ANALYZING VINEYARD SITE SELECTION IN CENTRAL OTAGO:

A GIS-BASED STUDY OF ENVIRONMENTAL CONTRIBUTING FACTORS

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Contents

1. Executive Summary

This project focuses on analyzing the primary environmental factors influencing vineyard site selection in Central Otago. By examining key factors such as soil type, slope, precipitation, and elevation, the study seeks to understand how these elements affect vineyard selection at both the regional level and within six categorized sub-regions.

The project involves several phases, including data collection and preprocessing, map verification and sub-region digitization, followed by detailed factor analysis using Ordinary Least Squares (OLS) and Geographically Weighted Regression (GWR). The results indicate that across the Central Otago, distance to water, precipitation, slope, and soil type are the primary factors influencing vineyard selection. However, there are spatial variations between sub-regions, with factors like January soil temperature also playing significant roles in specific areas, though not consistently across the entire region. These findings provide valuable insights for more targeted vineyard planning and development in the future.

2. Project Description

For centuries, French winemakers have believed that the quality and yield of wine are significantly influenced by the environment (Gordon, 1997). New Zealand, known for producing high-quality wines, has seen a rapid expansion of its wine industry. Vineyard location critically impacts the characteristics and quality of wine produced. As New Zealand's wine regions expand, understanding the environmental factors contributing to successful vineyard site selection becomes increasingly important.

2.1 Objectives:

The primary aim of this project is to analyse the main contributing factors to vineyard site selection in Central Otago using GIS tools. The specific objectives are:

1. **Digitize vineyards and categorize into sub-regions**: This involves mapping individual vineyards in the region and validating the data against aerial maps. Each vineyard is categorized based on its location within one of the six Central Otago sub-regions.
2. **Create profiles for each vineyard**: By processing selected environmental factors’ data- such as soil type, elevation, aspect, and temperature, detailed profiles are created for each vineyard.
3. **Analyse contributing factors**: Identify and compare the main environmental factors influencing vineyard site selection at both the regional level and sub-regional levels.

To address the research objectives, I reviewed several studies that used GIS to solve similar challenges in geographic analysis. Imre and Mauk (2008) used GIS to digitize vineyard locations and compare them with existing databases, analysing factors like geology, soil, and climate in vineyard site selection. Zhang and Imana (2017) applied a multi-factor GIS method, incorporating 27 input factors, to identify optimal locations for electric vehicle charging stations. Enea et al. (2019) applied a multi-criteria GIS analysis to integrate slope, soil, land use, temperature, precipitation, and frost days for optimal vineyard placement in Romania. Illescas-Manzano et al. (2023) employed GIS and GWR to examine the spatial dynamics of hotel locations and customer perceptions, offering insights into spatial competition and clustering.

Inspired by these approaches, this project utilized GIS to digitize and integrate the geographic factors, generating maps (Appendix Figures 6-13) that visualized their spatial influence across Central Otago. To analyse the impact of these geographic factors at both regional and sub-regional levels, I applied OLS and GWR methods, providing deeper insights into the optimal conditions for vineyard development in the region.

3. Methodology

3.1 Study Area and Factors Selection:

The study area (see Figure 1) for this project is Central Otago, the world's southernmost wine region, located at 45 degrees south latitude. It can be divided into several sub-regions: Wanaka, Gibbston, Bannockburn, Alexandra, Lindis Valleys, and Cromwell. Central Otago's cold and variable climate, along with elevations ranging from 200 to 450 meters, presents both challenges and opportunities for viticulture (Active Travel Experiences, n.d.).

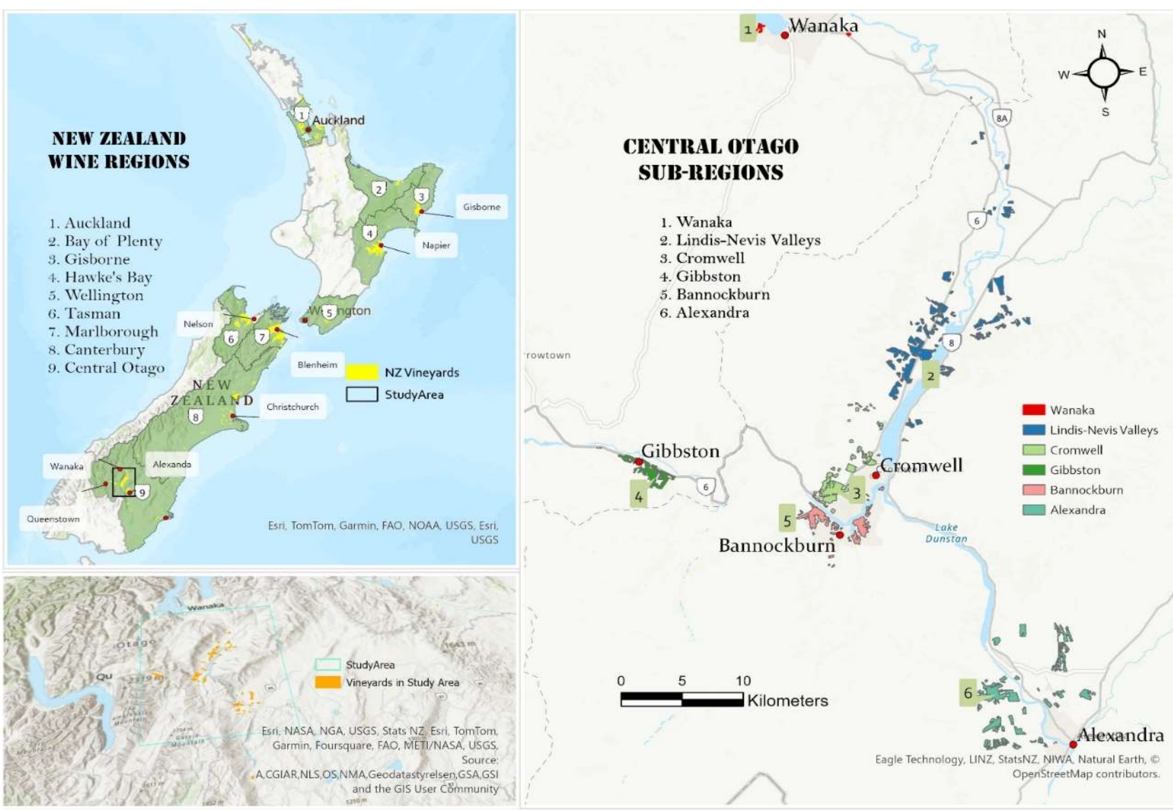

Figure 1. Study Area

While a wide range of factors can influence vineyard site suitability, terrain characteristics relating to slope, general climate, and soil properties are particularly important. (Blue Marble Geographics, n.d.). Based on the unique terroir of Central Otago, this study focuses on eight key factors: Slope, Soil Type, Aspect, Minimum Temperature of the Coldest Month, Precipitation, Elevation, Distance to Water, and January Soil Temperature.

3.2 Data Source and Feature classes:

The values for the eight geographic factors for each vineyard polygon were primarily derived from the raw data listed in Appendix Table 1. Additionally, layers such as administrative boundaries and NZ land districts were used for the subdivision of sub-regions and the creation of a New Zealand vineyard distribution map.

3.3 Map Verification and Sub-Region Digitization：

The first phase involved creating accurate maps of vineyard sub-regions in Central Otago by digitizing vineyard boundaries and validating them with aerial photos. Vineyard polygons were aggregated into six sub-regions using the "Dissolve" tool, and non-vineyard polygons were added for comparison and further analyses. This phase produced a digitized vineyard map with both vineyards and non-vineyard areas (see Appendix, Figure 2 for specific steps and GIS tools used).

3.4 Analysis of Contributing Factors：

The second phase derived eight key environmental factors from raw data (as listed in Table 1) and calculated their mean or majority values using the "Zonal Statistics" tool. These results were integrated into the Vineyards_with8factors layer, preparing detailed profiles for further analysis (see Appendix, Figure 3 for specific steps and GIS tools used).

