UNIVERSITÀ CATTOLICA DEL SACRO CUORE
Sede di Piacenza

Scuola di Dottorato per il Sistema Agro-alimentare

Doctoral School on the Agro-Food System

cycle XXV

S.S.D: AGR/12 – AGR/09

Modelling the impact of climate change on the Interaction between host and pest/pathogen phenologies at regional level: 'Trentino' - Italy

Candidate: Monica Fernanda Rinaldi
Matr. n.: 3811003

Academic Year 2011/2012

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Coordinator: Ch.mo Prof. Romeo Astorri

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To my mom, my sister, mis abuelos, Elisabeth & Valentina Carpella, amici della SAT

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"Se ho visto più lontano è perché stavo sulle spalle di giganti"
Isaac Newton

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GENERAL ABSTRACT

Control of agricultural pests and diseases is often based on forecasting models commonly based on real time monitoring of inputs variables. This information generally combines meteorological local databases and mathematical models designed to forecast pest and disease risk. The decision process starts when an alert or a potential risk event from the outputs of the models is issued.

Epidemiological models based on local datasets have been created and validated worldwide, for example in USA, the University of California developed the online Integrated Pest Management (IPM) program where each farmer can consult with his own database and make the pest management decision based on site-specific conditions.

Difficulties arise when no data from a close weather station are available, in mountain areas where weather conditions highly depend on the altimetry, or if data are not in a standard format to feed the model.

In a view of having a regional vision and an increased accuracy in the pest control management, the goal of this thesis was to run contemporaneously epidemiological (the pest *Lobesia botrana* and the pathogen causing Powdery mildew *Erysiphe necator*) and phenological models (grapevine cv. chardonnay) using environmental variables as temperature and to create maps at regional level, with 200 meters of resolution and daily scale or frequency. Running both models together helps to be more precise in the sensibility period of the host versus the pest or the disease and to understand the real final risk.

After calibrating and validating the models in the Trentino-Alto Adige Region (Italy) with local weather data, the forecasted climate was projected and statistically downscaled, based on the output of the Hadley Centre climate model - HadAM3 (Pope et al., 2000) under scenarios A2 and B2. The statistical downscaling algorithm was “transfer function method” (Eccel et al., 2009) at daily resolution.

In order to complete the analysis, the downscaled scenario from ENSEMBLES was also used with the datasets of 49 weather stations from FEM and the “RMAWGEN” packages (Cordano et al., 2012) created for this project in R statistical open source software (Gentleman et al., 1997).

In order to map the models, a friendly modular WEB-GIS platform called ENVIRO was developed. Modules are Open Source, follow international Open Geospatial Consortium (OGC) standards and were implemented as follows: i) enviDB is the database for spatial temporal

data, ii) enviGRID allows users to navigate through data and model in space and time, iii) enviMapper is the web interface for decision makers, a state of the art client to map vulnerability to climate change at different aggregation scales in time and space; finally, iv) enviModel is the web interface for researchers that provides a platform to process and share environmental risk models using web geo-processing technologies (WPS) following OGC standards.

With the aim of being even more accurate in pests and diseases spraying volumes and according with the Directive 2009/128/EC, the current work shows that the LIDAR sensor can be used to characterize the geometry of the grapevine and the Leaf Area Index (LAI) at each growth stage and calculate the Tree Row Volume (TRV) visualized in 3D maps in GRASS (Neteler et al., 2008, Neteler et al., 2012).

GENERAL INTRODUCTION

This thesis was developed as part of the Envirochange project (www.envirochange.eu) funded the Autonomous Province of Trento. The project focuses on global change and sustainable management of agriculture in a highly developed environment. It aims at assessing the short-term biological, environmental and economic impact of climate change on agriculture at the regional level (Trentino) particularly on quality and pest management that are more likely to be influenced by climate change also in short term.

With the aim of reducing the uncertainties between the regional and the local scale, a friendly web-GIS called ENVIRO was developed to help understand the variability in the pest and diseases development and thus improving their management. This open source tool can work at different aggregation scales in time and space.

In order to model the impact of climate changes on the interaction between host phenology and pest/pathogen development at regional scale the selection of the best spatial and the temporal scale was the first step. In fact the use of General Circulation Models (GCMs) issued in 1999 for the IPCC panel, characterized by the spatial resolution described by Russo and Zack (1997) and then by Seem et al. (2000), does not represent the spatial and temporal variability needed for the diseases models at local scale (Ghini et al., 2008). The GCMs scenarios have a spatial resolution of 2.5° latitude by 3.5° longitude. Furthermore, local (landscape) events require spatial resolutions on the order of 1 to 10 km (Seem et al., 2000). Almost all host and pest/diseases models running at daily or hourly frequency (Calonnec et al., 2008; De Wolf, 2005; Molineros et al., 2005; Caffi et al., 2011) cannot be represented by the temporal resolution of most GCMs, which consists of decadal averages of monthly means or totals.

Starting with these considerations, a downscaling from ENSEMBLES was made using the local weather stations networks to create the study area at a scale of 200 × 200 m per each pixel. This scale was selected from one of the most precise three-dimensional spatial optimal interpolation of surface meteorological observations, the temperature in this case, that was developed by Uboldi et al. (2008) and created for Lombardia Region at hourly frequency. A similar methodology for the interpolation of weather inputs was implemented one year later by ZEPP in Germany for Late Blight in potato using the SIMBLIGHT models at 1 km^2 spatial scale (Kleinhenz and Zeuner, 2010).

It is worth mentioning that, in the disease and pest management, the 200-meter-scale determined by the weather variables, is still too large for the management within the production unit. Generally, the management in the production unit is done with precision agriculture or precision viticulture (PA or PV), with a site-specific management and variable rate doses (Bragachini et al., 2002; Bongiovanni et al., 2004; Best et al., 2011).

Nevertheless, in the Envirochange project, the epidemiological models were run with spatialized weather conditions at daily frequency, and at 200 meters of spatial resolution, because the goal of the project was to have a regional overview of the phytosanitary status. This selection was based on optimizing the weather alerts and being more accurate in phytosanitary status, due to the fact that the Trentino province is characterized by high altimetry variation, from 100 in the valley to more than 1500 m a.s.l. at the highest altitude of grape growing. This height variation produces different conditions in each valley. Knowing the moment in which the thermal sum reaches a certain limit is important for management planning, e.g. placing pheromone traps for monitoring berry moth.

Another important decision in this work was to select the daily scale to run the epidemiological models, because the downscaling of climate change scenarios (IPCC scenarios) is commonly made at yearly or monthly scale. Eccel et al. (2012) outlined the methodology implemented on small-scale for simulations of future climate and the importance about an analysis of instrumental series, as a first step. This showed the importance of a spatially coherent homogenization protocol to carry out the statistical downscaling in the Alpine region.

Another step was to set up a system to standardize the information and make it user-friendly. We opted for an open source platform. As mentioned in Sboarina (2002), Uboldi et al. (2008) or Eccel et al. (2012), controlling the weather information before being spatialized is crucial because almost all measurement stations presented gaps in the data series. The same approach was used with the monitoring data of pests, diseases and phenological stages of grapevine.

Some difficulties were encountered: epidemiological and phenological data at regional level were only available for the period from 2007 to 2009. In some cases, data from the past were available, but in this case had discrepancy between the weather data with pest sampling, e.g. most of traps were positioned closer to the weather station, but others were far away, so the latter data were not fully trustable.

All these dataset, specially the weather dataset, are large in number and heavy in terms of megabytes. Hence, the computing power required was taken into account, as well as the computer processes to accelerate the calculations. This part of the work was carried out with the collaboration of Fondazione Bruno Kessler - FBK (Italy) and resulted in the development of the Enviro platform. Enviro has a specific profile for researchers and another for decision makers, but allows them to work together on the same platform.

Many DSSs in agriculture were developed over the years; one of the most known was created by the University of California (Statewide Integrated Pest Management Program- IPM Online web-site) that continues to upgrade it. In Italy, a DSS was created following a holistic approach on durum wheat for pasta production (Rossi et al., 2010), another one for the vineyard management in IPM (Salinari et al., 2012) and one for downy mildew management in organic vineyards (Caffi et al., 2012). Others tools were developed along the countries for example ZOO Project, open WPS platform (Fenoy et al, 2012), Cantina Mori WEB-GIS (Fontanari et al, 2007), UCSC model for downy mildew primary infection (Rossi et al., 2008) and Coptimizer (Kuflik et al., 2009) amongst others. De Wolf (2007) described a DSS created in USA and showed the *Fusarium* head blight of wheat for 23 states at 20 km of resolution. He described most commonly used diseases models and highlighted the importance of warning with a predictive model sufficiently in advance of the occurrence of diseases or disease risk. Furthermore, he remarked that the prediction of low disease risk may result in a reduced pesticide application with positive economic and environmental implications.

To be more precise and having in mind the objective of reducing the scale in the Enviro tool, the last part of the thesis is related with the period spent at the Polytechnic University of Catalunya – Spain (UPC). During this period, the thesis focused on the characterization of the geometry of the vine with LIDAR sensor, at each growth stage. The phenological stages used are the same used in the interaction between host and pest/pathogens models. The key issue of this part of the work was to find a relationship between the Leaf Area Index (LAI) and the number of LIDAR points in each stage. With the total volume of canopy (m^3) measured, the Tree Row Volume (TRV) (Byers, 1987; Gil et al., 2007; Llorens et al., 2011) was calculated. These last points are import to fulfil the requirements of the Directive 2009/128/EC establishing a framework for achieving a more sustainable use of pesticides, which should be reached by i) reducing the risk and impact of the pesticides use on human health and the environment and ii) promoting the use of IPM and of the alternative approaches such as non-chemical alternatives (Cotillon, 2009). The directive highlights the following concept: "to take all necessary measures to promote low pesticide-input farming, including integrated pest management, and to ensure that professional users of pesticides shift towards a more environmentally-friendly use of all crop protection measures, giving priority to low-risk, non-chemical alternatives wherever possible, and to the products with minimum impact on human health and the environment among the ones available for the same pest problem.

Member States have to ensure that all professional users of pesticides implement the general standards for integrated pest management at the latest by 1 January 2014". Thus adapting the volume of pesticide application to the TRV fulfils the objectives of the directive.

In agreement with the Directive 128 that calls for a pesticide use and risk reduction, the geometry characterization of plants is useful to determinate the amount of volume to spray. In the last years, many authors have worked to adjust the treated area in order to reduce the volume of treatments and keep the same efficacy. (Gil, 2001; Gil, 2003; Gil et al, 2007; Balsari, 2001; Koch, 2007; Llorens et al, 2011). In most cases, the structural canopy comes from many authors' surveys on crop height, crop width, Leaf Wall Area (LWA), and Leaf Area Index (LAI) with or without sensors. Gil (2003) showed that there is an interesting correlation between deposition and LAI and a direct relation between deposition and Tree Row Volume - TRV ($m^3.ha^{-1}$) (Gil et al., 2007; Llorens et al., 2010).

With the aim of increasing accuracy of measurement at each phenological stage and given that Light Detection and Ranging -LIDAR sensors offer an accurate scan of the plants (Walklate et al. 2003; Llorens et al., 2010; Gil et al., 2011), this thesis focused the relationship between both for future adjustments.

LIDAR technology is a remote-sensing technique based on the measurement of the time a laser pulse takes between the sensor and a target and in the recent years has been used for canopy characterization in fruits trees. (Rosell et al., 2009; Llorens et al., 2011). The selection of growth stages was based not only on dose adjustment, but also in order to link these data to mathematical predictive models of pests and diseases of grapevine. Disease models have been developed with the aim of adjusting the pesticide spray while the model simulates the risk of infection (Chellemi, et al., 1991; Rossi et al., 2008; Kuflik et al., 2009). For example, for downy mildew [caused by *Plasmopara viticola* (Berk & Curt) Berlese et de Toni] a potentially destructive disease in grapevine worldwide (Agrios, 2005; Rossi et al., 2008; Dagostin et al., 2011) it is common a 6-9-treatments are applied in the Northern Italy (Borgo et al., 2004). Most of the growers use the empiric rule "3-10" (Rossi et al., 2000) to start the fungicides applications and continue during the season. The rule is based on the simultaneous occurrence of (i) air temperature equal to or greater than 10 °C; (ii) vine shoots at least 10 cm in length; (iii) a minimum of 10 mm of precipitation in 24-48 h (Baldacci, 1947). Rossi et al. (2008) developed a new model based on a mechanistic approach to simulate the primary disease cycle and demonstrated that the sprays can be started only when the model simulates an infection (Caffi et al., 2011).

Gil et al. (2007) showed that the total amount of liquid applied could be 58 % less when taking into account the variations of crop width compared to the constant rate application with similar deposition on leaves. i.e., the canopy volume in BBCH 15 stage is small 0.02 m^3, for that it is important a precise adjustment of the applied dose to the shape and width of the canopy.

This thesis aims at calculating the optimal volume rate of canopy by using the number of LIDAR points in relation with the leaf area index – LAI, obtained through non-destructive methods and number of leaves.

According to many authors (Gil et al., 2011; Walklate et al., 2011; Toews et al., 2012), the LWA ($m^3.ha^{-1}$), WRV ($m^3.ha^{-1}$) and flow rate ($l.ha^{-1}$) was calculated to adjust better the quantity of volume to applied in the orchard, in this thesis the same models was calculated taking into account each phenophases of grapevine.

PART I: OBJECTIVES

I.1General Objective

The general objective of the present dissertation was to model the impact of climate change on the interaction between host phenology and pest/pathogen epidemiology.

I.2 Specifics Objectives

I.2.1 First Year

The goals of the first year were to collect phenological and epidemiological data and select, calibrate and validate models at regional level to study the relationship between host and pest/disease. In relation to the methodological aspects the aim was to create and standardize a geo-database, implementing the models into the web-gis Enviro.

I.2.2 Second and Third Years

In the second and third year the models were run in the Enviro platform with the climate change scenarios. New tools and forms to visualize the data were developed. Finally I followed a stage period in the Polytechnic University of Catalunya- Barcelona – Spain Supervised by Emilio Gil.

PART II: MATERIALS AND METHODS

CHAPTER 1: AREA OF STUDY

The research area was the administrative Province of Trento. The surface of this mountain region is 6212 km^2 (Eccel et al., 2012). The total surface cultivated with grapevine was 13.991 ha in 2010 (Accesses: <www.istat.it>, 2012). The altimetry of the area varies between 70 m a.s.l. in the valley to the 3,769 m a.s.l of the Cevedale peak. The productive grapevine area is mainly located from 200 to 700 m a.s.l. approximately, with a maximum altitude of 900-1000 m a.s.l.

Trentino has a humid temperate oceanic climate, particularly in the pre-alpine areas (Eccel, 2012) that can be ascribed to a Köppen classification "Dfc" (microthermal climate, humid all year round). Inner valleys have a cooler, drier and a more continental-alpine climate falling into a "Cfb" classification (temperate, middle latitudes climate, with no dry season). Precipitations are mostly distributed over two maxima, in autumn (main) and in spring (secondary), although, in some mountain areas, rainfall peaks in summer (Eccel et al., 2012; Eccel and Saibanti, 2005). The total annual precipitation in the low-middle elevations is reported to vary from approximately 800 to 1000 mm. On the hill the precipitations reached 1500 mm in the same period (Eccel and Saibanti, 2005).

CHAPTER 2: ASSESSMENT OF THE SPATIAL RESOLUTION AND TEMPORAL SCALE

2.1 Spatial Resolution/Temporal Scale or Frequency

The spatial resolution was selected considering important aspects as i) the range of the climatic scenarios, downscaling from global to local scale; ii) the accuracy of the environmental models, more precisely the spatial interpolation of temperature; iii) the host-pest/disease models, whose current accuracy was decided to be of secondary importance; iv) the computational requirements in storage and the velocity of processes.

In this work, the spatial resolution scale concepts developed by Seem (2000) were used: the global scale is considered to have a pixel of 2.5° latitudinal × 3.75° longitudinal, a mesoscale of 50 km × 50 km and a local scale of 1 km × 1 km, plus a more detailed sub-local scale of 200 m × 200 m specifically implemented in our work.

The climate change scenarios used were developed in 1999 by the IPPCC panel. Three models were used in this thesis. First the two HADCM3 scenarios A2 and B2 downscaled at a local scale of 1 km of spatial resolution by the "transfer function method" (Eccel et al., 2009). A third scenario was constructed from ENSEMBLES, that first had a 50 km a European–wide scale and later at a resolution of 20 km for specified sub-regions (RT3: Hesselbjerg and Rummukainen, 2009). From these data we downscaled at 200 m × 200 m of resolution, with an R package called "RMAWGEN" specifically created for this project (Cordano and Eccel, 2012). The RMAWGEN was constructed using 49 networks of weather datasets from Fondazione Edmund Mach (FEM), using the media value with partial least squared regression. Here the goal was to use the downscaled scenarios and an interpolation system that represented the weather variable.

The spatial interpolation at 200 m × 200m used to interpolate the weather variable, in this case the temperature, was developed by Uboldi et al. (2008) for Lombardia Region- Italy. The same interpolation was carried out from 61 weather stations from the networks dataset of Meteotrentino from 2007 to 2009 to validate the host and pest/disease models.

The temporal resolution was selected from downscaling scenarios, taken from global scale, which consists of decadal averages of monthly means or totals (Seem et al., 2000).

As above mentioned, the accuracy of the disease models was at hourly frequency, for daily temporal scale, according to the accuracy of downscaled scenarios and the research was circumscribed using only temperature as input. The total accuracy in disease models was because almost all of the models needed not only temperature as input but also relative humidity, precipitation and leaf wetness at hourly scale. The daily scale most commonly used in host phenological models takes into account the sum of daily mean temperature while in pest models the maximum and minimum daily temperatures are usually used. The system can advise when the weather conditions reach a given value that interests us, for disease or pest control. The priority was given to the regional scale and the computational capacity. In the future the same methodology could be used to run the same model with local weather datasets at hourly frequency.

In this thesis, Amazon web-services were used (Elastic Cloud 2). The computational capacity can be described with the following examples, i.e., the storage capacity to contain one year of disease risk maps at daily scale for all province of Trento, at 200m × 200m of pixel, was 700 megabytes and each map had 1.8 megabytes. The total dataset for the simulations have 4.5 terabyte (TB) and upload the information to the server takes just 5 minutes.

CHAPTER 3: HOST-PEST/PATHOGEN-ENVIRONMENT MODELS

3.1 Models

The models used in this thesis were: PHENOVITIS model developed by Caffarra et al. (2010), for the host (grapevine variety chardonnay); the European Grapevine Moth (*Lobesia botrana,* Den and Schiff., Lepidoptera: Tortricidae) model constructed from many submodels and developed by Arca et al. (1993), Quirico et al (1999) and Coop (2009) for the pest; the Powdery mildew [*Erysiphe necator,* (Schw.) Burr.] model, based in the daily progress of latency (Caffi et al., 2011) and disease pressure scenarios models developed for the Trentino Region (Caffarra, et al. 2012) for the disease.

Weather variables like temperature, relative humidity and precipitation regulate the development of host, pest and pathogen. However, only the temperature variable was used in this work, since relative humidity and precipitation are at the moment difficult to project.

The models were coded in R an open source language and environment (http://www.r-project.org).

3.2 Phenological model

PHENOVITIS model developed for grapevine by Caffarra and Eccel (2010) and based on mean daily temperatures as input variable, was used. The model was selected not only because it was developed and calibrated for the Trentino Region, but also because it has a period of 'chilling' and 'forcing' from when starting to calculate the beginning of the growth. Such models use for the 'chilling' period the sum of temperatures below a certain value, for example 6 °C in Botelho et al. (2007). In our case to simulate the 'chilling' period the temperatures used was below 10 °C starting from September of the previous year. When the sum of temperatures reaches at optimal chilling (79 chilling units), the model continues with the forcing units to determinate each phenological stage. The original model was developed with only three phenophases; bud burst (BBCH 08), flowering (BBCH 65) and veraison (BBCH 75). Following the main idea of the present dissertation, i.e., the interaction between host-pest and diseases, more phenological stages were included: in particular, i) the phase in which the plant has 10 cm of shoots or 5-6 leaves unfolded (BBCH 15), ii) the phase in which 50% of the grapes have an average of 8 °Brix (BBCH 78) and iii) the ripening stage (BBCH 89).

From 2009 to 2012, six different sites across the province of Trento were monitored. The selection was made for monitoring places at different altimetry, from 200 m a.s.l. in the valley to the common height in which the grapevine can develop, e.g. aproximately 700 m a.s.l.. Moreover, the study of phenological models was extended to other varieties both early, as Chardonnay, and late, as Merlot, for a total of six varieties: Chardonnay, Merlot, Pinot Gris, Pinot Noir and Sauvignon Blanc. For the objective of this thesis only the Chardonnay variety, which is one of the most important varieties for Trentino, was presented.

PHENOVITIS (2009) model was constructed in Pascal (Delphi). Then the model was then coded in R for analysis and the dataset was run with the different climate change scenarios.
To construct the maps on the website, the same script, was rewritten in JAVA in one matrix. The WPS platform writer in JAVA worked with 52° North WPS, PyWPS and GRASS. The script takes each pixel and runs the model. When the BBCH stage is reached, the output is one Julian day. In this case, the Julian days are coloured by one scale from 1 to 360 days of the year (DOY) from yellow to dark red.

3.3 Pest model

The pest model was constructed from some sub-models based in daily minimum and maximum temperatures. The growing degree day (GDD) was used, which is an accurate unit to measure the heat requirements between two time points of the life cycle using the biologic upper and lower threshold for each growth stage of the moth. Moreover, the choice of using GDD also allows standardizing the information with other regions or plant protection services.
To calculate the GDD, the 'double sine method' was used, where the inputs are the maximum temperature of the day and the minimum temperatures of the previous day and that day, (Coop, personal communication). To determinate the maximum and minimum biologic threshold of the codling moth, and to simulate the time of flight of each generation of *L. botrana*, the correlation estimated by Arca et al. (1993) was used, where each flight was established by the sum of the GDD from 1st January.
The maps of *L. botrana* model were constructed from java statements. The same codec in R can be useful to analyse the data. i.e. to make the climate change scenarios in plots or statistics analyses. One common practice to calibrate or validate the models was to discharge the dataset from a certain latitudinal and longitudinal coordinate, where the pest monitoring was carried to evaluate the output.

3.4 Disease model

Powdery mildew, caused by *Erysiphe necator*, was selected as case study, being one of the major diseases affecting grapevine worldwide (Caffi et al., 2011; Newsome, 2011; Caffarra et al., 2012). For example the mean yield loss per season in Australia can reach 5 to 7.5 % in hot zones and 10% in warm and cool climatic zones (Scholefield et al., 2010). Blake (2009) calculated that the total annual amount of money spent for *E. necator* control, plus the yield loss reached 10% of the entire crop value in California.

With the aim of reducing uncertainties regarding at the daily progress of latency at regional scale the powdery mildew model was run at daily scale with only the daily mean temperature as input. A daily model was selected instead of a more accurate hourly model, but a regional vision of the disease was indeed obtained. The first model used was the daily progress of latency developed by Caffi et al. (2011). It was calculated by fitting data from Delp (1954), Chellemi and Marois (1991) and Gadoury and Pearson (1988), to a quadratic equation with R_{adj}^2=0.89 and normalized root mean square error (RMSE) = 0.0095. These fitted data represent the relationship between the number of days needed at a given temperature to sporulate and it helped us to understand the number of cycles that the disease can make at certain sum of temperatures. The selected model was developed from the relationship between latency period (days), and daily temperature (°C), where the latency period increased at low and high temperatures. According to many authors (Gubler, et al., 1999; Caffi et al., 2011) the lower and upper thresholds were between 5 and 33°C, with an optimum at 21 to 25°C. Gubler et al. (1999) mentioned that conidia germinate at leaf temperatures between 6° and 33°, and the time between conidia germination and production of new conidia by the new colony at favourable temperature periods, takes only 5 days. Conidia and powdery mildew colonies can be damaged by exposure to temperatures above 33°C. The fungus is killed when air temperature rises above 35°C for 12 hours or more and if colonies are directly exposed to UV light (Gubler et al., 1999).

For the objective of this thesis, the daily progress of latency was sufficient to develop the general methodology and to adjust the output. Detailed phenological models of grapevine (PHENOVITIS), was then combined with the disease model. The disease model was run within the data outputs from the host model (grapevine). Specifically from the BBCH 08 (bud burst), when the green shoot tips are clearly visible, to BBCH 78 (when the grape reaches 8° Brix), The most susceptible period is between two weeks before and after the flowering stage (BBCH 65), however infection can start from budburst (in presence of mycelium overwintering in the bud) and berries are reported to be susceptible to *E. necator* infections until soluble solids levels reach 8° Brix; the established fungal colonies are reported to sporulate until soluble solids levels reach 15° Brix (Delp, 1954; Chellemi and Marois, 1991). It means that the host can increase its resistance to powdery mildew as it ages by developing “ontogenic” resistance, which may be active on the whole plant or in specific organs or tissues (Gadoury et al., 2003).

Then a second model, based on disease severity at daily scale, was developed and implemented. It was constructed with monitoring data from the region during the period

2002 to 2008. Starting with the number of cycles in the study area, was established a relationship with a local dataset of disease severity from powdery mildew infections. Two scenarios were developed: one with low-intermediate disease pressure scenario and another one, with high disease pressure. As mentioned before, we selected this model based on the unavailability of hourly projections of weather variables as relative humidity or precipitation, even if other more accurate models exit (Chellemi and Marois, 1991; Kast, 1997; Carisse et al., 2009; Caffi et al., 2011). For example, Caffi et al., (2011) developed an accurate model to simulate ascosporic infections of *E. necator* along the season allowing timing of fungicide applications improvement. Inputs of this model are hourly data of temperature (°C), precipitation (mm), relative humidity (%) and duration of wetness (hours) starting from 1st of January.

This thesis does not include many aspects that can be developed in order to improve the accuracy of the whole system. i.e., a map of sensibility can be developed for each variety at a regional scale, maps that represent one classification about the rate of initial inoculum from past databases of each orchard; moreover, other important weather variables like relative humidity, wetness duration and rainfall can be incorporated. According many authors (De Wolf et al., 2007; Caffi et al., 2011) temperature and moisture (meaning both precipitation and relative humidity) are the inputs for most of the diseases models.

However, this thesis reached the goal of being more accurate in term of spatial scale (below 200 meters of resolution). Future work may include the assessment of the models based on hourly data run in the same ENVIRO.

3.5 Construction of risk maps at 200 m based on the combination of host and pest/disease models.

3.5.1 Improved Risk Maps

The result of the analysis can be an individual output (i.e., a map of the day when the model reaches a determinate BBCH stage, or the day of the year that the moth reaches a specific stage) or originating from models interactions (i.e., mildew model that run from BBCH 08 to BBCH 78). The maps were improved as follows. The maps were constructed based in maps of temperature into a grid at 200 m × 200 m. The total amount of pixels that cover the province was 156887. The location projection was created in Universal Transverse Mercator (UTM), zone 32 North – datum World Geodetic System (WGS84). The interpolation is based on the optimal three-dimensional interpolation and suitable for observations from high-resolution local networks (Uboldi et al., 2008).

The meteorological information to create the maps is taken from the 61 Meteotrentino weather stations and the information to cross-validate the models is taken from 21 first order weather stations and 46 second order weather stations provided by Meteo-IASMA. The differences between first or second order are in the variables measured and the frequency of the observations. In the first order stations the important variable are recorded either hourly or by self-registering instruments; in the second order less variable are observed and the frequency is hourly or less frequent.

The following models were implemented to create the maps: Powdery mildew (Caffi et al., 2011; Caffarra et al., 2012), *Lobesia botrana* (Allen, 1976; Arca et al., 1993; Coop, 2009) and *PHENOVITIS*: phenological growth stages of grapevine (Caffarra et al., 2010).

In order to make the risk map the codec were run in programming languages such as R (Gentleman et al., 1997), GRASS GIS (Neteler et al., 2008, Neteler et al., 2012), Java GIS toolkit (Gosling, 1984), PyWPS (Becchi et al., 2006), and 52° North WPS in the ENVIRO platform starting the Web Processing Services (WPS). The output of the maps was a classification, index or DOY from the model. The models were run in R language and GRASS statements to validate the model in spatial form with the sampling performed in the region. The scripts were coded into JAVA language to upload the output in the website. These scripts allowed analysing data with the weather variables and the forecasted climate change scenarios. The maps were constructed from JAVA language or GRASS statements running in the WPS that was specially created for the Enviro web-gis. Originally, all models maps were based on a daily frequency. Then if a monthly or annual output is needed, it can be calculated from the daily outputs.

3.5.2 Host model maps

The host model is based on the daily temperatures, 'chilling' and 'forcing' phases were used and when it reaches a certain level, the growing stage is reached. The map has the same structure that the model. The output in each pixel of the matrix is a number where the first value is the BBCH stage and then the Julian day. The phenological growth, BBCH scale (Lorenz et al., 1994) was used to standardize the phenological information. The colours used for the DOY were scaled from 1 to 360 days with a step of one colour per day, from yellow to red.

3.5.3 Pest model maps

The Pest maps were constructed with the same methodology than host maps. However the inputs of the model were here the maximum and minimum daily temperatures. The codec takes each temperature and calculates the GGD, then when the pixel reached a certain sum of GGD the output is printed. The printed output can be the number of flights (1 to 4) or the DOY when the pixel has reached the specific flight number. The colour of the maps could be by flight with the scale 1 to 4 (from yellow to red) or with one scale by the number of days that the pixel reaches the specific flight number.

3.5.4 Disease model maps

The disease maps were implemented using the same methodology as above. They show the interaction between the host and the disease, because the calculation starts when the pixel reaches bud burst (BBCH 08) and ends when the host reaches 8° Brix (BBCH 78). That means that the disease model run into the phenological model. From BBCH 08 the daily progress of latency was calculate using the daily temperatures, and when the model reached one disease cycle, a map can be construct. The colour of disease cycle had one range from 1 to 15 from yellow to dark red. The outputs of disease risk can also be scaled from 1 to 100 % or 0 to 1 non dimensional scale.

3.6 Calibration and Validation of Diseases / Pest Models and Phenological Grape Models

In the calibration we compared the outputs of the models with the monitored variable, and based on the result the offset and tolerance of the model was adjusted. The dataset for this part of the work is different than the validation dataset.

A model validation test is the ability of the model to predict future behaviour. Validation requires comparing the model predictions with information other than the ones used to calibrate the model. It is important to mention that a project at regional scale needs a large dataset to be statistically more representative. Model predictions and measured data, trends over time are one of the most used tools to evaluate model performance. In the calibration or validation, qualitative information can be useful. Only a large number of experimental data allows a meaningful evaluation of model performance in statistical terms. The lack of data, as a pest monitoring site closer to the weather station or a systematic monitoring, makes the calibration process more difficult.

In our case, given that models were adapted from another region, it was necessary to calibrate and validate them with data from the region. The output of the models was therefore compared with local dataset of host, pest and disease monitoring. For example, the parameters estimated in phenological models were the standard deviations (SD) and Mean Absolute Error (MAE) measured in days, between the minimum and maximum date of the observed and simulated phenophases. In pest models, a Bayesian analysis (Yuen and Hughes, 2002) was used. Contingency table, sensitivity, specificity and likelihood ratios of the model predictions were evaluated.

In the models the temperature requirements or threshold for each growth stage was assumed to remain constant over time. This last point is questionable when the variables are live organisms, which can adapt to the environment. For the purpose of this thesis, we did not assess the degree of adaptation of the organisms to the environment.

CHAPTER 4: CLIMATE CHANGE SCENARIOS

Two approaches were used to downscale scenarios, both based in the Special Report on Emission Scenarios (SRES) of the Intergovernmental Panel on Climate Change (IPCC, 1999), where mean global temperature is estimated to increase between 1.8 and 4.0 °C (with a likely range of 1.1 to 6.4 °C), by the end of the present century, depending on the greenhouse gas emission scenario (Easterling et al., 2007).

Two of the forecasted scenarios were based on the output of the Hadley Centre's Atmosphere-Ocean General Circulation Model (AOGCM). HadAM3 (Pope et al., 2000) was used: the A2 and B2 created at 250 km × 350 km of resolution. (Russo and Zack, 1997).

The statistical downscaling algorithm used was the "transfer function method" (Eccel et al., 2009) and it was applied by each series. This methodology was based on two steps: i) a linear interpolation based on the triangulated irregular network technique where each geographical point maintained the linear trend and ii) the daily transfer function based in the General Linear Model (GLM) to obtain the daily frequency.

The special Report on Emission Scenarios (SRES) from IPCC describes A2-B2 scenarios (see cit. <http://www.ipcc.ch/ipccreports/tar/wg1/029.htm>, for detailed information). Briefly, the A2 storyline and scenario family describes a very heterogeneous world: the underlying theme is self-reliance and preservation of local identities, fertility patterns across regions converge very slowly, which results in continuously increasing population. In this scenario economic development is primarily regionally oriented and *pro capita* economic growth and technological change more fragmented and slower than other storylines.

The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social and environmental sustainability. It is a world with continuously increasing global population, at rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the A1 and B1 storylines. While the scenario is also oriented towards environmental protection and social equity, it focuses on local and regional levels.

A third scenario was constructed from ENSEMBLES, which first had a European –wide scale and a resolution of 50 km and a resolution of 20 km for specified sub-regions (RT3: Hesselbjerg and Rummukainen, 2009).

The ENSEMBLES project developed an ensemble climate forecast system, to be use across a range of timescales (seasonal, decadal and longer) and spatial scales (global, regional and local). The modelling system is used to produce probabilistic scenarios of future climate for a quantitative assessment of impacts in a range of applications, in order to provide policy-relevant information. (Accesses: <http://www.ensembles-eu.org>, 2012). The downscaling model, which was mentioned above, was constructed using the mean value with partial least squared regression (Cordano and Eccel, 2012).

The datasets used to calibrate the models, were the place where the pest was monitored. Some were outside the province and the weather dataset to calibrate the models was obtained from the Agenzia Regionale per la Prevenzione e Protezione Ambientale del Veneto – ARPAV (Dolcè – Verona) and from the Servizio Meteorologico della Provincia Autonoma di Bolzano and Südtiroler Beratungsring für Obst- und Weinbau.

3.2 Temperature maps

The temperature maps were constructed using the three-dimensional interpolation developed by Uboldi et al. (2008). The dataset used from 2001 to 2009 was from Meteotrentino. To test the performance, the cross validation was made with the weather stations from Meteo – IASMA. Then the datasets used was constructed from the downscaling scenarios and the FEM networks.

