Modelling new potential wine growing areas in the context of climate change

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Abstract
Modifications caused by climate change hold implications for wine regions worldwide. In this context, new climatic zones potentially favourable to viticulture are emerging. However, these areas are sometimes subject to significant pressures which raises several issues regarding the integration of new vineyards. In order to evaluate the potentialities of these areas, this contribution will present a spatial and multi-objectives optimization approach. Based on prospective simulation, this approach is proposed to calculate optimal agroclimatic zones according to different physical and regulatory constraints. To exemplify the approach, two scenarios dedicated to Brittany (France) will be presented: the first one is an optimization per variety, and the second one is an optimization between varieties, both with a simulation period from 2006 to 2100.

Introduction

Climate change impacts regional and local climates, which in turn affects the world's wine regions (Hannah *et al.* 2013; Mosedale *et al.* 2016). Due to the potential modifications caused by climate change, adaptation represents a major challenge for viticulture both in the short and long term (Keller 2010). In this context, a first issue concerns the identification, in the current production areas, of the most adapted pattern for different scenarios of climate change. A second issue is related to the identification of new opportunity areas in emerging wine regions due to climate change. Beyond the definition of potential zones, the issue of the conditions of integration of a new activity in zones that are sometimes already highly coveted is raised. For example, in a context of increasing temperatures and due to their particular climatic conditions, coastal and island areas could become "refuge areas" for wine growing, but they are subject to multiple pressures that make the establishment or extension of viticulture complex. To answer these different questions, it seems relevant to assess the evolution of agroclimatic potentialities of existing vineyards and emerging areas according to different climate change scenarios. In this way, the proposed approach is based on two major steps: 1) an identification of relevant criteria to account for agroclimatic characteristics and biophysical constraints for viticulture, and 2) the optimization process to compute optimality zones according to several scenarios. The first identification step tends to highlight characteristics and constraints thanks to an in-depth bibliography. A global inventory on a worldwide scale has been realised and enabled to document different climatic configurations and agronomic practices of these vineyards in the world. Applied in particular to coastal and island vineyards, this method showed that it was possible to identify relevant criteria to describe and categorise wine areas (Thibault *et al.* 2020b; 2020a). This typology can be divided into three main sections associated with agronomic characteristics, biophysics characteristics and economical aspects of the vineyard.
In the second part, an optimization process tends to identify suitable areas for wine-growing establishment according to different scenarios of climate change. In our approach, the criteria from the typology are mobilised in a spatial optimization process and can be used as constraints or objectives to be optimised. The spatial optimization is an "*optimal spatial planning which […] involves identifying the best locations for activities and resources in relation to objectives and constraints*" (Yao *et a*l. 2018).

Materials and methods

The spatial optimization model presented in this contribution is based on a multi-objective paradigm that calculates optimal solutions according to different objectives and constraints. The model is divided into two main steps: 1) the creation of a scenario which includes the constraints and objectives' definition, and 2) the simulation process. The optimality calculation is based on an elitist approach that only keeps optimal solutions according to the objectives (Francisci, 2002).

The scenario's construction

For each scenario, several parameters are defined such as the study area, the simulation period, the climatic projection, grape varieties and agronomic management system planned (including minimum planting duration). To complete these information constraints and objectives to implant vines are specified. A constraint is a condition that limits or even prohibits some solutions. Currently, constraints that hinders vines planting are related to land use and soils aspects and constraints that limit implantation are related to neighbourhood (proximity of other vineyard plots) and the existence of a historical viticultural activity. Concerning objectives, they can be defined as goals to be reached by maximising a criterion (environmental or agronomic) or by minimising a risk (climatic or economic). Currently, four objectives aimed at minimising annual occurrences are implemented. The first and the second objective tend to minimise the number of frost days and heat waves. The third objective is to minimise the potential exposure to pathogen risk. The last objective focuses on reaching technical maturity according to grape variety and targeted wine style.
The objectives are calculated from daily occurrences globalised annually. This yearly accumulation includes the number of days corresponding to threshold defined at the initialization step : 1) when the minimal temperature is below 0°C (Webb *et al*. 2017; Gavrilescu *et al*. 2019), 2) when the maximal temperatures is up to 35°C (Gambetta *et al*. 2021) and 3) when climatic conditions are favourable to the development of pathogen risk (Tissot *et al*. 2020). For each objective, thresholds are defined as acceptable and limits. Under acceptable limits, the risk is considered as low; between acceptable and limit thresholds, the risk is moderate and above the limit thresholds, the risk is too high and the model removes the area concerned. The date of potential technical maturity is calculated for each year according to the Grapevine Sugar Ripeness (GSR) index (Parker *et al*. 2020). If the maturity is not reached, it is possible to set a lowering of the maturity threshold, and to re-calculate a maturity date with the lower threshold. Then, if an area does not reach maturity again, it is dropped from the optimization process. The choice to lower or not this threshold can be set in the scenario, and can be limited with limits like for the three previous objectives.