To begin the analysis, Ordinary Least Squares (OLS) regression was conducted. OLS is a commonly used linear regression technique that investigates the relationship between the dependent variable (vineyard presence) and independent variables (the selected eight geographic factors). By analysing the P-values of OLS, we could determine the significance of the associations between the variables, with smaller P-values indicating stronger relationships.

However, OLS assumes there is no spatial correlation between the data, which does not account for the spatial dependency of geographic variables, as highlighted by Tobler’s First Law of Geography: "Everything is related to everything else, but near things are more related than distant things" (Tobler, 1970). Additionally, as Goodchild (2004) explained, geographic variables often exhibit uncontrolled variance, meaning that different locations can have different influencing factors. If there is spatial autocorrelation or heterogeneity within the data, OLS results may not be entirely accurate.

Given the spatial heterogeneity of vineyard suitability factors, Geographically Weighted Regression (GWR) was applied after detecting spatial dependency in the OLS analysis. GWR measures how relationships vary across space, providing localized insights (Matthews & Yang, 2012). This approach is crucial for regions like Central Otago, where environmental factors vary across sub-regions.

By employing both OLS and GWR, where GWR was configured with the "Distance band" neighbourhood type and the "Golden search" neighbourhood selection method, this project analysed global relationships between environmental factors and vineyard site selection across Central Otago (using OLS), while also accounting for local variations at the sub-regional level (using GWR).

4. Results

4.1 Digitized Vineyards and Sub-Region Categorization:

After clipping the original vineyard dataset to the study area, 237 established vineyard polygons were identified. An additional 82 newly identified vineyards were recognized through satellite image comparison, resulting in a total of 319 vineyard polygons. Additionally, 161 non-vineyard polygons were created as a control group and for further analysis, totalling 480 polygons across six sub-regions (see Appendix Figures 4-5).

4.2 Geographic Profiles of Vineyards:

A joined feature class, **Vineyards (480) _with8factors**, was created by incorporating eight geographic factors for each vineyard (see Appendix Figure3). This dataset includes detailed values for factors like slope, soil type, and aspect in the study area, visually illustrated in Appendix Figures 6-13. These maps compare the geographic characteristics of vineyards and non-vineyard polygons, highlighting both commonalities and differences.

4.3 OLS Analysis Results:

The OLS analysis identified four significant factors influencing vineyard locations in Central Otago: distance to water, precipitation, slope, and soil type, based on their Probability [b] values and coefficients (see Table 2).

4.3.1 Significant Factors:

- **Distance to Water (NEAR_DIST_WA)**: Negative coefficient (-0.000274), indicating vineyards tend to be located closer to water.
- **Precipitation (PRECIPITATIO)**: Positive coefficient (0.001030), showing that areas with more rainfall are more likely to host vineyards.
- **Slope (SLOPE)**: Strong negative coefficient (-0.023518), indicating vineyards are found in areas with gentler slopes.

- **Soil Type (SOILTYPE)**: Positive coefficient (0.002474), suggesting certain soil types are more favourable for vineyards.

Table 2. Summary of OLS Results-Model Variables

Summary of OLS Results - Model Variables

Variable	Coefficient [a]	StdError	t-Statistic	Probability [b]	Robust_SE	Robust_t	Robust_Pr [b]	VIF [c]
Intercept	1.701138	2.562188	0.663940	0.507051	2.492164	0.682595	0.495195	--------
NEAR_DIST_WA	-0.000274	0.000061	-4.516915	0.000010*	0.000059	-4.614698	0.000007*	1.516845
MIMTEMP_COLD	0.001041	0.006123	0.170016	0.865062	0.006262	0.166248	0.868025	1.880762
PRECIPITATIO	0.001030	0.000521	1.977142	0.048602*	0.000541	1.905612	0.057307	4.627028
EVELATION	-0.001362	0.000984	-1.383494	0.167180	0.001023	-1.330703	0.183939	11.944871
SLOPE	-0.023518	0.004086	-5.755565	0.000000*	0.003593	-6.545465	0.000000*	1.318734
ASPECT	0.000019	0.000268	0.070817	0.943559	0.000263	0.072274	0.942400	1.219682
SOILTYPE	0.002474	0.000689	3.588191	0.000381*	0.000703	3.521258	0.000485*	1.370355
JANUARYSOILT	-0.065348	0.133103	-0.490954	0.623700	0.129729	-0.503725	0.614701	10.081814

4.3.2 OLS Model Diagnostics:

According to Table 3, the model diagnostics provide further insights:

- **R-Squared and Adjusted R-Squared**: The model explains approximately 19-20% of the variance in vineyard location ($R^2 = 0.203$, Adjusted $R^2 = 0.189$), suggesting additional variables may be needed.
- **Koenker (BP) Statistic**: significant result suggests heteroskedasticity, meaning the relationships between the variables may vary across different parts of the study area.
- **Jarque-Bera Statistic**: Indicates non-normal residuals ($p < 0.01$), suggesting that the model may miss certain influential variables.

Table 3. OLS Diagnostics

OLS Diagnostics

Input Features	Vineyards_Clip	Dependent Variable	IS_VINEYARD
Number of Observations	480	Akaike's Information Criterion (AICc)['d']	553.255540
Multiple R-Squared['d']	0.203022	Adjusted R-Squared['d']	0.189485
Joint F-Statistic['e']	14.997829	Prob(>F), (8,471) degrees of freedom	0.000000*
Joint Wald Statistic['e']	197.341831	Prob(>chi-squared), (8) degrees of freedom	0.000000*
Koenker (BP) Statistic['f']	32.738961	Prob(>chi-squared), (8) degrees of freedom	0.000069*
Jarque-Bera Statistic['g']	48.619412	Prob(>chi-squared), (2) degrees of freedom	0.000000*

4.3.3 OLS Residuals Plot Interpretation:

The residuals plot (Figure 14) shows standardized residuals across Central Otago, highlighting areas where the model overestimated (negative residuals in blue) or underestimated (positive residuals in red/orange) vineyard locations. Residuals closer to 0 indicate a better fit. The distribution reveals limitations in the OLS model, with some subregions showing systematic errors. Geographically Weighted Regression (GWR) could address these spatial variations and improve accuracy.

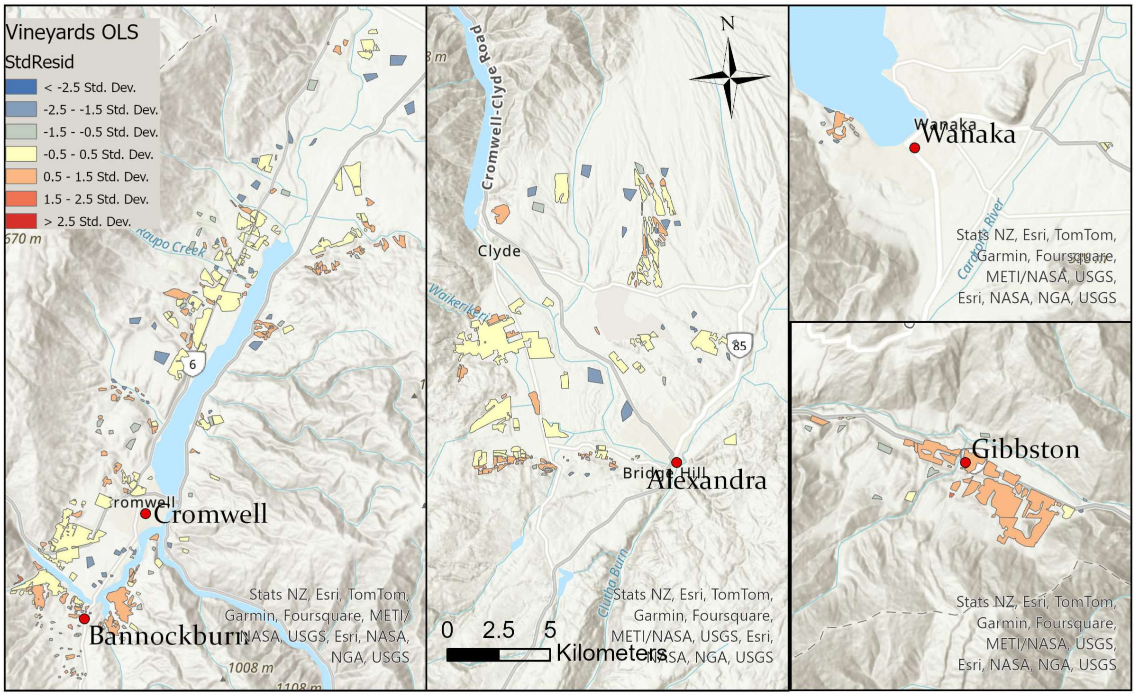

Figure 14. Residual Distribution from OLS Model for Vineyard Site Selection in Central Otago