CHAPTER 5: STANDARDIZATION GIS NETWORK DATABASE AND MANAGEMENT OF THE DATASETS

5.1 Weather datasets

The grid of the region has 153178 pixels in total, to process one year data takes 5 minutes. The total storage of weather data is 4.5 TB.

5.2 Disease and Pest datasets

All maps of biological information are stored in 1 TB.

Each disease, pest and host assessment value (measured variable) is linked to the geographical position, with latitudinal and longitudinal information and has a specific ID to make the traceability and the precision management of each process easier. Each assessment value is also linked to the cadastral information. The dataset in PostGIS is available to users and could be analysed with GRASS GIS.

Standardizing all continuous monitoring of pest and diseases is an advantage, the search time has been reduced, because all information has one format and is in the same server.

For the samples performed in the past that were not linked with latitudinal and longitudinal data, it was necessary to take the geographical position and store all data in the new server. It was an advantage that the people that made this job, now work in the same place.

5.3 Computational requirements for dataset

The capacity of the computational equipment and the speed of process (CPU speed, RAM and disk storage) is crucial as reported by several authors (Russo and Zack, 1997). ENVIRO platform solves issue of speed of process, because the full maps of each pest, per year, in the entire region need only 5 minutes.

CHAPTER 6: ENVIRO WEB-GIS DEVELOPMENT BY FBK – ITALY

A decision support systems (DSS) in agriculture, more specifically in plant protection, commonly has as inputs weather conditions (different variables) from a closer local weather station and epidemiological models that run with at a different spatial and temporal scale (Chakraborty et al., 2000). The ENVIRO tool was created to be user-friendly for two types of users: users who take decisions (enviMapper) and researchers interested in studying models and interaction among different organisms (enviModel). Being the web mapping interfaces a dynamic system, enviDB and enviGrid are the tools used to understand and study the dynamics of actual and future agricultural systems.

The data in Enviro can be aggregated in daily, monthly and annual values, municipal or valley community and presented in production unit and row scale. Enviro WEB-GIS is a multiscale framework where data and models are harmonized and aggregated in space and time using different resolutions. In space, the resolution range from 1 m of the digital terrain model to 200 m of temperature maps. The Open Geospatial Consortium (OGC) Web Processing Service provides rules for standardizing how inputs and outputs for invoking geospatial processing services was used as web service (Accesses: <

http://www.opengeospatial.org/standards/wps >, 2012). This part was developed in collaboration with Fondazione Bruno Kessler in Trento.

CHAPTER 7: LIDAR SENSOR

7.1 Experimental Vineyard

Catalunya region is one of the most important wine-growing areas in Spain with Mediterranean climate. The altimetry of the researched area was 161 m a.s.l. close to the sea. A field experiment was located in a vineyard in Sant Pere Ribes (399999,4570579 UTM 31N-WGS84). The distance between rows was of 2.9 m and between the plants on the row it was 1.4 m. The grapevine variety was Chardonnay and cordon was the trellis system.

7.2 Manual Canopy and Sugar Measurements

The geometry characterization was determined from manual measurements as crop height, crop width and the number of leaves in each stage of growth. The measuring was carried out randomly in four sites with three repetitions in each position. The measuring started when the shoots were 10 cm of long and five/six leaves were unfolded (BBCH 15), and continued during the growing season (from April to August): inflorescences fully developed and flowers separating (BBCH 57), full bloom (BBCH 65), pea-sized berries (BBCH 75), the berries at 8° Brix (BBCH 78) and ended when the berries were ready to be harvested (BBCH 89). Leaf Area Index (LAI) was measured indirectly using pictures of leaves from a four representative samples in each phenological stage using ImageJ 1.45 open source software (NIH, 1997).

Our routine was constructed one macro with ImageJ software to remove the background of the leaves to calculate the area. Basically, the scale was set then the threshold was adjusted using Image>Adjust>Color Threshold statements of the ImageJ, and finally the area was calculated with the Particle Analyzer to calculate the area.

The LAI was calculated as follows:

$$LAI\ (m^2/m^2) = \text{Number of leaves/plant} * \text{Leaf Area}\ (m^2)\ /\ (\text{row spacing}\ (m) * \text{in-row distance}\ (m))$$

The degree Brix was measured using the optical refractometer Milwaukee- MR32ATC. It measures the concentrations of soluble substances in aqueous solutions, and worked using the principle of light refraction through liquids.

7.3 LIDAR LMS-200 – DGPS GARMIN

LIDAR scanner was placed at 1.10 m from the plant line and at 0.7 m above the soil. The total scan distance in each test was of 1.85 m on both sides of the plant (north and south position). Three different measurements were taken on each side of each sampling point, with a total of 6 scans per plant at each phenological stage. Each field sample has been positioned with a differential DGPS Garmin. DGPS antenna was located on the front of the measured plant (centre). The geo-positioning data obtained, was corrected during post-processing in GRASS GIS using the orthophoto. The laser scanner used was a LMS-200 model (Sick, Dusseldorf, Germany), a fully-automatic divergent laser scanner based on the measurement of time-of-flight (TOF) with an accuracy of ± 15 mm in a single shoot measurement and 5 mm standard deviation in a range up to 8m. The time between the transmission and the reception of the pulsed near-infrared laser beam is used to measure the distance between the scanner and the reflecting object surface. The laser beam is deflected by a rotating mirror turning at 4500 rpm (75 rps), which results in a fan shaped scan pattern where the maximum scanning angle is 180°. (Llorens et al, 2011).

7.4 Canopy characterization with LIDAR sensor.

Dataset was processed with LidarScann v.1® software. The configuration used was continuous scan at ratio 38400 and angle 180° at 0.5°. Statistical analyses were performed with R. Actually; one package called PROTOLIDAR (PRocess TOol LIdar DAta R v.1) was developed with all functions for future research and users.

The package has the following functions:

Extract_plant_grapevine_function: which cuts the excess data and extract grapevine plant from all dataset.

Extract_plant_3D_function: helps to position the axis in the centre of the plant.

Height_canopy_function: to measure the height of canopy from the LIDAR scan.

Width_canopy_function: to measure the width of canopy from the LIDAR scan.

Number_LIDAR_points_function: to calculate the number of points into the canopy.

LAI_function: to calculate the leaf area index.

LWA_lidar_function: to calculate the leaf wall area.

TRV_lidar_function: to calculate tree row volume in m^3*ha^-1.

Rotate_function: to rotate plants to match with the planting line.

Replicate_plants_function: to replicate plants.

LIDAR_data: is the dataset of the LIDAR scan. Represent the grapevine plant (BBCH 65).

The methodology employed with R was cutting the surplus areas because LIDAR scan read 180° and each sample performed in the orchard read more that one row. This surplus area of the canopy was cut and the height, width, volume and number of LIDAR points were calculated.

Analysis of variance and differences between means were tested according to Tuckey test ($p < 0.05$). From these measurements (manual and LIDAR) the Leaf Wall Area (LWA) in $m^2.ha^{-1}$ was calculated and the relationship with LIDAR points was constructed as follows:

$$\text{LWA manual } (m^2.ha^{-1}) = 2^* \text{ Canopy height manual (m)} * (\text{ground area } (m^2)/\text{row spacing (m)})$$

$$\text{LWA lidar } (m^2.ha^{-1}) = 2^* \text{ Canopy height LIDAR (m)} * (\text{ground area } (m^2)/\text{row spacing (m)})$$

Where ground area is 10000 m^2 = 1 ha

Another parameter calculated was the Tree Row Volume ($m^3.ha^{-1}$) this method calculates the optimal volume rate (Steefek et al., 2000) according to the canopy volume per unit ground area ($m^3.ha^{-1}$) (Gil and Escolà, 2009). TRV manual was calculate from data measured in manual form, that mean the height and width was measured in each plant, TRV LIDAR used the data collected for the sensor.

$$\text{TRV manual } (m^3.\ ha^{-1}) = \text{crop height manual (m)} * \text{crop width manual (m)} * 10000\ (m^2.ha^{-1}) / \text{row spacing (m)}$$

$$\text{TRV LIDAR } (m^3.\ ha^{-1}) = \text{crop height LIDAR (m)} * \text{crop width LIDAR (m)} * 10000\ (m^2.ha^{-1}) / \text{row spacing (m)}$$

CHAPTER 8: OPEN SOURCE SOFTWARE USED

The open source software's, languages and environments used were: GRASS GIS (Geographic Resource Analysis Support System). GRASS open source GIS was used for maps production, spatial modelling, geospatial data management and visualization. It is released under the GNU General Public License (GPL). Grass statements were lunched into the WPS and the maps were constructed. R is a language and environment for statistical computing and graphics and free software. It was inspired by the S environment, which has been principally developed by Chambers et al., in 1992. R can be extended via packages available through the CRAN family. For computationally –intensive tasks, C, C++ and Fortran code can be linked and called at run time. Plots and graphs to model the interaction between host/pest-disease/environment with the climate change scenarios were developed using R.

JAVA GIS toolkit (GeoTools API): is a library, a Java language application-programming interface (API). This toolkit helped to manipulate geographic information and was structured following the specifications of the International Organization for Standardization (ISO) and the Open Geospatial Consortium (OGC).

ImageJ: is a Java-based image-processing program developed at the National Institutes of Health (NIH- USA). It was created to process images in many formats (TIFF, PNG, GIF, JPEG, BMP into others)

The environment of ImageJ worked with Java plugins and recordable macros, this last important to re launch the procedure because first it was recorded. LAI was calculated using a macro developed with this goal.

PART III: GENERAL RESULTS AND DISCUSSION

CHAPTER 9: ENVIRO AND MAPS

ENVIRO is a suitable tool, which can offer a lot of information addressed to different users.
The outputs maps produced by ENVIRO can be summarized as follows.

- Vectorial map of the study area: Trento province and some monitored sites of the region in points (Fig.1.).
- Raster maps of temperature, at daily scale for the region (Fig.2). The temperature maps were available at daily scale all years. Mean, maximum and minimum temperatures were represented with a range of colours where red are indicate warm temperatures and blue cold temperatures.
- Digital Elevation Model at 200 meter of resolution (Fig.3). The altimetry was represented in blue colours for the bottom valley and maroon colour for the mountains.
- Toponimus (Fig.4). Enviro has the option to show the name of the cities, monitoring places and others.
- *L. botrana* Maps (Fig.5). The maps represented the number of flights a fixed date: 21/09. Yellow colour represented the first flight, orange the second, red the third and dark red the fourth. The same output but in a graph, with the forecasted climate change scenario (Fig.6) shows that when the pest was simulated together with the phenological model, the output in San Michele all'Adige, using A2 scenario, showed that the number of flights were only two. Three flights occur in the end of the growing season.
- Phenovitis Maps (Fig.7). The maps represented each day of the year. They represented a hypothetical region of growing, because only temperature was used, that means that

cities and rivers were not represented. The altimetry of the maps is restricted to altitudine up to 1100 m a.s.l. to estimate the potential growing area.

- Maps of Interaction between grapevine phenology and *E. necator* (Fig.8). The beginning and end of BBCH stages (BBCH08 to BBCH 78) delimit the time of mildew models. In this case, outputs represented in this case the number of cycles that the disease can make at certain sum of temperatures.

Examples of maps under past and future climatic conditions are the following:

- Map Chardonnay phenology: from 2000 to 2010 (Fig.9). The maps are the output of the forecasted climate change scenario using ENSEMBLES. The scenario represented a warm period.
- Map Chardonnay phenology: from 2070 to2100 (Fig.10). The same methodology used in the Fig. 9 but during the period 2070-2100.
- Map Merlot phenology: from 2000 to 2010 (Fig.11). The same methodology used in Fig. 9 but using grapevine variety Merlot (unpublished model) during the period 2000-2010.
- Map Merlot phenology: from 2070 to 2100 (Fig.12). The same methodology used in the Fig. 11 but during the period 2070-2100.
- Number of powdery mildew cycles using past weather data: from 2002 to 2007 (Fig.13). The output represented the number of cycles that the disease can make at certain sum of temperatures.
- Number of powdery mildew cycles: from 2070 to 2100 (Fig.14). The maps are the output of the forecasted climate change scenario using ENSEMBLES.

Graphics with data from one pixel can also be produced as follows

- Disease Forecast Trend (Fig.15). This output was published in Caffarra et al., (2012).

A view of the initial web-gis platform Enviro, where the user can select the proper profile is shown in Fig.16. In the following Fig.17 the flexibility of views of the website can be appreciated. It showed the possibility of using different aggregations scales, and overlapping the data. The information can be represented in raster maps, images, points and vector maps. In this case, the point maps overlapped. In the following figure the view of monitored sites in Enviro is shown (Fig.18). Examples of a script in R showing one of the functions created and a script in JAVA with a common WPS statements in GRASS are shown in Fig.19 and 20, respectively.

CHAPTER 10: LIDAR MEASUREMENTS

Results showed that LIDAR is a powerful tool that helps to describe the volume canopy.

Beginning the dataset obtained from the scanning of the grape a statistical correlation with significance between numbers of LIDAR impacts and LAI in each growth stage was constructed as shown in Fig. 21.

The dataset LIDAR, was analysed using R. A package call PROTOLIDAR in R, is being created. The output of this package not only helps to calculate volumes of plants but rather the output could be represented in two or tree dimensions (2D - 3D) canopy maps in GRASS. (Fig. 22 - 23).

In R environment the canopy of each growth stage was represented like shows Fig.24 where we can see the relationship between height and width measurement in meters and the variability that reached the vine in each phenological stage. A similar view but using the relationship between height (m) and front view (m) (Fig.25) was constructed.

Other graph considering only the canopy volume was elaborated, for example the relationship between the numbers of points measurement with LIDAR sensor and LAI obtained from manual measurement (Fig.26).

Using the same dataset the TRV and the Leaf Wall Area (LWA) was calculated and enabled us to build the graphs shown in Fig.27 where the top left represented the TRV obtained from manual measurement, top right show the TRV calculated with data measurement with LIDAR. The bottom left LWA obtained from manual datasets and the corner bottom right are the LWA using LIDAR datasets.

Discussion

Information and Communication Technologies (ICT) can make agriculture more efficient and reduce the risk of losses thanks to real time communications, the reduction of transport needs and the dissemination of best and safer practices. The use of ICT has several advantages on the management of risk and the environmental sustainability of agriculture, among others:

- it increases knowledge and thus reduces the uncertainty intrinsic to biological and environmental processes;
- it delivers information in a faster way, even in real time;
- computational processes can support agricultural research and development through the sharing of different experiences which lead to interdisciplinary work and the co-learning among players;

- its social networking applications make a better use of time, reducing the cost and pollution associated with travelling.

The Enviro tool was developed to help in all the items above. The current results show all the various outputs that the users may get. In the future researchers may develop their own models, because the programming language is easy and dynamic.

This thesis showed the different steps needed to reach a powerful web-gis platform at regional level. The climatic variables and phenological/epidemiological models have been used to obtain clear and simple outputs useful to project the future risk of pests and diseases in a view of climate change. The system can also be used to process real-time data in order to visualize the current behaviour of a specific pest/pathogen or phenological stage according to models. The information presented on each map or graph indicates a date when the model reaches a certain growth stage or a non dimensional value that represent a risk (the trend of the models with the projected climate change scenarios. It can be used for decision-making in the long term, but also to monitor the current situation (for example in case of planning the scouting for a disease).

The outputs could be visualized and analysed in few seconds, but the process to implement the specific models is much longer. First one has to make the protocol of each standardization, and coded and to implement the calculations in a way that the calculation process is as fast as possible. Calibration and validation of each model is always necessary, so one has to consider that a sufficient number of monitoring samples should be available. The monitoring samples must be obtained from the entire studies area. Collecting biological monitoring samples is always time consuming and expensive.

The selection of the results from each model should be discussed with the user. For example the time of each flight of *L. botrana* could be visualized at daily frequency, with the aim to advise when each zone reached the amount of temperature necessary to reach a new generation of the insect or the same output can be seen with annual frequency, being able to estimate the risk or the number of generations than could be reached.

The users can see the outputs in maps, graphs or, if they need to know a specific latitudinal and longitudinal point, they can release the information in .csv or .txt format. Then they can run the data in R to make the statistical analysis.

The interaction between host plant and disease models was modelled, for example running the model of the disease within the date output obtained from the plant phenology model or by running powdery mildew model from bud break to 8° Brix. Running the model within this time period helps to evaluate the actual number of dangerous disease cycles. Another interaction could be obtained by running the European moth model within susceptible phenological stage and see for example how many days the larvae stage growth and the optimal treatment time.

LIDAR measurements can help in being more accurate in the recommended volume rate per treatment. A future challenge is to link the LIDAR radar and the sprayer machine for real time variable rate doses. One previous step at this option can be achieved by scanning with LIDAR, constructing the prescription maps and then, from this output, obtain the volumes of application.

PART IV: CONCLUSIONS AND RECOMENDATIONS

Enviro is a powerful tool for research, to model climate change potential impacts and to help in better timing treatments at the optimal volume of application based on pest/disease risk and plant canopy. The web-gis allow map visualization of the models shows trends under climate change scenarios, with the adventage that each point of the grid can be analysed with latitudinal and longitudinal reference. The outputs could also serve to plan pest or disease managements by taking into consideration the specific weather conditions.

The computational capacity of Enviro makes each analysis process of the epidemiological models more fast and precise. The standardization process gave trustable outputs. However in the future, if projected hourly relative humidity and precipitation will be available, more precise models requiring more specific weather variables could be implemented.

The theoretical volume applied in each phenological stage could be adjusted using LIDAR. Height and width measured with this tool could be used to determinate the variability of each plant and identify the optimal variable rate doses of application. Maps in three dimensions could be an easy way to display data for the growers.

The combination of better timing of treatments by the use of plant and pest/disease models and calibration of the optimal spray volume on the canopy size can help in reaching a more sustainable use of pesticides.

Highlights for the future

This thesis opens new questions, which can be addressed in the future.

- Quantifying the spatial distribution of disease in agreement with De Wolf (2007) the description and quantification of disease provides important information about the potential sources of inoculum. The primary inoculum is the most important factor that has to be controlled in monocycles diseases to reduce the total risk, and in the polycyclic diseases it is necessary to quantify the level of inoculum into the orchard.

- According with Campbell (1990) predicting when a disease will raise to a threshold that causes significant economic loss in each grid point is crucial for pest management. Enviro needs other inputs to help to reach that knowledge, like the variety types within the production unit or a grid with the degree of susceptibility to disease or resistance of crops.
- Maybe that with more samples performed in the land, the output of these models can be validated and the question made by Seem et al. (2000). Answered. They asking about, it will be possible to estimate changes in geographical distribution of pest and disease by running pest models for all sites where the downscaled weather data is produced?

To answer to this question, this thesis proved that the epidemiological models have a different output each year but the spatial variability cannot be proved because the monitoring datasets are not large enough. Each valley shows a different time, in which the pest reaches the sum of degrees days according to each flight, but: what is the total distance that the month can fly? What is the distance at which the plague may oviposit?

PART V: CANDIDATE'S PUBLICATIONS

Caffarra A, **Rinaldi M**, Eccel E, Rossi V, Pertot I. 2011. **Modelling the impact of climate change on the interaction between grapevine and its pests and pathogens: European grapevine moth and powdery mildew**. Agriculture, Ecosystems and Environment. 148, 89:101.

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E Eccel, A Caffarra, E Cordano, **M Rinaldi**, V Rossi, R De Filippi, S Droghetti, C Zarbo, C Furlanello, M Storari, C Gessler, R Tomozeiu, I Pertot, 2012: **ENVIROCHANGE: Simulazione degli effetti fitosanitari del cambiamento climatico sulla vite in Trentino**. Italian Journal of Agrometeorology, Extended Abstracts del XV Convegno Nazionale di Agrometeorologia, Palermo, 5-7 giugno 2012:43-44

A Caffarra, **M Rinaldi**, E Eccel, I Pertot, 2012: **Cambiamento climatico e tignoletta della vite: come cambiera' l'interazione pianta parassita in Trentino?** Extended Abstracts del XV Convegno Nazionale di Agrometeorologia, Palermo, 5-7 giugno 2012:39-40.

PART VI: EXPERIENCE ABROAD

Polytechnic University of Catalunya. Barcelona. Spain: **6 months**. Referent PhD. **Emilio Gil Moya**, Department of Agricultural Engineering and Biotechnology (emilio.gil@upc.edu)

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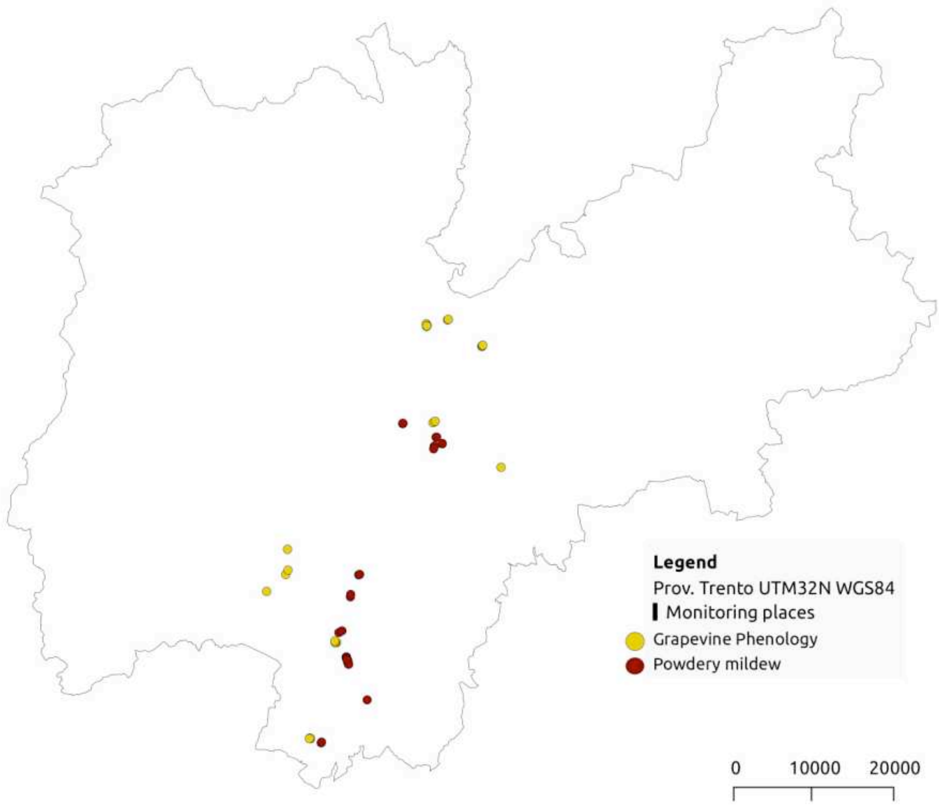

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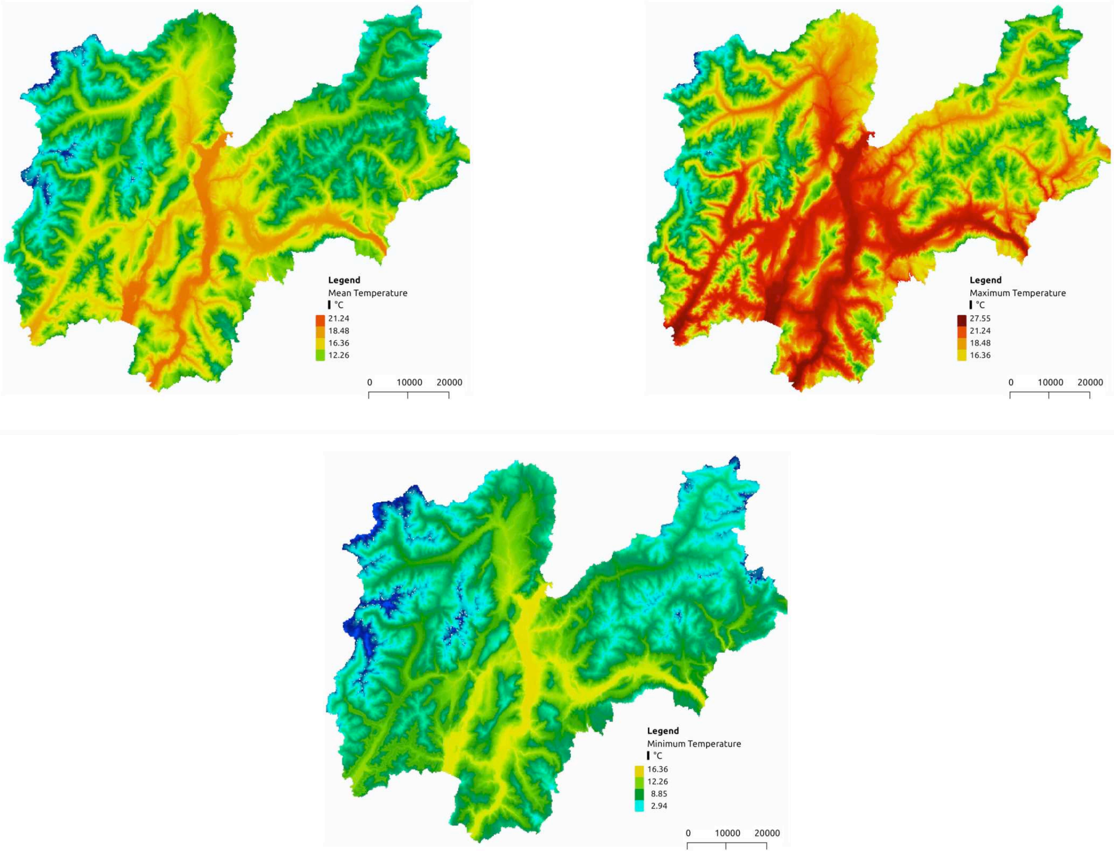

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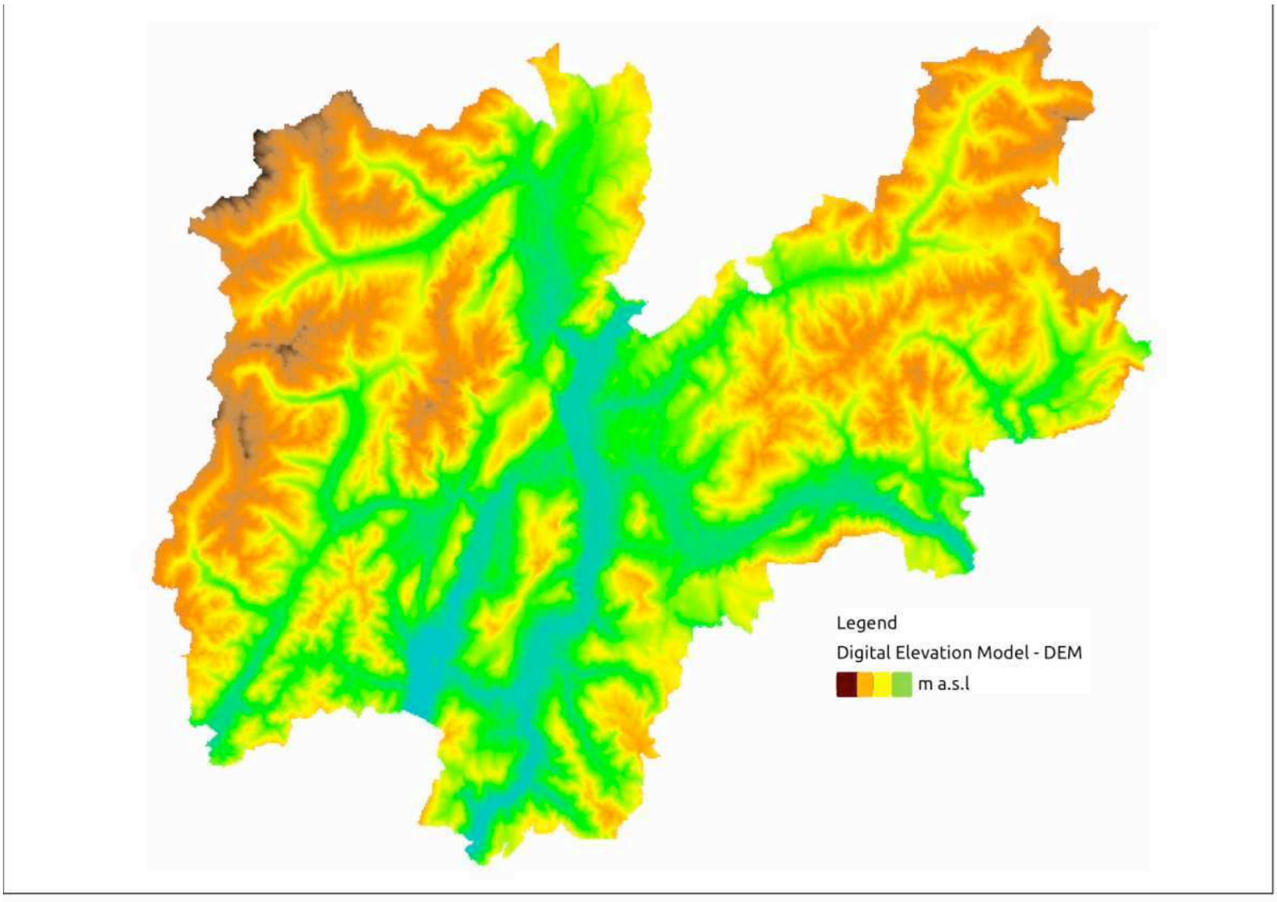

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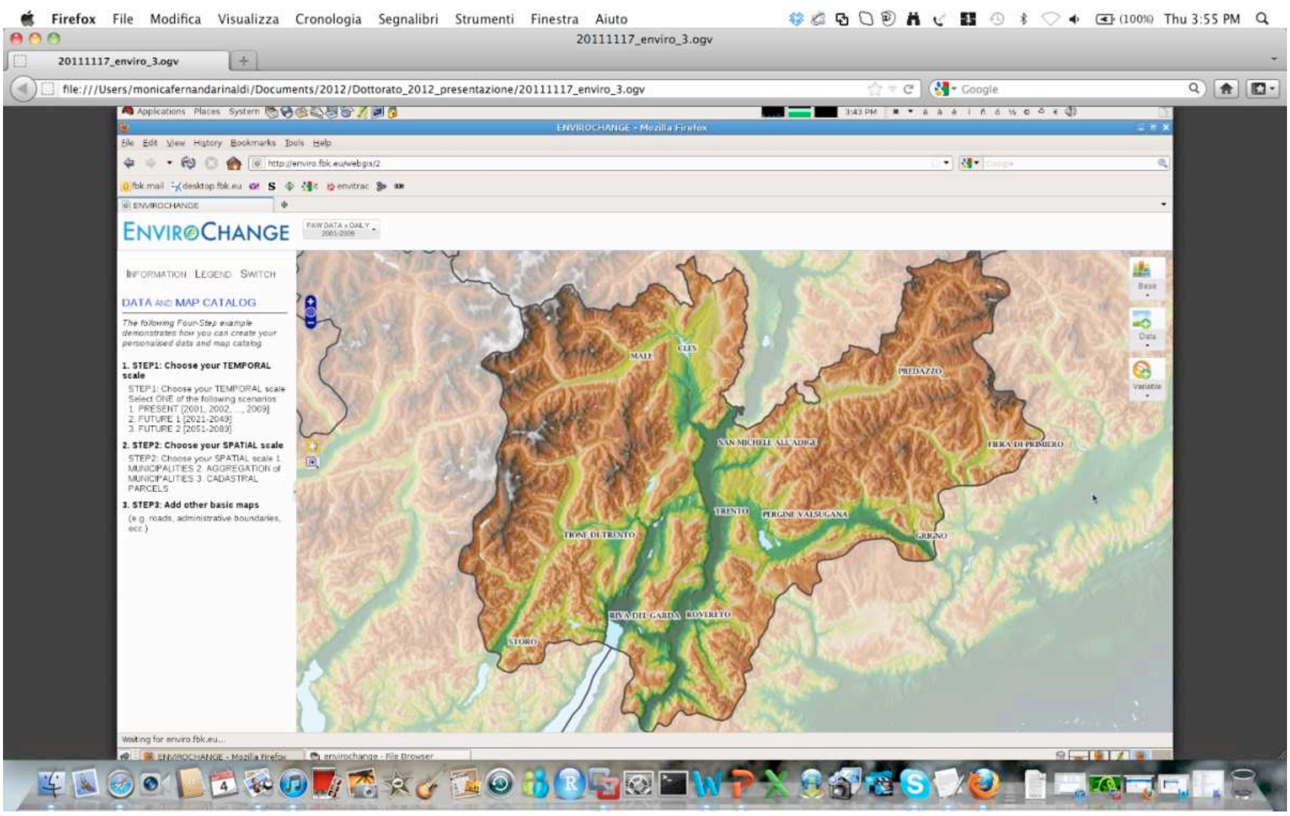

