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High spatial resolution modelling of spring frost risk in the Waipara wine region (New Zealand)

Hervé Quénol^{1*}, Andrew Sturman², Tony Dale², Marwan Katurji², Amber K. Parker³, Erika Collet⁴, Albin Ullman⁴, Benjamin Pohl⁴, Benjamin Bois⁴ and Renan Le Roux⁵

¹ UMR6554 LETG, CNRS, Université Rennes 2, place du recteur Henri le Moal, 35043 Rennes, France.

² School of Earth and Environment, University of Canterbury, Private Bag 4800, Christchurch, 8140, New Zealand.

³ Department of Wine, Food and Molecular Biosciences, Faculty of Agriculture and Life Sciences, Lincoln University, PO Box 85084, Lincoln 7647, Christchurch, New Zealand.

⁴ Centre de Recherches de Climatologie, UMR 6282 Biogeoscience, CNRS, Université de Bourgogne Franche-Comté, Dijon, France.

⁵ US1116 Agroclim, INRAE, Centre de recherche PACA, Domaine Saint Paul - Site Agroparc 228, route de l'Aérodrome, CS 40509 – 84914 Avignon Cedex 9, France.

*Corresponding author: herve.quenol@cnrs.fr

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ABSTRACT

This paper describes an international study into the climate variability within the Waipara region of Canterbury, New Zealand and its importance to viticulture. The complex terrain of the region results in intricate patterns of climate variability, which can create significant spatial variability in the optimal conditions needed for high quality wine production. This high spatial variability depends on climatic conditions throughout the vine's growing season, but also on the frequency and intensity of extreme weather events. Such is the case with spring frosts, which often occur after vine budburst and represent a major risk for winegrowers, potentially resulting in significant yield losses. Winegrowers require precise information at the scale of their vineyards, which means they need to improve their forecasting of the areas most exposed to the risk of frost,

based in particular on local topographical features and atmospheric conditions. This research uses an advanced approach to map key climate parameters at high spatial resolution during spring frost events by applying a combination of field measurement (climate and phenology) and climate modelling techniques. This approach was initiated during the spring of 2020, when several frost episodes (e.g. 30 September, 2020 and 16 October, 2020) caused significant damage in New Zealand winegrowing regions, particularly in the Waipara region. The results have made it possible to map precisely the spatial variability of minimum temperatures identifying the most frost-sensitive areas as a function of atmospheric conditions. This information can then be used to identify optimal locations for varieties having later budburst in at-risk areas, or locations with reduced

frost risk. The outputs also provide a general framework within which to evaluate adaptation of viticulture to frost risk in other vineyard regions of New Zealand and elsewhere.

Introduction:

The Waipara region is a relatively new wine-growing region, where the first vines were planted in the early 1970s. It currently has around 1,250 hectares of vines. Located on the east coast of New Zealand's South Island, the Waipara wine region benefits from a unique climate created by the topography, which protects the vineyards from the cool sea breezes that affect the Canterbury region north of Christchurch. However, it is still considered a cool climate, which is reflected in the predominant grape varieties grown here (mainly Pinot noir, Riesling and Sauvignon blanc). In recent decades, the increase in global temperature has been favourable for this region, providing better conditions for the grapes to ripen. However, this has also had an impact on the growth characteristics of the vines, in particular with earlier budburst and a consequent increase in the plant's vulnerability to spring frosts (Molitor et al. 2014; Sgubin et al. 2018; Cukierman et al. 2024).

As most vineyards are regularly faced with the risk of spring frost, they are equipped with frost control systems such as sprinklers, wind machines (fixed and mobile), helicopters and heaters. In September 2020, southerly winds generated a severe cold period lasting several days. This was characterised by a perturbed atmospheric situation with cloudy and windy weather. On the night of 29 to 30 September 2020, the skies cleared and the southerly wind dropped considerably, causing a rapid drop in temperature and severe spring frosts. The vines suffered significant damage as budburst was around two weeks ahead of the normal time. The intensity of the cold snap (down to -5°C)

severely reduced the effectiveness of the frost protection systems. These spring frosts had a significant impact, with yields around 30% below average for all South Island wine-growing regions (e.g., Marlborough, Waipara, and Central Otago).

A number of questions were raised following these events as vineyards that were thought to be well protected sustained significant damage due to the intensity and duration of the frost (up to 8 hours with a negative temperature). There was also significant spatial variability of temperature linked to local atmospheric conditions. Based on this event, we aimed to investigate how to improve simulation and forecasting of frost at high temporal and spatial resolution in the frostiest areas in order to optimise the effectiveness of frost protection systems.