In summary, The OLS results indicate that Distance to Water, Precipitation, Slope, and Soil Type are the primary geographic factors influencing vineyard location in Central Otago. However, the model's R^2 suggests other factors may need to be considered. Additionally, the presence of heteroskedasticity and non-normal residuals suggests that further investigation or alternate methods (like GWR) could improve model accuracy.

4.4 GWR Analysis Result:

4.4.1 Geographic Factors Analysis:

The GWR analysis revealed substantial variations in the influence of different factors across sub-regions. Table 4 highlights the following key insights:

- **January Soil Temperature (MEAN_C_JANUARYSOILTEMP)**: Plays a crucial role in most sub-regions, especially in Subregions 1 (Wanaka), 4 (Gibbston), and 6 (Alexandra). Its positive coefficient suggests that higher January temperatures favour vineyard development, emphasizing the importance of warmer conditions during the growth period.
- **Precipitation (MEAN_C_PRECIPITATION)**: Has a notable positive impact in Subregion 4 (Gibbston), indicating rainfall is especially important for vineyards there.
- **Distance to Water (MEAN_C_NEAR_DIST_WATER) and Slope (MEAN_C_SLOPE)**: Show negative correlations across all sub-regions, with small coefficients. While proximity to water and flatter

terrain are generally beneficial, their influence is less significant compared to other factors like soil temperature in each sub-region.

Table 4. Summarized Coefficients for Geographic Factors in Sub-Regions (GWR)

	JECTID *	Subregion_ID	Subregion	MEAN_C_NEAR_DIST_WATER	MEAN_C_MIMTEMP_COLDESTMONTH	MEAN_C_PRECIPITATION	MEAN_C_EVELATION	MEAN_C_SLOPE	MEAN_C_ASPECT	MEAN_C_SOILTYPE	MEAN_C_JANUARYSOILTEMP	FREQUENCY
1		1	Wanaka	-0.000273	0.256818	-0.007474	0.015949	-0.036843	-0.001172	0.004096	1.793874	4
2		2	Lindis Valleys	-0.000303	-0.076666	0.004621	-0.00887	-0.011453	-0.000026	0.002142	-0.298735	114
3		3	Cromwell	-0.000326	-0.000998	0.004057	-0.004414	-0.014418	0.000546	0.002859	-0.074584	43
4		4	Gibbston	-0.000196	-0.107277	0.009943	-0.01281	-0.018185	-0.000476	0.004592	0.281039	22
5		5	Bannockburn	-0.000332	0.014013	0.003839	-0.003044	-0.014937	0.000489	0.002436	0.095048	37
6		6	Alexandra	-0.000424	0.015248	-0.000182	0.003282	-0.028589	-0.000435	0.001005	0.535363	99

4.4.2 GWR Model Diagnostics:

Table 5. GWR Diagnostics

Analysis Details

Number of Features	480
Dependent Variable	IS_VINEYARD
Explanatory Variables	NEAR_DIST_WATER
	MIMTEMP_COLDESTMONTH
	PRECIPITATION
	EVELATION
	SLOPE
	ASPECT
	SOILTYPE
	JANUARYSOILTEMP
Distance Band (Meters)	26729.9288

Model Diagnostics

R2	0.3248
AdjR2	0.2714
AICc	519.3668
Sigma-Squared	0.1624
Sigma-Squared MLE	0.1505
Effective Degrees of Freedom	444.9518
Adjusted Critical Value of Pseudo-t Statistics	2.4396

Compared to the OLS model, the GWR model showed improvements in explaining vineyard site selection, with an R^2 value of 0.3248 and an Adjusted R^2 of 0.2714 (see Table 5). This indicates GWR more effectively captures spatial variability, better accounting for localized effects across Central Otago.

4.4.3 GWR Residuals Plot and Comparison with OLS

The GWR residuals plot (Figure 15) shows a greater concentration of residuals closer to zero compared to the OLS plot, indicating a better model fit at the local level. GWR provides a more accurate representation of vineyard suitability by capturing spatial variations that OLS could not.

In summary, the GWR model outperformed the OLS model in explaining vineyard site suitability in Central Otago by incorporating spatial heterogeneity and providing localized insights. Table 4 presents the calculated GWR coefficients for each geographic factor across the six sub-regions, confirming that distance to water, precipitation, and soil type remain key influencing factors in vineyard selection throughout the region. Additionally, by comparing the coefficient values for each factor across sub-regions in Table 4, we can determine the relative influence of each geographic factor, as well as whether their impact is positive or negative in each sub-region.

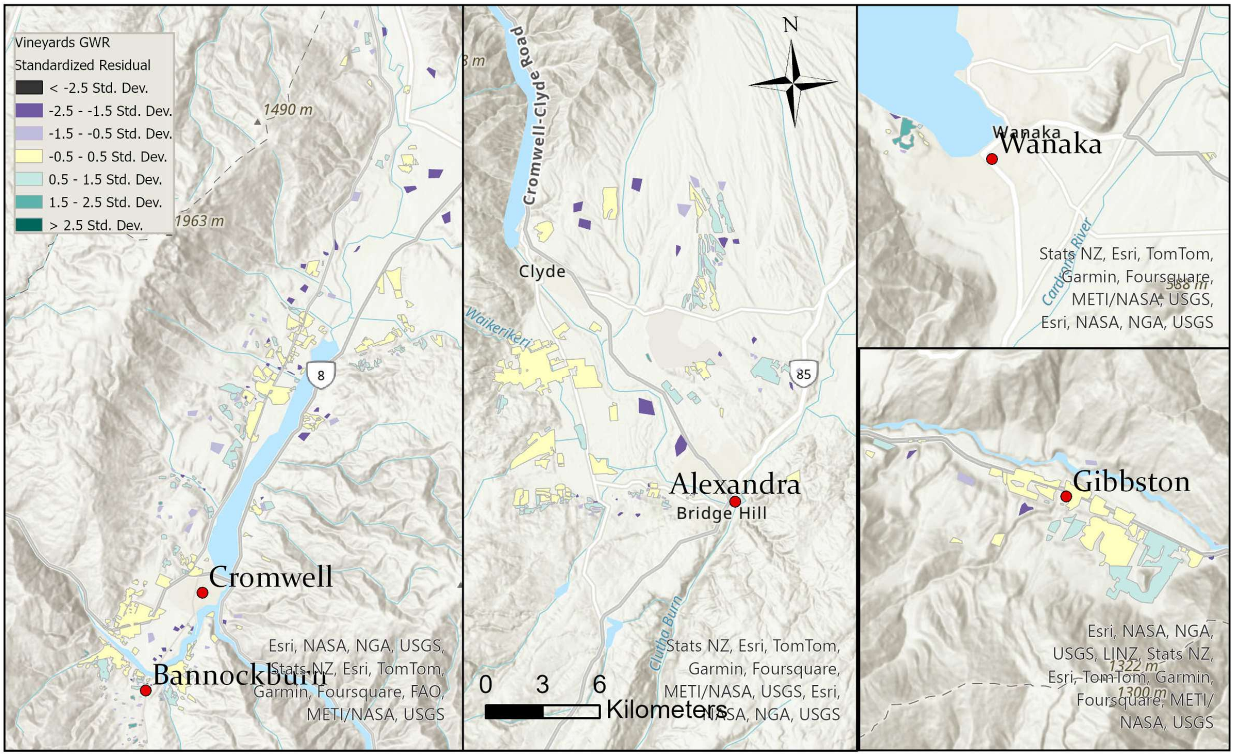

Figure 15. Residual Distribution from GWR Model for Vineyard Site Selection in Central Otago

