KEYNOTE LECTURE

Data integration via modeling for adaptation to climate change and efficiency breeding in grapevine

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Keywords: climate change, modeling, data management, grapevine, breeding

INTRODUCTION

Climate can greatly affect grape yield and quality (van Leeuwen et al., 2024). Growing suitable cultivars in a given region and or breed environmental resilient cultivars are essential for maintaining viticulture sustainability, particularly in the face of climate change (Wolkovich et al., 2018). Moreover, as a perennial plant with long productive span of 30–50 years, grapevine may experience cross-lifespan climate change, which can also modify wine quality and challenge viticultural sustainability (Bai et al., 2022b). Using models to integrate available data and knowledge for accurately predicting environment impacts on fruit productivity and quality as well as for designing ideotypes to ameliorate the cultivars represent a huge challenge (Dayer et al., 2022).

RESEARCH OBJECTIVES

In this review, we aimed to summarize the advances in data management and modeling related to phenology, grape growth, the build-up of grape quality (i.e. sugars, anthocyanins, organic acids etc), as well as zoning. In addition, the application of modeling and phenomics with dynamic phenotyping over berry development in combination with quantitative genetics for identifying pertinent molecular markers during breeding will also be introduced.

RESULTS

Data management for precision viticulture and adaptation to climate change

Precision viticulture and efficient adaptation strategies to climate change require multi-sourced and heterogenic data. Among them, climate, soil, topography etc can all exert important influences on growth and quality of grapevines, as well as the matching between a specific region with the most suitable cultivars (Bai et al., 2022b). To mange those multi-sourced and heterogenic data, specific dataset or database should be established. As an example, Bai et al. (2022a) digitized and curated multi-sourced data (Figure 1), including (i) harvest dates, quality records of musts and wines, and wine tasting notes for 148 grape cultivars from 1935 to 1941 across five contrasting climatic regions, (ii) climate data from 1911-2018 for the corresponding regions, (iii) harvest dates and must sugar content (ºBrix) records under the past (1935-1941) and current (1991-2018) climates. These heterogenic data were integrated to form a unique and interconnected dataset, for assessing the fitness between cultivars across environments in order to mitigate the effects of climate change. The data can be also combined with additional records to develop phenological and process-based growth models of grape. More examples of such kind databases, such as for grapevine phenology and cold hardness will also be summarized.

Modeling berry growth and quality in a changing environment

Mathematical models can mechanically integrate various processes to reproduce the plant and fruit responses to climatic conditions and management practices, making them a promising tool to study the response of fruit quality to those factors. Various mathematical models at different biological scales have been developed for grapevine to model the response of grapevine growth and grape berry quality to environment (light, temperature and water) and trophic factors (carbon and nitrogen), in order to assess plant plasticity and genetic diversity for a better adaptation in the face of climate change. For example, process-based models have been developed for sugar accumulation and anthocyanin composition in grape berries, which allowed to determine the key processes responsible for these two important quality components (Wang et al., 2023). At the whole-plant scale, a 3D structure-functional model (GrapevineXL) was developed to simulate water transport, leaf gas exchanges, carbon allocation, and berry growth in various genotype x environment scenarios in the field over 13 vintages (Figure 2, Yang et al., 2023). In addition, this model was used to predict the potential effects of climate-induced advancements in vine phenology and found that early veraison led to reduced berry FW, shortened ripening duration, and increased [Sugar] on average (Yang et al., 2023). These results showed that the models can accurately predict berry growth and quality in various environmental conditions and therefore could serve as a valuable tool for designing sustainable vineyard management strategies to cope with climate change.

Designing ideotypes and assisting in breeding with models

Breeding environment resilient cultivars with premium quality is one of the potential strategies to mitigate the effects of climate change. To this end, models were used to design ideotypes for hotter and drier climate scenarios, either with the focus on the plant hydraulics (Dayer et al., 2022) or on the leaf carbon acquisition functions (Millan et al., 2025). Dayer et al. (2022) used a process-based model to create *in silico* genotypes with various trait combinations and revealed specific virtual genotype with certain specific trait combinations showing higher drought tolerant. On the other hand, Millan et al. (2025) used a functional-structural model to identify grapevine architectural ideotypes with multi-objectives, including maximizing net carbon assimilation and water use efficiency (WUE) while minimizing leaf temperature. With a large amount of virtual experiments, ideotypes for dry and hot conditions were identified. In the future, quantitative genetic analyses could be conducted to explore the relationships between modeled ideotypes and genetic diversities to assist in targeted breeding of environment resilient cultivars.

CONCLUSION

Efforts to create database by integrating multi-sourced and heterogenic data have been reviewed. These data are useful for developing various types of models for grapevine growth and berry quality. Models have shown clear advantage to assess the relationship between environmental factors and berry growth and quality (sugar, anthocyanins etc). In addition, models may also offer rational foundations for breeding of environment resilient grapes better adapted to different climate scenarios.

ACKNOWLEDGEMENTS

We thank all the contributors to the cited work and more papers in the related topic which could not be cited because of the limitation of number of literatures (10 max). This work is also conducted as part of the LIA INNOGRAPE II International Associated Laboratory.

