Bayesian-Network Insights for Sustainable Viticulture in Australia

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Background

- Australia's wine industry grapples with growing uncertainty from climate change (heatwaves, frost, water scarcity) and volatile trade conditions.
- Previous studies seldom link **operational choices** to both **economic returns** and **ecological impacts**, leaving growers with siloed advice.
- We bridge this gap by quantifying trade-offs via General Linear Models, XGBoost cost–revenue ensembles, and expert-elicited Bayesian Networks.
- Case studies in **Coonawarra** and **Riverland** reveal region-specific leverage points.
- Climate-projection scenarios show how targeted practice changes can boost profit while reducing resource footprints.

Methods and Objectives

Objective 1 – Quantify trade-offs between resource use, yield and grape price
- Analysed a 10-year Sustainable Winegrowing Australia dataset (57 regions, 1 441 sites) to establish regional baselines
- Applied exploratory techniques (correlation matrices, K-means/OPTICS clustering, decision-tree variants) to explore relationships
- Fitted Ordinary Least Squares and General Linear Models to relate yield and average sale price under differing resource-input levels and climates
- Validated models across Geographical Indication (GI) regions to confirm regional contrasts

Objective 2 – Model economic drivers of vineyard costs and revenue
- Built XGBoost gradient-boosted ensembles, optimising a regularised loss to predict operating cost and revenue per site
- Extracted variable importance to explain regional cost–revenue patterns
- Compared driver hierarchies across regions to highlight geographic cost and revenue sensitivities

Objective 3 – Structure complex systems governing environmental sustainability
- Conducted expert workshops to elicit causal links between vineyard practices, economics and ecology
- Developed Bayesian Networks to encode conditional dependencies
- Applied conditional-probability-table (CPT) interpolation to minimise elicitation burden and bound best/worst cases
- Implemented region-specific networks for Coonawarra and Riverland to capture climatic contrasts

Objective 4 – Balance economic and environmental sustainability in decision-making
- Fused separate economic and environmental BNs using prior linear pooling to create an integrated sustainability engine
- Stress-tested the combined network under Wine Australia climate scenarios (baseline, mild adverse, extended adverse, swing-node for worst- and best-case scenarios)
- Performed sensitivity analysis to identify high-leverage variables for decision-support system (DSS) design and grower guidance

Methodological Contributions

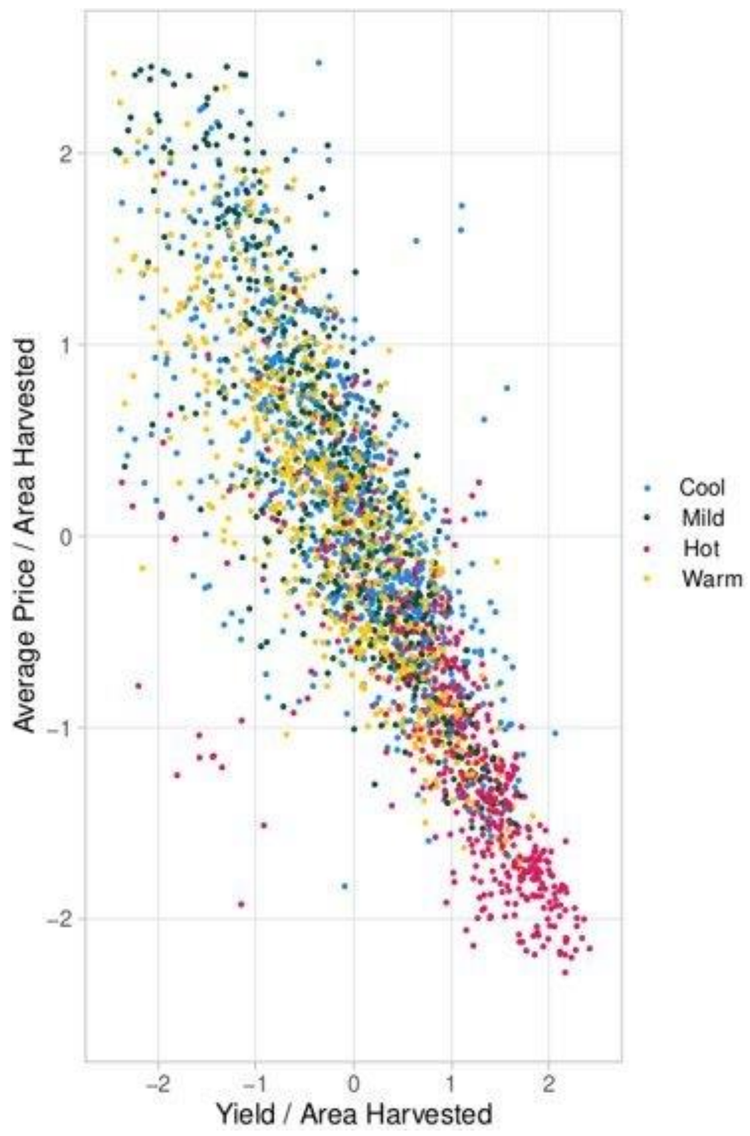
- Novel BN framework combining cost–revenue dynamics with environmental impact in viticulture.
- Linear-pooled scenarios demonstrate a **decision-focused** sustainability lens for industry and policy.