5. Discussion and Conclusion

This study successfully identified the primary geographic factors influencing vineyard site selection in Central Otago using OLS and GWR analyses. The OLS model revealed key global factors, such as distance to water, precipitation, slope, and soil type, which are critical to understanding vineyard suitability across the entire region. GWR provided more detailed insights into local variations, showing that factors like minimum temperature and January soil temperature significantly impacted specific sub-regions. These findings provide a nuanced understanding of vineyard site selection.

GIS proved to be an essential tool in this research, particularly in visualizing spatial patterns, conducting detailed geographic analysis, and generating high-quality maps. It allowed for efficient handling of large datasets and facilitated the spatial analysis of geographic factors across various subregions, making it instrumental in presenting complex results in an accessible way.

5.1 Challenges and Limitations:

Despite positive outcomes, this study has several limitations. The relatively low R-squared values (<0.5) for both the OLS and GWR models suggest that the current set of variables does not fully explain all factors influencing vineyard site selection. Certain unexpected outcomes emerged. For instance, January soil temperature did not appear as a significant factor in the OLS model but became important in specific subregions according to the GWR model, indicating potential data inconsistencies or limitations in the OLS approach.

Key limitations of the study include:

- **Non-vineyard sample size**: The study included 319 vineyard polygons but only 161 non-vineyard polygons. These non-vineyard areas were primarily located on flat terrain near existing vineyards, excluding steeper slopes. This decision may have limited the representativeness of the dataset. Also, some non-vineyard areas may have future vineyard potential, introducing bias into the analysis.
- **Area weighting in subregion aggregation**: GWR coefficients were aggregated using a simple average without considering varying polygon sizes, which may have affected accuracy.
- **Satellite image resolution**: The resolution of satellite images used for digitizing vineyard areas was insufficient to clearly distinguish all vineyard polygons. This limitation may have impacted the accuracy of the vineyard boundary identification, leading to potential errors in the analysis.
- **Variable selection**: The variables selected in the analysis may not fully explain the factors influencing vineyard site selection.

5.2 Future Improvements:

To address the limitations, several areas for future improvement are suggested:

- **Expanding sample size**: Increasing the number of non-vineyard areas, especially in varied terrain, would create a more balanced dataset. Using land-use data to select more meaningful non-vineyard areas could further refine the analysis.
- **Incorporating more suitable variables factors**: Adding more relevant variables, such as vineyard yield, as the dependent variable, and other geographic factors like frost-free days or even non-geographic factors like economic conditions, to improve model accuracy. Using the OLS model to progressively retain significant variables without multicollinearity to enhance explanatory power.
- **Better data handling**: Future analyses should apply polygon area weighting when aggregating GWR coefficients to better represent geographic influences. Alternatively, using vineyard yield data as the dependent variable could provide a more accurate reflection of subregional geographic factors.
- **Improving data resolution**: Higher-resolution satellite imagery could enhance the precision of vineyard identification and mapping, leading to more accurate results.

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Appendix

Table 1. Data Type and Source

Data	Feature Class	Type	Source
NZ Vineyard Polygons (Topo, 1:50k)	Digitized Vineyards	Polygon	https://data.linz.govt.nz/layer/50367-nz-vineyard-polygons-topo-150k/
Otago 0.3m Rural Aerial Photos		Raster	https://data.linz.govt.nz/layer/106403-otago-03m-rural-aerial-photos-2019-2021/
Queenstown Lakes 0.1m Urban Aerial Photos		Raster	https://data.linz.govt.nz/layer/112781-queenstown-lakes-01m-urban-aerial-photos-2022-2023/
NZ Lake Polygons (Topo, 1:50k)	Distance to water	Polygon	https://data.linz.govt.nz/layer/50293-nz-lake-polygons-topo-150k/
NZ River Polygons (Topo, 1:50k)		Polygon	https://koordinates.com/from/data.linz.govt.nz/layer/50328-nz-river-polygons-topo-150k/
SoilTemperature(January)	January Soil Temperature	Raster	J\NZClimateGridsTM\SoilTemperature
NZEnvDS_Total annual precipitation	Precipitation	Grid	https://koordinates.com/from/lris.scinfo.org.nz/layer/105725-nzenvds-total-annual-precipitation-v10/
LENZ - Mean minimum temperature of the coldest month	Min_Temperature _Coldest Month	Grid	https://lris.scinfo.org.nz/layer/48092-lenz-mean-minimum-temperature-of-the-coldest-month/
NZDEM South Island 25 metre	Aspect	Grid	https://koordinates.com/from/lris.scinfo.org.nz/layer/48127-nzdem-south-island-25-metre/
	Slope		
	Elevation		
FSL New Zealand Soil Classification v1.1	Soil Type	Polygon	https://lris.scinfo.org.nz/layer/112060-fsl-new-zealand-soil-classification-v11/