The simulation process

Several studies have shown that the main phenological stages of vine are in relation with a sum of temperatures (Duchêne *et* Schneider 2005; van Leeuwen *et al*. 2008), and can be modelled according to the Baggiolini's classification (Baggiolini 1952). In the model, for each variety and each year, dates of bud break are calculated according to the Growing Degree Days from Winkler (Winkler 1974; van Leeuwen *et al*. 2008), date of véraison according to the Grapevine Flowering Véraison (GFV) model (Parker *et al*. 2013) and technical maturity to according to Grapevine Sugar Ripeness (GSR) model (Parker *et al*. 2020). Periods between these key stages are considered as phases of increased sensitivity to climate risks (Cantat *et al*. 2019) and occurrences related to objectives are calculated during vegetative growth. With the limits pre-defined previously, if the sum of occurrences for one objective is above specified threshold, the area is dropped from the process. This sum calculation is repeated for each chosen variety for one year and during all the duration of vines' plantation. At the end of this step, each area has a global score for each variety, which sums every score per objective.
A second step consists in selecting the optimal varieties and areas according to the objectives and limits set during the initialization. The first selection is set area per area, and tends to determine the better variety per area. For each area, the global score is compared and the smallest "score-variety" couple is chosen. Because the objectives predefined tend to minimise risks, the smaller the scores, the closer the solutions are to the goals. At this point, the model highlights varieties more adapted to each area. The second step is to compare the score-variety couple at the study area scale. Thus, the scores are sorted in ascending order and only scores in the 1st quartile are considered as optimal solutions (this segmentation can be specified at initialization). This second selection tends to choose the areas with well suited variety for one year and during the duration of plantation (usually 30 years). When an area is considered as optimal, the variety is considered as planted for a fixed period predefined in the scenario. The considered area is excluded from the process during the period. The entire

selection process is repeated for each year of simulation including neighbourhood computing (areas near an optimal solution are highlighted). A constraint of historicity is adding too: A constraint of historicity is repeated each year: if an area has already been covered by vines (e.g. during the past or during the process), it will be favoured by the model.