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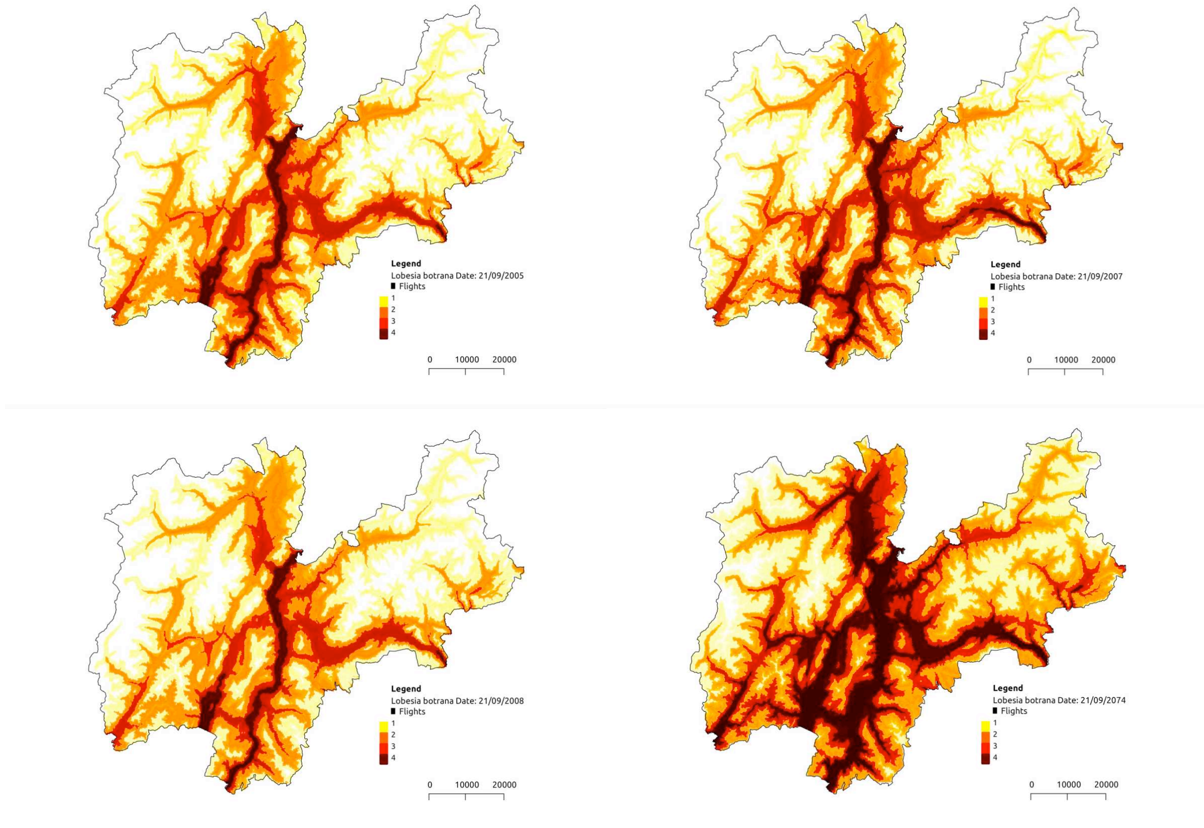

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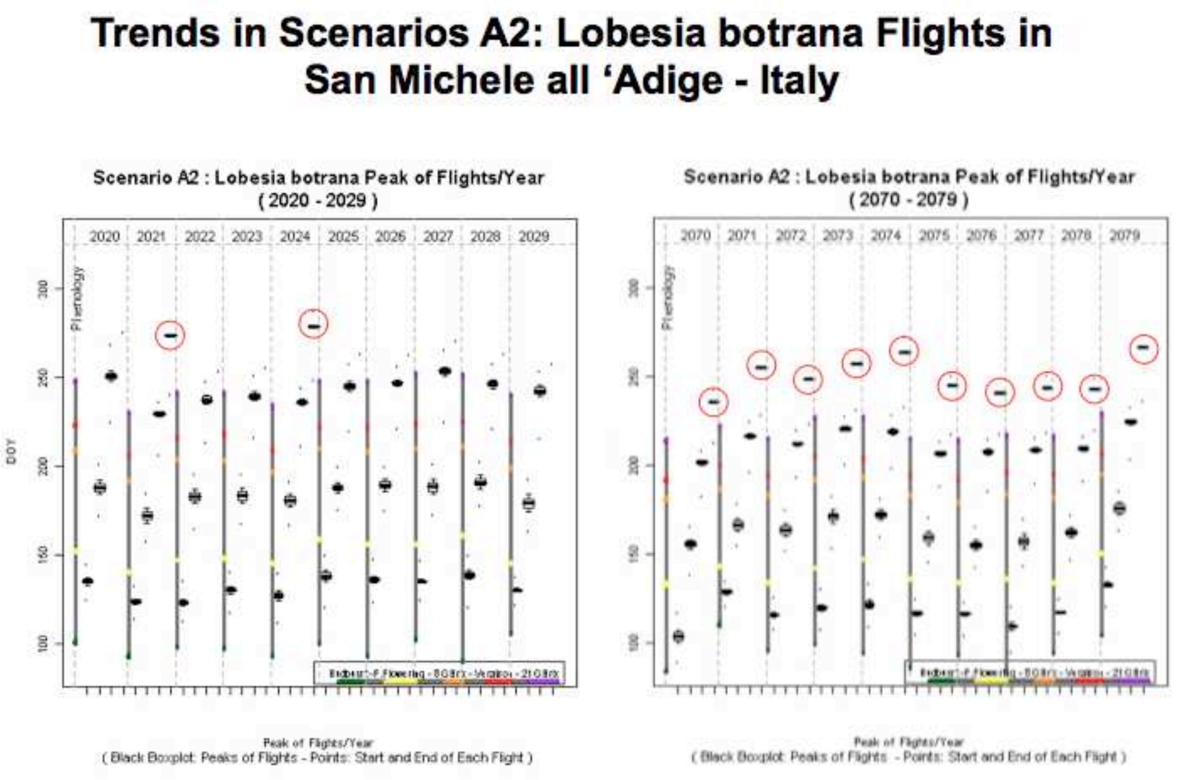

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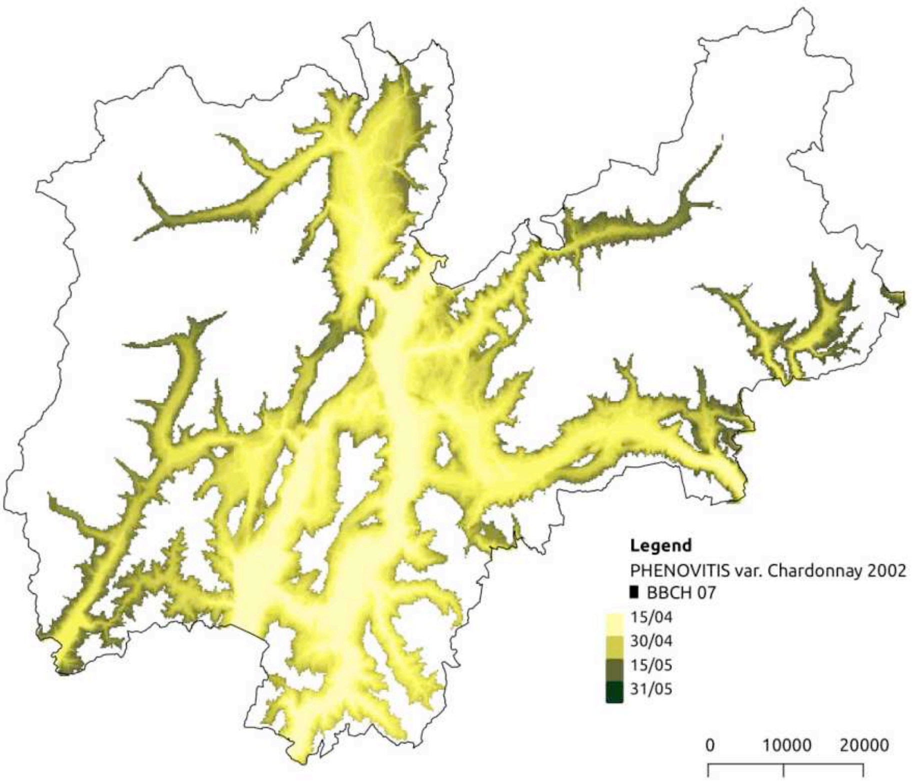

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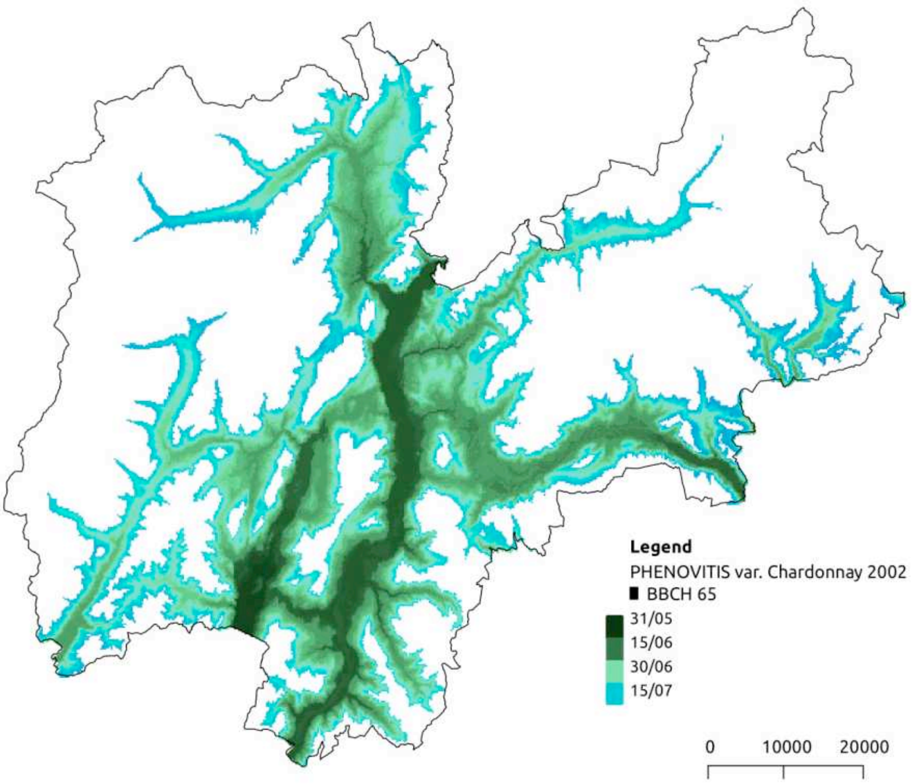

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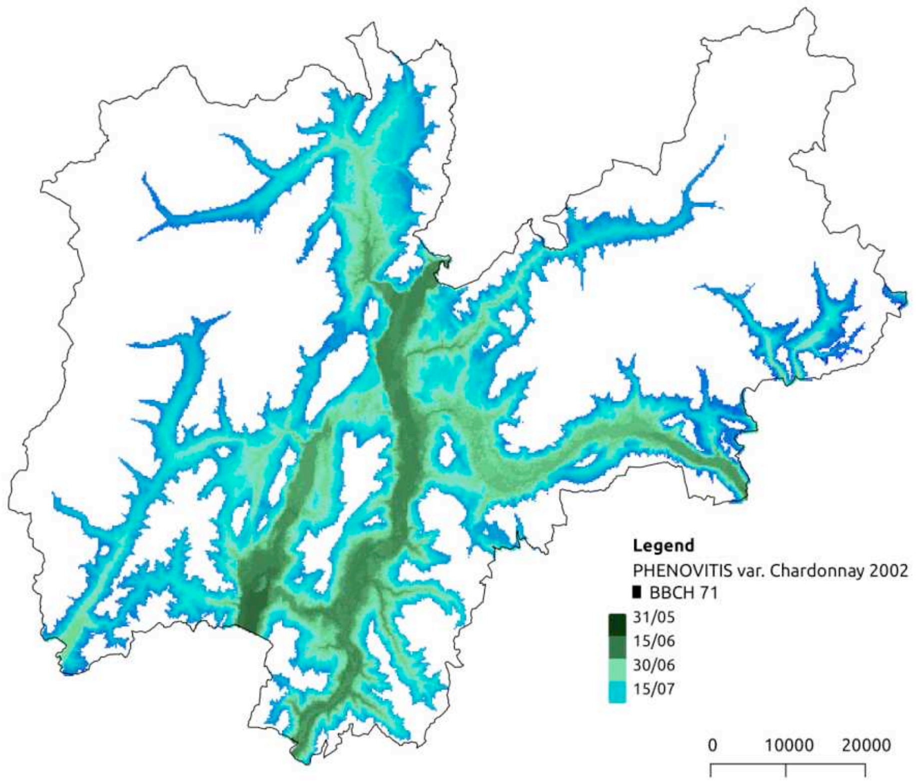

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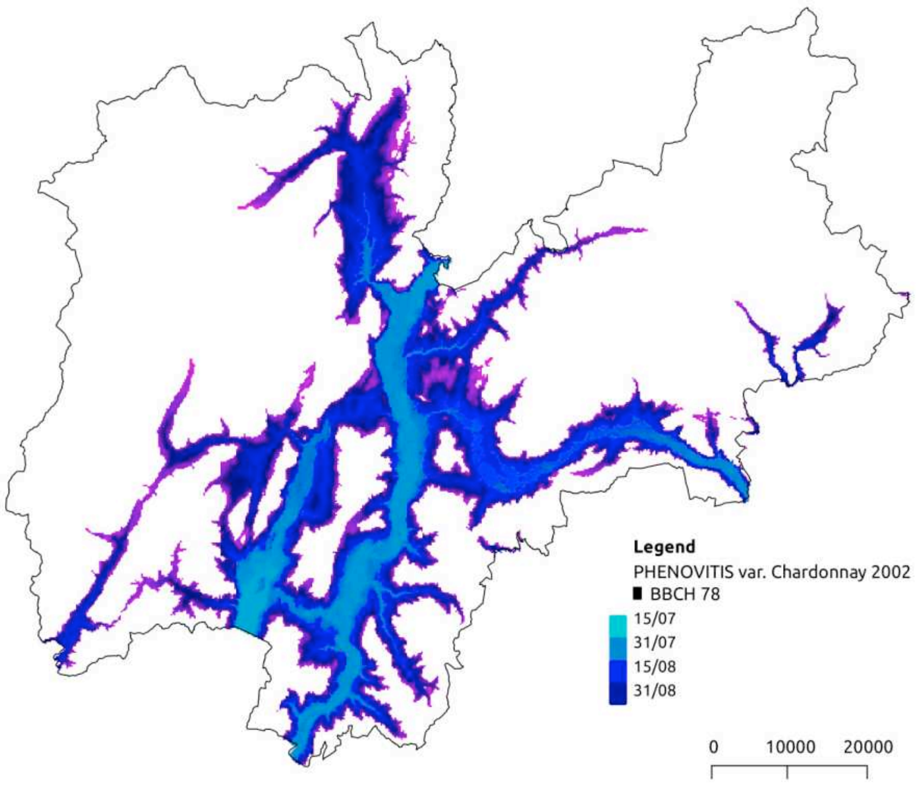

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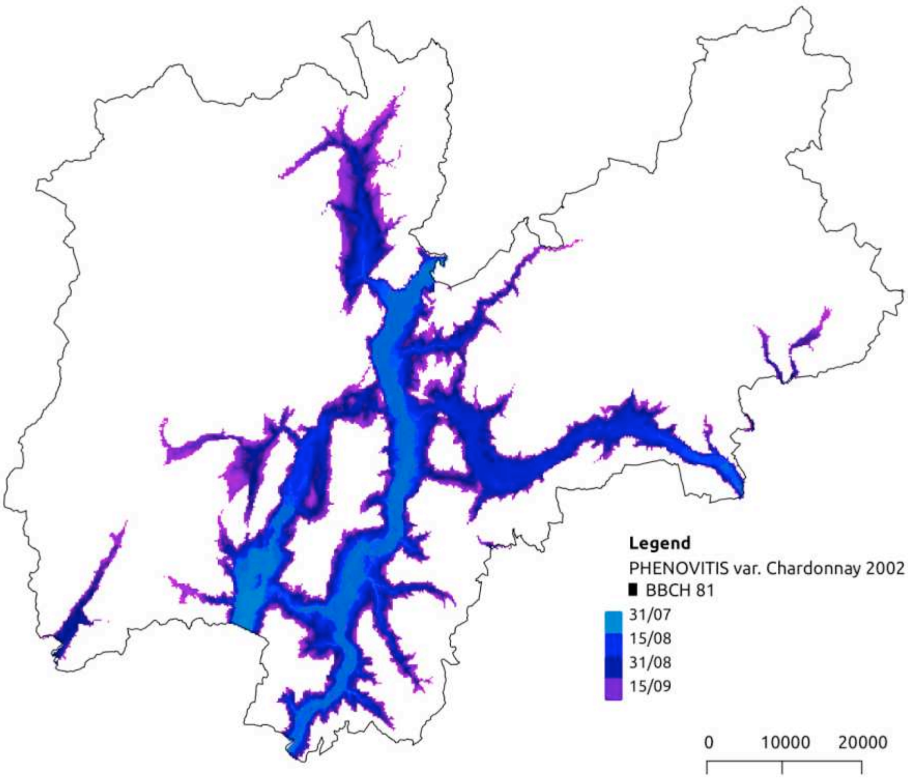

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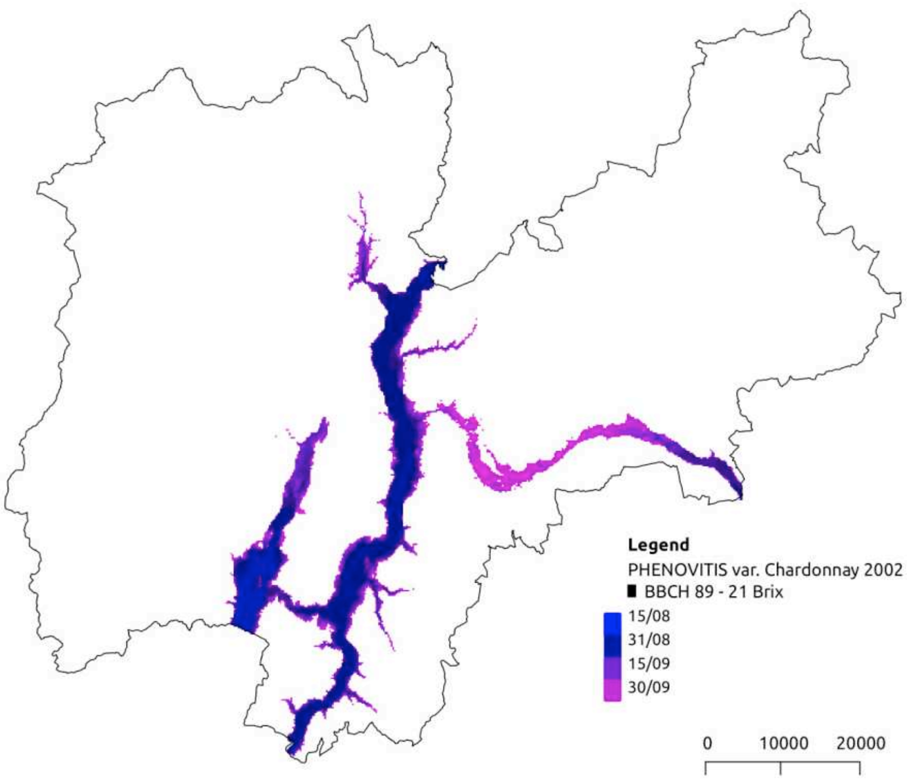

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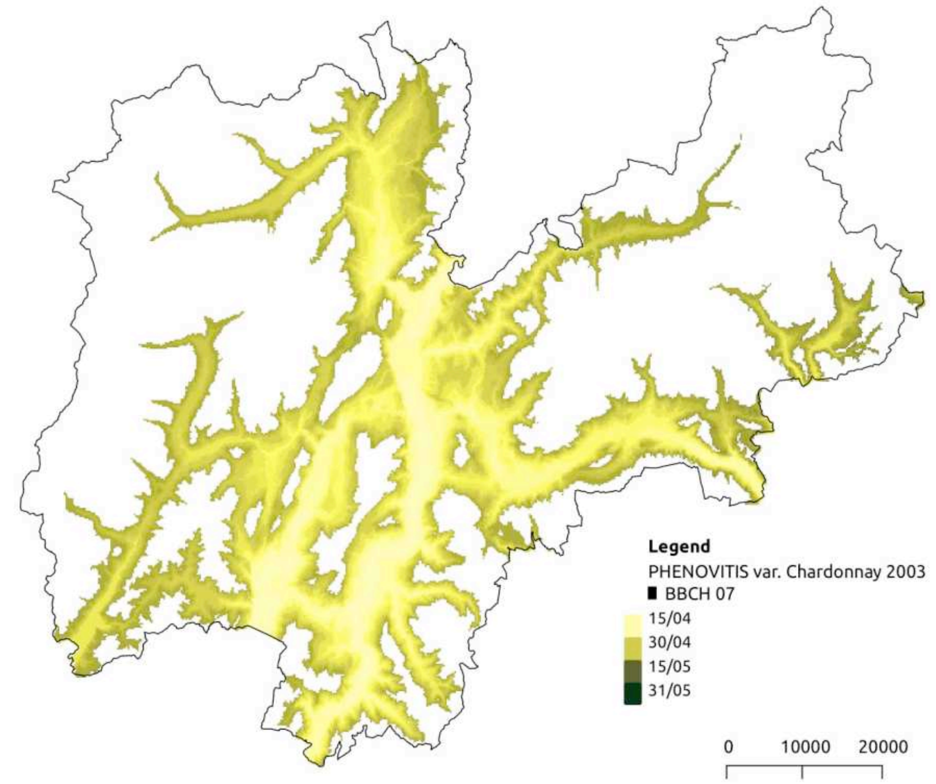

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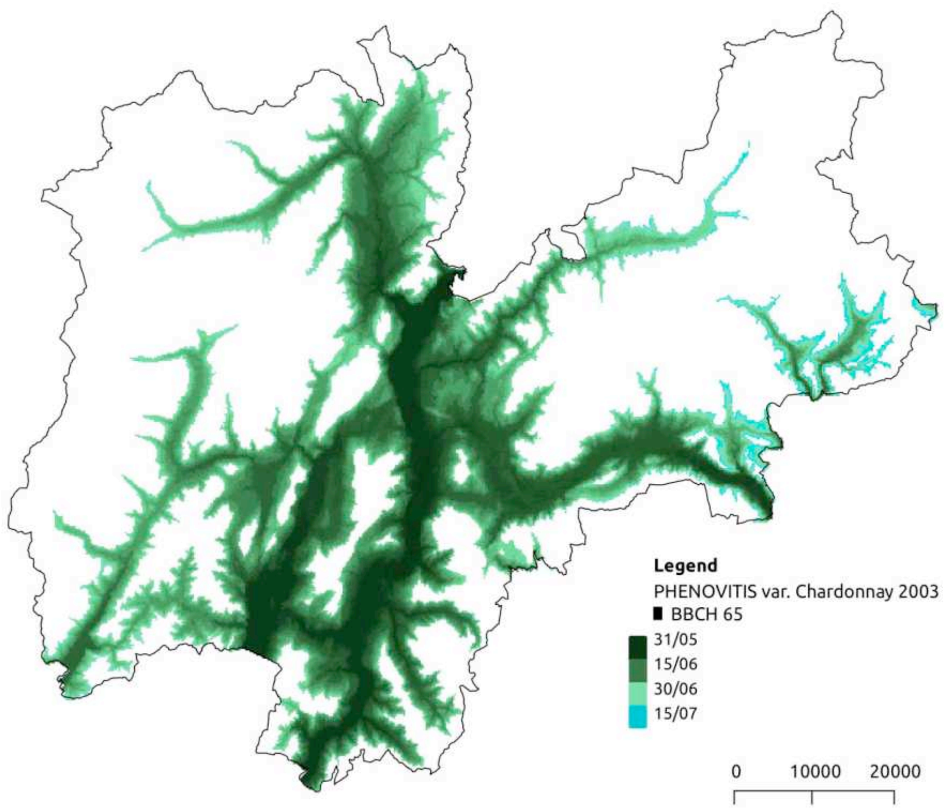

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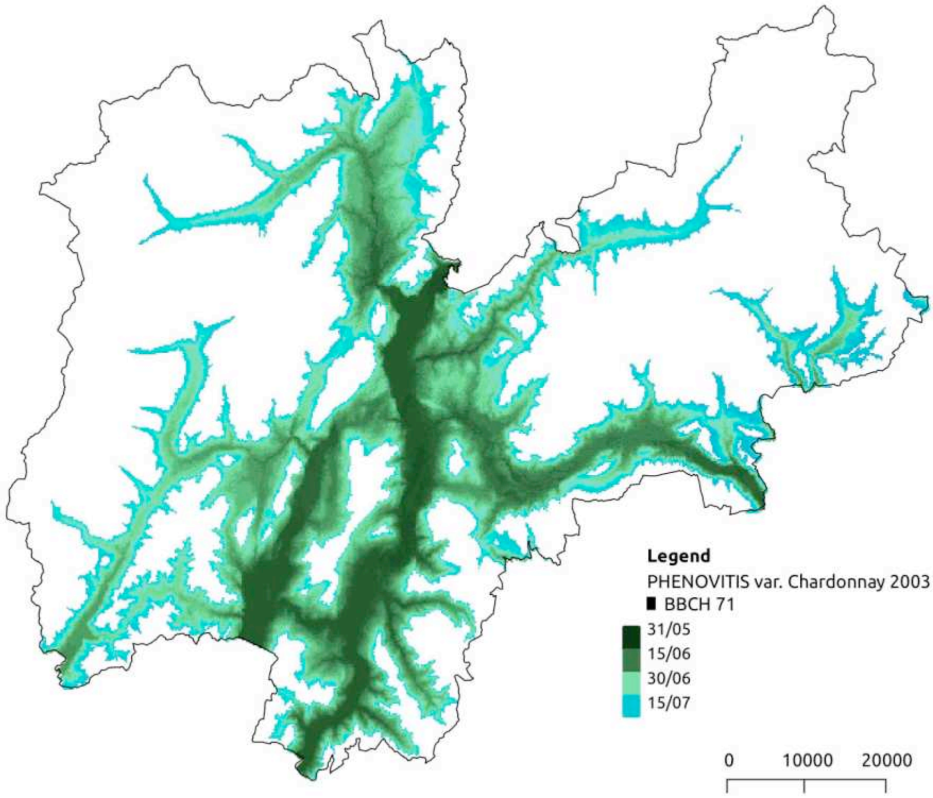

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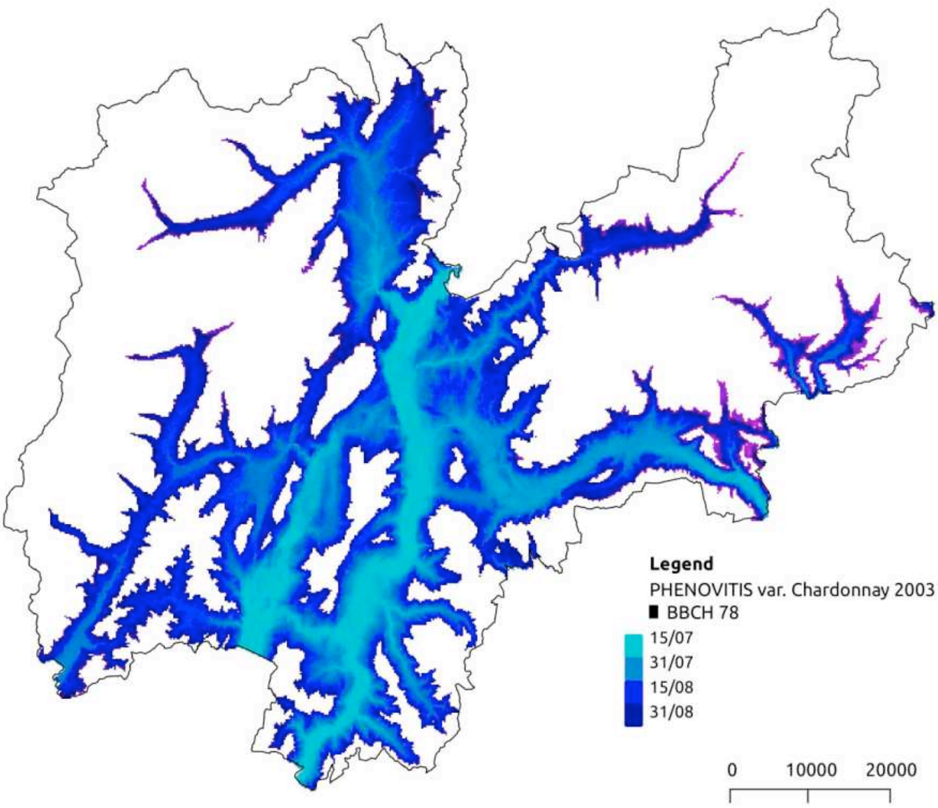

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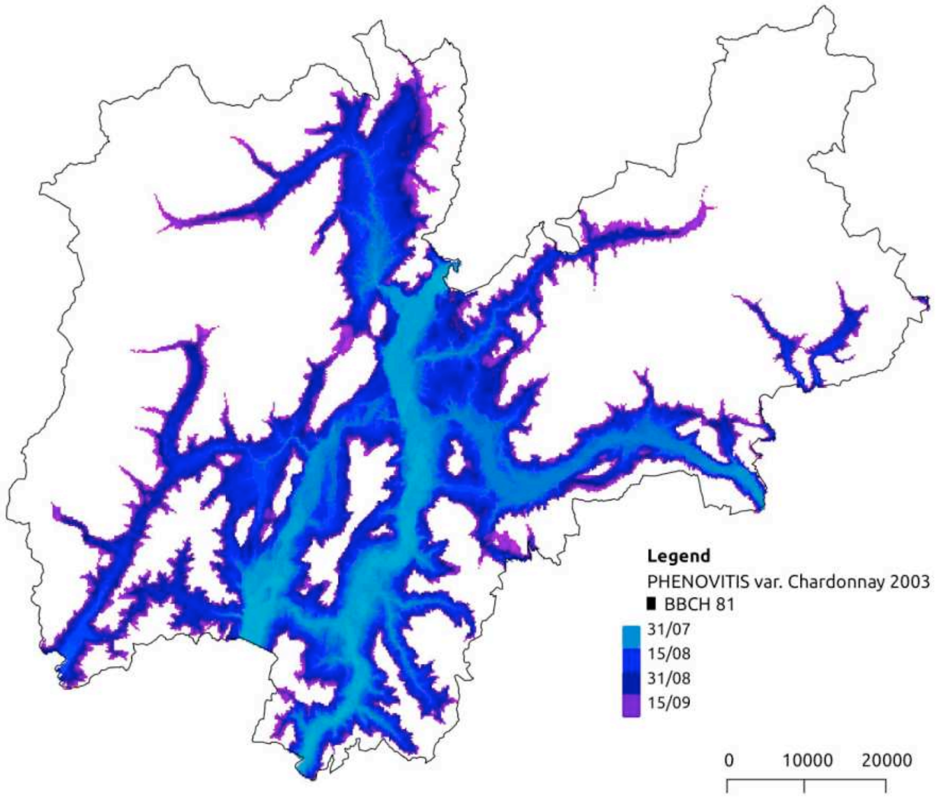
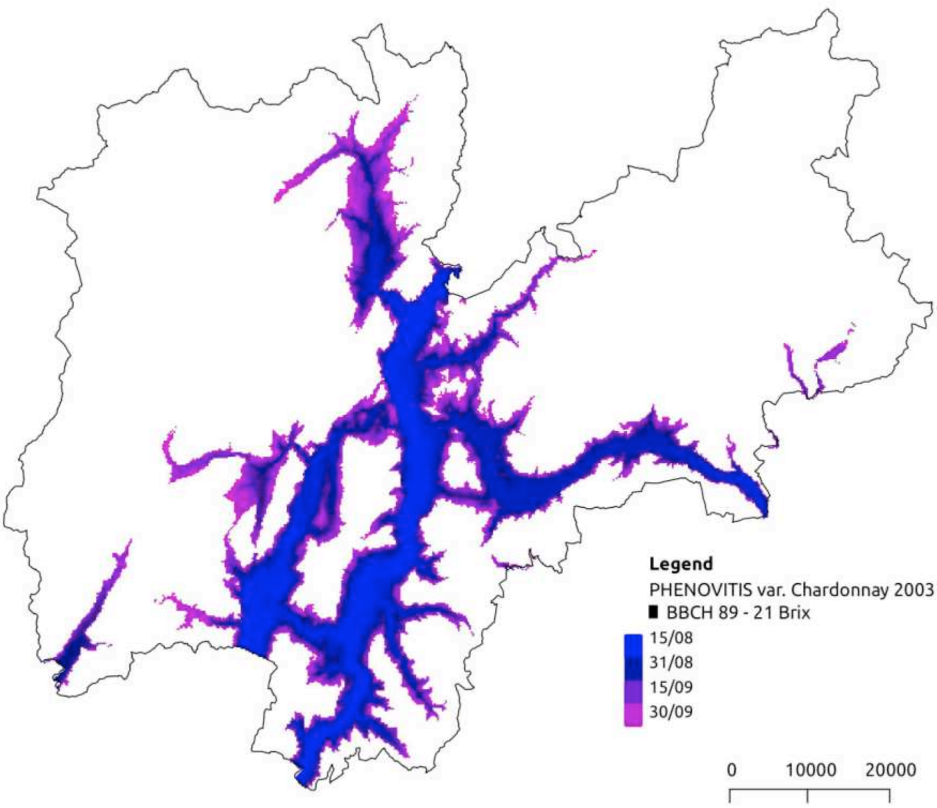
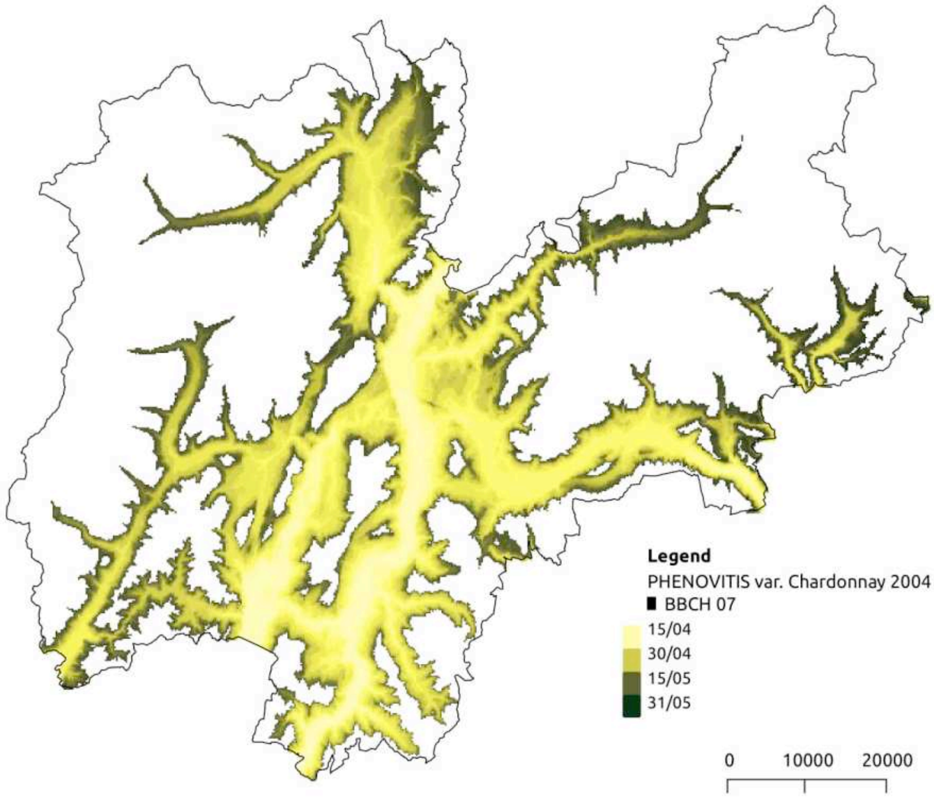


