Preparing rural communities for the future: spatiotemporal optimisation of rotation sequences - STORS

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Abstract
Past production choices and short-term seasonal weather forecasts have directed food and fibre production, inhibiting preparedness for operating under a changed climate, which requires longer planning horizons.

This paper qualifies model uncertainty of a temporal dynamic agricultural tool – a spatiotemporal optimiser of rotation sequences (STORS). A generic framework connects abiotic parameters with biotic attributes, allowing the evolutionary algorithm, STORS, to generate Pareto-optimal land use alternatives from which farms and regional planners can select. A case study of the Murrumbidgee Irrigation Area (MIA) is used, where five agricultural production systems, across six soil types, under five water scenarios is investigated.

Outcomes will facilitate answering two key research questions 1) Can STORS identify feasible rotation sequences? 2) Is there a temporal shift in crop species under a changed climate?

Keywords
Crop rotation, optimisation, climate change, land use, climate smart landscape, ant colony optimisation,

Introduction
Simulations of agricultural production systems have served decision makers well. However, this approach is resource hungry and lacks objectivity; the tradeoff between orthogonal objectives is difficult to reconcile in simulations (Mainuddin et al., 1997). Identifying activities which satisfy multiobjective requirements, such as maximizing farm revenue, with climate aware crop choices, while minimising water and other resources, is the future focus for agriculture and regional planners. However, prior to 2015 there was scant published research using optimisation to answer crop planning questions (Randall et al., 2024). Of deeper concern is the lack of agricultural-water nexus research using future predicted climatic data (Randall et al., 2024). A further shortfall is the lack of qualification and quantification of a model's uncertainty; a component required to build trust in outputs for stakeholder usage (Rötter et al., 2011, Maier et al., 2016).

This research seeks to address these challenges. It takes a regional scale approach to identify long horizon temporal crop rotations, using predicted climatic parameters to end of century, under five available irrigation water scenarios for five production systems. Qualification of model uncertainty enhances its use as a Decision Support System (DSS) (Hochman and Carberry, 2011); with outputs unveiling possible food security gaps and industry transformation. The research's purpose is to identify transition points, providing lead time for regional economic adjustments.

Approach
A transdisciplinary research project in computational modelling and optimisation applied to an agriculture system is explained. It spotlights areas of model uncertainty, how they were ameliorated and why the approach taken makes the STORS fit-for-purpose. STORS model components and linkages are presented, namely: climate data which drives the agricultural and water inputs; the agricultural framework capturing farm production strategies and capacity based on soil type; available

water under differing scenarios, and an ant colony optimisation (ACO) solver (Dorigo et al., 2006) which searches these elements informed by elimination rules to generate rotation sequences which satisfy objective criteria. Each input has a component of uncertainty, potentially compounding in outputs. To mitigate this issue, inputs were evaluated and selected based on appropriateness for the research objective.

Climate data is the most crucial element of this research. NARCliM1.5 was chosen for its local scale, relevant for decision-making and coverage of the case study area and water catchment. NARClim1.5 uses the most recent global climate models (GCMs) from the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). The emissions representative concentration pathway (RCP) 8.5, the 'worst-case scenario' was selected based on a lag period between reduction in emissions and atmospheric greenhouse gas (GHG) concentrations. It reflects the current and mid-century reality, based on current legislation and political action.

The *Framework* strives to capture real-life agricultural production systems via three elements: 1) land management unit (LMU) defined as parcel of land with distinct attributes which guide the agricultural economic benefit capacity; 2) agronomic rules which exploit seasonal conditions (Bell et al., 2017); and 3) gross margins derived from secondary sources of government agency and industry. The framework is an innovative addition to agricultural optimisation, portraying real world production decisions and operational economics.

Available irrigation water
Actual water flow volumes into the Murrumbidgee Irrigation Area (MIA) main canal were derived for five available water determinations, representing water scenarios of drought; very low; low; mid and high. Volumes are discounted across the 80-year research horizon to reflect catchment precipitation degradation (CSIRO, 2008).

STORS
A variant of the knapsack problem of crop allocation to land is solved using implementation of an ACO to perform the optimisation. Due to the complexity of this component, it has been omitted from this manuscript; however, the detail of this cornerstone element is planned to be published in an extended publication at the end of the research project.