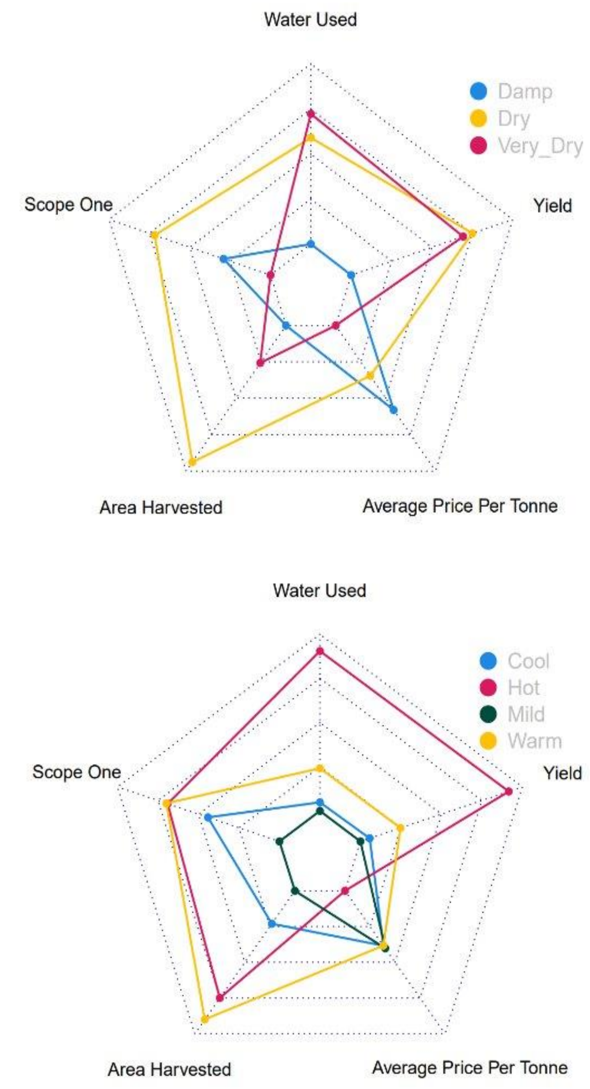
Key Findings

- **Scenario assessments** – Reveal the critical trade-offs growers face under projected climate and market shifts.
- **Grower resilience & reactions** – Map how management flexibility buffers shocks and triggers adaptive responses.
- **Foundational decision-support models** – Provide Bayesian-Network cores that can plug directly into DSS tools.
- **Adverse-event forecasting** – Quantify likely economic and environmental fallout from drought, frost, tariffs, and pests.
- **Optimised decision pathways** – Identify management choices that maximise profitability while minimising resource use.
- **Cost–benefit insights** – Deliver clear return-on-investment profiles for key practices across climates.
- **Information dissemination** – Package results in an open framework for rapid extension to industry stakeholders.

Conclusions & Implications

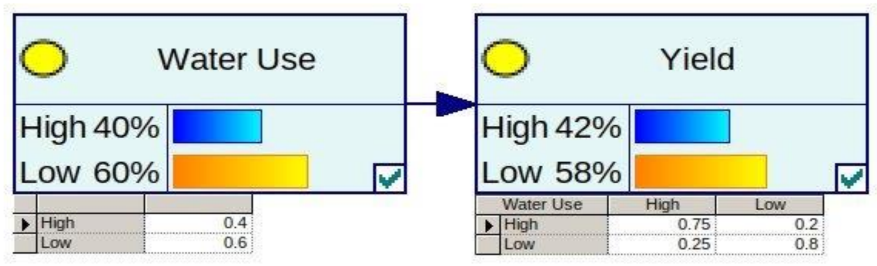
- Integrating economic and environmental indicators clarifies trade-offs and win–wins.
- Results inform region-specific best practice and guide targeted incentives (e.g., carbon-smart irrigation).
- Approach is transferable to other agri-food systems facing coupled climate and market pressures.