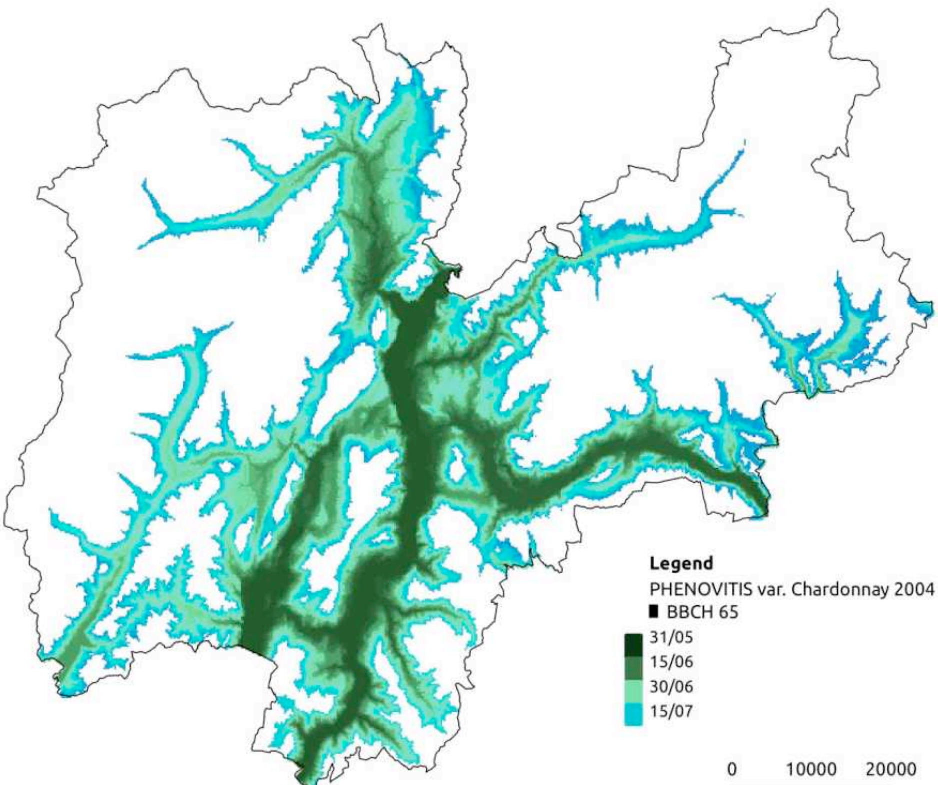
BBCH 81 - 2003



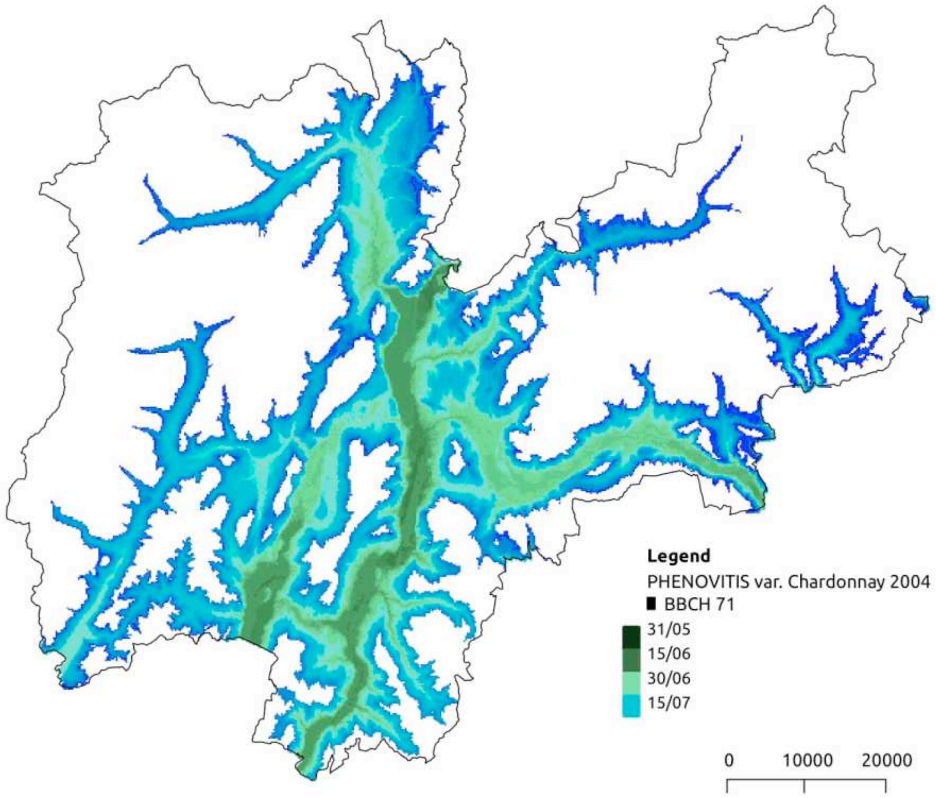
BBCH 89 - 2003



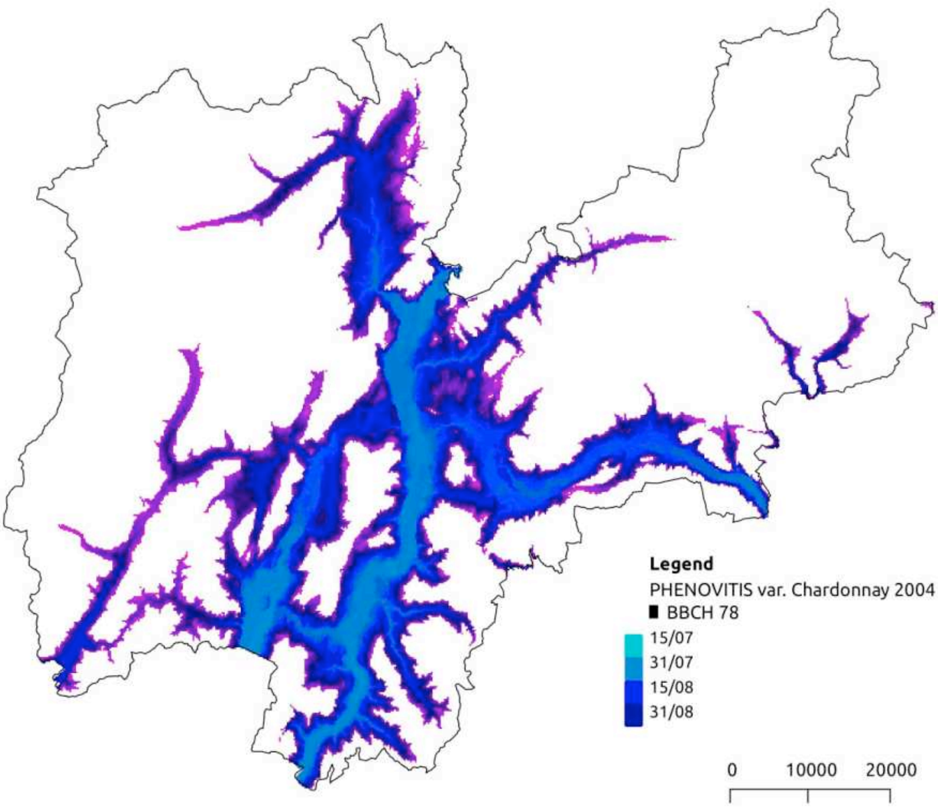
BBCH 08 – 2004



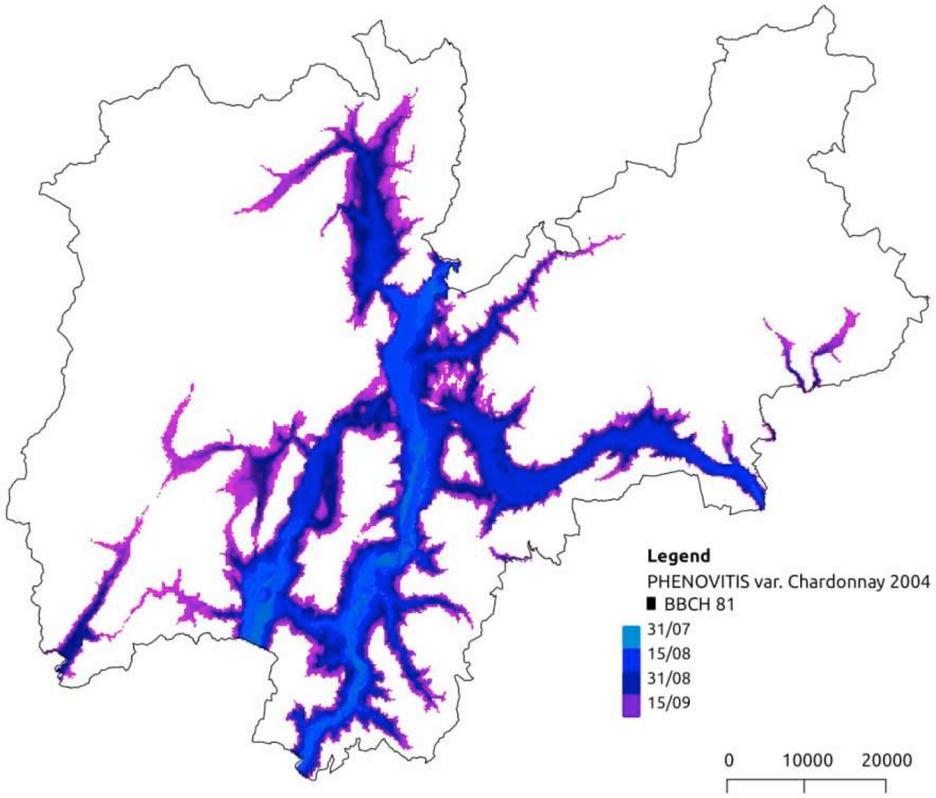
BBCH 65 - 2004



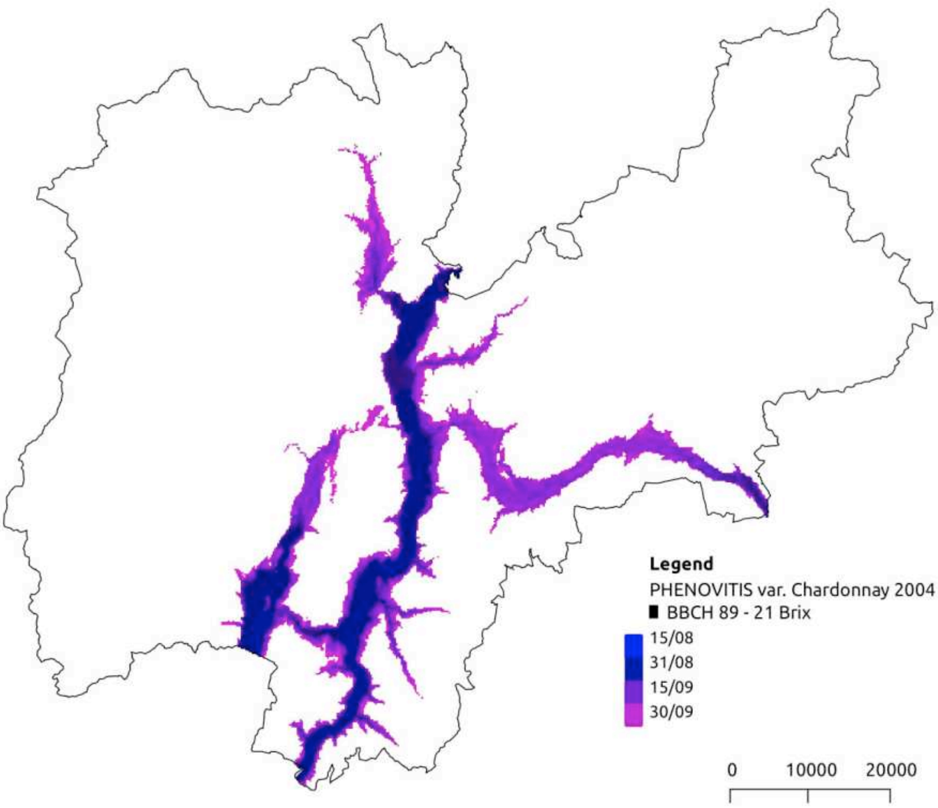
BBCH 71 - 2004



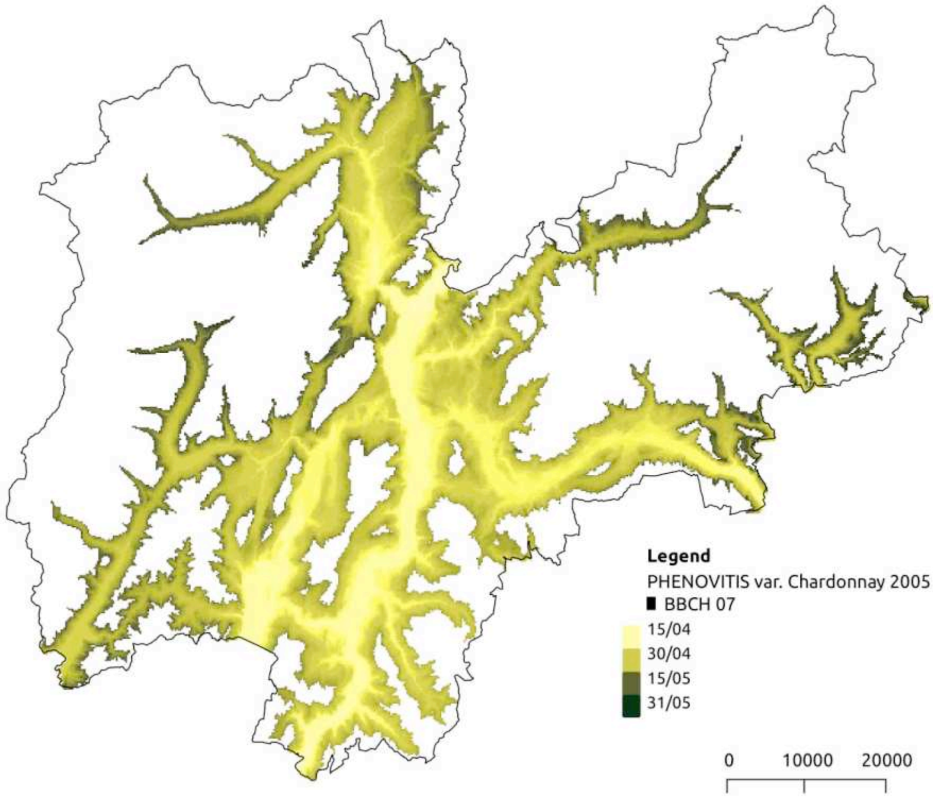
BBCH 78 - 2004



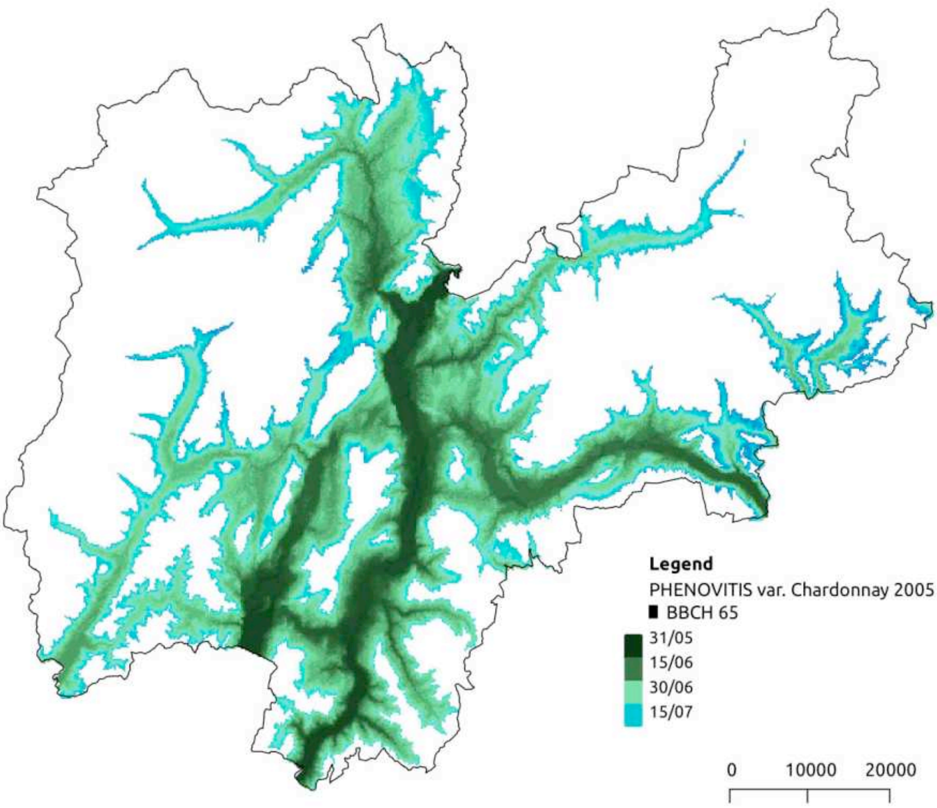
BBCH 81 - 2004



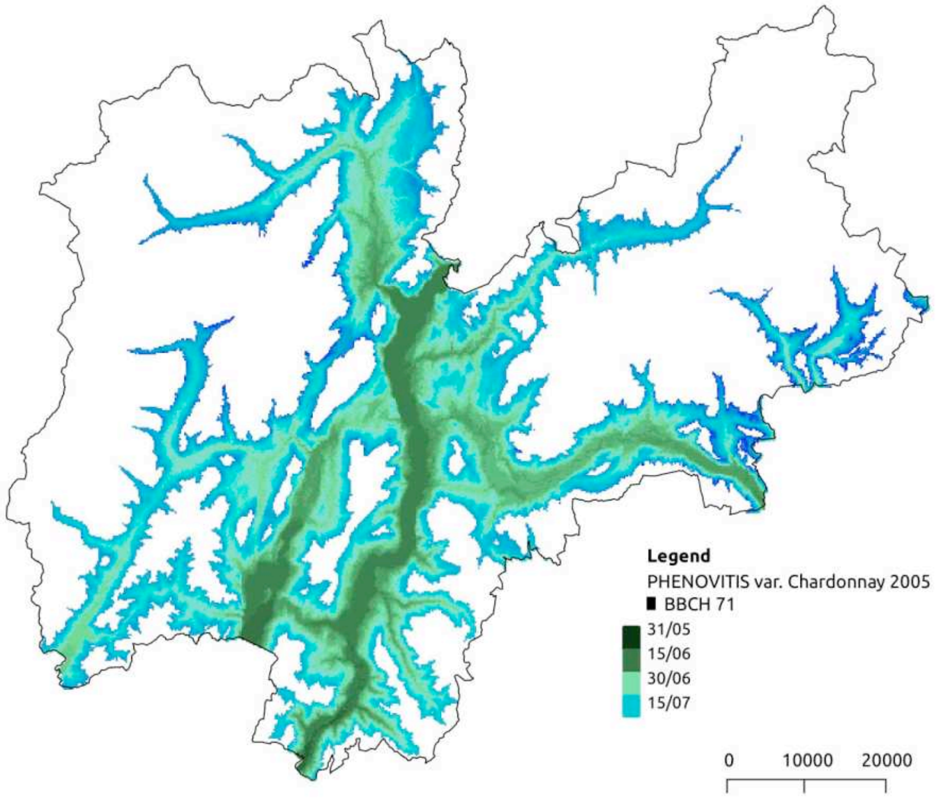
BBCH 89 - 2004



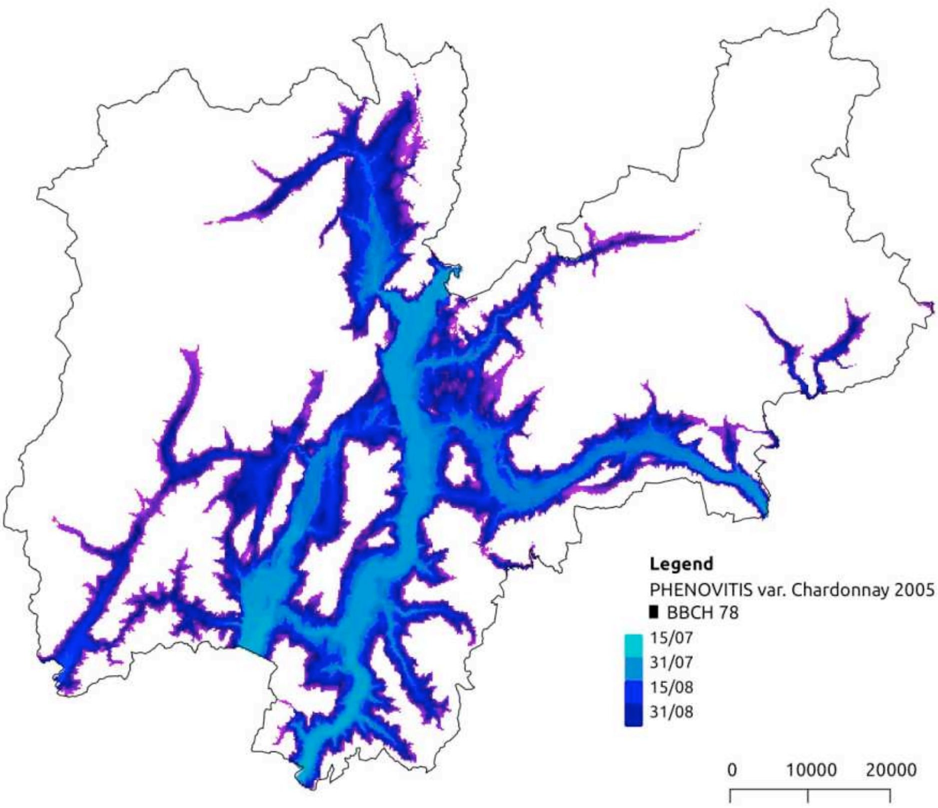
BBCH 08 - 2005



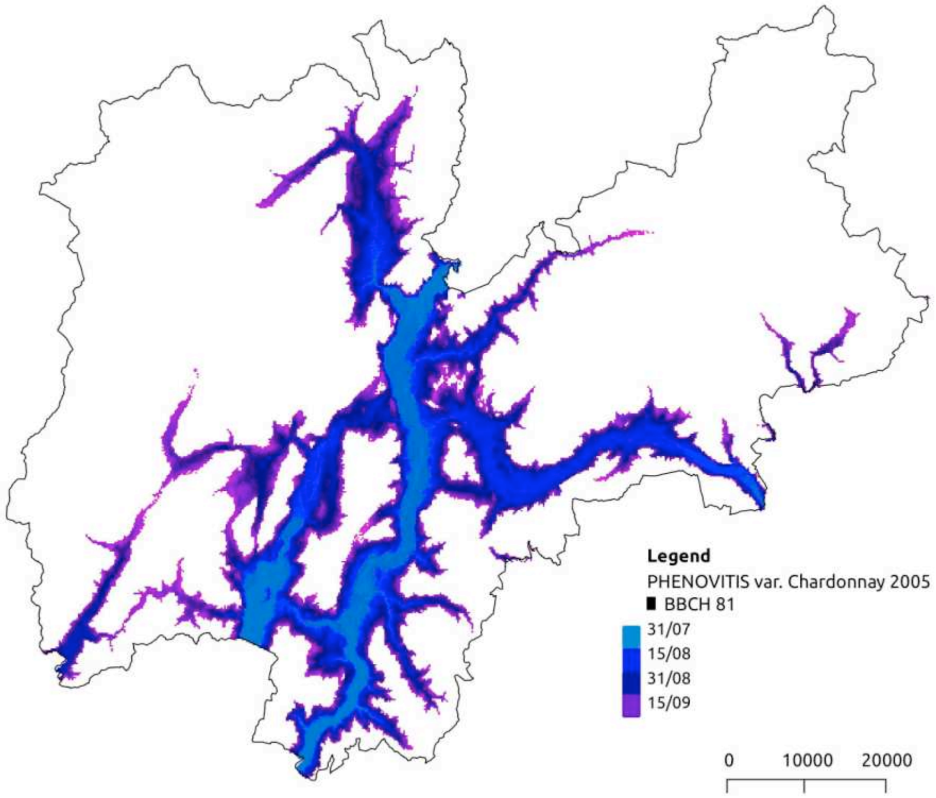
BBCH 65 - 2005



BBCH 71 - 2005

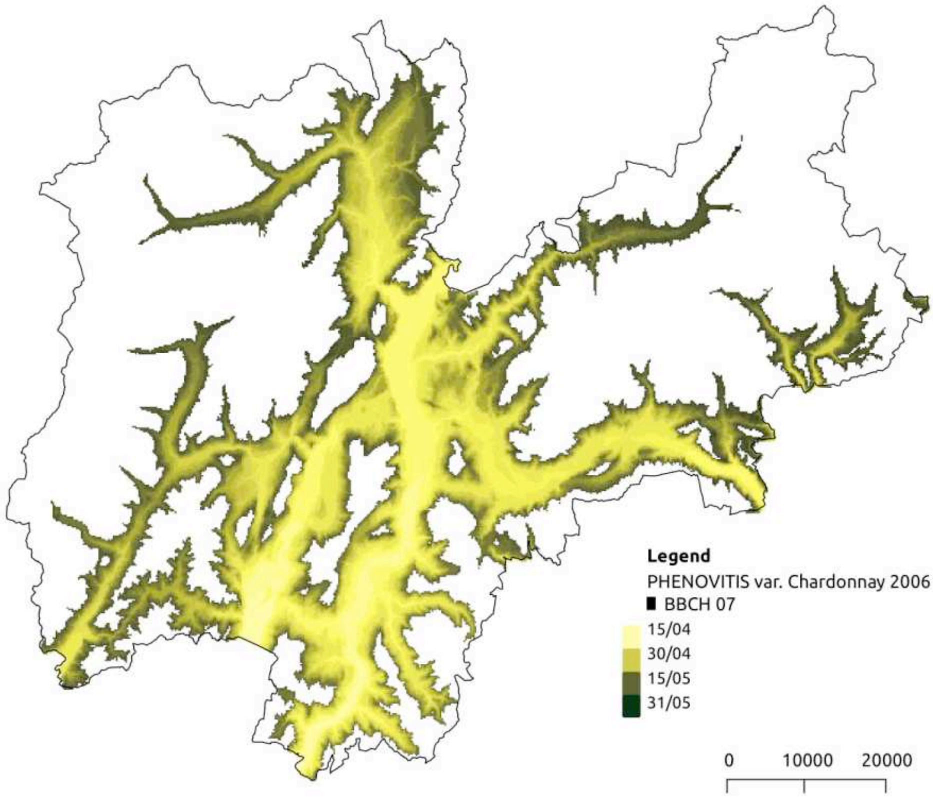


BBCH 78 - 2005

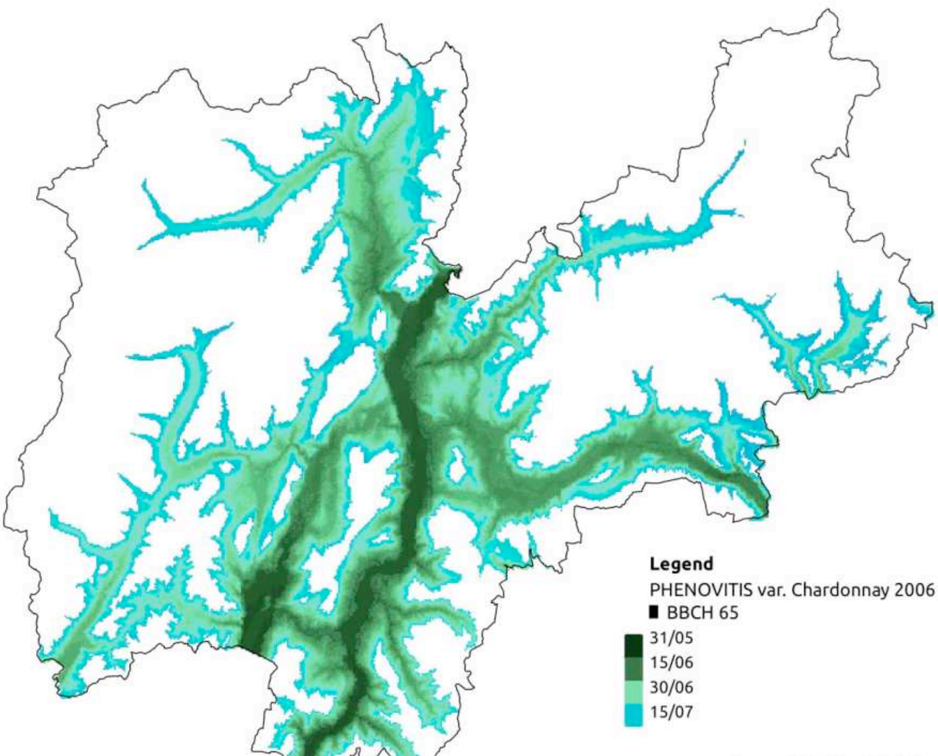


BBCH 81 - 2005

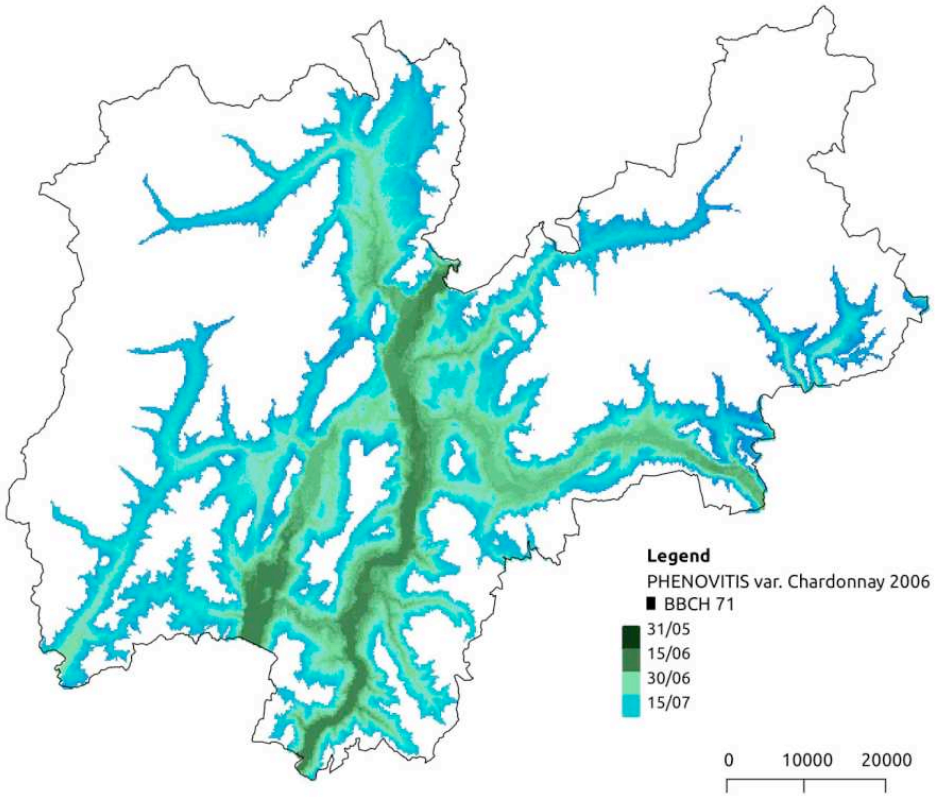
BBCH 89 - 2005



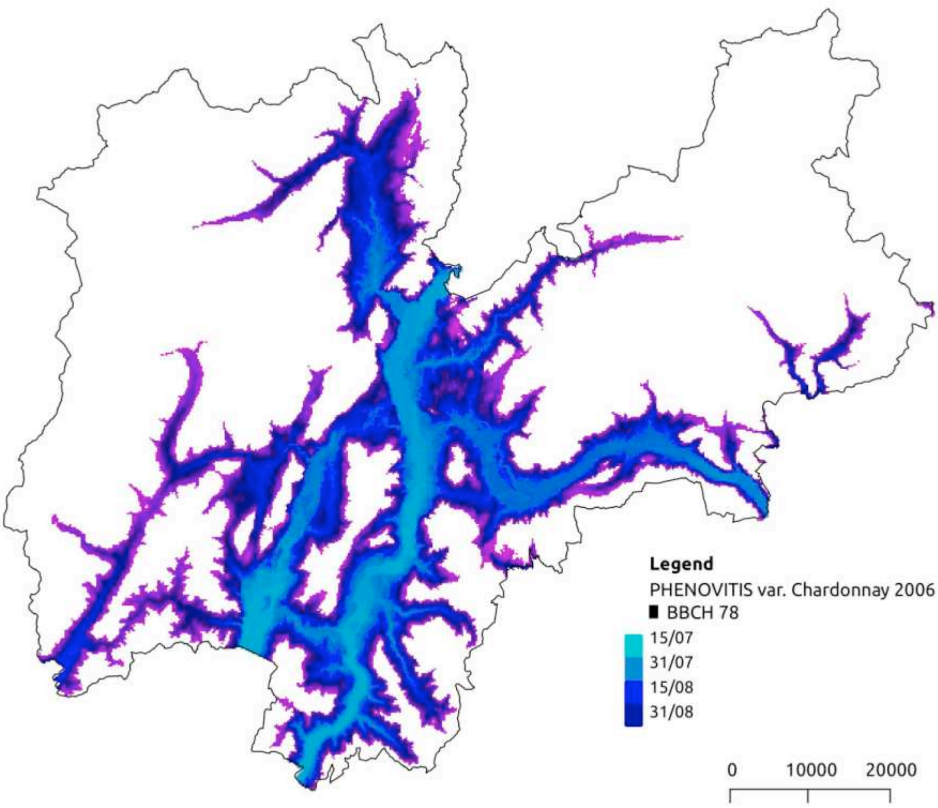
BBCH 08 - 2006



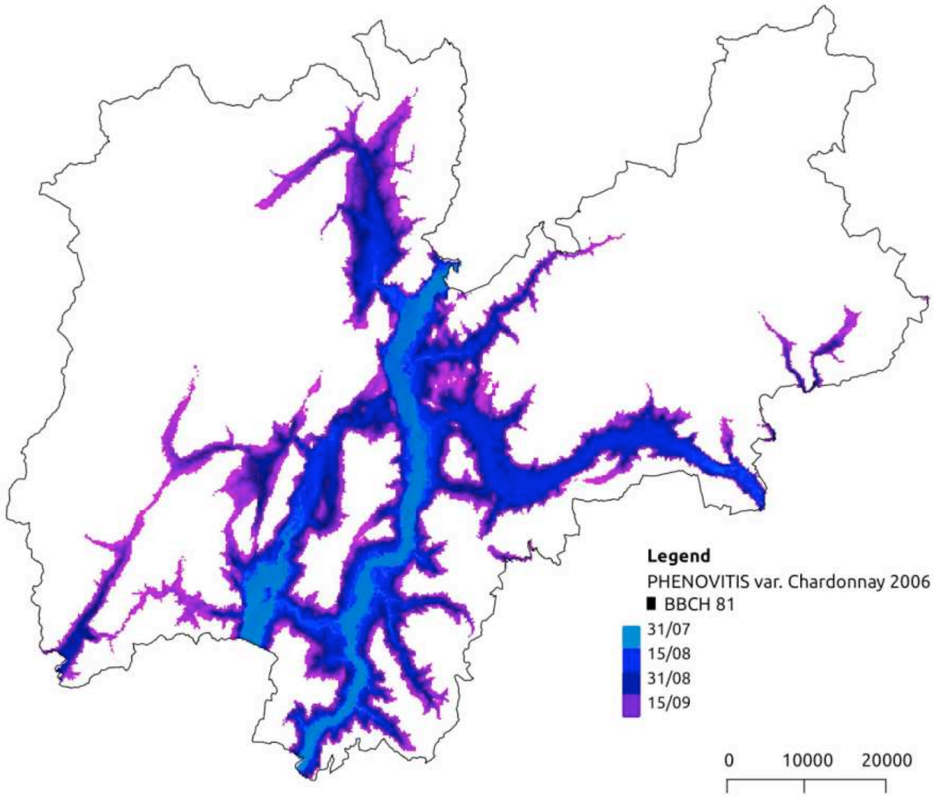
BBCH 65 - 2006



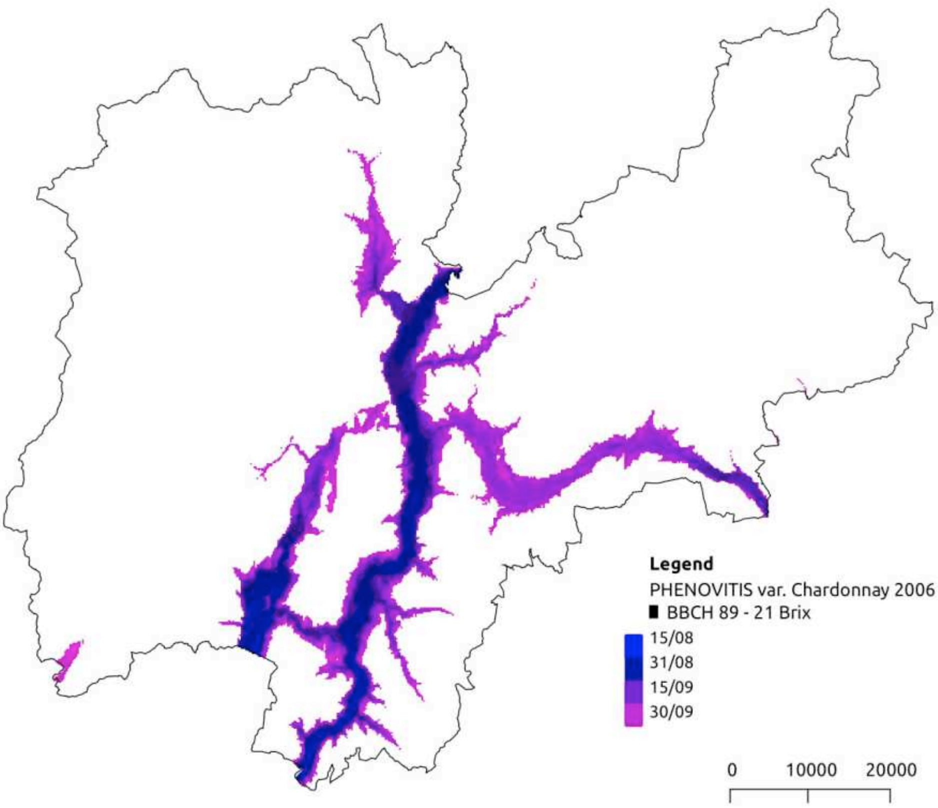
BBCH 71 - 2006



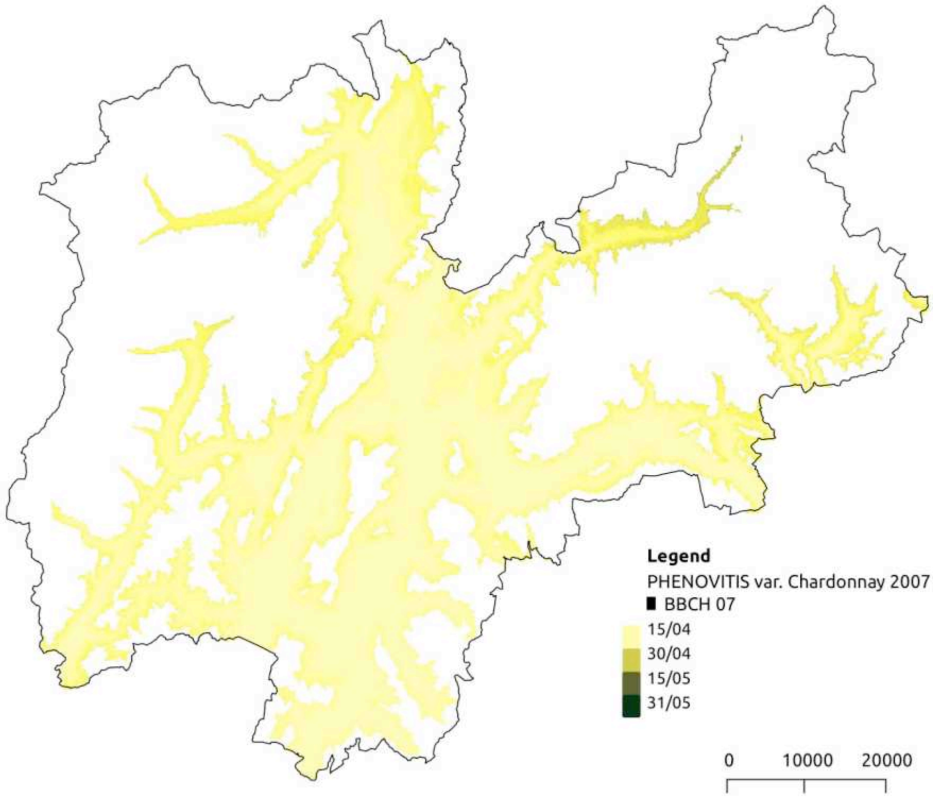
BBCH 78 - 2006



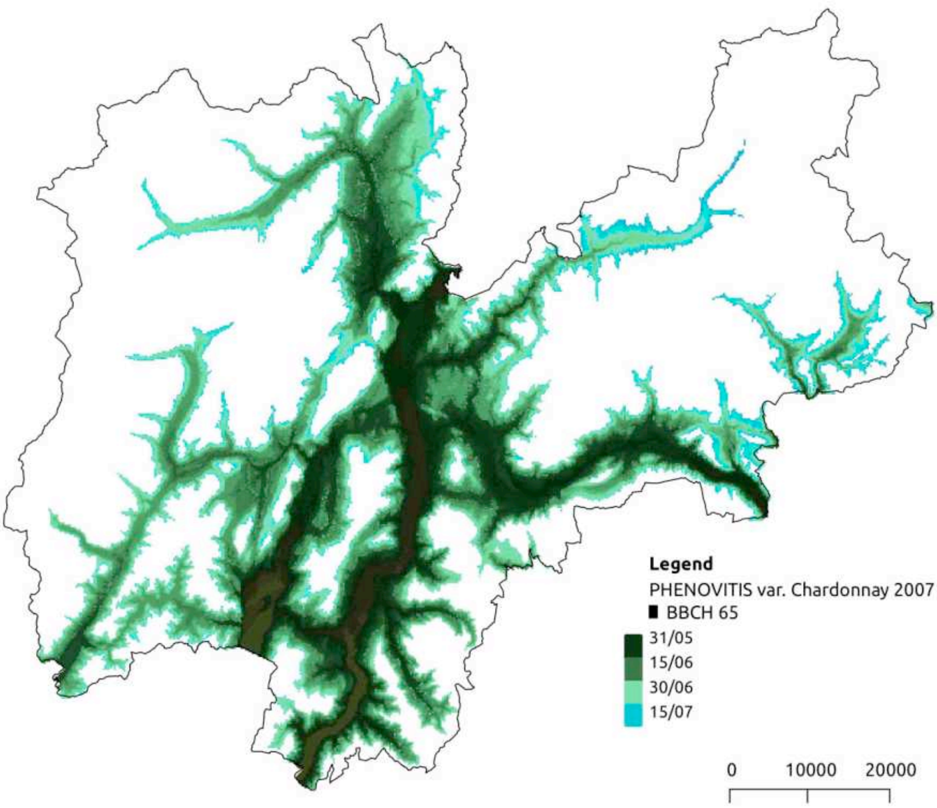
BBCH 81 - 2006



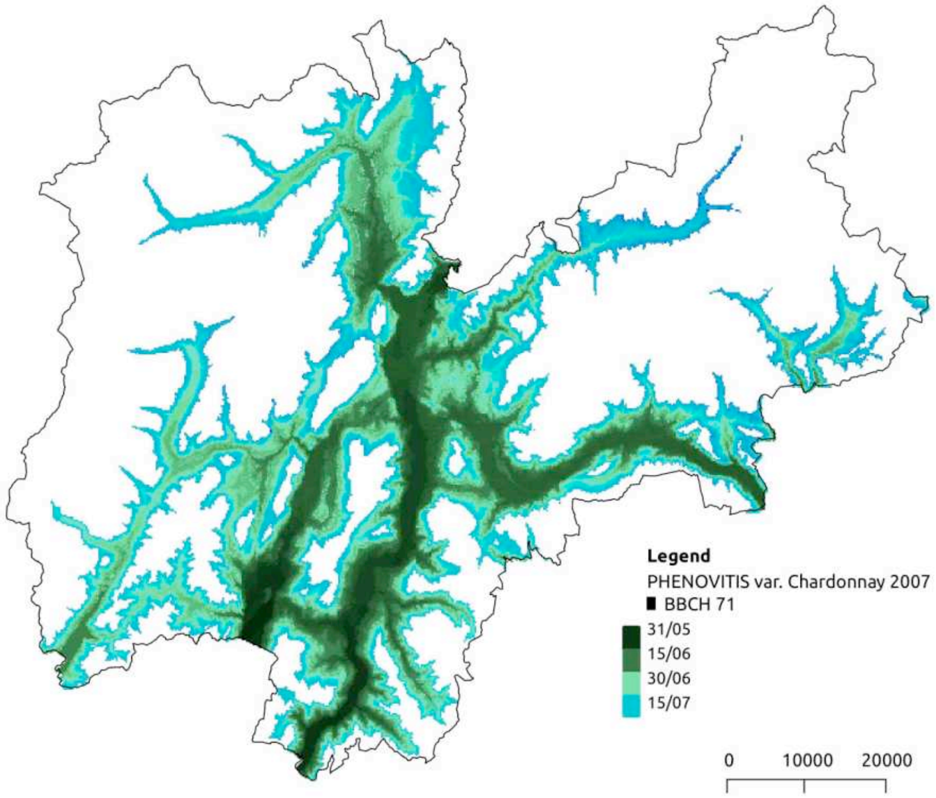
BBCH 89 - 2006



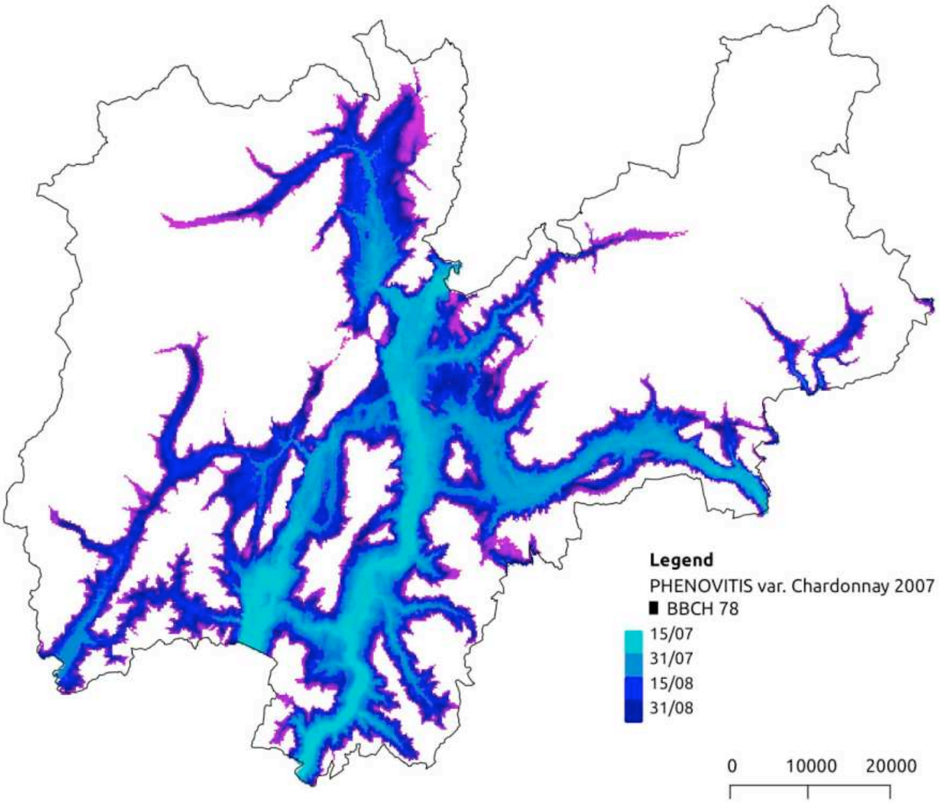
BBCH 08 - 2007



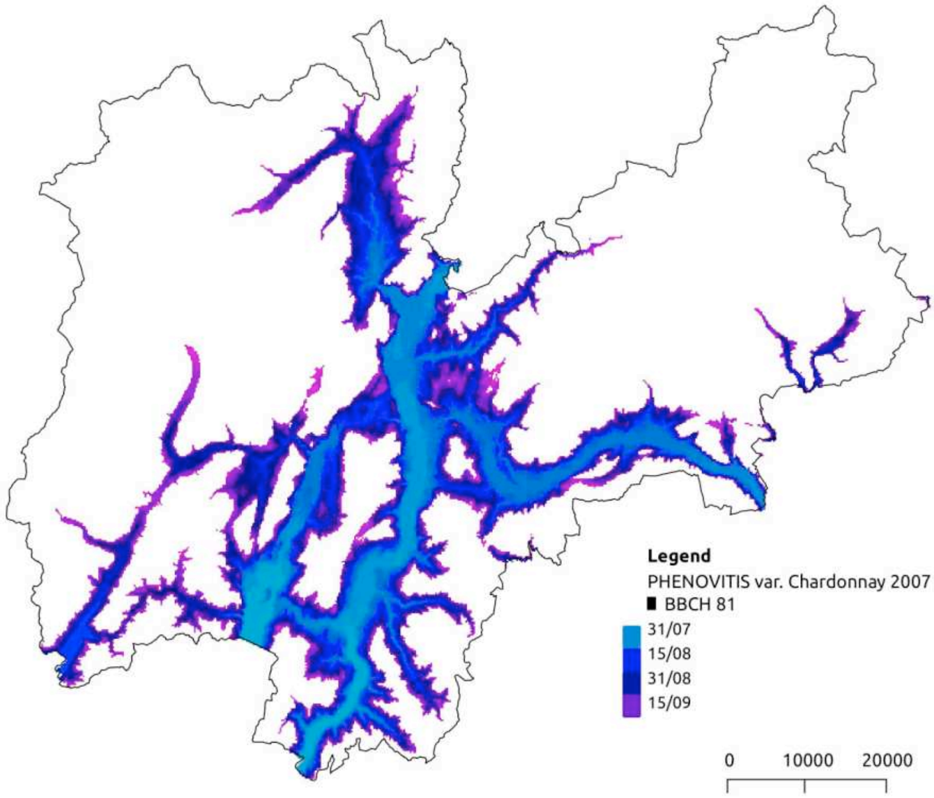
BBCH 65 - 2007



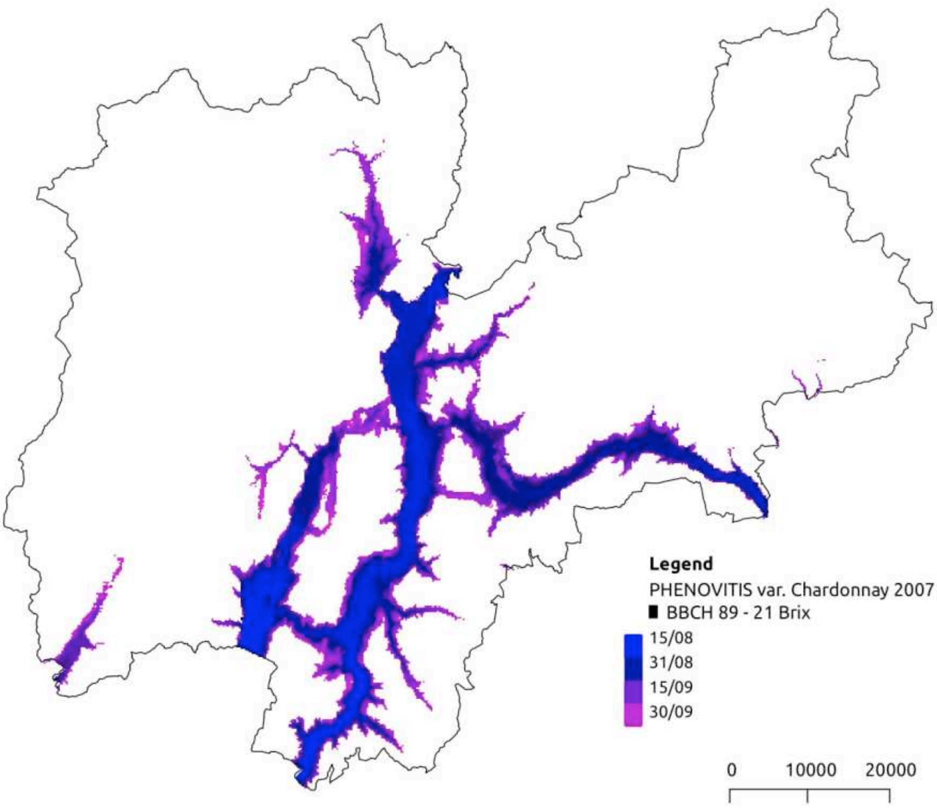