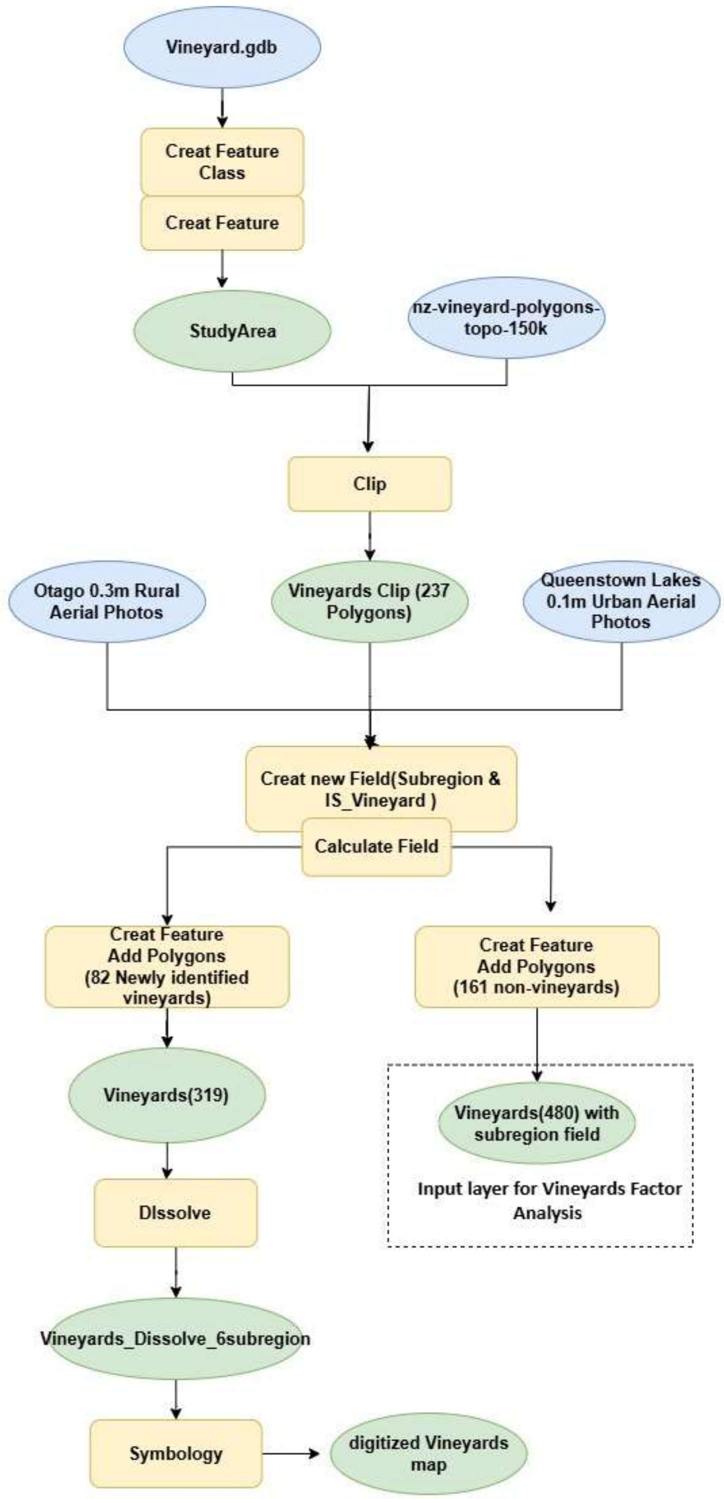

Figure 2. Digitizing and Creating Sub-Regions in Central Otago Vineyards

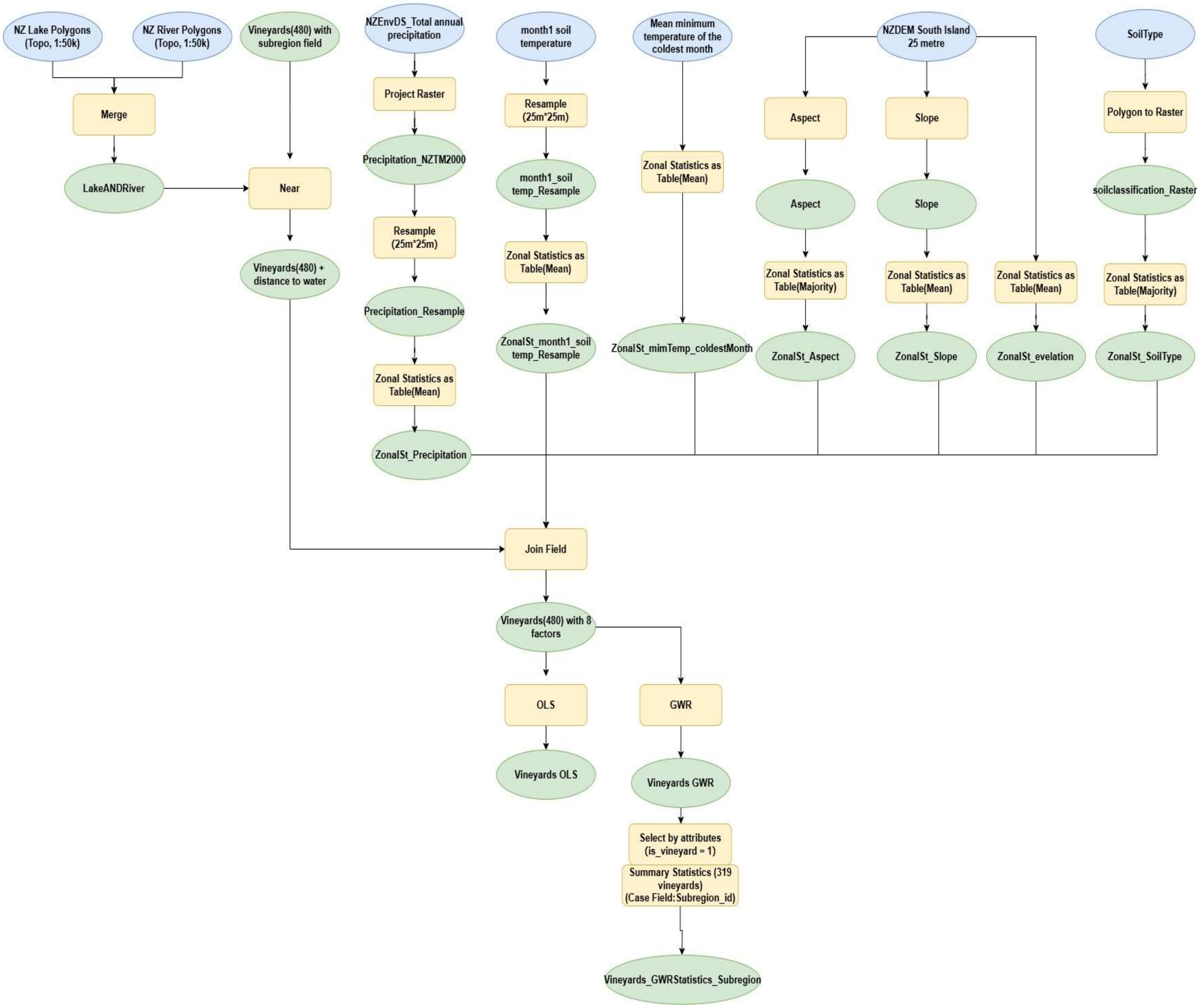

Figure 3. Vineyards Factor Analysis in Central Otago

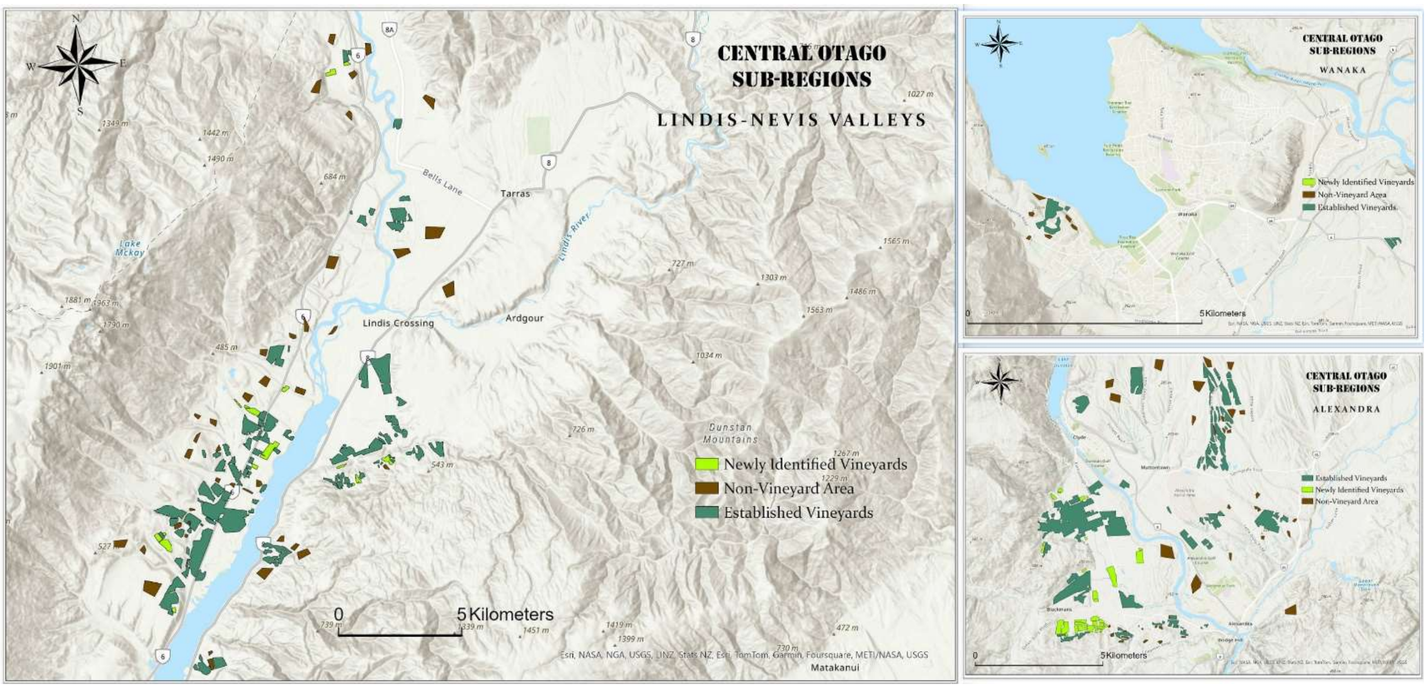

Figure 4. Distribution of Vineyard Polygons Across Six Sub-Regions (Lindis Valleys, Wanaka, Alexandra)

