viticulture because they enjoy an inherently low risk of plant disease attack and/or suitability due to the healthiness of the environment.
- The flexibility with which the system allows farmers to draw their own farms and get information strictly relating to their specific territory proved itself to be very important. It was perceived of as a "taking care" procedure by farmers.
- The ability to get *GeoVit* information relating to spatial constraints (legal restrictions) and fragmentation of rural land (caused by urban infrastructure) was also found to be important for better planning.
- On a more general theme, some other key technical lessons learned refer to the importance of using free, open-source geospatial libraries and programs which allow the potential involvement of a large community of developers and the flexibility/interoperability of the system that enables data/models from different sources and formats to be included and processed.

Despite this positive feedback, we consider it important here to highlight the main problems that require further development:

- On-the-fly simulation of crop modeling. There is neither a deterministic crop model nor an on-the-fly crop modeling simulation in our system since most of these procedures are executed off-line. This is a limit of the system since it does not permit everyday crop management to be supported properly.

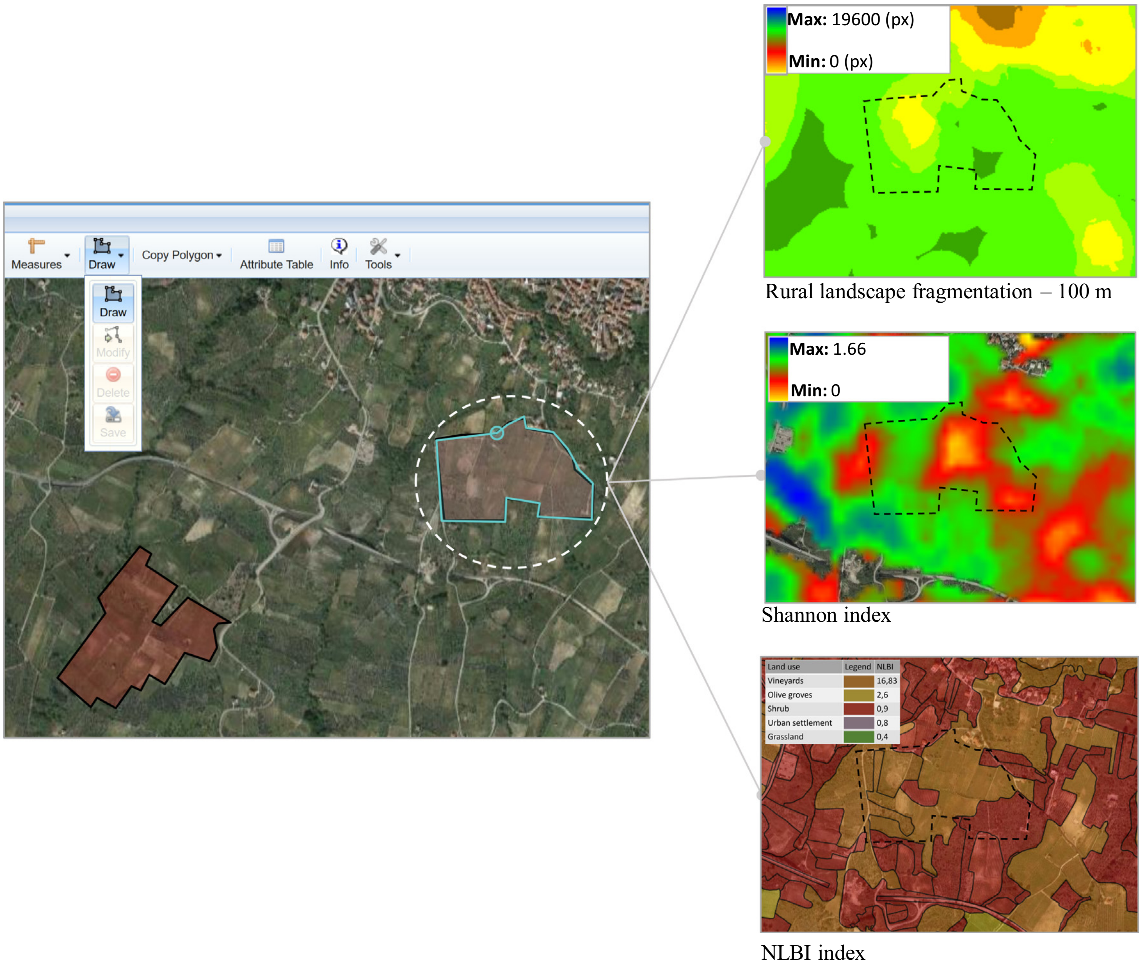

Fig. 5. Example of a territory "exploration", evaluating environmental factors that might facilitate organic vineyard management.