Model uncertainty amelioration
This paper identifies and acknowledges model elements which either intrinsically, based on the problems complexity, or due to data limitations, add uncertainty to model outputs. This uncertainty is qualified and evaluated for its impact on STORS' usefulness. Further, these considerations function as a touch stone for future optimisation and simulation research.

Climate To capture the future spectrum of possibilities, three GCMS were selected based on high scores for historic climates and better than median errors (CSIRO and Bureau of Meteorology, 2021). To enhance reliability, two of the selected models (ACCESS1.0 and ACCESS1.3) use a warming drift from preindustrial control, a hotter and drier future. The third, CanESM2, is hotter coupled with a small positive shift in precipitation but, more importantly, it soundly represents extreme events of El Niño, an important feature for Australian research.

Uncertainty appears in catchment precipitation categorisation, where a misalignment of catchment precipitation to available irrigation water may arise. Of 10 approaches to calculate evapotranspiration ET_o specific to the case study area, all underestimate daily ET_o (Azhar and Perera, 2011), While the Penman-Griffith method (Barton and Meyer, 2008) offers a more accurate ET_o for the case study area, it requires equation data not accessible to this research. Rather, the FAO Penman-Montieth data available within NARCliM1.5 was employed, due to the Hargreaves and Samani (1985) tendency for underestimation in high wind conditions (> 3m/s), which is the predicted future reality for the MIA

(Barton and Meyer, 2008). The implication of underestimating ET_o is that STORS outputs may represent a more positive position than the projected reality.

The innovative *framework* is the cornerstone of the research and as such its representation of agricultural production determines the STORS acceptance as a DSS. Extensive networking by the first author generated several soil maps. However, their differing soil categorisation requiring guidance from a local soil expert for the allocation of areas across soil types.

The reductive approach applied to agronomic rules is tempered by the triangulation of data from published research, industry reports and local experts. To facilitate STORS search capability, rules were further reduced to a Boolean expression, while elimination rules based on real world agronomic rules ensure only feasible solutions are generated. Thus, the output of this research can be relied upon to draw suitable inferences concerning cropping patterns into the future.

Crop water consumption was calculated using single crop coefficients (Allen et al., 1998), an appropriate technique; as neither plant density nor irrigation scheduling are considered in this iteration of STORS. It was determined any uncertainty arising from this approach does not compromise the investigation or devalue output usefulness.

Consideration of degree days permits investigation of future climate impact on crop growing timeframes and possible shifts in production seasons. As STORS optimises across annual and perennial species, degree days were determined to be the appropriate common parameter permitting comparison in the model's first iteration. A proxy chill portion using RCP8.5 for Shepparton, Victoria was used (Hort Innovation, 2018). This value was scaled across the research horizon and all crop vernalisation requirements were satisfied. This instrument's influence on results is determined to be minimal.

Weighted average purchase price for monthly irrigation water in the representative water allocation years is employed (NSW Government, 2023). In some months, values were not reported; in these instances, interpolation of proxy water prices were applied using the regulated river systems of the Lower Darling and Murray River. Despite the above attempts to represent reality, the inability to forecast market behaviour over such a large research horizon, and the non-linear relationship between commodity prices and water costs, means that economic evaluation of the outputs must be viewed as indicative and not absolute, an acceptable risk for such an optimisation problem.

Quantifying future *Available irrigation water* based on future catchment precipitation excludes other hydrological modelling parameters of ET_o; topography; vegetation cover. This simplified approach increases uncertainty; however, it can be overcome in future iterations by the incorporation of catchment specific hydrology modelling into the model framework.

Conclusion

The strongest element of the research is inclusion of long range predicted climate data, an important feature adding confidence to STORS rotation solutions to the end of century. The rule-based approach to rotation creation incorporates production plasticity sensitive to climate changes. Solutions informed by farm decisions are pertinent at the regional scale, circumventing scale discrepancy issues. Available irrigation water based on actual historic volumes which incorporate reservoir management, and align to catchment precipitation, imparts faith that irrigation system outputs are sensible. Qualification of model uncertainty and quantification in STORS outputs acts as an exemplar to future optimisation research. Consideration of annual and perennial crops along with irrigated and dryland production systems exposes possible industry transformation and regional economic capacity. This research demonstrates STORS' merit as a DSS to facilitate change at a regional scale to reach stated goals. Extension results and implications will be released later this year.

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