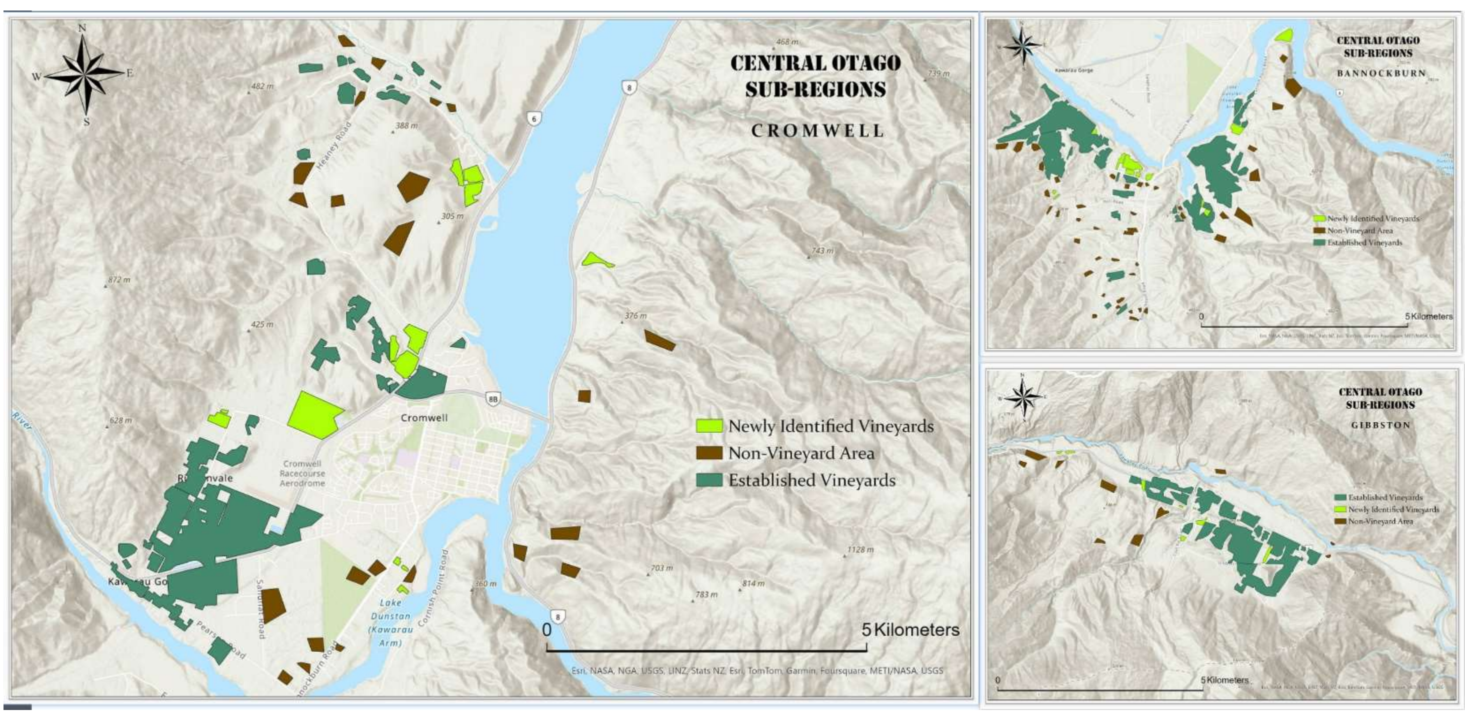

Figure 5. Distribution of Vineyard Polygons Across Six Sub-Regions (Cromwell, Bannockburn, Gibbston)

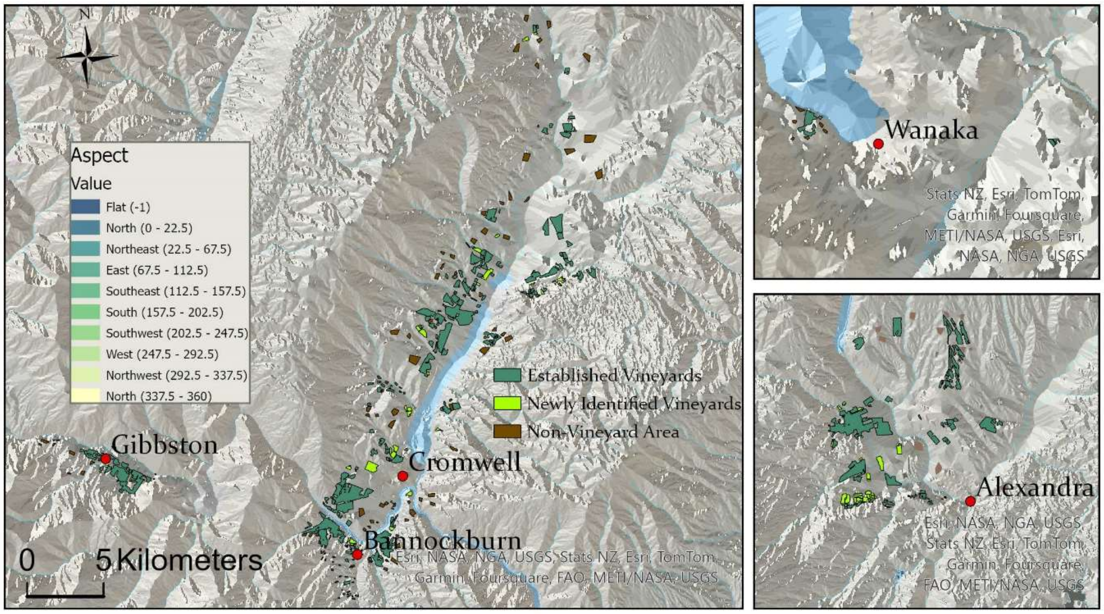

Figure 6. Aspect Distribution of Vineyards Across Six Sub-Regions in Central Otago

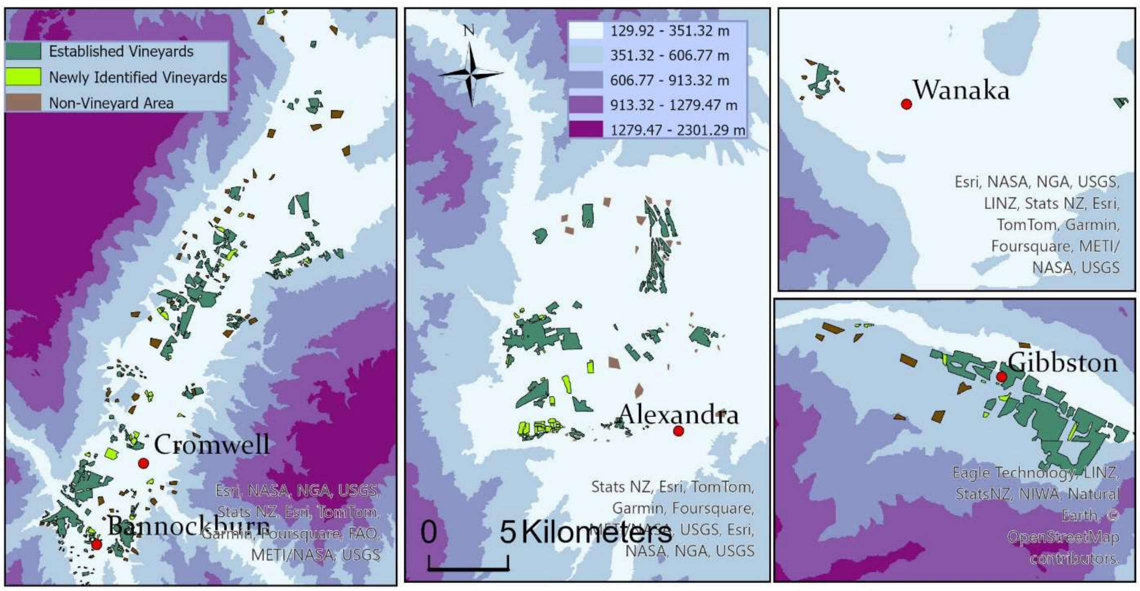

Figure 7. Elevation Distribution of Vineyards Across Six Sub-Regions in Central Otago