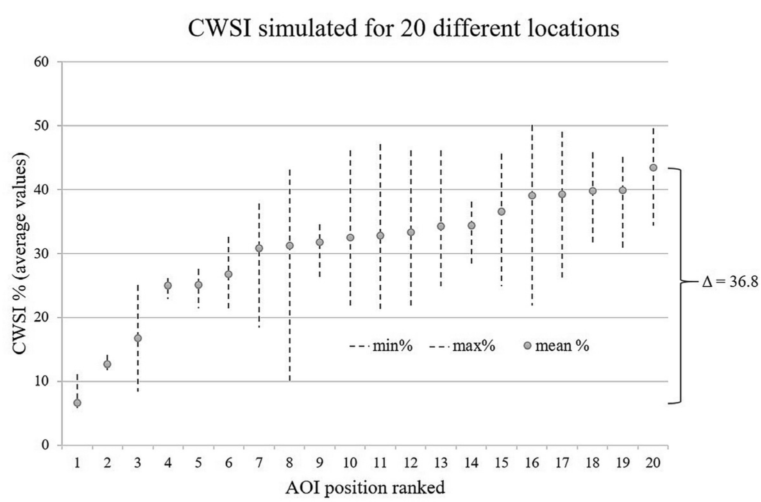

Fig. 6. Results from sensitivity analysis performed by the *GeoVit* tool on soil water stress. Simulation for a time period of 25 days between August and September 2016; min/max bars represent the extreme values achieved during the simulation for each location.

- It is most important to incorporate remote sensing data concerning plant growth, through data assimilation algorithms, into crop modeling. Data assimilation could also be applied by using proximal sensing technologies and data obtained by adopting drones.
- Application over larger areas is highly desirable to support viticulture at district and regional levels. In order to deal with this change of scale, it is important to address: (i) the balance between the quality/availability of input data and the resolution

of the information provided on a large spatial scale; (ii) the need for high-performance computing systems to process large amounts of data in real time.
- Modeling plant disease. This is a key issue in the development of Spatial DSSs for application from field to landscape scales. In attempting to tackle this issue, *GeoVit* implements an early version of a new model, the correct functioning and usability of which will need additional calibration and validation tests. Therefore, this is a key area that requires much development.
- Contribution and feedback by end-users and stakeholders are fundamental in developing suitable dashboards and useful data processing. In this sense, direct meetings involving the potential users were organized during the SOILCONSWEB project, but the much wider user community should be involved in the future.
- The supposed powerful decision support deliveries due to the *GeoVit* platform (and thus on SOILCONSWEB) are extremely fragile if adequate maintenance of the system components is not guaranteed. This was the case with the malfunctioning of the weather stations in the entire Regione Campania in the year 2014. Therefore, the *GeoVit* management tool encountered serious problems over the whole of this period.
- Spreading the approaches. Although there is already a history of the application of DSS systems in viticulture, in most cases these DSS systems have been closed systems, designed for individual farms, whose application to larger areas would require n-replications. Thus, we argue that there is a need for widespread adoption of the *GeoVit* approach, moving towards its application on a landscape scale with a relative cost reduction.

6. Conclusions

Despite the general agreement that sustainable high quality viticulture, which combines high income and land conservation, can play a crucial role for many areas, including inland landscapes and marginal areas, there is an evident lack of an operational tool which can help farmers pursue this attractive goal. DSSs can indeed produce such type of tool to support farmers in viticulture planning and management. However, most DSSs are designed to support individual farms and make much use of high technology and sensors and, therefore, fail to deliver at the level of the viticulture landscape, where there are generally many farms that may not be technologically advanced. Moreover, these DSSs often fail to connect single farms to their environmental surroundings.

In this sense, the *GeoVit* takes a different approach, but also retains a very different perspective from current trends towards agriculture 4.0 approaches; indeed *GeoVit* does not require a viticulture landscape with "*n*" farms, each of which has sensors and technologies to support decision making, but rather aims at producing a freely available, well distributed geospatial system to support the entire viticulture landscape where technologies, data monitoring, and HPC (when required) are all integrated into a unified modular system. This may be an answer to the fear that, in many agriculture territories, the fashionable agriculture 4.0 approaches are closer to being the dream of researchers and private companies than a widespread factual reality.

Moreover, *GeoVit* proves that the demand for combining high quality viticulture with environmental protection (e.g. climate change) can be satisfied if data/models are integrated into a DSS-GCI (e.g. geo-processing, simulation modeling, etc.).

Thus, it can be concluded that it is possible to combine into a single system the critical ensemble of the following features: (i) user friendly (complexity is embedded); (ii) makes the concept of viticulture multifunctionality more operational; (iii) potentially adaptable to the needs of many viticulture end-users including viticulture districts, cooperatives and winemaker associations, as well as individual farmers.

The system does not always aim to provide best "solutions", but through modeling it may provide "options" for the user to choose from, and we believe that new farmers generation will increasingly be able to make better-assisted choices.

Finally, an important issue to be raised here is the relatively low cost of implementation (not considering data, calibration and validation) when applying *GeoVit* to new areas. In this sense, the *GeoVit* system, shown here for the Valle Telesina site, has actually been applied in two other areas (the Etna volcano area of southern Italy and Wachau area of eastern Austria). More specifically, we applied well-known empirical models – based on historical climatic data series – such as those for the estimate of bioclimatic indexes. Therefore, the transferability of the GeoVit tools, thanks to the high level of generalization of the employed models, was showed.

Despite these positive points, there are still many problems to be dealt with. The most important being (i) the need to expand further the farm module by completing the calibration and validation of plant disease modules, (ii) the incorporation of a true crop management module (e.g. pruning, distribution of pesticides, etc.), (iii) the implementation of DSS-GCI potentialities to incorporate bottom up contributions from farmers and farmer associations and also, most importantly, (iv) the cultural aspects such as ecotourism.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.compag.2017.05.02.

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