Materials and methods:

An approach based on fine-scale climate measurement and modelling has been implemented in the Waipara wine region. The complex terrain of the region creates intricate patterns of climate variability, resulting in significant spatial disparity in temperature fields during spring frost events. In addition to the application of fine-scale climate models, a network of meteorological stations and temperature recorders was used to study the effects of the complex terrain on frost patterns in the region. Observations of the phenology of the vines (in particular, budburst) were carried out on several plots of Pinot noir near the climate measurement points.

Two climate modelling approaches were adopted in order to map the risk of frost at high spatial resolution as a function of synoptic weather conditions and their interaction with the terrain:

1. Numerical modelling using the Weather Research and Forecasting (WRF) model with a high temporal (hourly) and spatial (1 km) resolution

WRF is a regional climate model based on the physical equations of the atmosphere, which enables climate dynamics to be transcribed as a function of surface conditions (e.g. surface cover, topography, etc.). Hourly modelling of various meteorological parameters such as temperature, atmospheric pressure, wind speed and direction and relative humidity enables us to study the influence of local atmospheric conditions on the behaviour of air masses during spring frost episodes in September and October (Sturman et al. 2017). The hourly resolution of the simulations provides information on the spatial and temporal variability of temperatures during frost nights, such as the evolution of the thermal inversion at different points in the study area. WRF modelling was used to estimate the spatial variability of spring frost as a function of atmospheric conditions. Simulations were carried out during all frost episodes ($<0^{\circ}\text{C}$) over the spring seasons of 2016-2020 (Figure 1).

2. Geostatistical modelling with a spatial resolution of 80 m

Geostatistical modelling is based on the statistical relationship between temperatures (recorded by sensors) and local factors (e.g. altitude, slope, exposure, etc.). This approach requires the installation of a network of measurements to both build and validate the model. Spatial resolution depends on the spacing of the measurement network (Le Roux et al. 2017). In the Waipara region, a network of meteorological stations and temperature sensors has been established within the vineyard area, enabling minimum temperatures during frost episodes to be mapped at a resolution of 80 m (Figure 2; Morin et al. 2018). The mapped temperatures enabled us to determine the areas with the lowest minimum temperatures. Phenological observations carried out during spring 2020 were used to integrate the spatial variability of vine

budburst in order to assess areas of highest risk of frost damage.

The vineyards most vulnerable to spring frost as a function of synoptic conditions and the local characteristics of the study site were mapped using these two complementary approaches of fine-scale numerical modelling and empirical analysis of sensor data.

Results and discussion:

The WRF modelling revealed different ‘patterns’ of spatial variability in the risk of frost depending on the atmospheric conditions specific to each frost event. Figure 1 provides a summary of the spatial variability in the number of spring frost events over the period 2016-2020. The WRF simulations indicate that the highest number of events (10-15 episodes per season with temperatures below 0°C) occurred in the northeastern area and also on the flat valley floor and terraces of the Waipara region, while the sectors with steeper slopes or strong exposure to local katabatic winds had fewer than 5-7 frost nights.

The influence of topography on the geostatistically mapped spatial distribution of minimum temperatures on the night of 30 September 2020¹ showed that the flat areas recorded minimum temperatures up to 2°C lower than on the sloping areas, even though they were only a few tens of metres apart (Figure 2). It should be pointed out that the highest temperatures (around 0°C) correspond to the highest slopes of the vineyard region, which are logically the least exposed to frost. The high spatial variability of damage occurred as a result of local factors and the timing of budburst. Observations of Pinot noir budburst in the spring of 2020 showed a difference of around one week between the coldest ar-

¹ Temperature sensors are located far enough away from frost protection systems to limit their direct influence during frost events.

areas (the valley floor) and the warmest areas (plots on the hillslopes). Consequently, the plots with the worst damage were not necessarily in the coldest areas (experi-

encing -5°C on the Waipara valley bottom) but on the terraces and slopes ($t_{\min} = -3^{\circ}\text{C}$) where budburst was earliest.