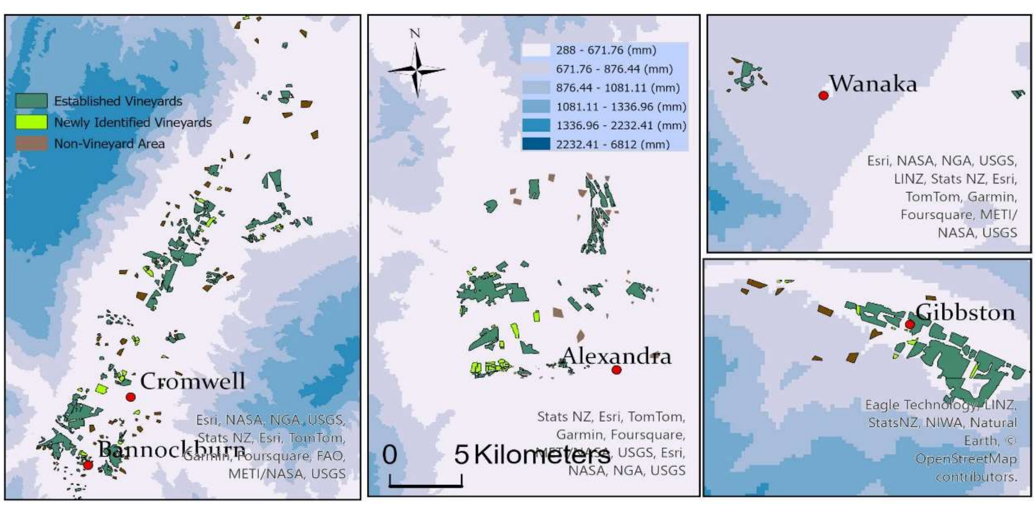

Figure 8. Precipitation Distribution of Vineyards Across Six Sub-Regions in Central Otago

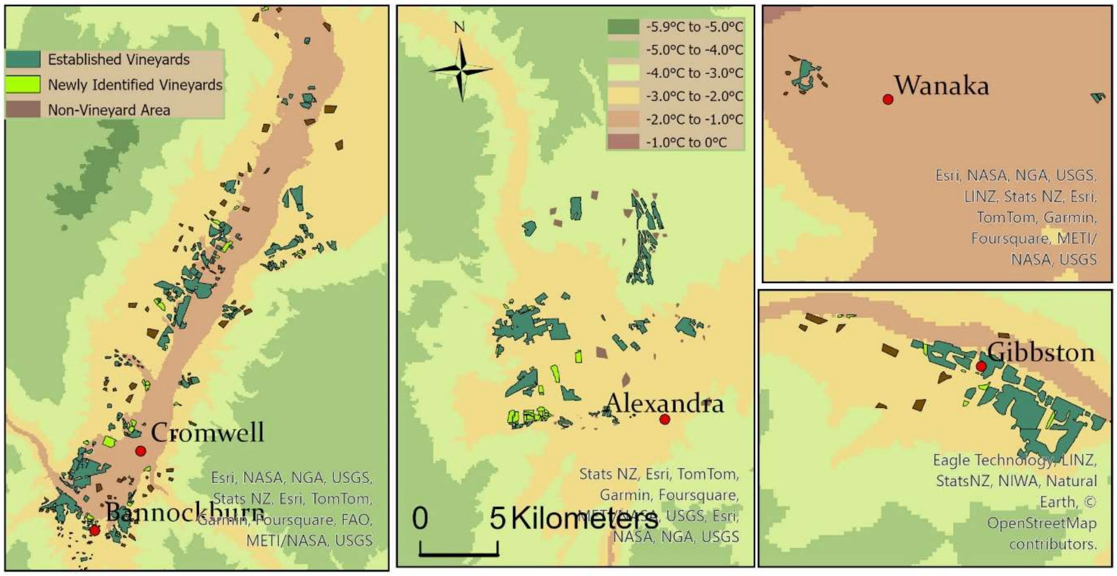

Figure 9. Minimum Temperature of the Coldest Month Distribution of Vineyards Across Six Sub-Regions in Central Otago

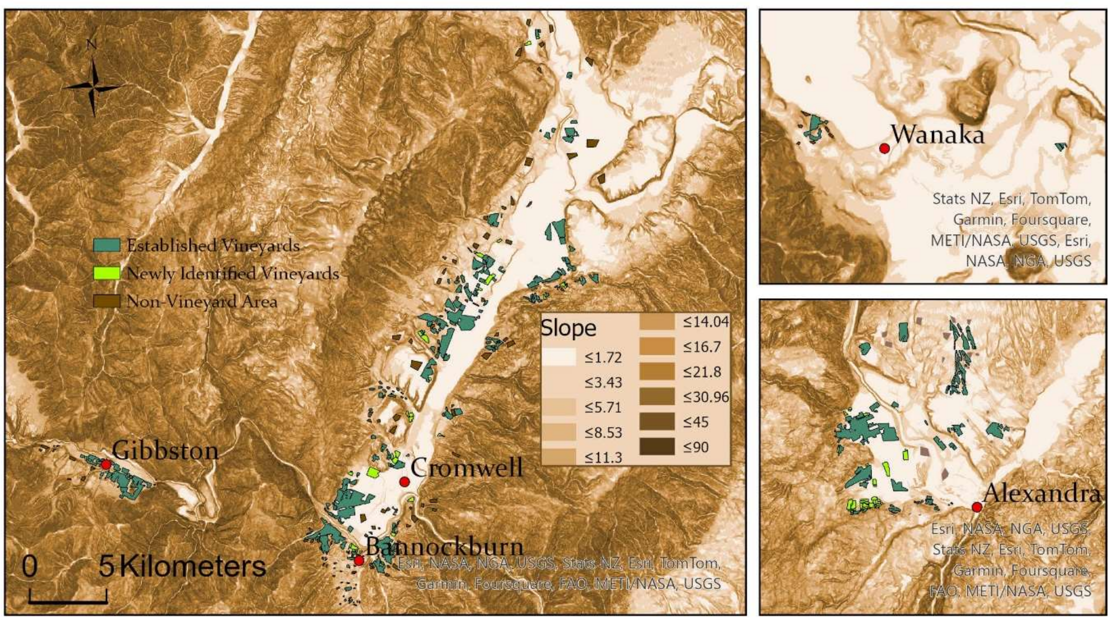

Figure 10. Slope Distribution of Vineyards Across Six Sub-Regions in Central Otago