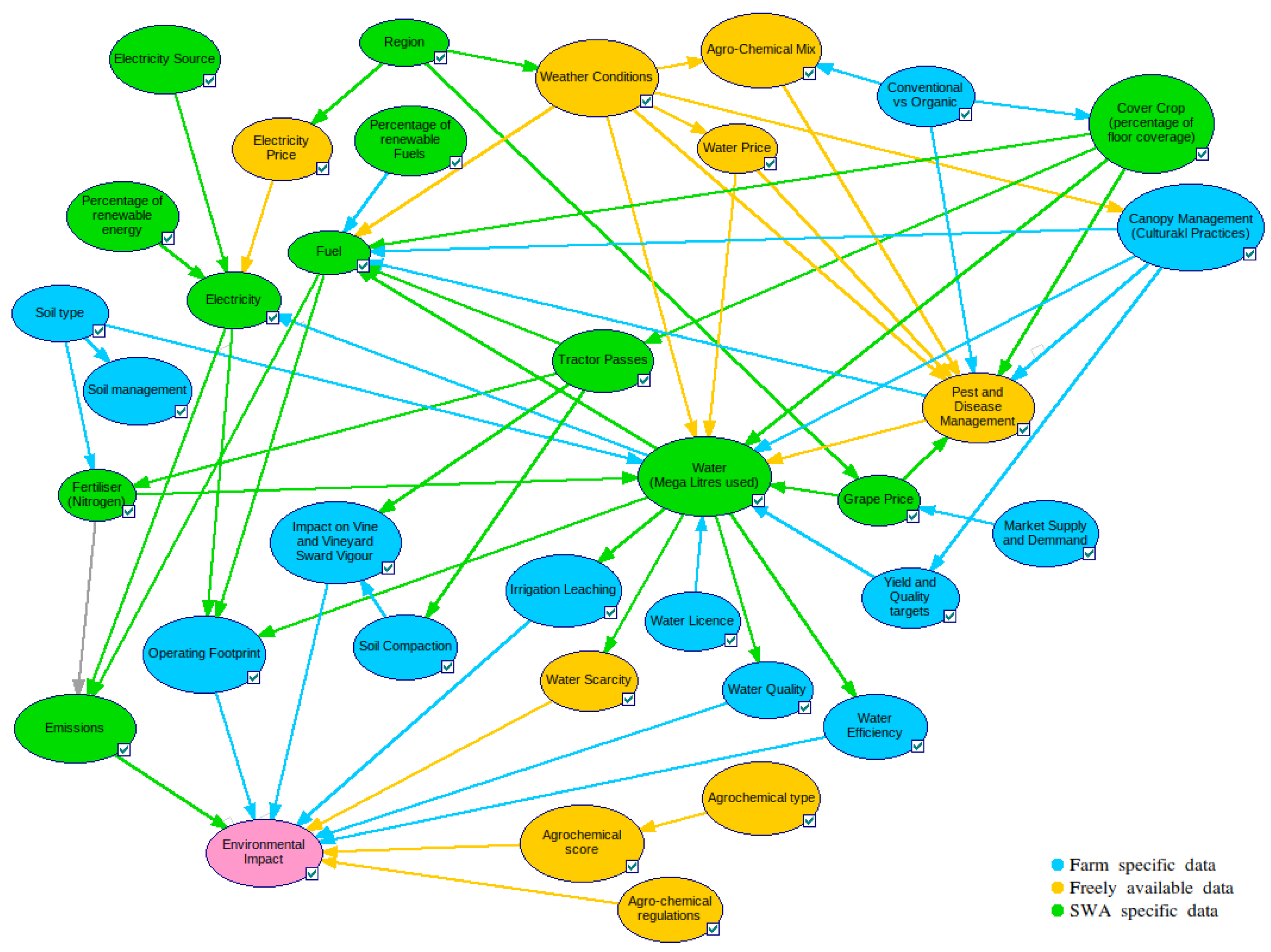


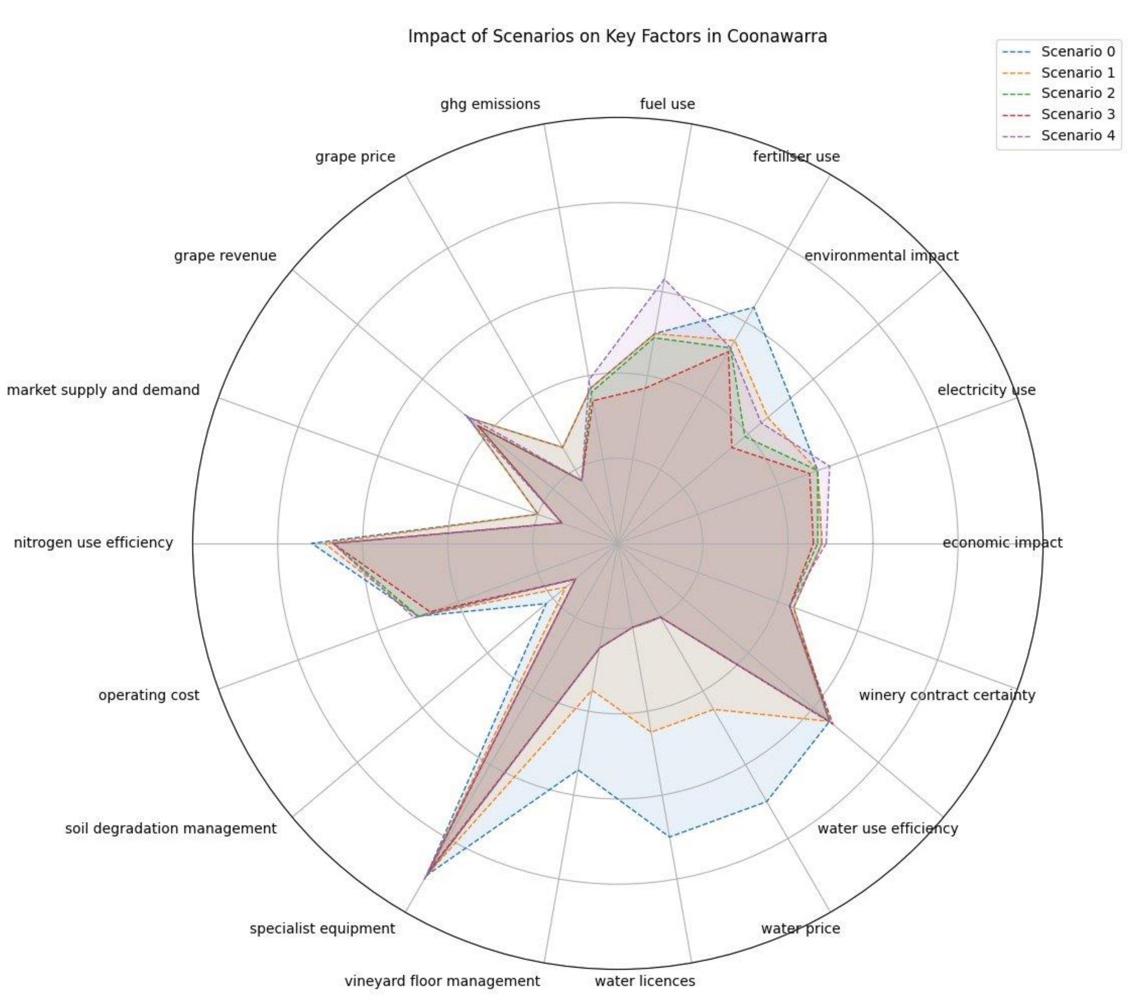


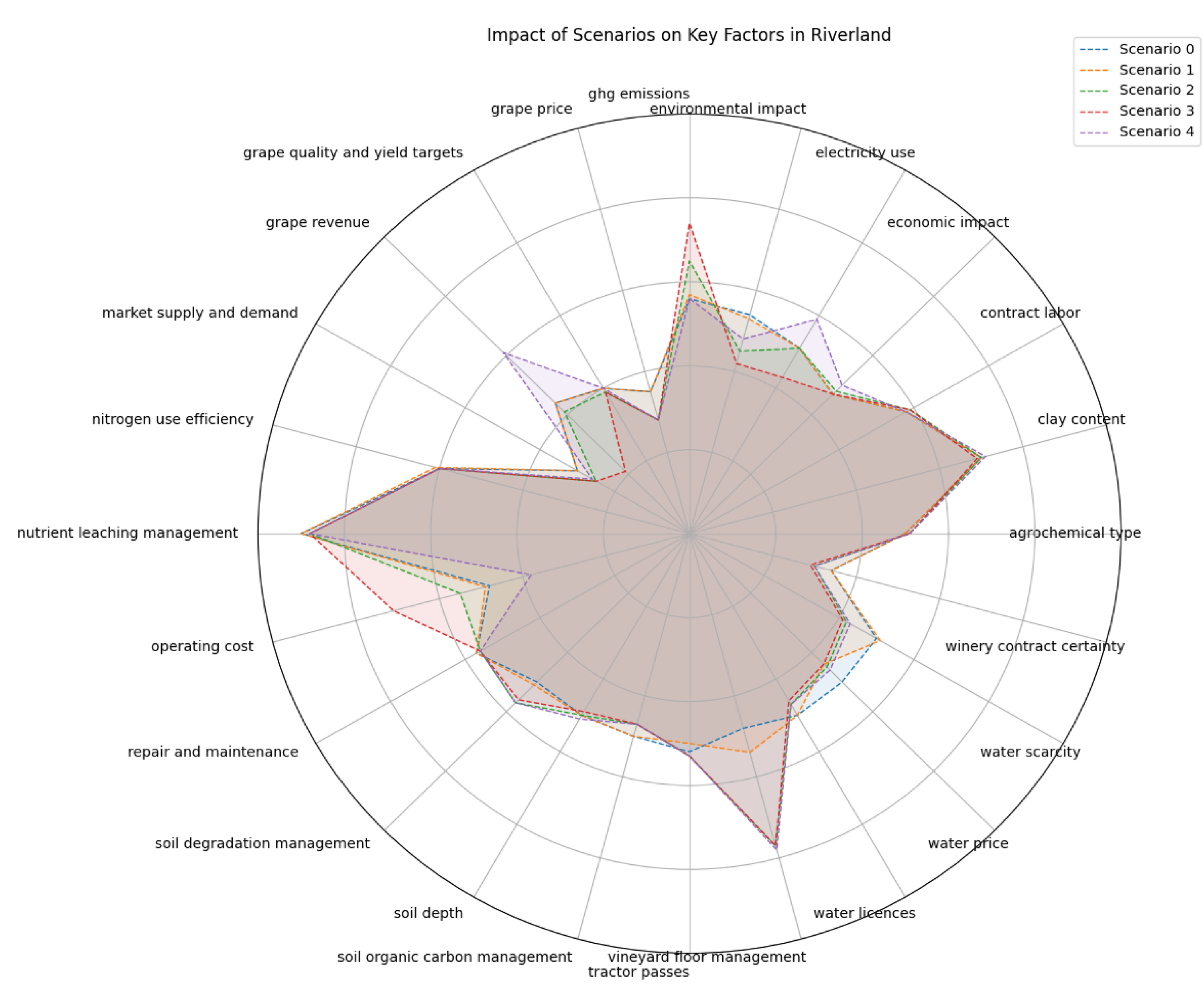
Figures – Method Example

- Above data and relationships were explored. We looked at how relationships changed over climate, size, and the trade-offs of different approaches in viticulture. Metrics are in standard deviations.
- Below we illustrate how we combined types of data and relationships to create conditional dependent models. First a node is created to represent data or a process in a vineyard and then its relation to other nodes is shown by connecting them to create a directional acyclic graph (example below of water effecting yield, is not real data!)
- The below example is a simple representation, but nodes can contain any number of categories, be continuous variables and even represent relationships shown above, such as regression models.









Scenarios

1. Simulates non-ideal seasonal conditions, representing a decline in the seasonal state. This allows for an assessment of how the probability of ideal outcomes changes across different nodes in response.
2. Extends the effects of adverse seasonal conditions to variables one degree removed from climate, incorporating indirect impacts such as increased water and electricity demand, heightened pest pressure, and water scarcity.
3. The third scenarios investigate the role of management decisions that simultaneously influence both economic and environmental outcomes, the 'swing state nodes'. The third scenario is the ideal outcome for these nodes given the extended effects in scenario 2
4. The fourth scenario is the counter example to scenario 3. Where, 'swing nodes' represent not-ideal outcomes.

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