BBCH 71 - 2007



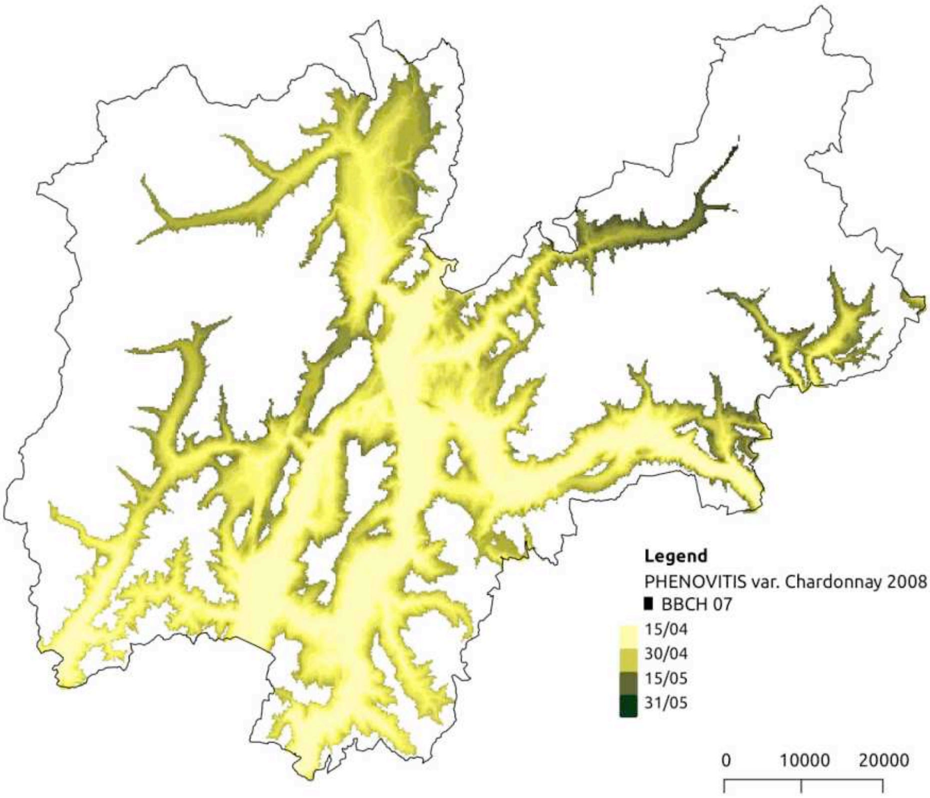
BBCH 78 - 2007



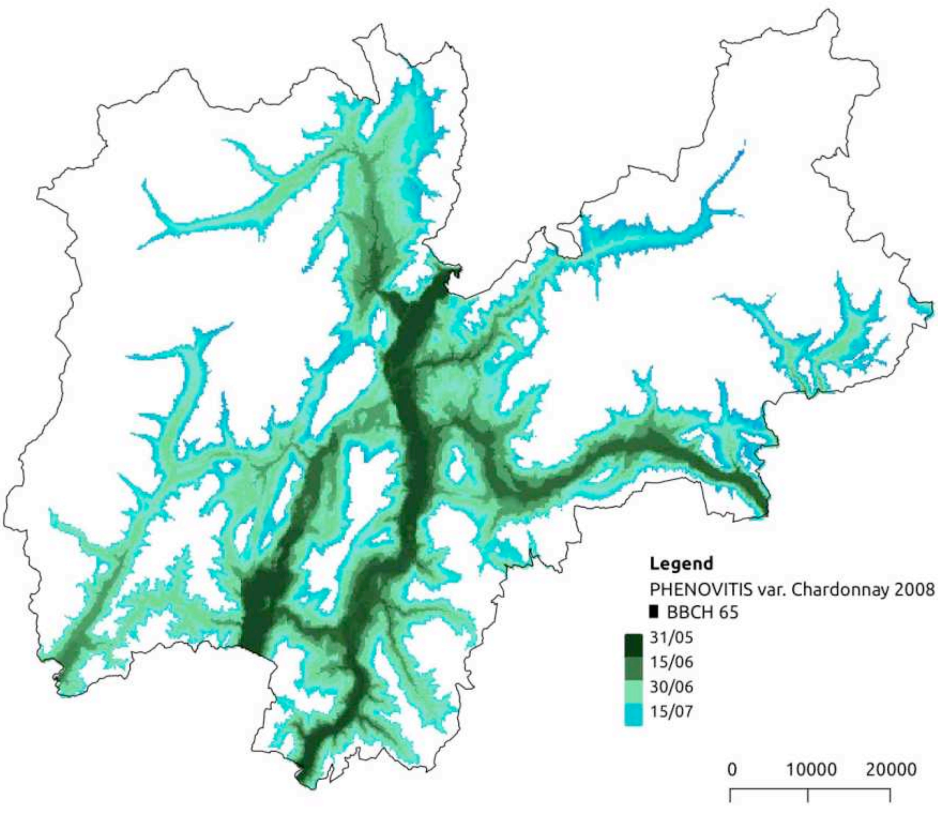
BBCH 81 - 2007



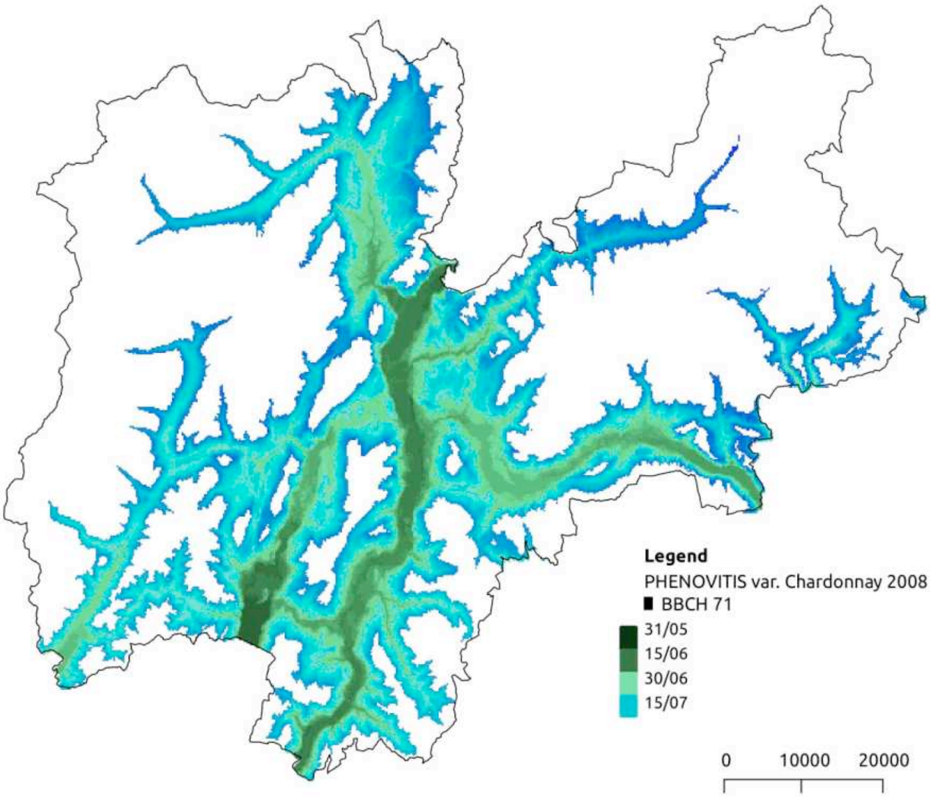
BBCH 89 - 2007



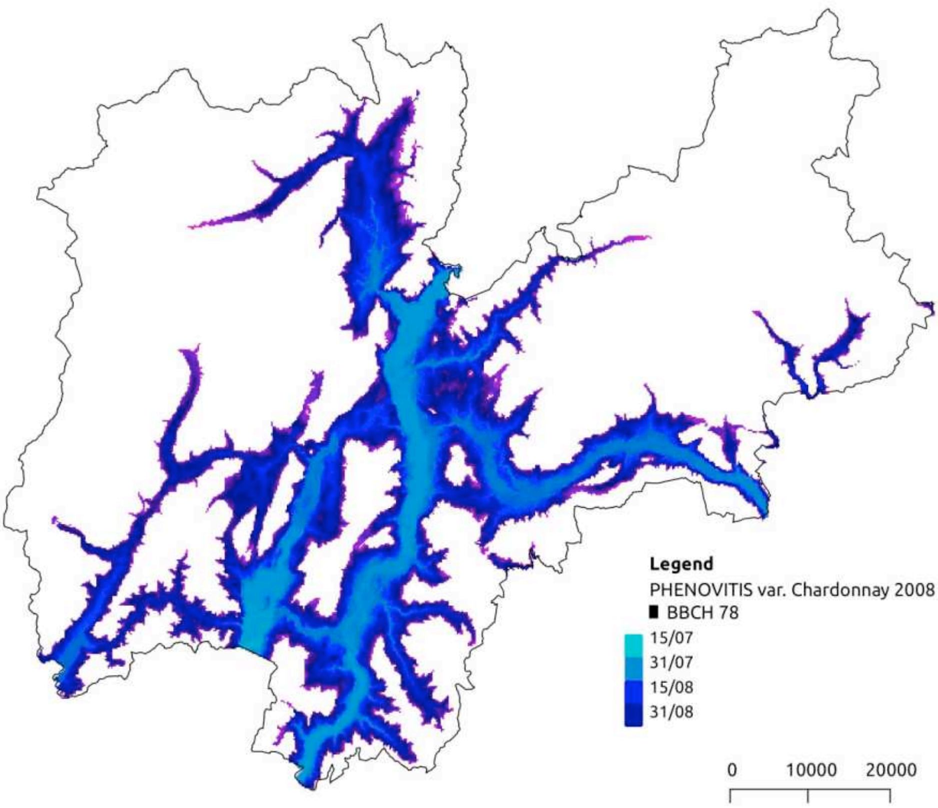
BBCH 08 - 2008



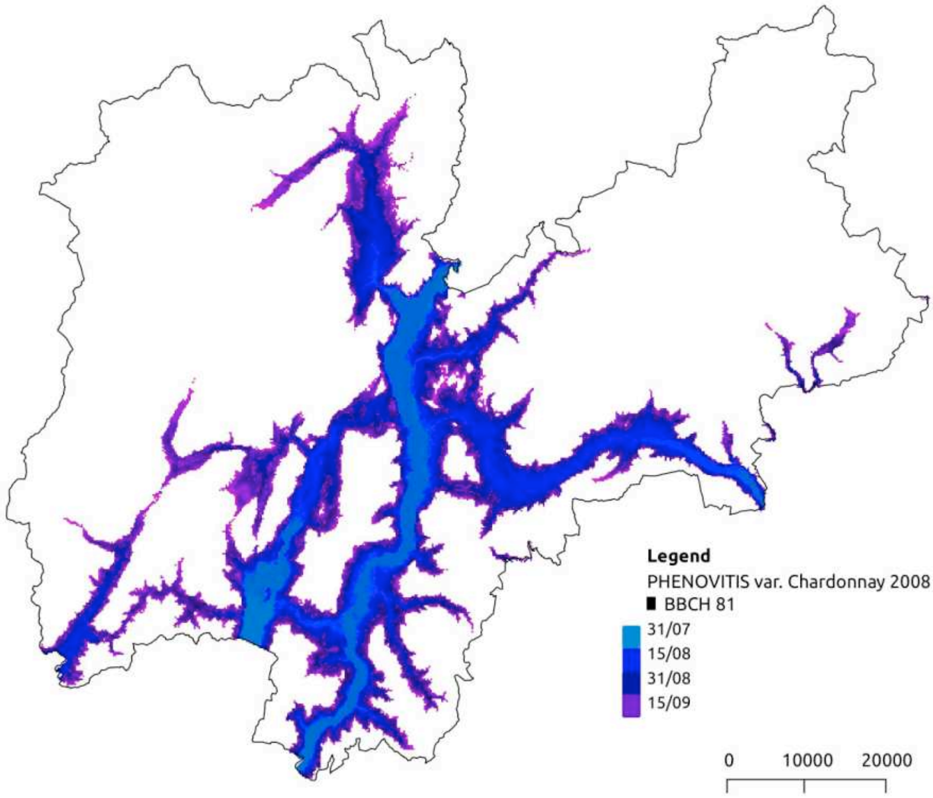
BBCH 65 - 2008



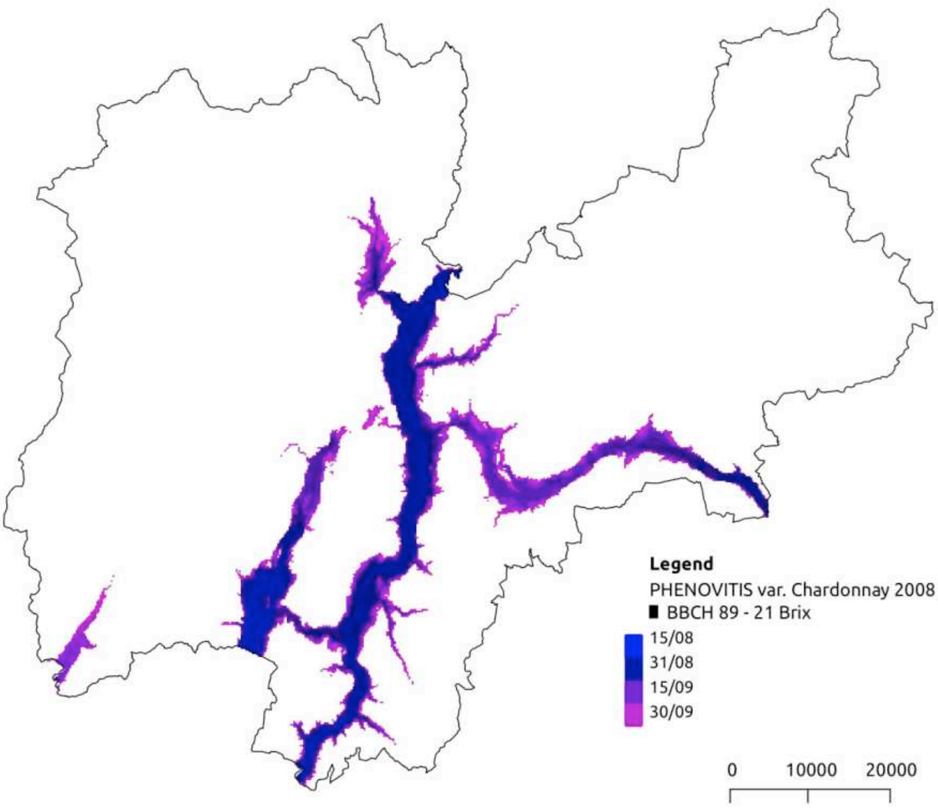
BBCH 71 - 2008



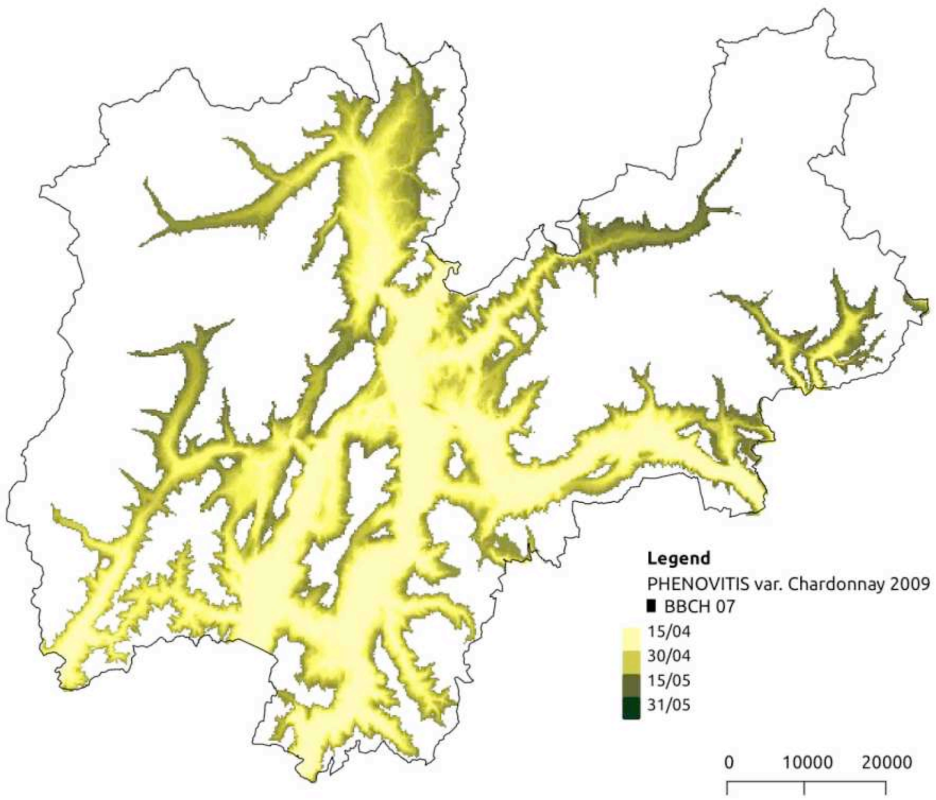
BBCH 78 - 2008



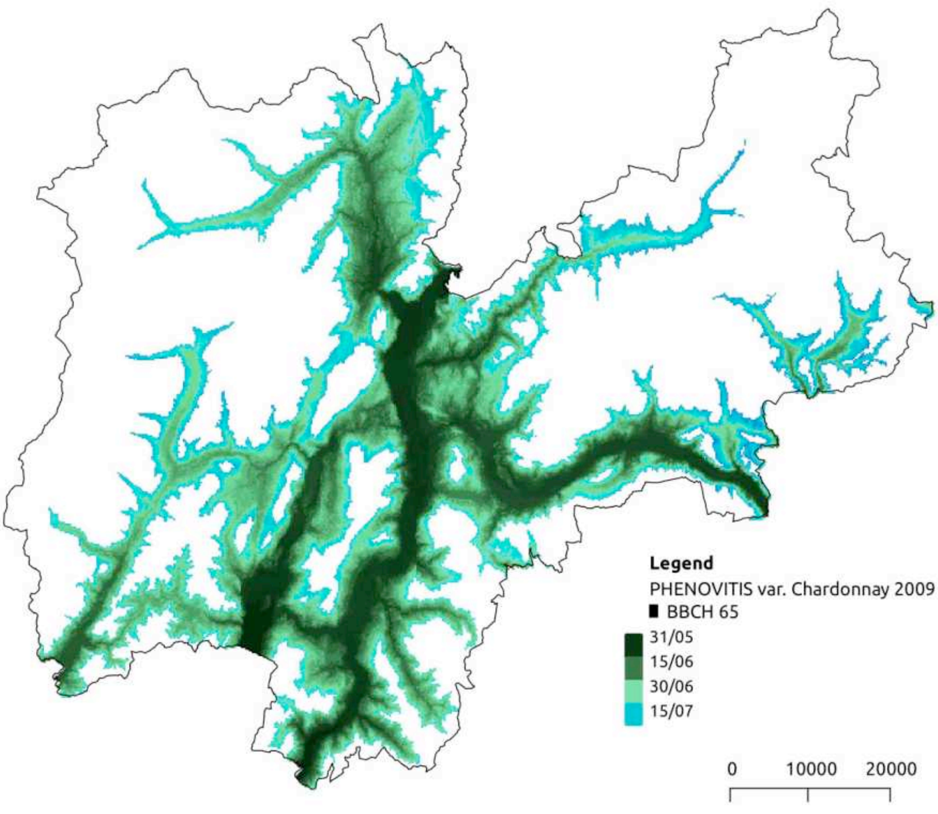
BBCH 81 - 2008



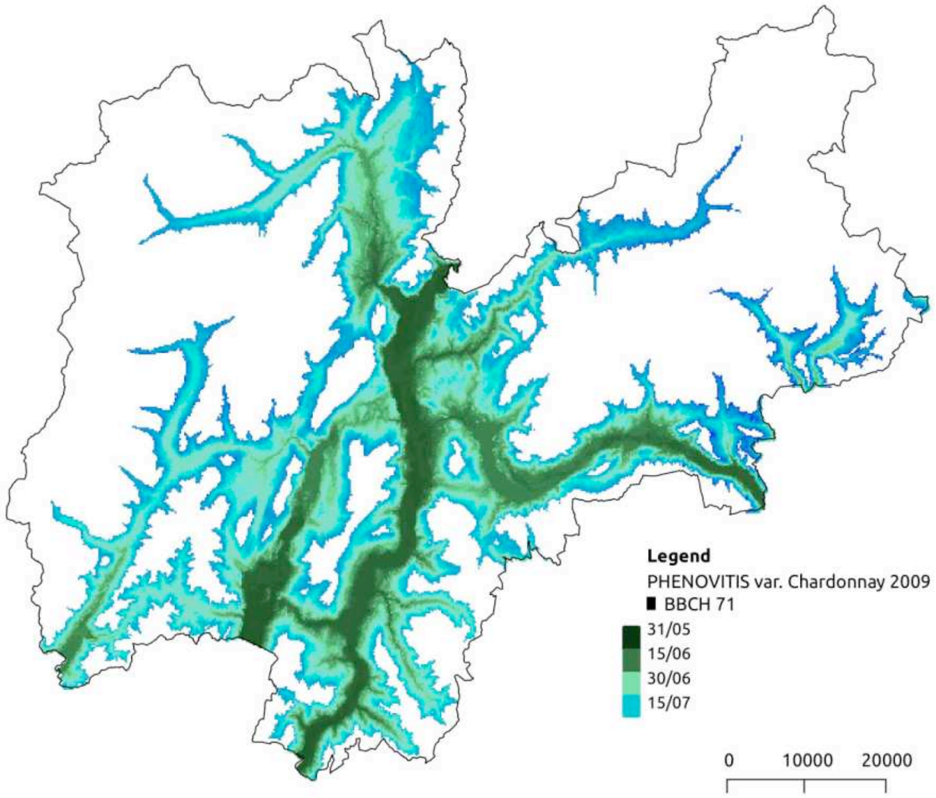
BBCH 89 - 2008



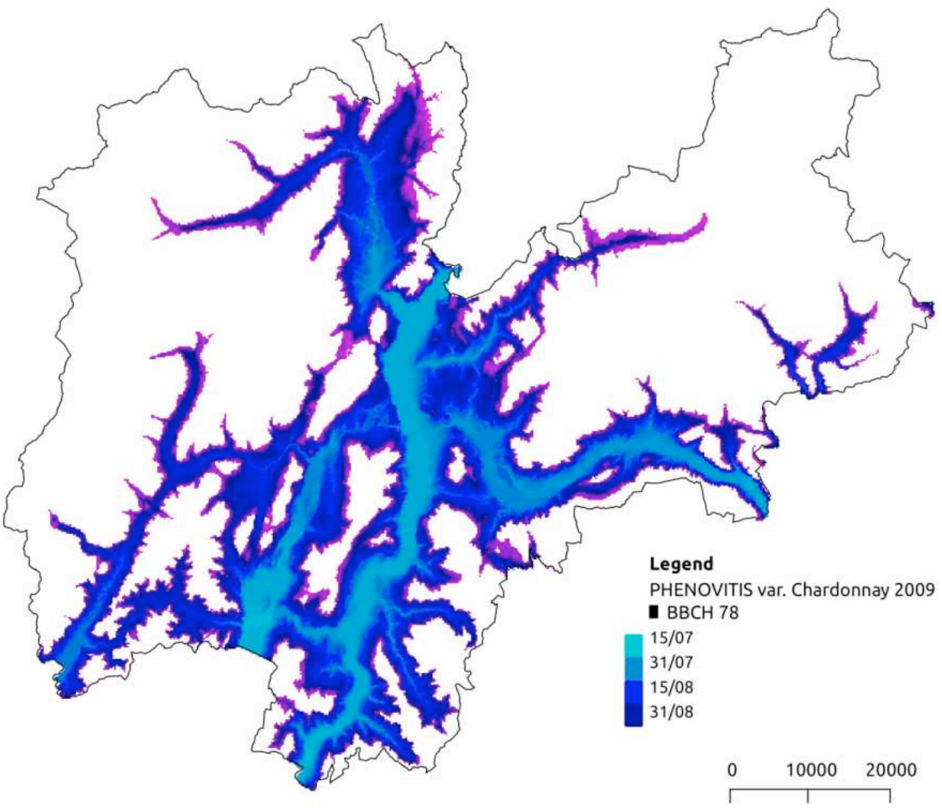
BBCH 08 – 2009



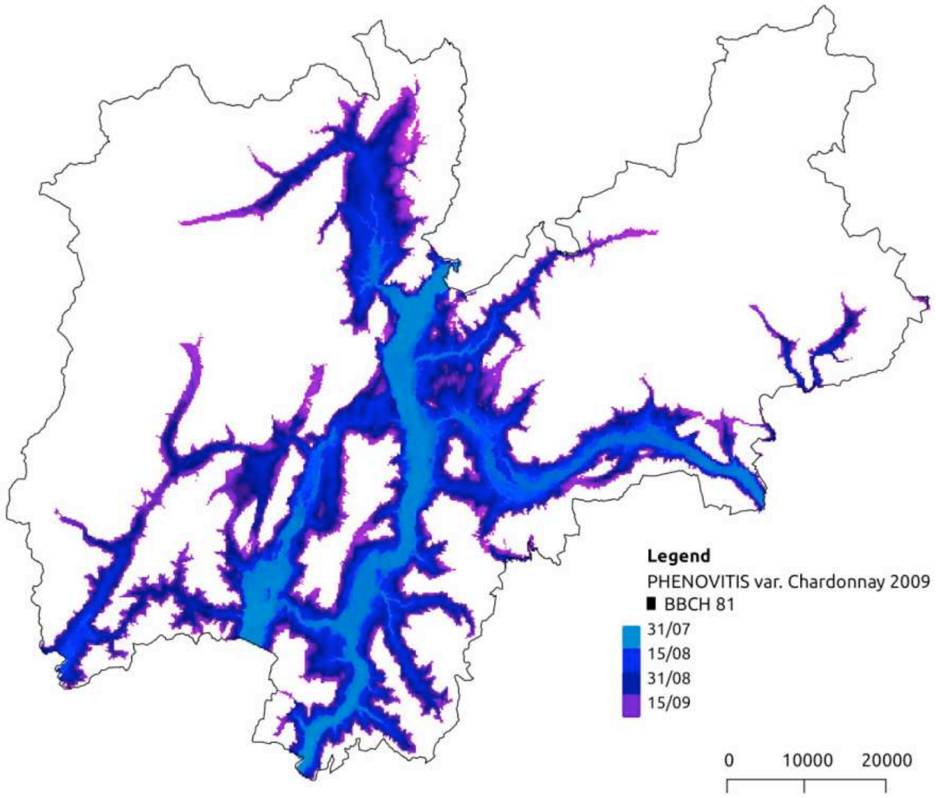
BBCH 65 - 2009



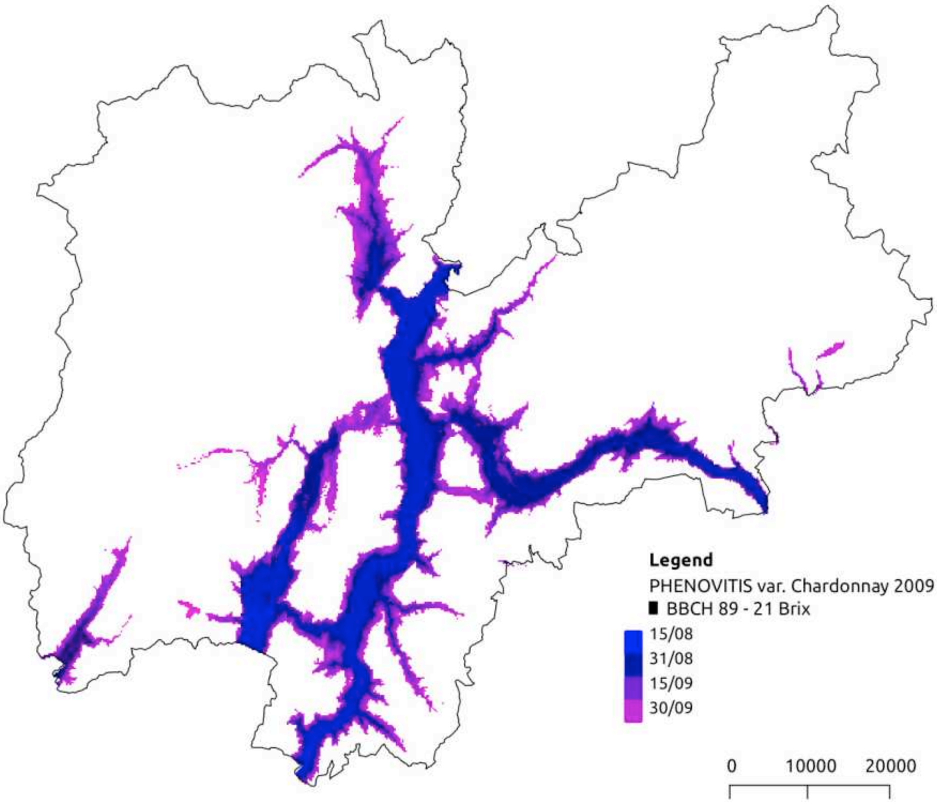
BBCH 71 - 2009



BBCH 78 - 2009

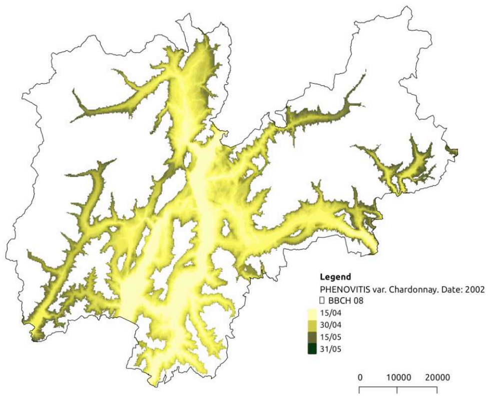


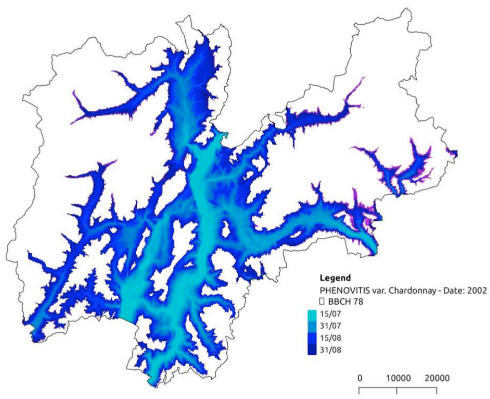
BBCH 81 - 2009

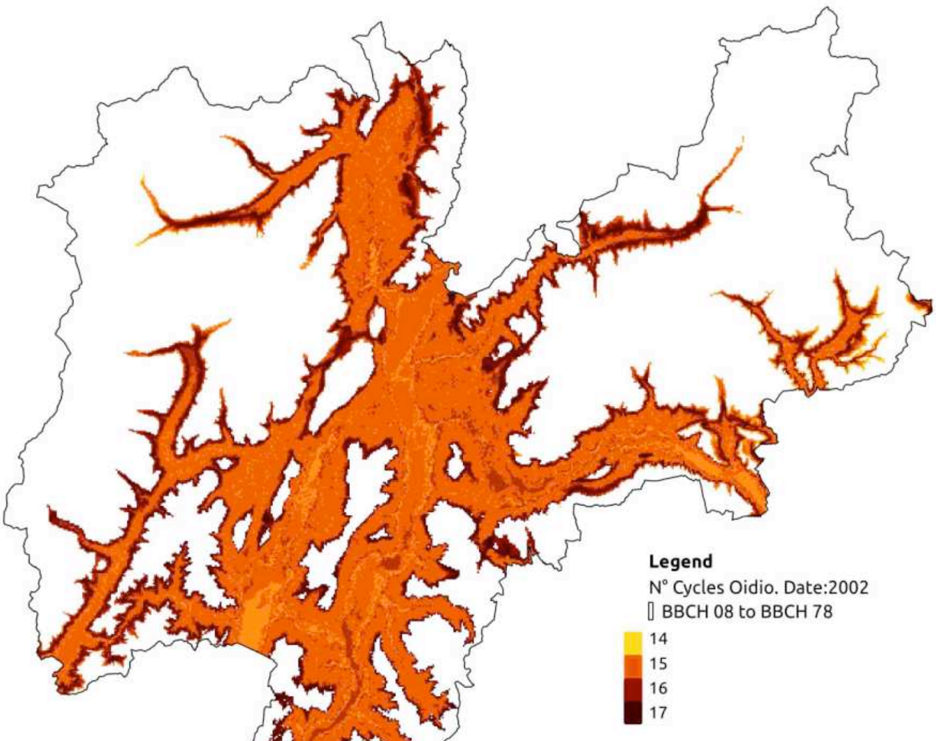


BBCH 89 - 2009

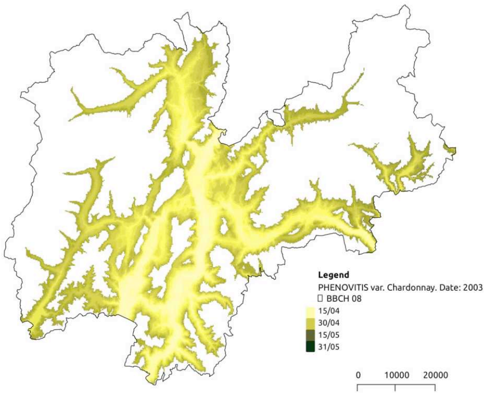
Fig.7. *Phenovitis Maps: output date of BBCH starting in the top to the bottom: BBCH 07 (top), BBCH 65, BBCH 71, BBCH 78, BBCH 81, BBCH 89 (bottom). The first six corresponding at the year 2002 (top), then each year was represented with six phenological stage and continuing to in increasing year: 2003, 2004, 2005, 2006, 2007, 2008 to 2009 (bottom). The legend for each plot is displayed at the bottom right of the plot.*