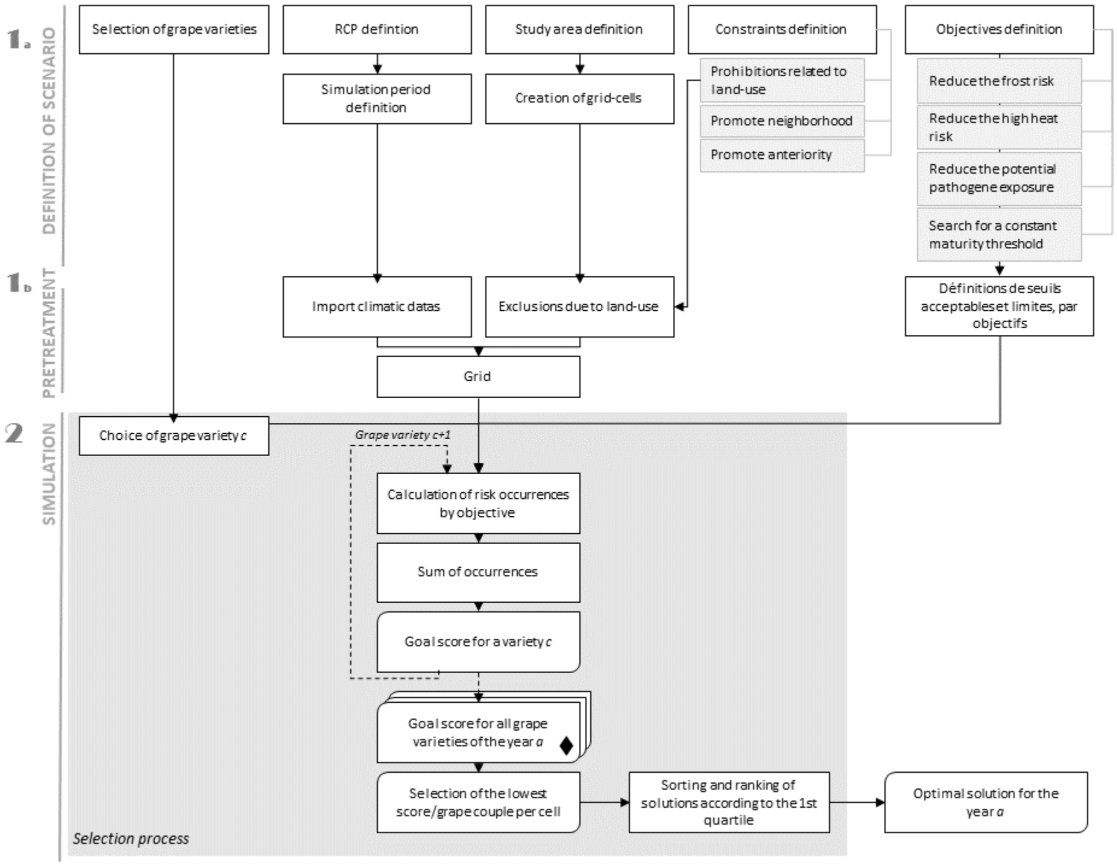

Figure 1. Scenario and simulation process for the identification of suitable areas for viticulture

Results and discussion

Scenario definition

Until the phylloxera crisis at the end of the 19th century, vine was present in Brittany. Several studies on the impacts of climate change in viticulture, have identified Brittany as an emerging area suitable for grape growing (Hannah *et al*. 2013; Bonnardot *et* Quénol 2020). In this context, an experimentation to determine potential viticulture areas at regional scale was developed. In this experiment, climate data were provided by the National Meteorological Research Centre (CNRM-CM5 model outputs) for the most pessimistic scenario of climate change (RCP 8.5) and covered years from 2006 to 2100. For this scenario Potentially authorised grape varieties are Cabernet franc and Sauvignon. Once a grid cell is considered as optimal for a grape variety plantation, the planting period is fixed at 30 years. The simulation was carried out with a conventional production system for the entire study area.

Concerning spatial constraints, it is only possible to plant vines in a grid cell that is at least 70% covered by agriculture. Land use information is based on the lastest Corine Land Cover geographic information database (2018). In order to limit a possible fragmentation effect, cells adjacent to an already cultivated area are preferred. The anteriority of plantations is also considered. Currently, four objectives are implemented into the model and concern the limitation of frost risk, the limitation of heat waves, the limitation of the potential exposure to pathogen risk and the research of a technical maturity threshold. The first objective counts annually the number of days below 0°C; the grid cells considered with an acceptable threshold do not exceed 3 days of frost, the maximum limit is set at5. Concerning the limitation of heat waves risk, occurrences of daily temperature above 35°C are cumulated with an acceptable threshold up to 4 days and a maximum limit of 10 days. Pathogen risk exposure refers to a number of fungicide treatments to be optimized. Finally, the search of technical maturity is taken into account with a threshold provided by the GSR model for each grape variety. If the target value is not achieved one year, the threshold maturity can be lowered. In this experimentation, the GSR threshold corresponds to a concentration of approximately 200 g/l for Sauvignon and 190 g/l for Cabernet Franc.

Results of simulations at the Bretagne scale

The figure 2 presents results provided by the experiment described above. The simulation covers the period from 2006 to 2100. Two varieties have been optimized with the model: Sauvignon associated to GSR threshold of 200 g/l and Cabernet Franc associated to GSR threshold of 190 g/l. During the simulation process, the model determined the grid cells with the lowest scores for each of the grape varieties at the 2040 and 2080 time horizons.