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FIGURES

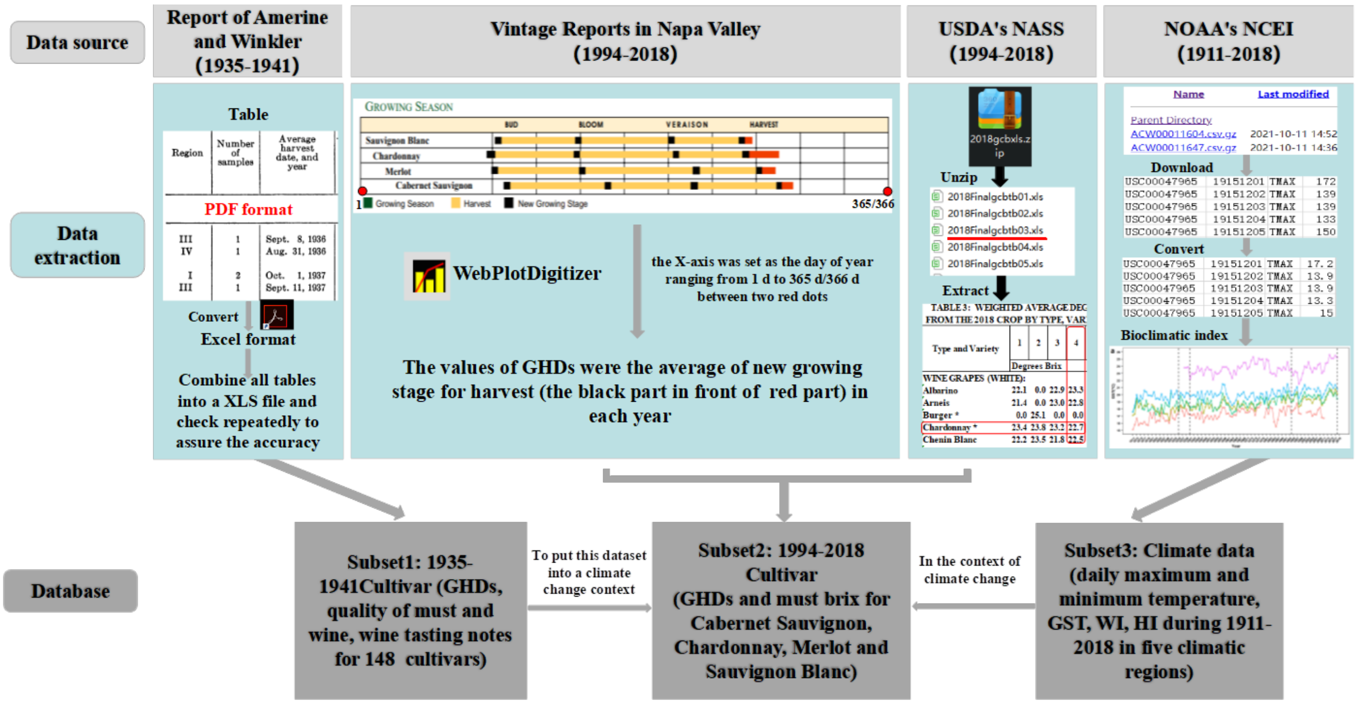

Figure 1. An example of data digitalization and integration for viticulture adaptation to climate change (Bai et al., 2022).

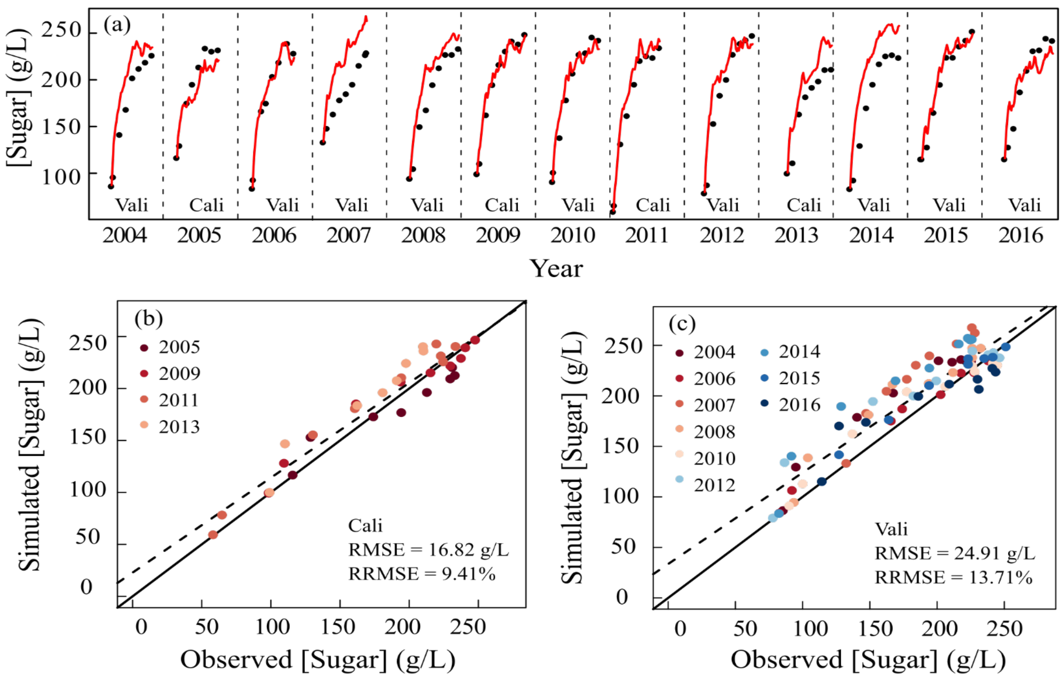

Figure 2. Model prediction for a 13-year series of grape berry quality in the field conditions (Yang et la., 2023)