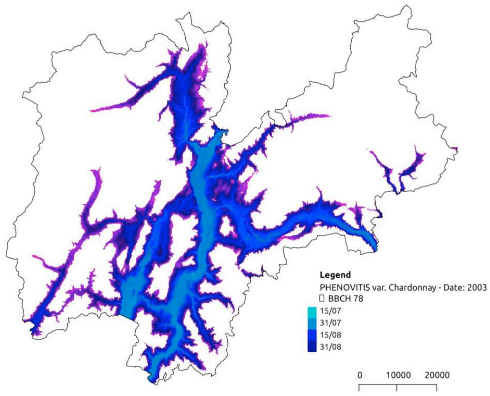




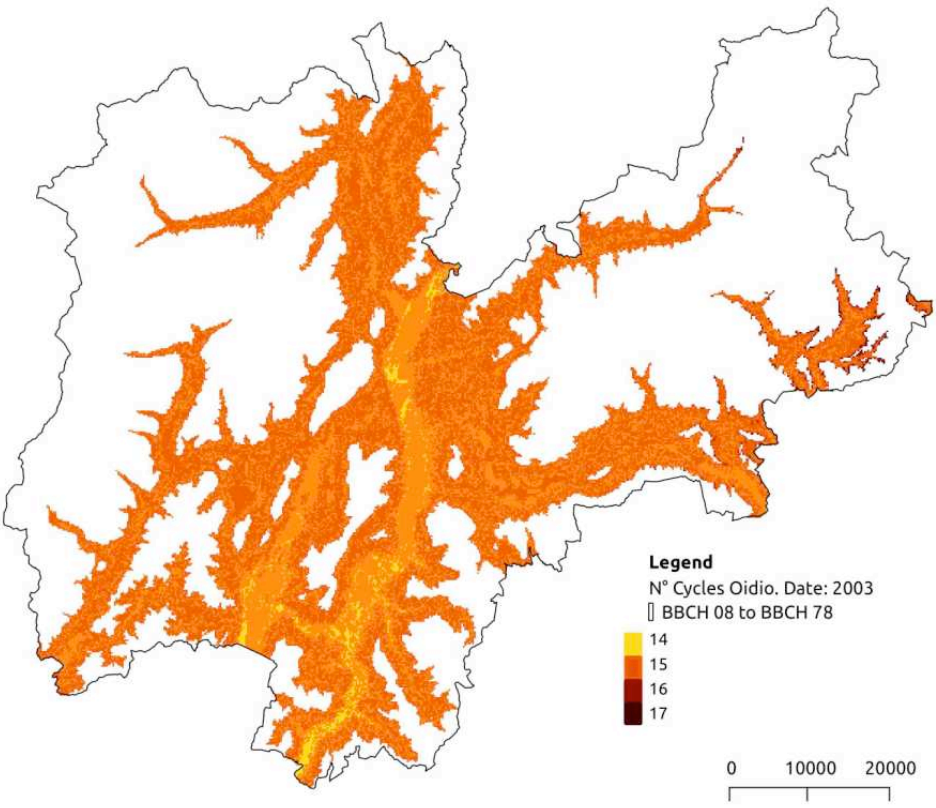
2002



Legend
PHENOVITIS var. Chardonnay. Date: 2003
BBCH 08
15/04
30/04
15/05
31/05
0
10000
20000

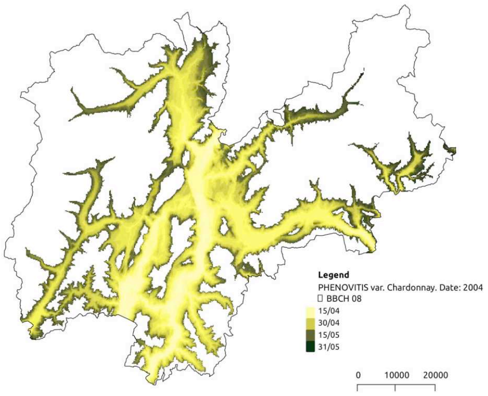


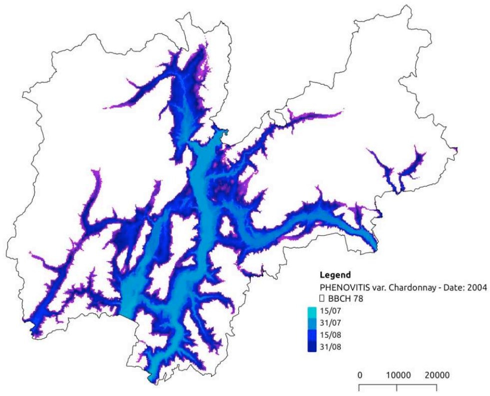
Legend
PHENOVITIS var. Chardonnay - Date: 2003
BBCH 78
15/07
31/07
15/08
31/08
0
10000
20000

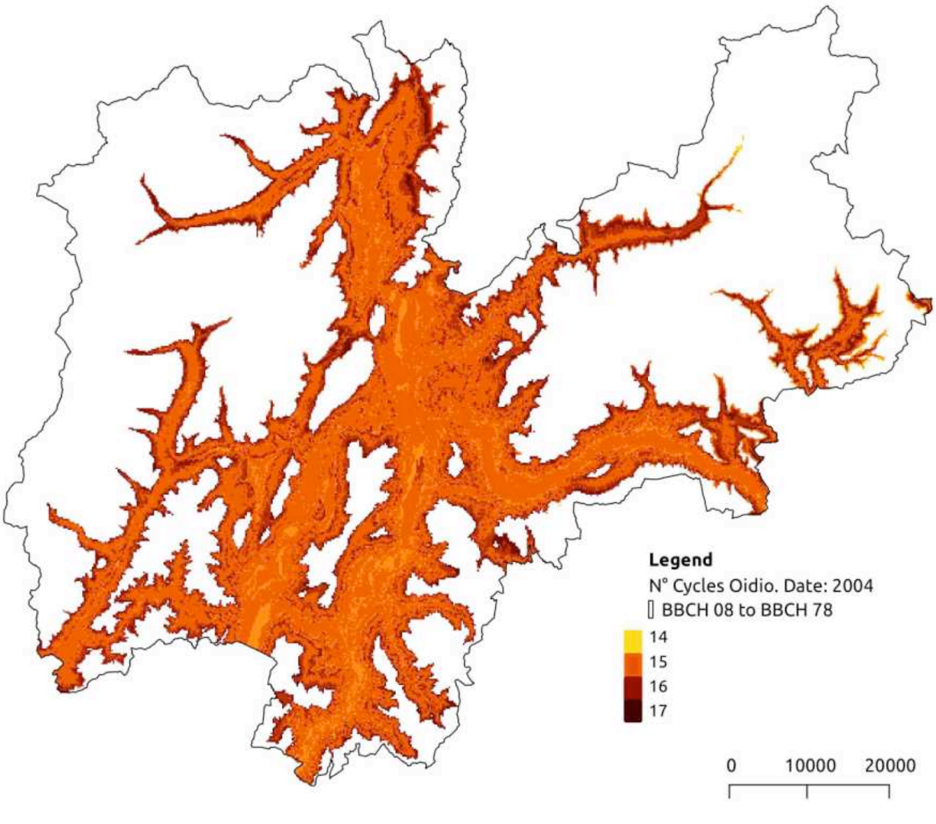


Legend
N° Cycles Oidio. Date: 2003
BBCH 08 to BBCH 78
14
15
16
17
0
10000
20000

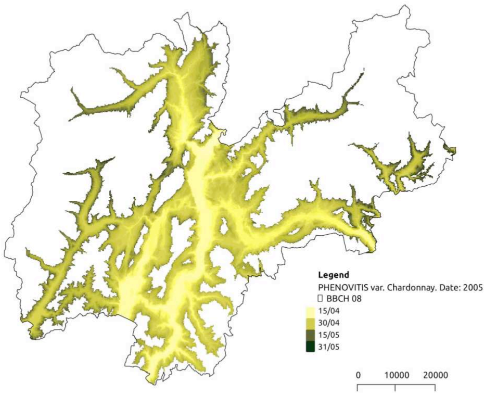
2003

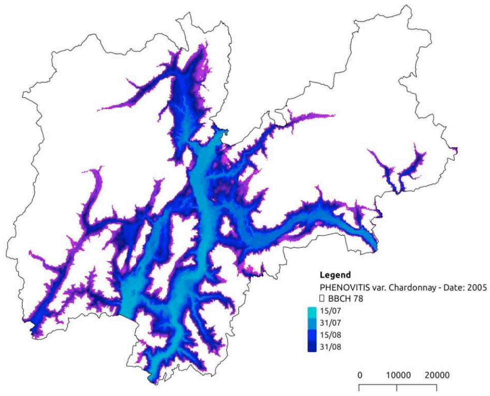

Legend
PHENOVITIS var. Chardonnay. Date: 2004
BBCH 08
15/04
30/04
15/05
31/05
0
10000
20000

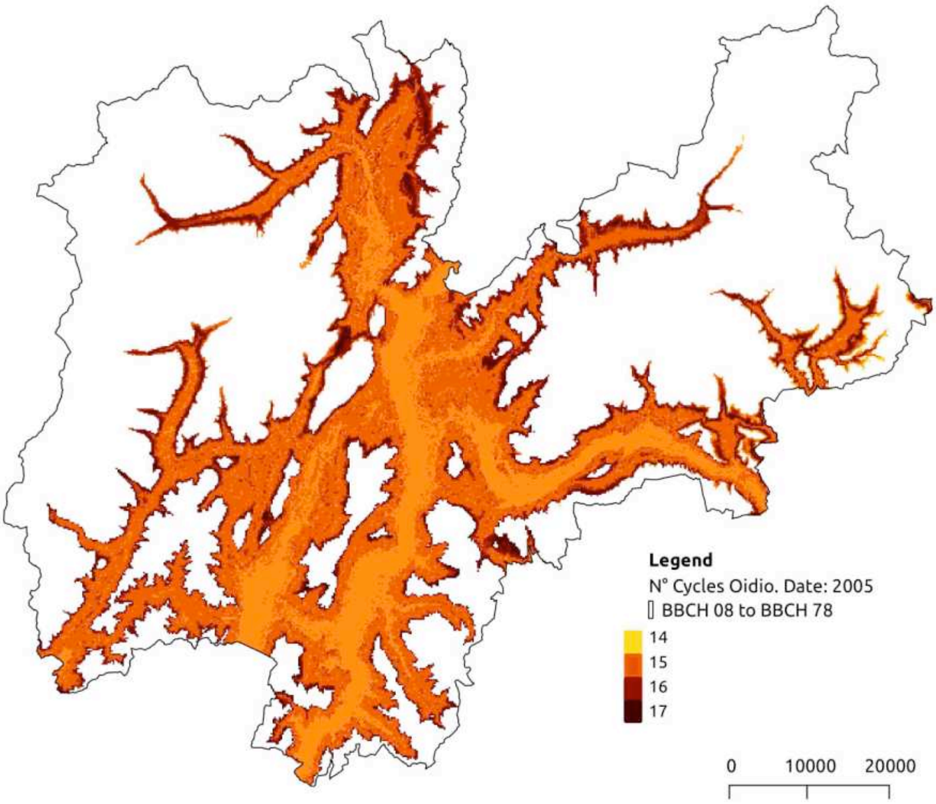

Legend
PHENOVITIS var. Chardonnay - Date: 2004
BBCH 78
15/07
31/07
15/08
31/08
0
10000
20000


Legend
N° Cycles Oidio. Date: 2004
BBCH 08 to BBCH 78
14
15
16
17
0
10000
20000

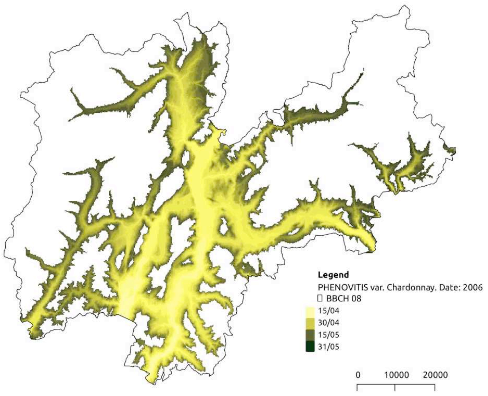
2004

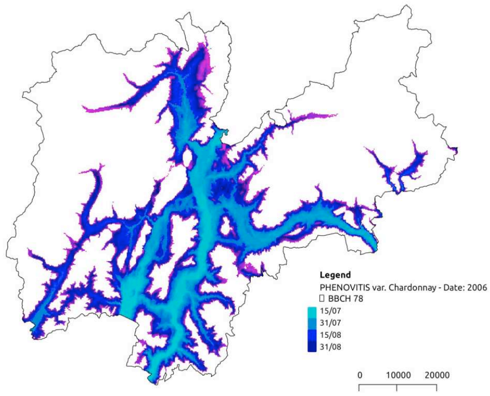

Legend
PHENOVITIS var. Chardonnay. Date: 2005
BBCH 08
15/04
30/04
15/05
31/05
0 10000 20000

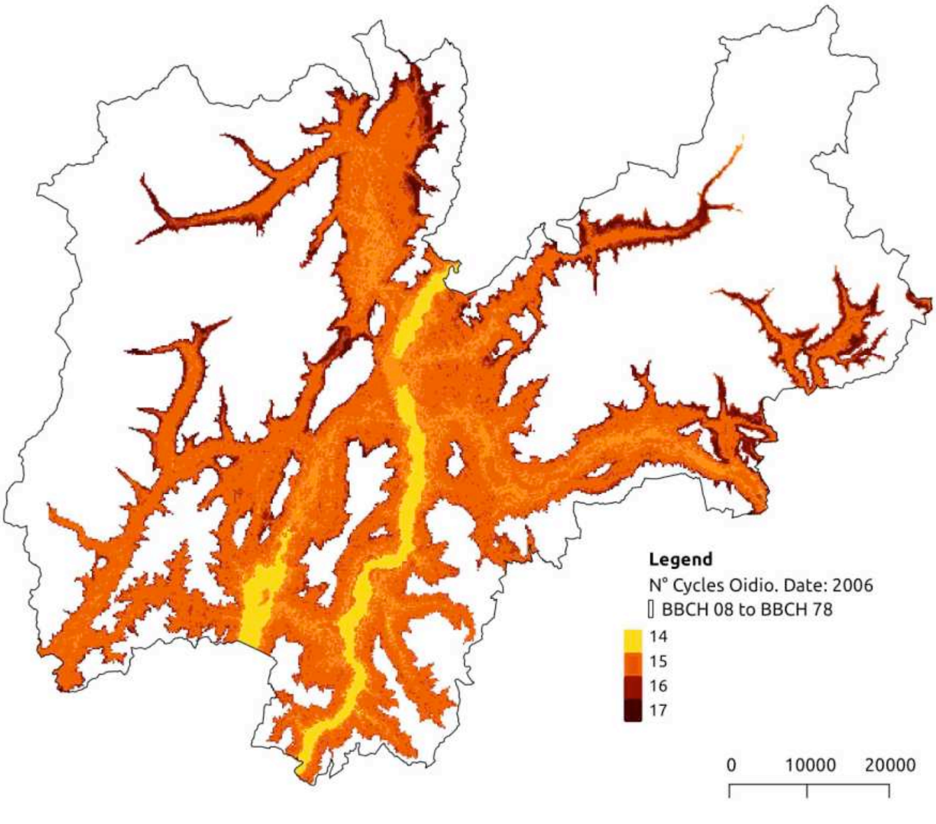

Legend
PHENOVITIS var. Chardonnay - Date: 2005
BBCH 78
15/07
31/07
15/08
31/08
0 10000 20000