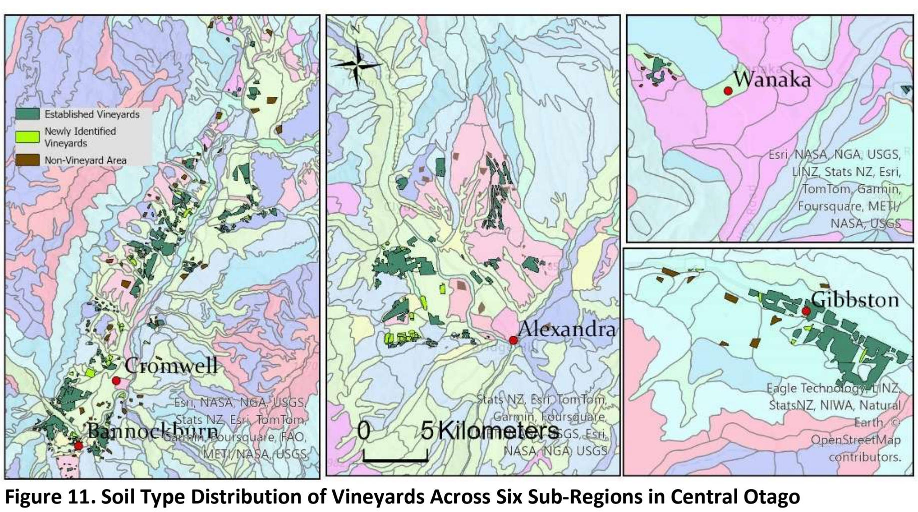

Figure 11. Soil Type Distribution of Vineyards Across Six Sub-Regions in Central Otago

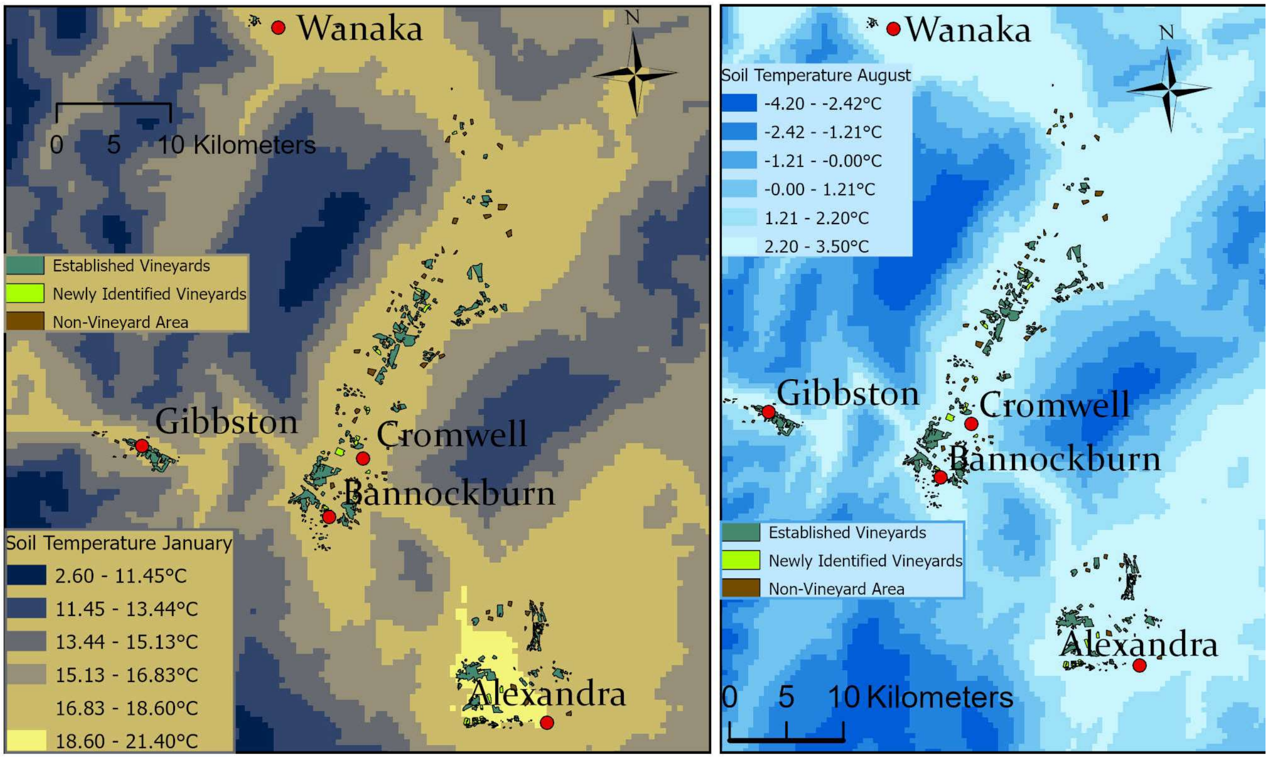

Figure 12. Soil Temperature Distribution of Vineyards Across Six Sub-Regions in Central Otago

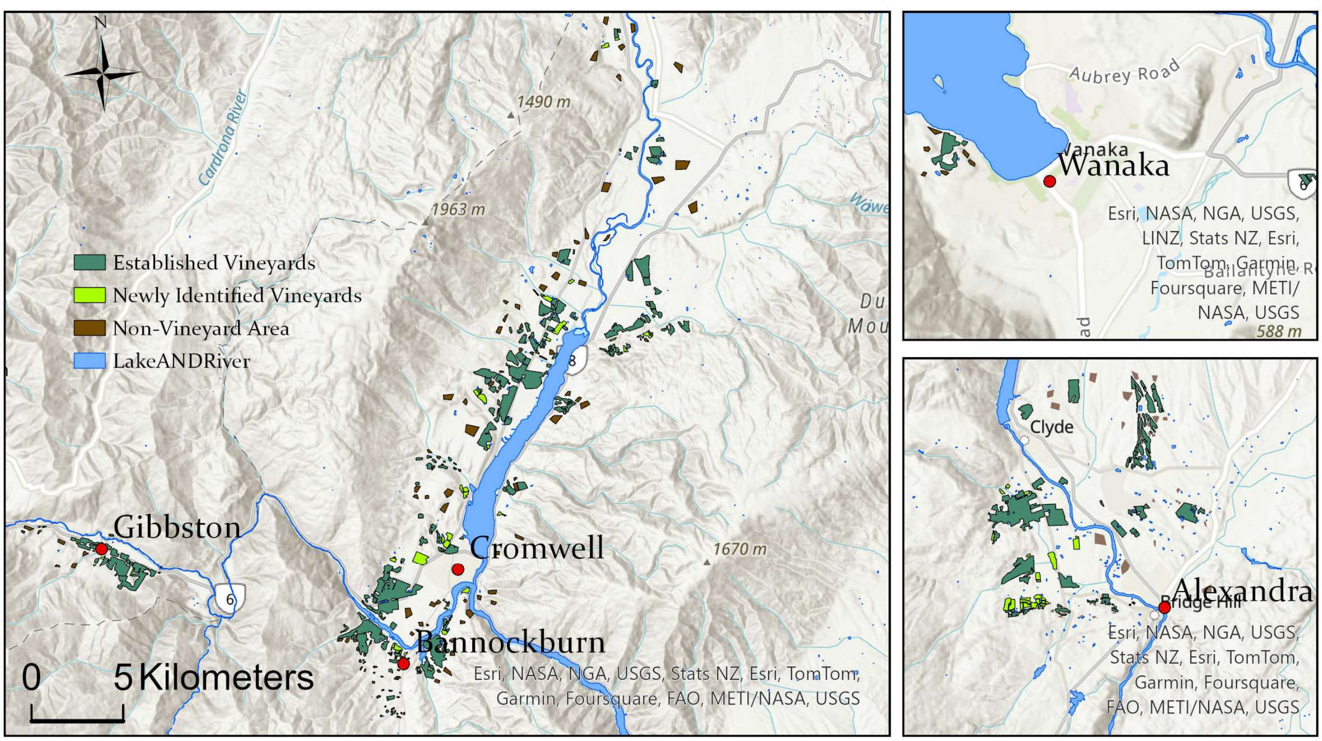

Figure 13. River and Lake Distribution of Vineyards Across Six Sub-Regions in Central Otago