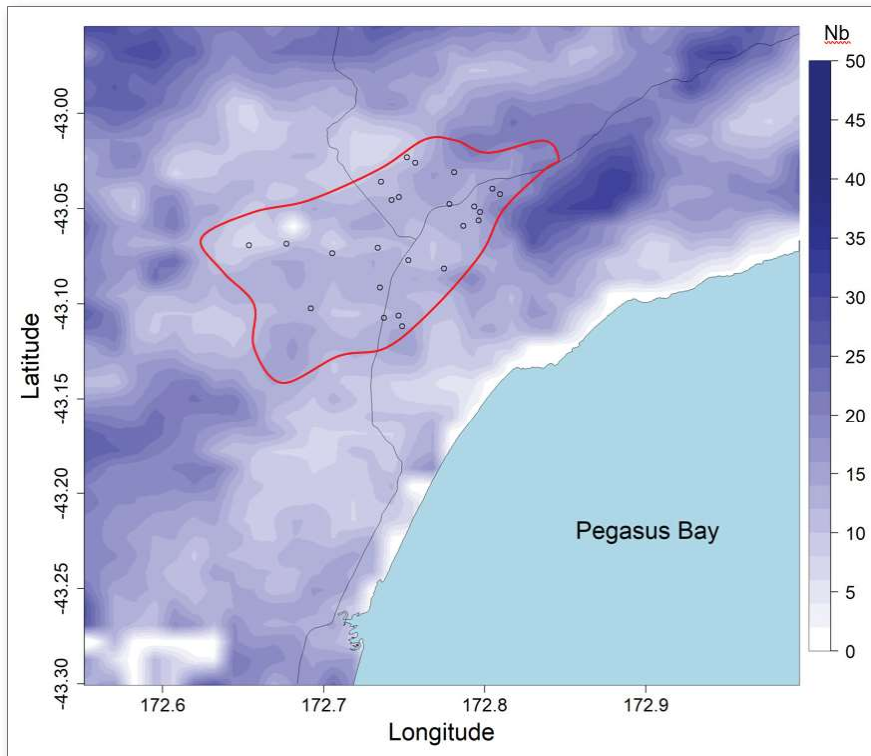


Figure 1. WRF numerical modelling of the number of spring ground frost events (September/October) mapped at 1 km resolution over the period 2016-2020 in the Waipara region. The red line indicates the approximate boundary of the vineyard area.

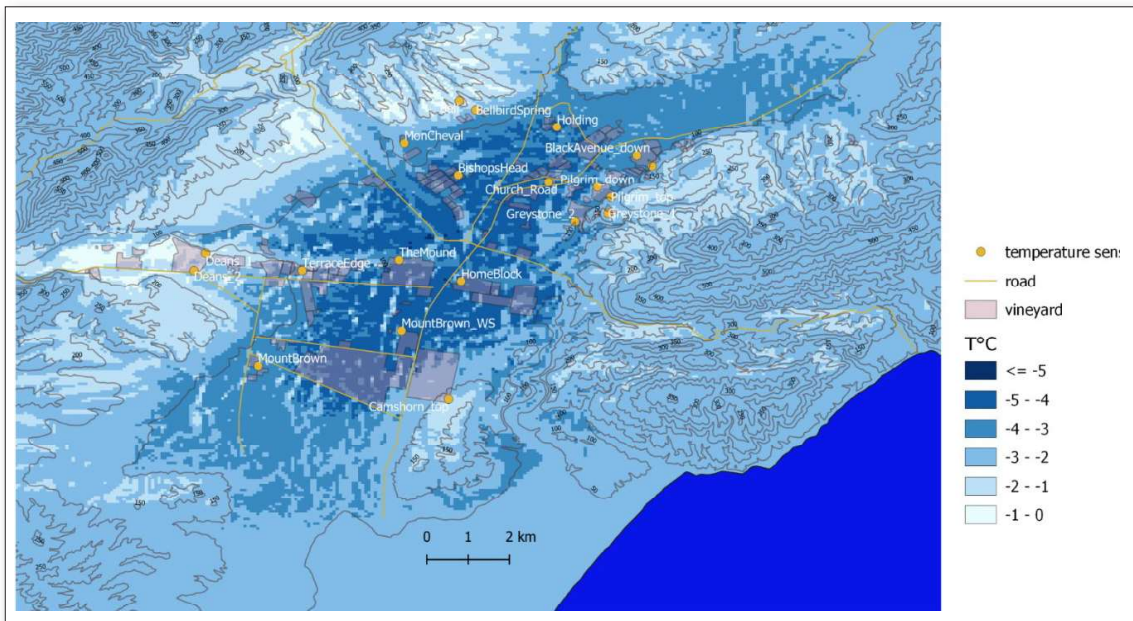


Figure 2. Geostatistical modelling at 80 m resolution of the minimum temperature in Waipara Region during the spring frost night of 30 September 2020.

Conclusion:

Our integrated approach to fine-scale climate analysis and modelling have demonstrated consistent a spatial pattern of frost occurrence over a five-year period that is affected by the local complex terrain. Temporal variability of the risk of frost has also been identified under different synoptic conditions. Our results highlight that a deeper understanding of the complexity of the local climate is essential for better forecasting of frost risk and for making decisions about frost control operations.

Further work is needed to improve our understanding for the impacts of frost risk on vine development, including investigating the relationship between budburst date and frost date and its likely change over time as global warming continues. By combining budburst models with our fine scale-climate modelling, we will be able to further evaluate the spatio-temporal variability of the risk of spring frost for different grapevine varieties.

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