Legend
N° Cycles Oidio. Date: 2005
BBCH 08 to BBCH 78
14
15
16
17
0 10000 20000

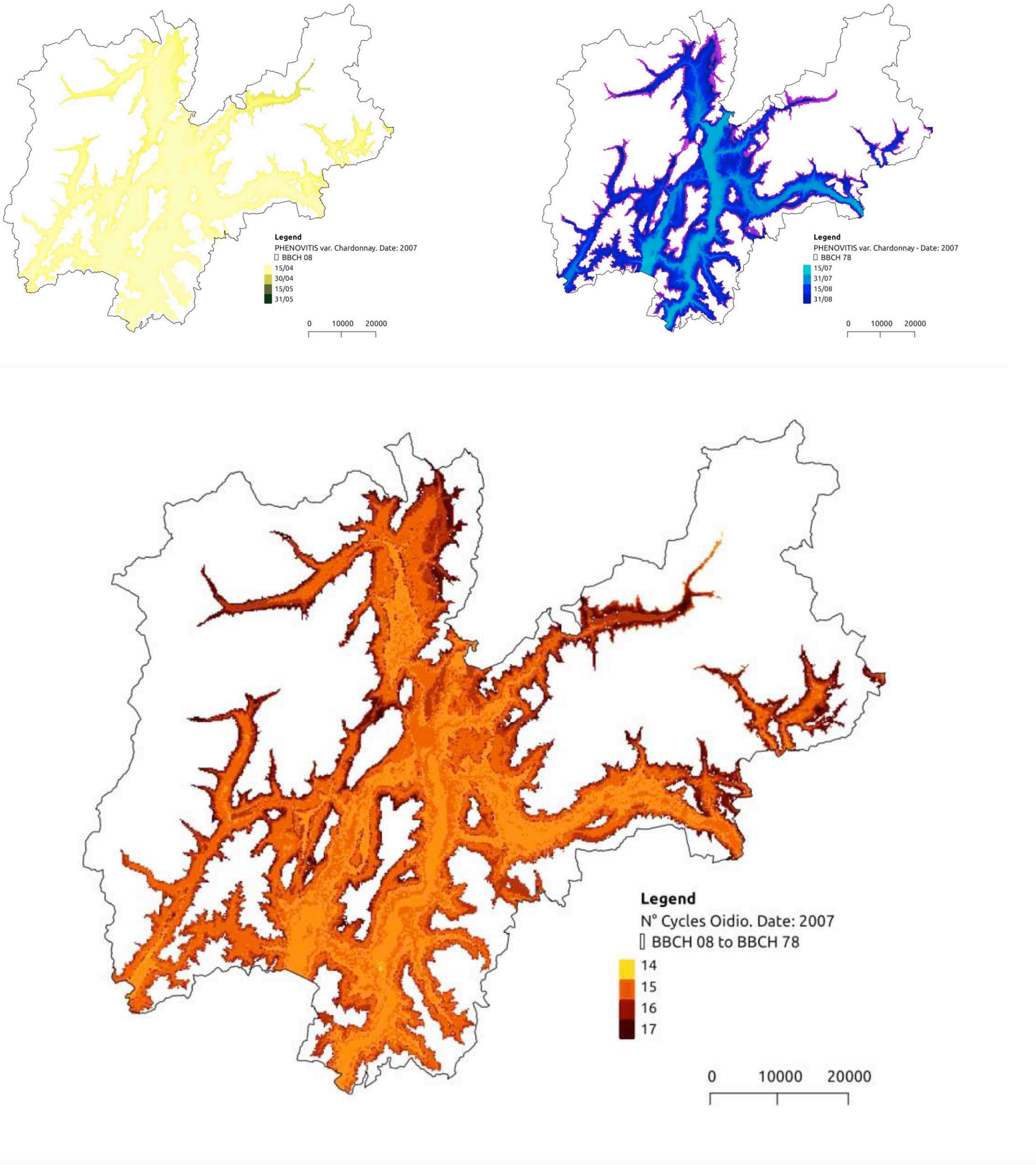
2005


Legend
PHENOVITIS var. Chardonnay. Date: 2006
BBCH 08
15/04
30/04
15/05
31/05
0
10000
20000


Legend
PHENOVITIS var. Chardonnay - Date: 2006
BBCH 78
15/07
31/07
15/08
31/08
0
10000
20000


Legend
N° Cycles Oidio. Date: 2006
BBCH 08 to BBCH 78
14
15
16
17
0
10000
20000

2006



2007

Fig.8. *Maps of Interaction between host phenology and Erysiphe necator. BBCH 07 (left plot) – BBCH 78 (plot right) – Number of cycles of Erysiphe necator (middle bottom) in 2002 (top plots) – 2003 – 2004 – 2005 – 2006 – 2007 (bottom plots). The legend for each plot is displayed at the bottom right of the plot.*

Forecasted Maps:

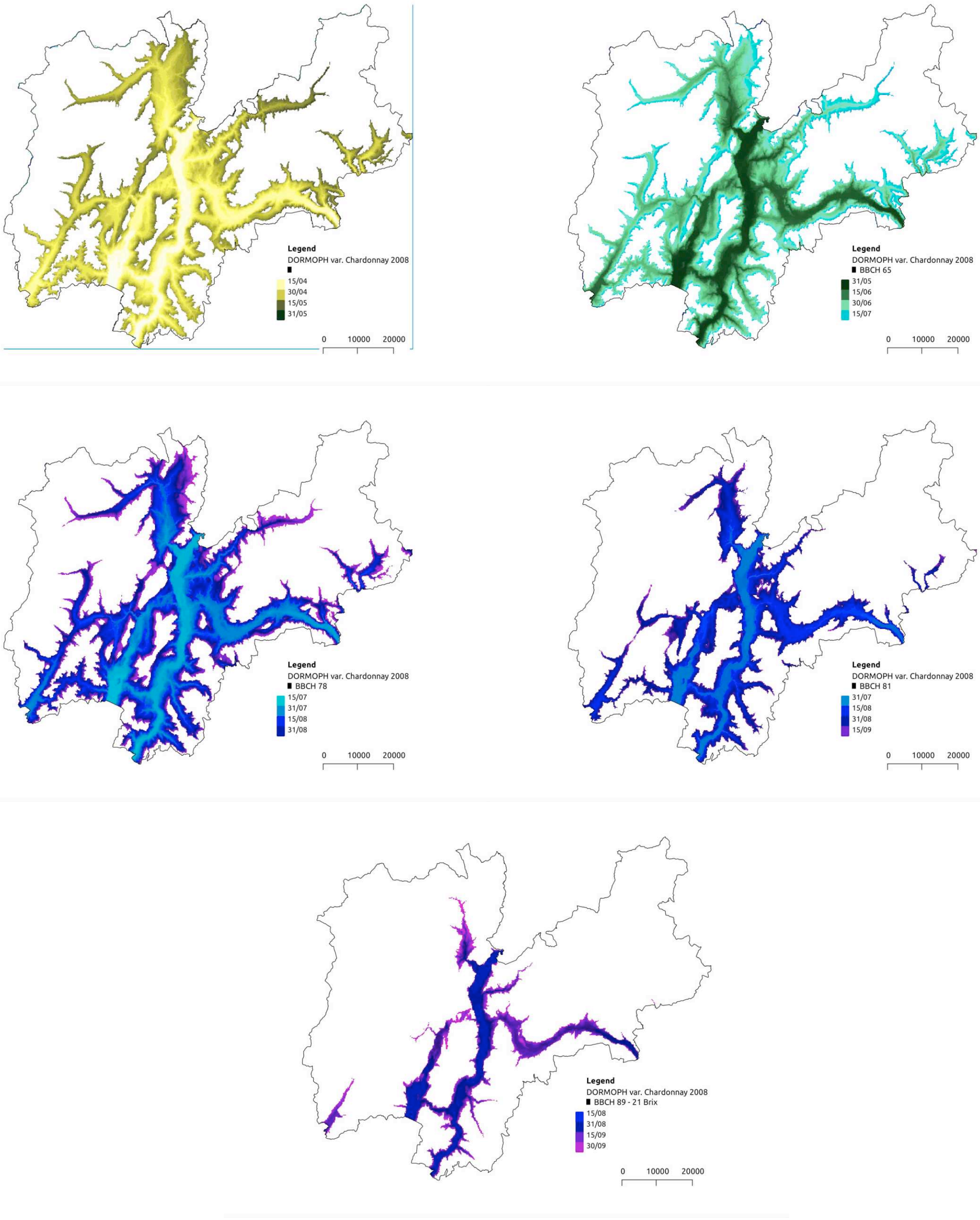


Fig.9. *Map of Chardonnay Phenology: BBCH 07 (top left plot), BBCH 65 (top right plot), BBCH 78 (middle left plot), BBCH 81 (middle right plot), BBCH 89 (bottom left plot) in the period 2000-2010. The legend for each plot is displayed at the bottom right of the plot.*

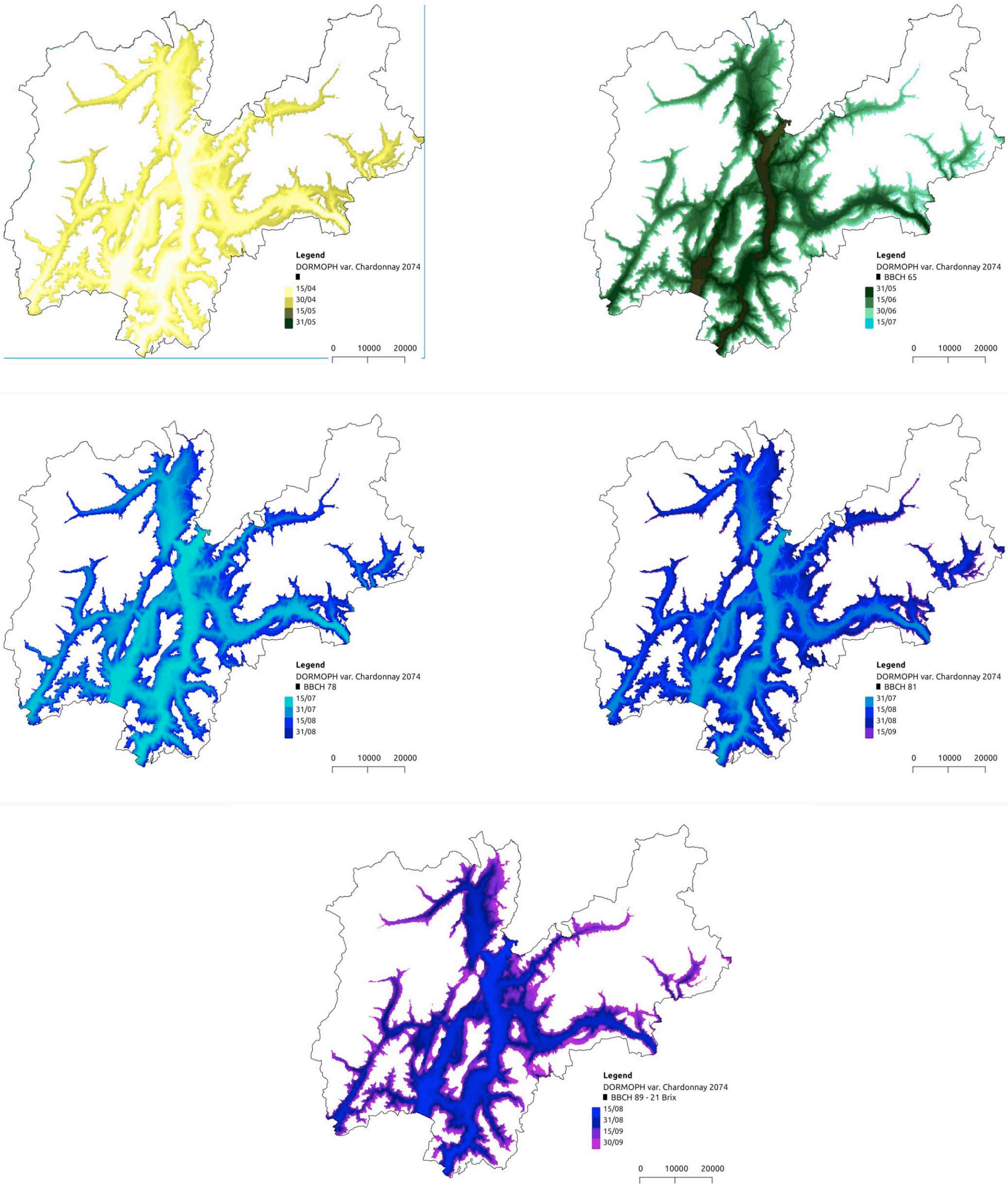


Fig.10. *Map of Chardonnay Phenology: BBCH 07 (top left plot), BBCH 65 (top right plot), BBCH 78 (middle left plot), BBCH 81 (middle right plot), BBCH 89 (bottom left plot) in the period 2070-2100. The legend for each plot is displayed at the bottom right of the plot.*

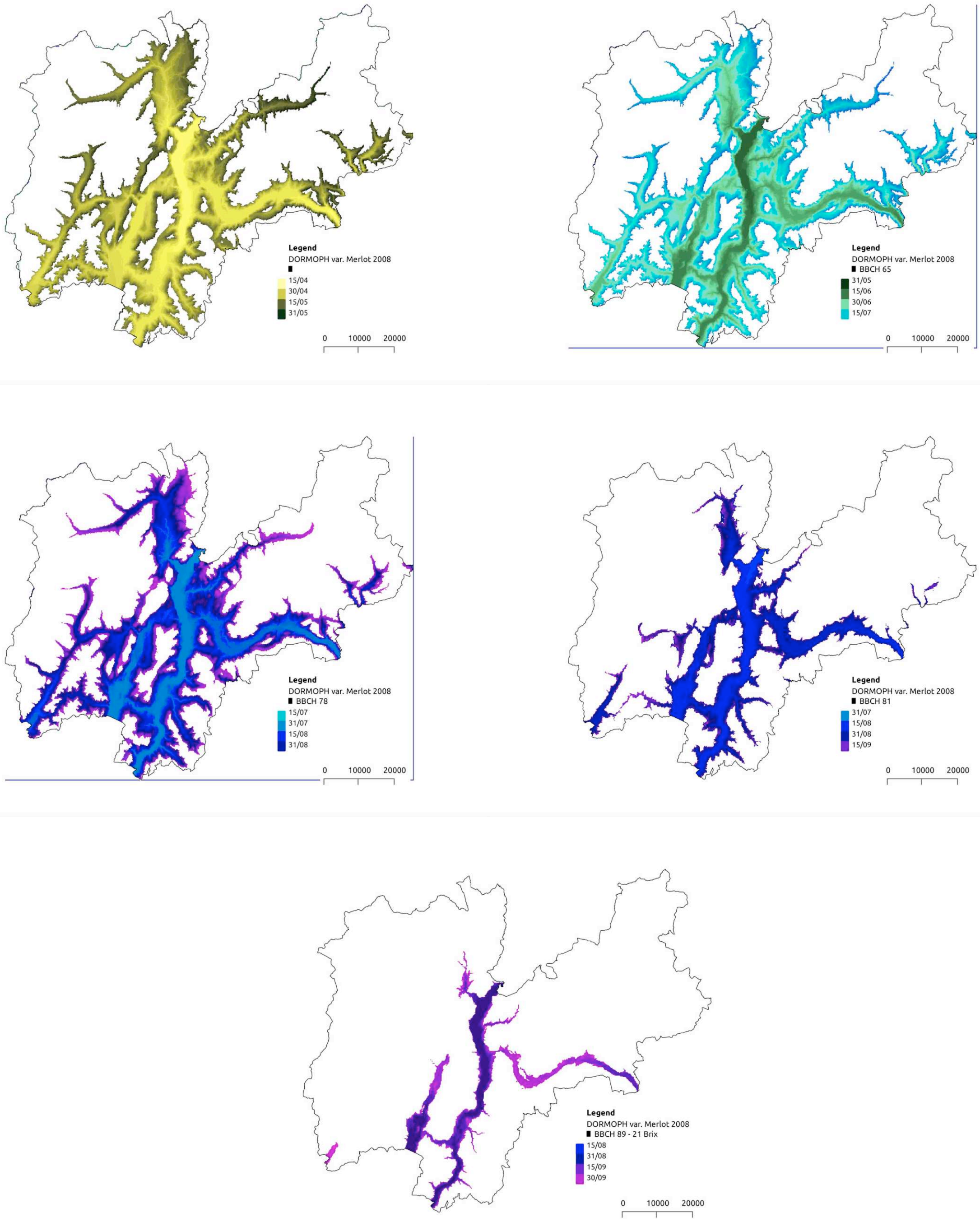


Fig.11. *Map of Merlot Phenology: BBCH 07 (top left plot), BBCH 65 (top right plot), BBCH 78 (middle left plot), BBCH 81 (middle right plot), BBCH 89 (bottom left plot) in the period 2000-2010. The legend for each plot is displayed at the bottom right of the plot.*

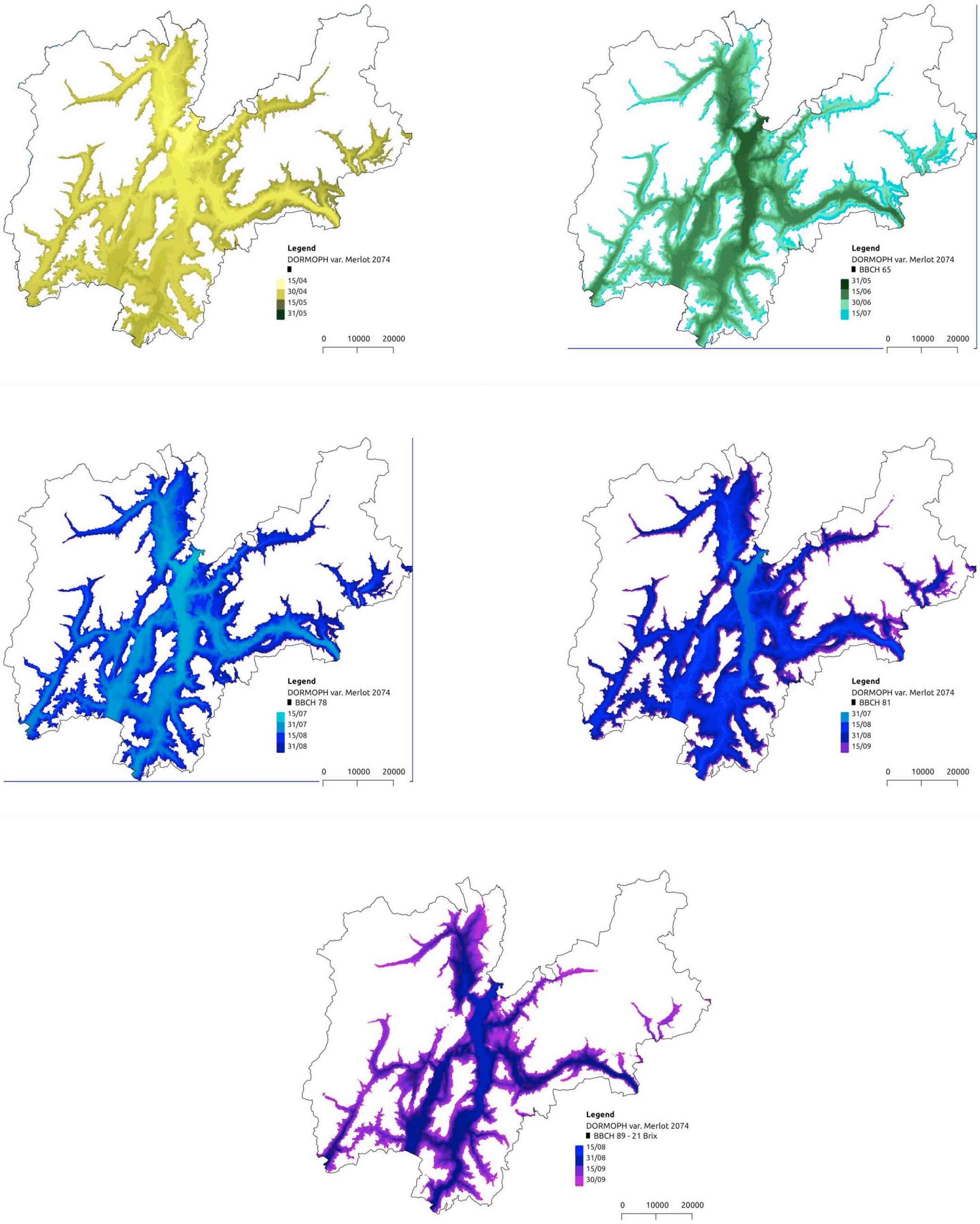


Fig.12. *Map of Merlot Phenology: BBCH 07 (top left plot), BBCH 65 (top right plot), BBCH 78 (middle left plot), BBCH 81 (middle right plot), BBCH 89 (bottom left plot) in the period 2070-2100. The legend for each plot is displayed at the bottom right of the plot.*

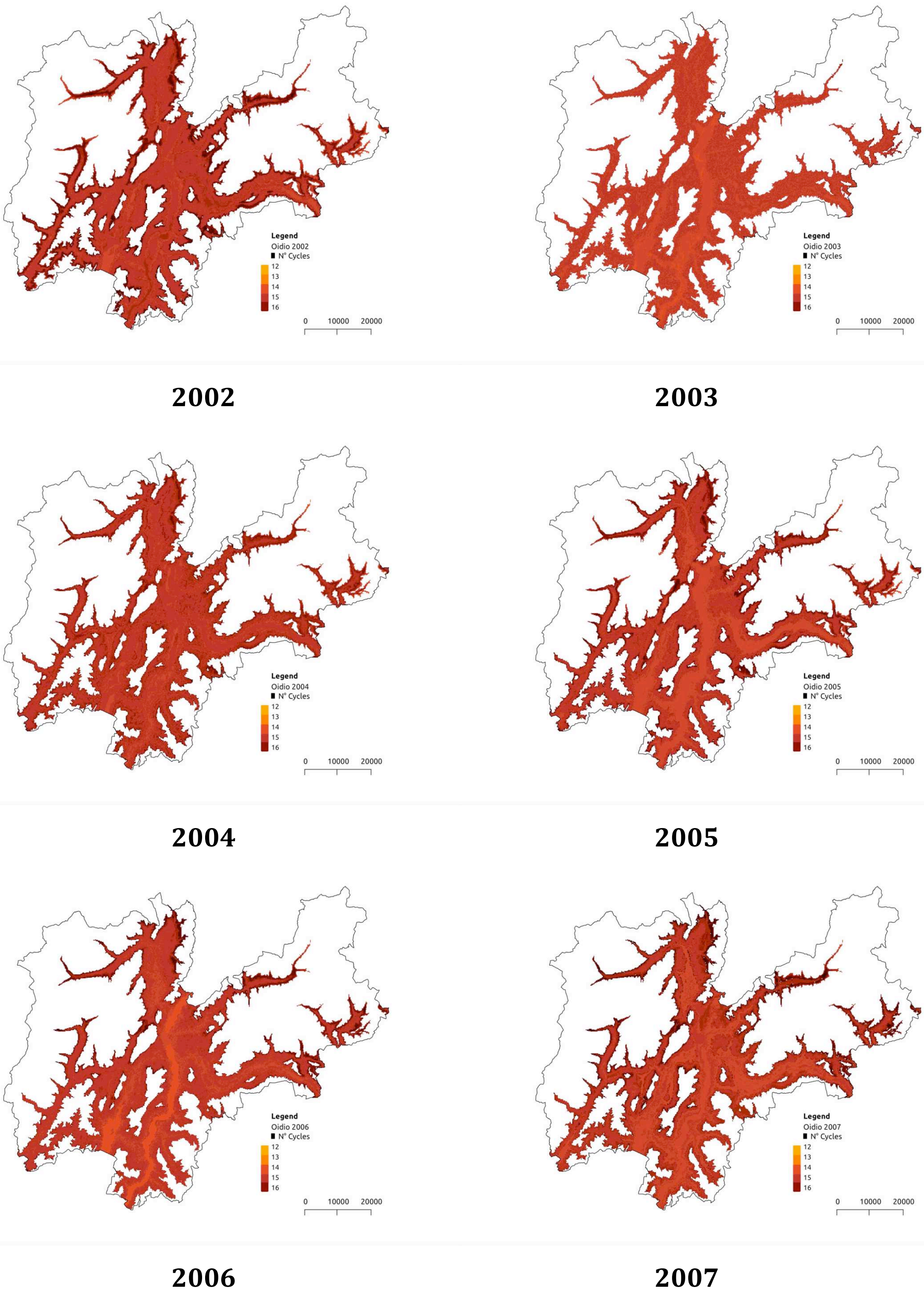


Fig.13. *Number of Powdery mildew cycles using past weather data, from BBCH 08 to BBCH78. Period 2002 (top left plot) -2003 (top right plot) -2004 (middle left plot) -2005 (middle right plot) -2006 (bottom left plot) -2007 (bottom right plot). The legend for each plot is displayed at the bottom right of the plot.*

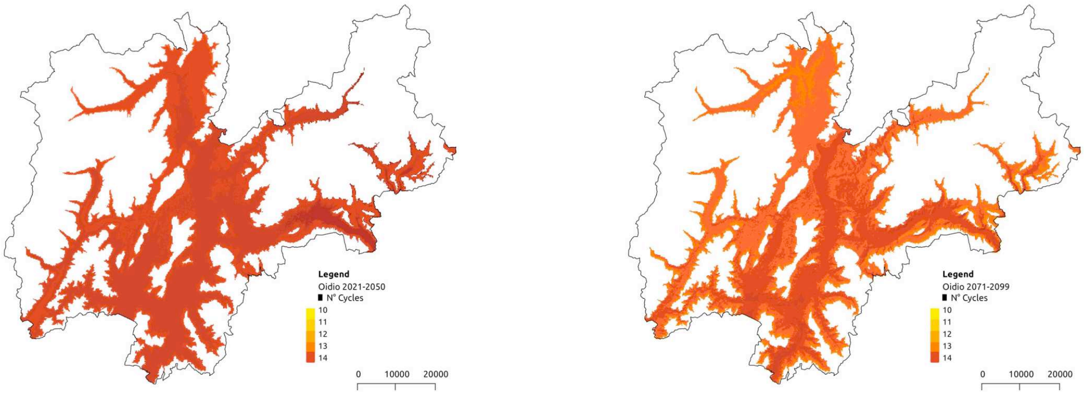


Fig.14. *Number of Powdery mildew cycles with the warmer climate change scenarios. The total cycles modelled were from BBCH 08 to BBCH 78 using PHENOVITIS in Chardonnay. Period 2021-2050 (left plot) and period 2070-2100 (right plot). The legend for each plot is displayed at the bottom right of the plot.*

Graphics with data from one pixel:

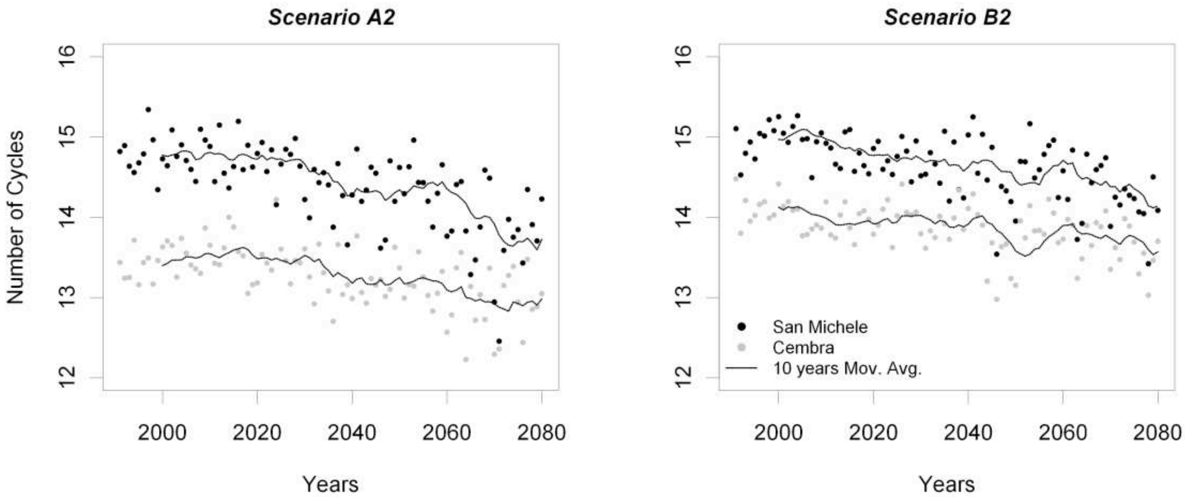


Fig.15. *Disease Forecast Trend in A2 (left plot) and B2 (right plot) climate change scenarios. The legend of all plots is displayed at the bottom left of the right plot.*

Enviro web-gis:

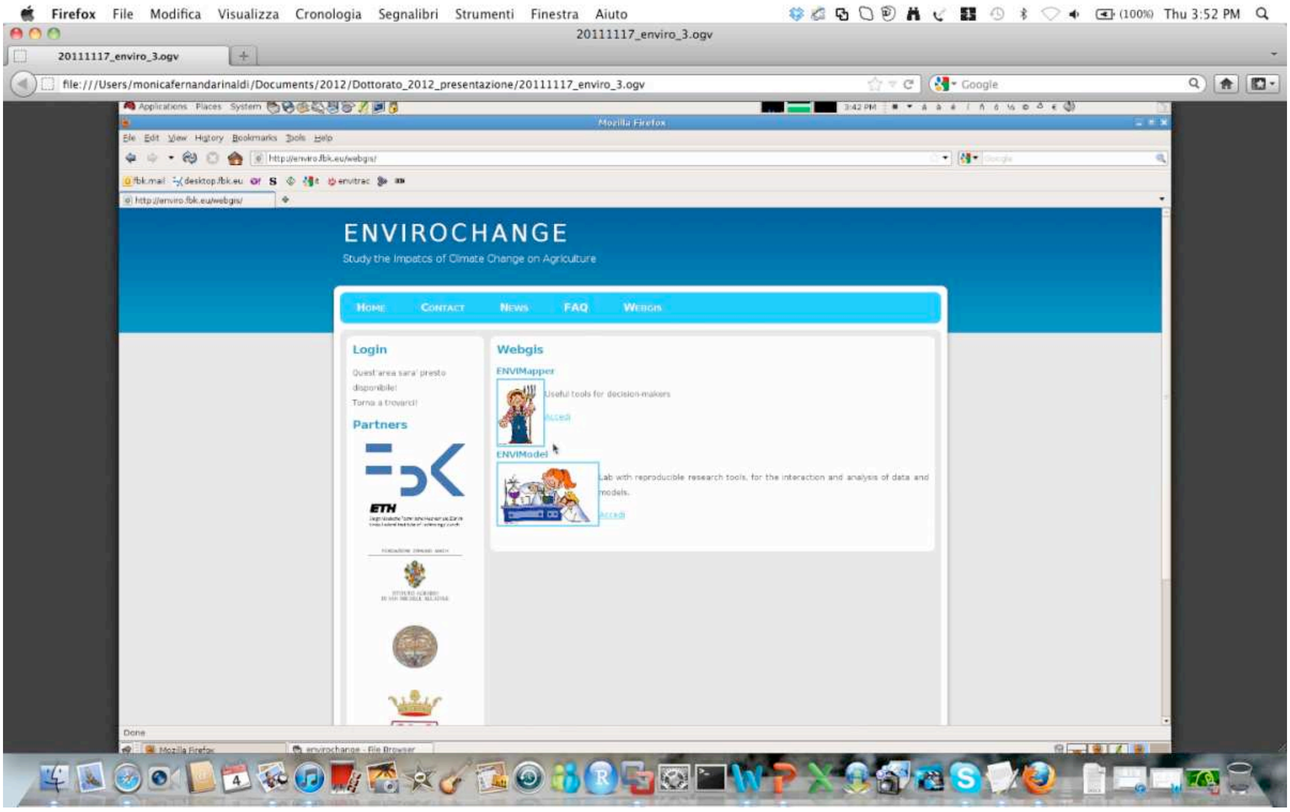


Fig.16. *Enviro web*

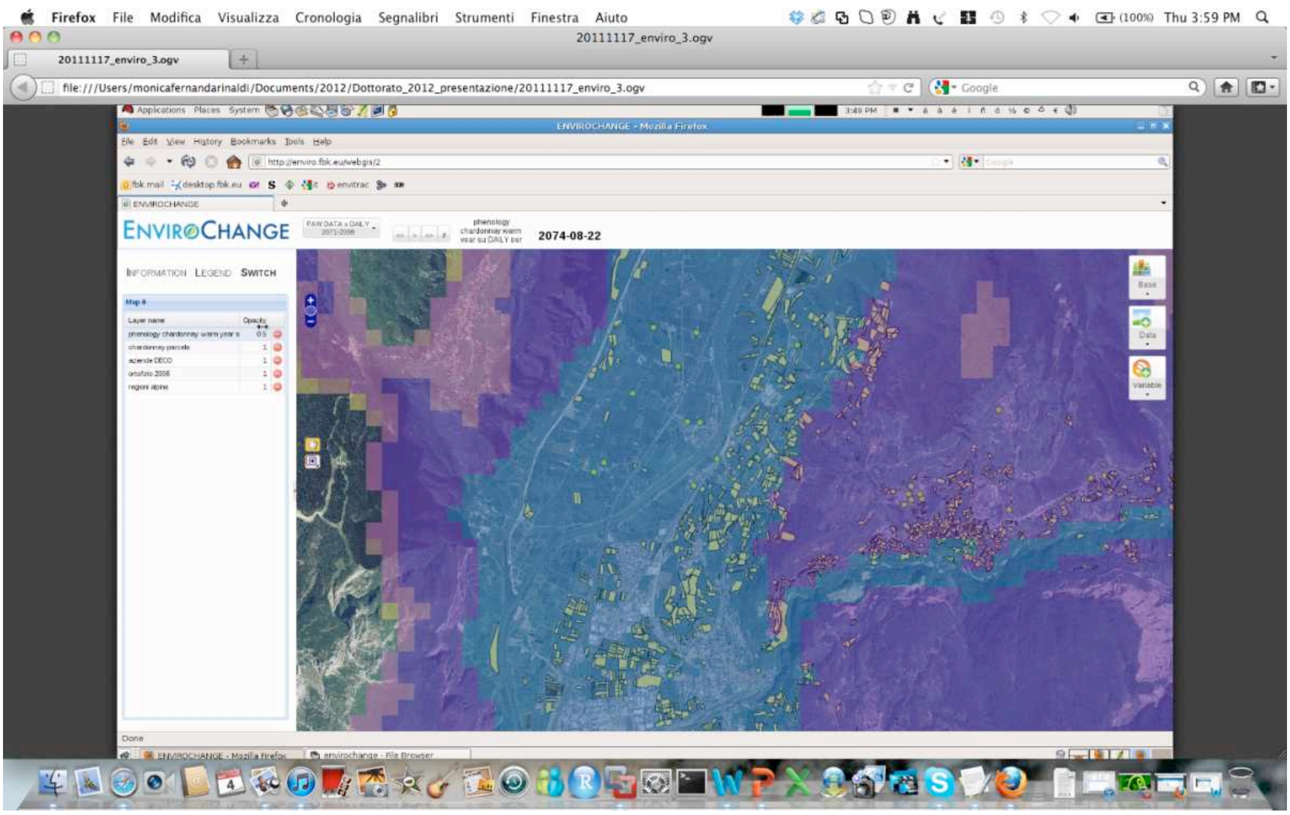


Fig.17. *Overlapped view into Enviro: Orthophoto image in the base, yellow vectors represent the chardonnay's orchards and raster map is phenological model overlapped.*