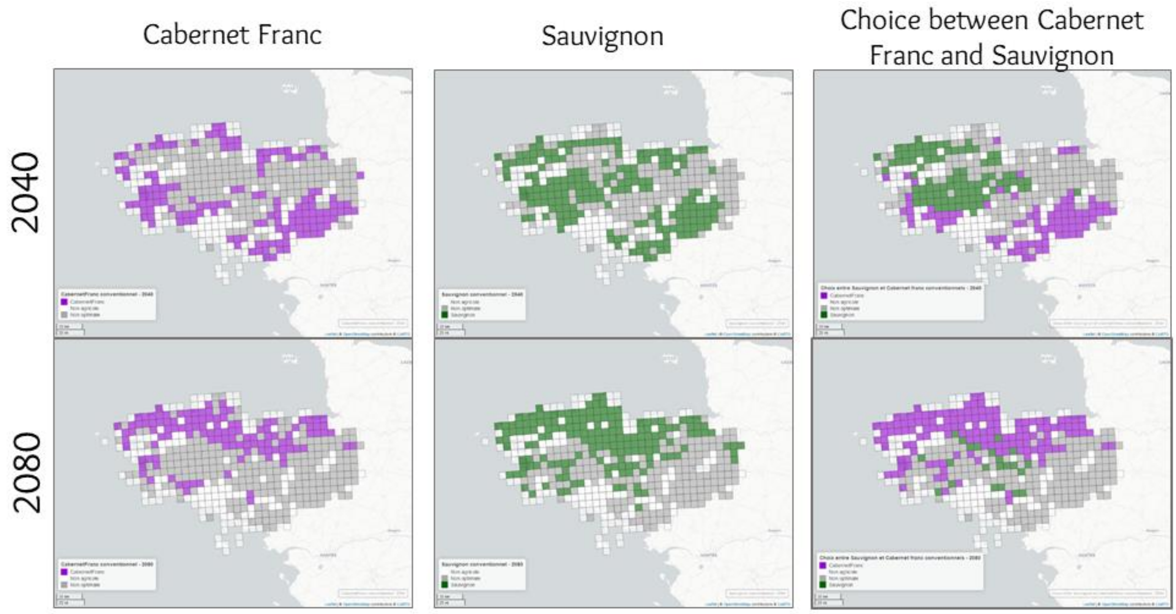

Figure 2. Identification of potential wine-growing areas (Cabernet Franc and Sauvignon) in Bretagne, by 2040 and 2080

For the first two simulations, respectively Cabernet Franc and Sauvignon, each grape variety are treated individually by the model. About the third simulation, both permitted grape varieties were treated simultaneously in the optimization process. The model chooses for each cell, the grape variety associated with the better score according to the objectives and constraints. Thus, the selection process between the two authorised grape varieties allows us to highlight the most optimal cells and grape varieties with respect to the objectives and constraints set at initialization step. In one or other of the simulations, more north areas are considered optimal by the model in Brittany in 2080 than in 2040. In the third simulation in 2040, the number of optimal areas per grape variety seems to be balanced with Cabernet Franc more optimal in the south, southeast of Brittany, and Sauvignon more optimal in the west of the region. In 2080, the distribution between grape varieties seems to be more unbalanced with a dominance of Cabernet Franc, and a clear migration of the optimal areas for this variety to the north of the region.

Conclusion

Based on a scenario approach, the proposed approach addresses issues relating to the adaptation of traditional wine-growing areas or the identification of new areas for implantation. The spatial optimization model implemented allows us to test different hypotheses and constraints (agronomic, anthropic, environmental, economic, etc.). This type of model has many advantages according to the multiplicity and diversity of criteria that can be mobilised. Thanks to the non-superiority of one criterion, various optimal solutions can be highlighted. They represent different configurations that reflect compromises in relation to the initial scenario. Spatial properties of the model allows to integrate neighbourhood, contiguity or distance relationships, and thus reduce the risk of fragmentation or conflicts of use between neighbouring cells. The integration of the temporal dimension allows to change or add constraints and objectives during the simulation period. Finally, the model can also be used at different scales depending on the resolution of the available data.

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