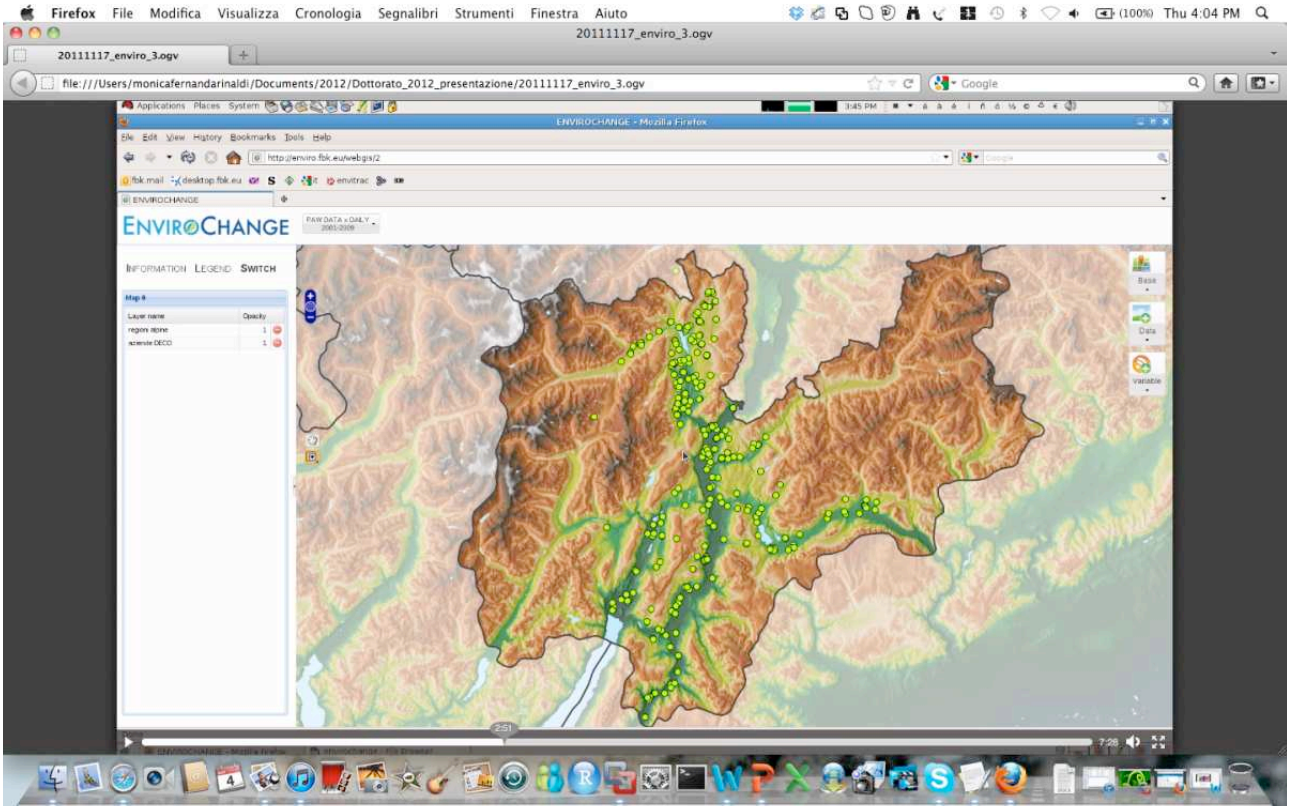


Fig.18. *View of monitored sites into Enviro: Green circles*

```
##################################################################
#  Author: Rinaldi Monica Fernanda
#  IASMA - Envirochange
#  13-05-2009
#  PM Model:
#                          Equation:
#                            Latency: 0,067*T_ave^2-3,2438*T_ave+44,703
#                            Tasso: 1/Latency
#                            Validation:
#                                       Rsquared:0.89
#                                       STD: 2,14
#
# Source Weather Data
#      FBK interpolated data base
#      IASMA (2003-2007): http://meteo.iasma.it/meteo/
#
#                 Model:
#                          Input variables:
#                                        # Environmental: Daily average temperature (in Celsius)
#                                        # Host: Grapevine – BBCH 08 to BBCH 78
#
################################################################
rm(list=ls(all=TRUE))#clean all

#### Inputs
#### Climate Change Scenario
```

```
SM <- read.table("G:\\GRAPHIC_A2\\Oidio\\Tn_Tx_27_1990-2098_A2_corr.txt",header=F, sep="\t",
dec=".")
#### Phenology
Feno_A2_SM <- read.table("G:\\pen_drive\\GRAPHIC_A2\\Oidio\\Phenol\\SM_A2.TXT",header=T, sep="\t",
dec=".")

#### A2
SM <- SM[366:39812,]
Tmax <- SM[,5]
Tmin <- SM[,4]
YEARS <- SM[,1]
YEARS <- as.factor(YEARS)
MONTH <- SM[,2]
DAYS  <- SM[,3]
Tmed <- (SM[,5]+SM[,4])/2 #AVERAGE CALCOLATO PER IL SCRIPT
SMA2 <- data.frame(YEARS,MONTH,DAYS,Tmax,Tmin,Tmed)

#### A2 phenological stages
BUDBREAK_A2  <- as.integer(Feno_A2_SM[,3])
FLOWERING_A2 <- Feno_A2_SM[,4]
BRIX8_A2     <- as.integer(Feno_A2_SM[,5])
VERAISON_A2  <- Feno_A2_SM[,6]
BRIX21_A2    <- Feno_A2_SM[,7]

##### PM Model
 oidio_latencys    <- array()
 oidio_tassos      <- array()
 oidio_num_cycless <- array()
 Tmedcal           <- array()
 Cycles <- function(SMA2){
   for (t in 1:length(levels(YEARS))){
        Tmedcal[t] <- subset(SMA2,SMA2$YEARS == (levels(YEARS)[t]), select = c(Tmed) )
        oidio_latencys <- 0
        oidio_tassos   <- 0
        x <- 0
          for (x in (BUDBREAK_A2[t]:BRIX8_A2[t])){
                oidio_latencys[x]    <- 0.067*Tmedcal[[t]][x]^2-3.2438*Tmedcal[[t]][x]+44.703
                oidio_tassos[x]      <-  na.omit(1 /oidio_latencys[x])
                }
          oidio_num_cycless[t] <- as.integer(sum(na.omit(oidio_tassos)))
        }
return(oidio_num_cycless)
}
n_cycles <- Cycles(SMA2)

#### HIGH PRESSURE
Predicted_HIGH_SEVERITY <- function(n_cycles){
  a <- 9.11993547092718
  b <- 0.997560095988557
  c <- 0.98
  Pred_HIGH_SEVERITY <- 0
  Pred_HIGH_SEVERITY <- c/(1+exp(a-b*n_cycles))
  return(Pred_HIGH_SEVERITY)
}
outputHIGHSeverity <- Predicted_HIGH_SEVERITY(n_cycles)
```

```
#### INTERMEDIATE PRESSURE
Predicted_INTERMEDIATE_SEVERITY <- function(n_cycles){
  a <- 14.6321466553581
  b <- 1.21449201910416
  c <- 0.49
  Pred_INTERMEDIATE_SEVERITY <- 0
  Pred_INTERMEDIATE_SEVERITY <- c/(1+exp(a-b*n_cycles))
  return(Pred_INTERMEDIATE_SEVERITY)
}
outputINTERMEDIATESeverity <- Predicted_INTERMEDIATE_SEVERITY(n_cycles)
Results <- data.frame(n_cycles,outputHIGHSeverity,outputINTERMEDIATESeverity)
```

Fig.19. *Example of script in R*

```
from pywps.Process.Process import WPSProcess
import random
import sys
class Process(WPSProcess):
     def __init__(self):
          # init process
         WPSProcess.__init__(self,
              identifier = "WPS_Monica_Confronto", # must be same, as filename
              title="Dummy Process",
              version = "0.1",
              storeSupported = "true",
              statusSupported = "true",
              abstract="",
              grassLocation ="StartLocation_EPSG_32632")
         self.Input1 = self.addLiteralInput(identifier = "input1",
                                            title = "Input1 number",
                                            default="100")

         self.Output1=self.addLiteralOutput(identifier="output1",
                                            title="Output1 add 1 result")
     def execute(self):
        log= open("/wps_monica_confronto.txt", "w")

       r = random.randrange(sys.maxint)
        tmplocation = "wps_monica_confronto_"+str(r)
       log.write("Importo il raster CUMSUM e creo location\n")
       log.flush()
       self.cmd(["r.in.gdal", "input=/ apache/htdocs/data/Oidio_Tasso_2009/Oidio_CUMSUM_2009.tif",
"output=cumsum_oidio_2009" , "--overwrite", "location="+tmplocation])
       log.write("Importo completato\n")

       log.write("Changing current working Location to the new one created in the step before\n")
       log.flush()
        self.cmd(["g.mapset","mapset=PERMANENT","location="+tmplocation])
```

```
log.write("Changing complete\n\n\n")
  log.write("Applico la maschera per il -9999.\n")
log.flush()
self.cmd(["r.mask", "-i", "input=cumsum_oidio_2009@PERMANENT", "maskcats=-9999"])
log.write("Completato.\n")

log.write("Importo il CSV con le stazioni meteo, convertendolo in vettoriale.\n")
log.flush()
self.cmd(["v.in.ascii", "input=/grassdata/anagrafica.csv", "output=stazioni", "fs=;",
"skip=1","x=2", "y=3"])
log.write("Importo completato.\n")
log.write("Aggiungere una colonna al DBF del vettoriale con il dato puntiale del CUMSUM.\n")
log.flush()
self.cmd(["v.db.addcol","map=stazioni@PERMANENT", "layer=1", "columns=SUM_PM double
precision"])
log.write("Completato.\n")
log.write("Importo il raster DTM\n")
log.flush()
self.cmd(["r.in.gdal", "input=/GEODATA/orotn200m.tif", "output=orotn200m" , "--overwrite"])
log.write("Importo completato\n")
  log.write("Estraiamo il valore del raster nel punto del vettoriale da aggiungere alla
colonna appena creata.\n")
  log.flush()
  self.cmd(["v.what.rast", "vector=stazioni@PERMANENT","raster=cumsum_oidio_2009@PERMANENT",
"layer=1","column=SUM_PM"])
log.write("Completato.\n")
log.write("Cancelliamo le righe con -9999.\n")
log.flush()
self.cmd(["v.extract", "input=stazioni@PERMANENT", "output=stazioni_normalizzate",
"type=point", "where=SUM_PM <> -9999"])
log.write("Completato.\n")
log.write("Interpoliamo con RST.\n")
log.flush()
self.cmd(["v.surf.rst", "input=stazioni_normalizzate@PERMANENT",
"elev=output_rst","maskmap=orotn200m@PERMANENT", "zcolum=SUM_PM","smooth=0.1"])
log.write("Completato.\n")

log.write("Rimuovo la maschera sul -9999.\n")
log.flush()
self.cmd(["r.mask", "-r"])
log.write("Completato.\n")
self.cmd(["r.null", "map=cumsum_oidio_2009@PERMANENT", "setnull=-9999"])
self.cmd(["r.mapcalc", "result=cumsum_oidio_2009-output_rst"])
self.Output1.setValue("Success")
return
```

Fig.20. *Example of script in JAVA*

LIDAR measurements:

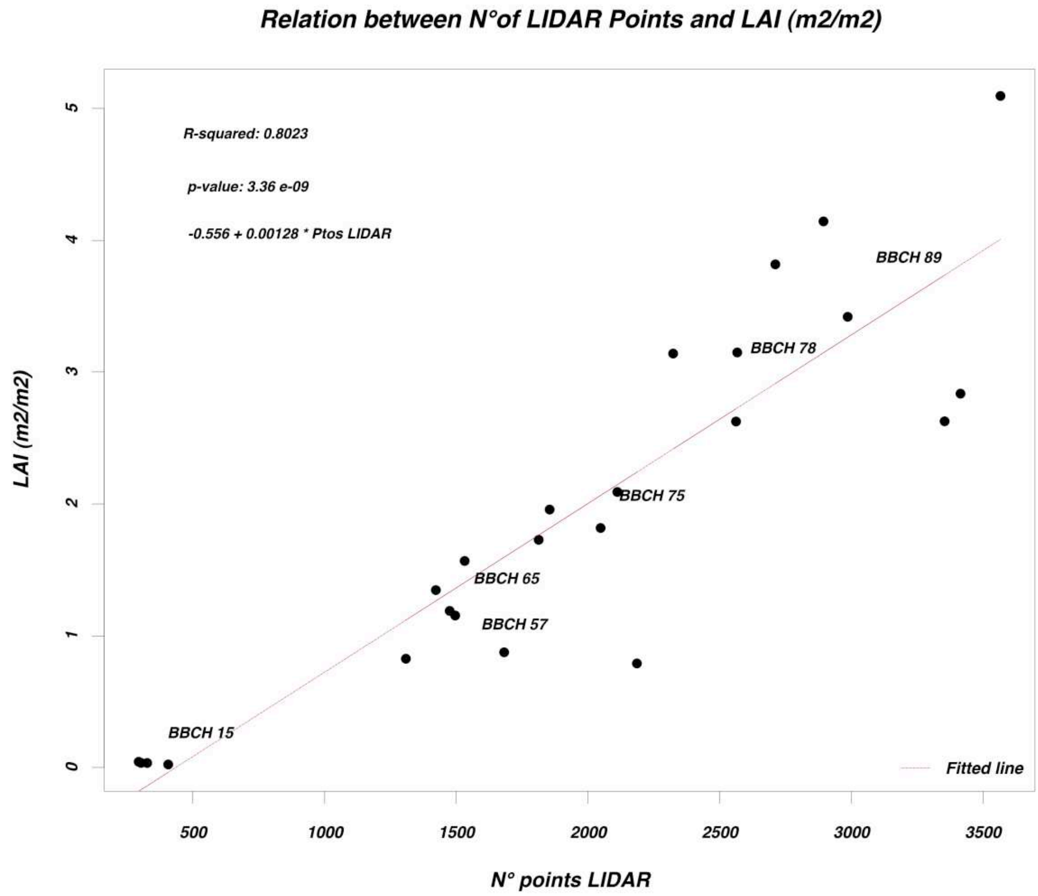


Fig.21. *Relationship between the numbers of points measured with LIDAR sensor into the canopy volume and LAI manual measurement.*

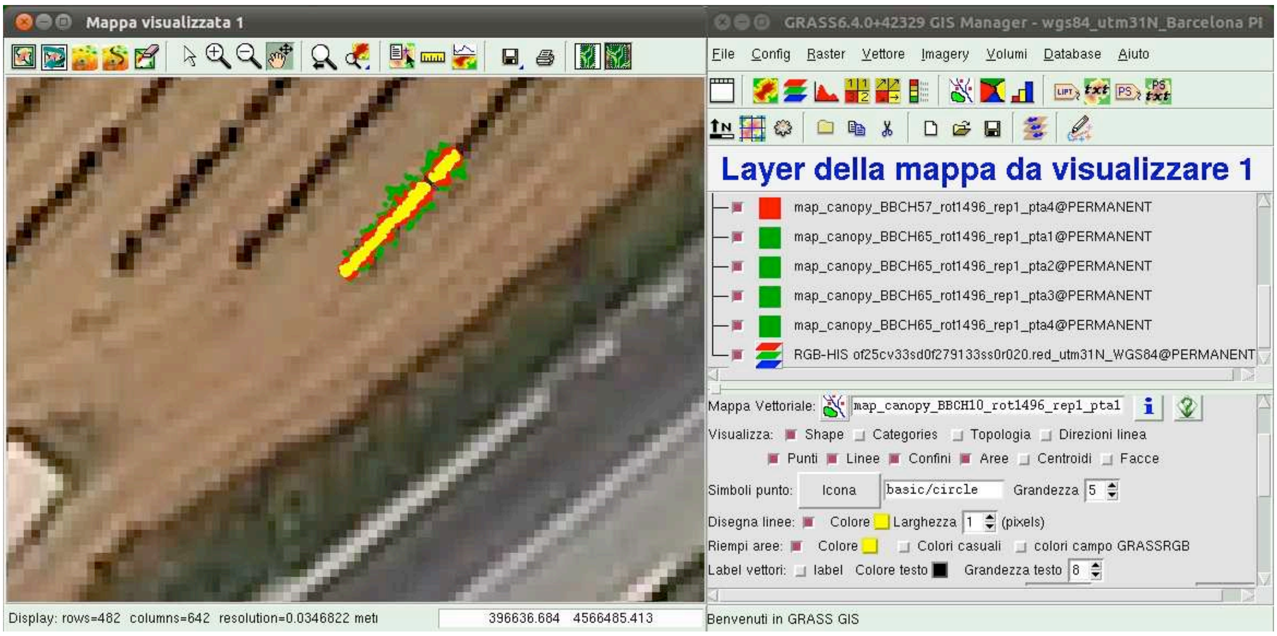


Fig.22. *2D Canopy View (top) where BBCH 15 (yellow points), BBCH 57 (red points), BBCH 65 (green points).*

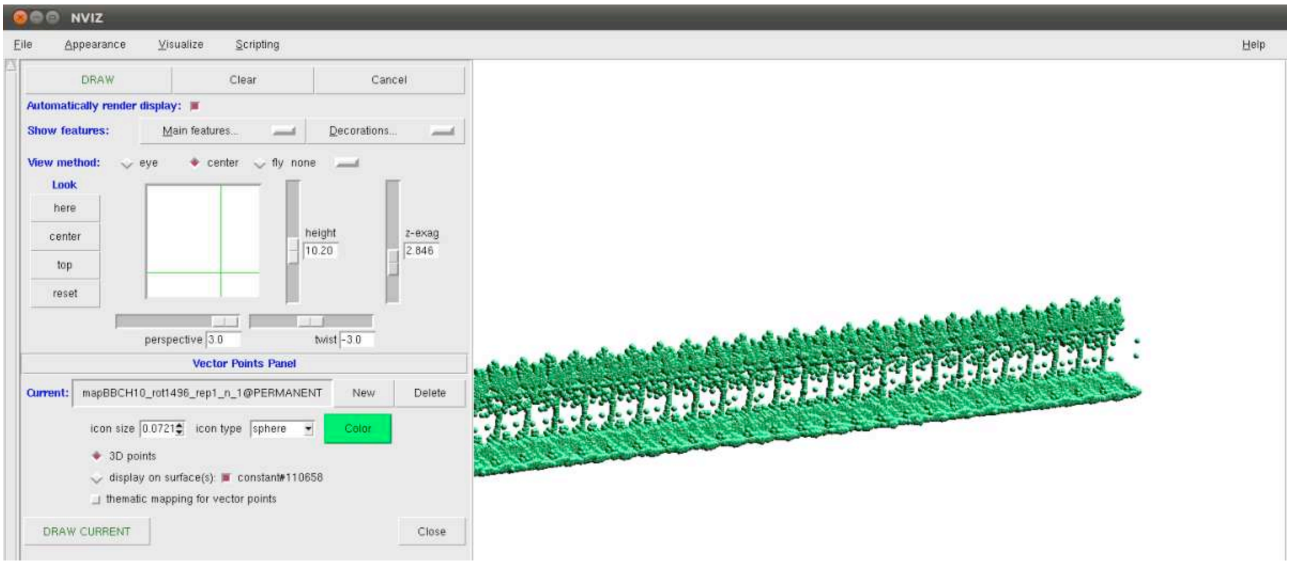


Fig.23. *3D Canopy View (bottom): BBCH 15 in NVIZ tool from GRASS-GIS.*

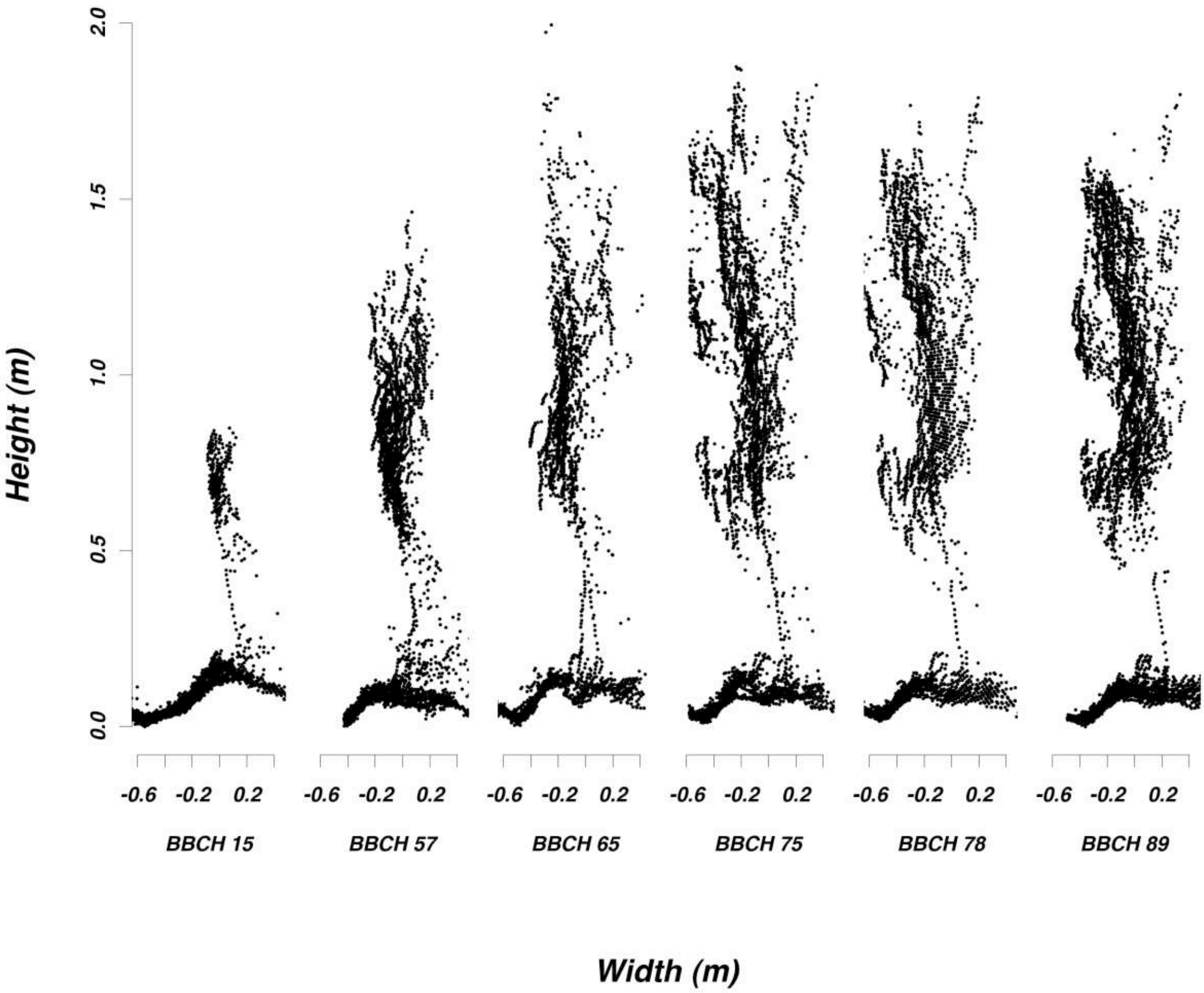


Fig.24. *LIDAR measurements: Relationship between height (m) and width (m).*

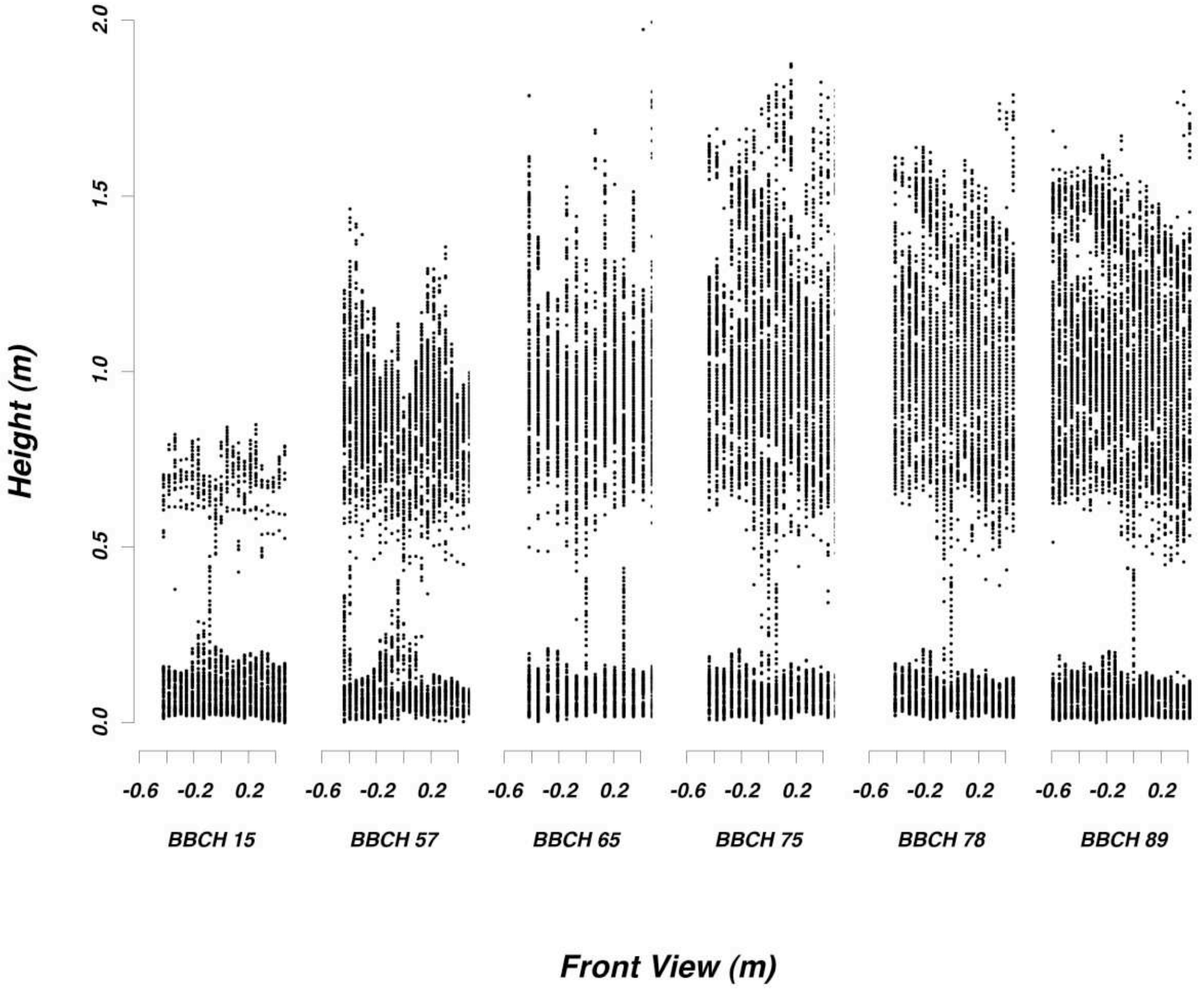


Fig.25. *LIDAR measurements: Relationship between height (m) and front view (m).*

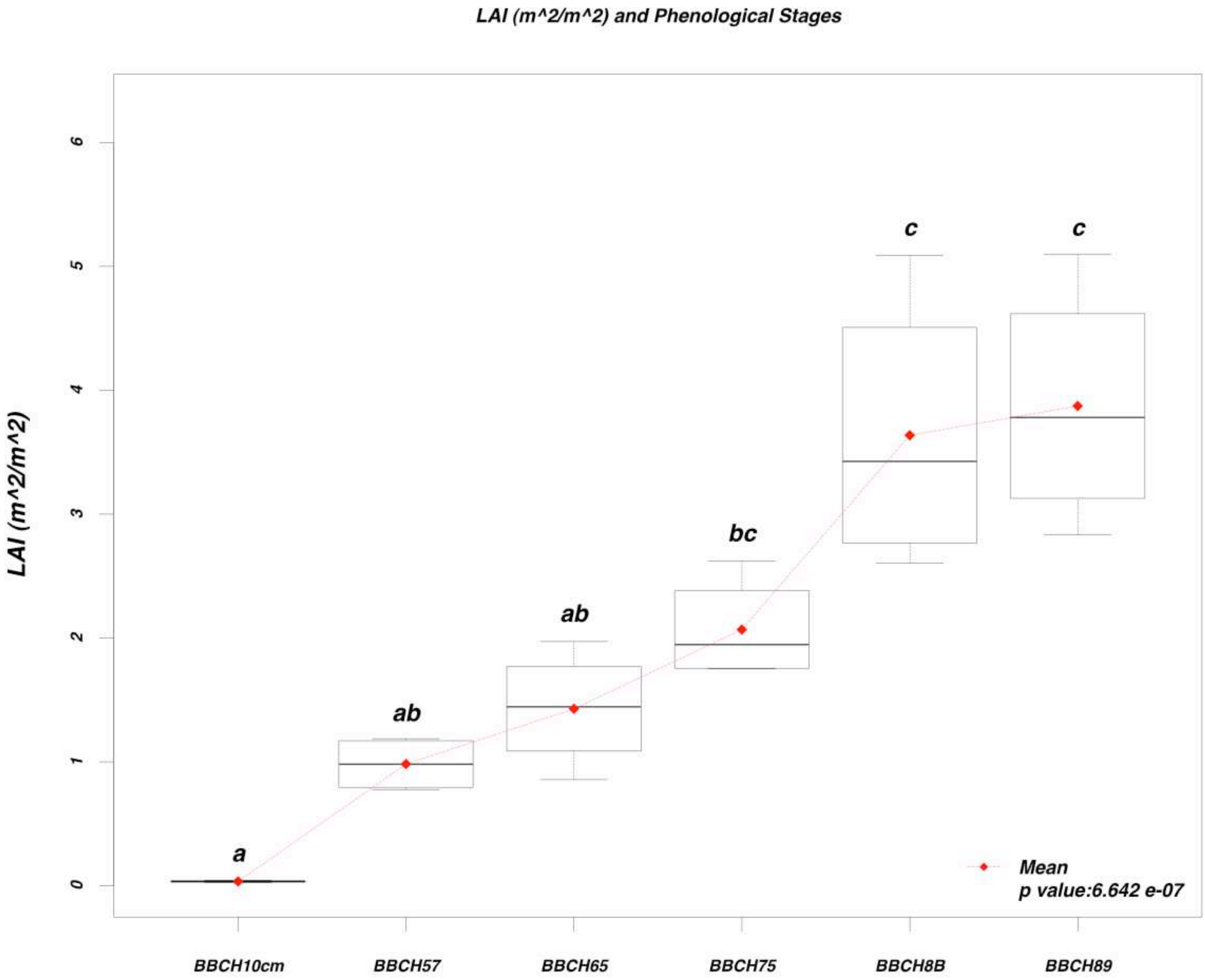


Fig.26. Leaf Area Index -*LAI measured in each phenological stage.*

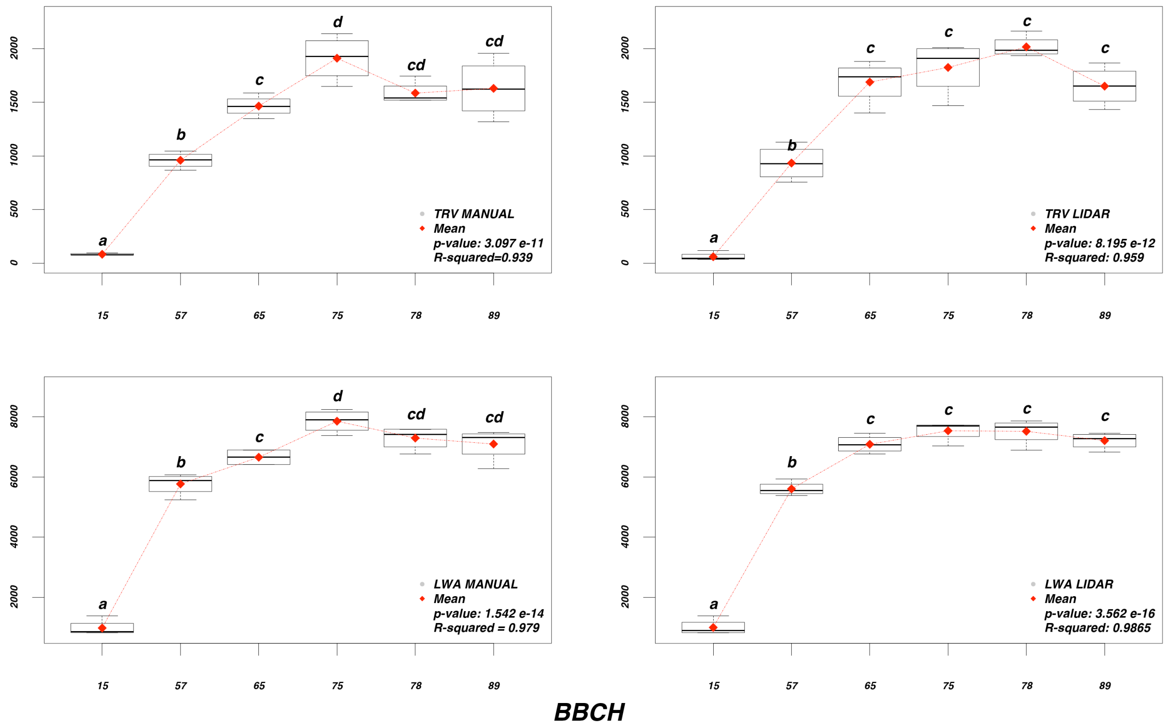


Fig.27. *TRV with manual measurement (top left) TRV measurement with LIDAR (top right), LWA with manual measurement (bottom left), LWA with LIDAR measurement (bottom right).*