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Transferring Paddock Histories to Optimise Crop Rotations Using LP: a New, Unrestricted Approach

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Abstract

Modelling of cropping or crop-pasture rotations to date has been based on a predetermined, restricted set of rotations as “activities” of a Linear Programming matrix. This approach limits the use of such models to evaluate new crop varieties and potential rotations. It also results in the necessity to build entirely new models for each agro-climatic region due to differences in crop and rotation choices that are available.

This paper presents an alternative model that solves for the optimal rotation from all theoretically possible rotations. Each crop in the optimal solution is determined given the paddock history of the previous two years.

The choice of options to maximise farm profit (or gross margin) depends mainly on the crop yields and prices. The expected yield of a crop may differ according to its paddock history. These yields can be determined by conducting group discussions with extension and research scientists. The same model can be calibrated to a different agro-climatic region, by replacing the crops and their prices, yields and inputs.

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Introduction

Victoria has been using LP models to estimate water demands and water use efficiency levels in irrigation areas (Eigenraam and Stoneham, 1997; Eigenraam et al, 1996). Benefit-cost analysis of research and development (R&D) projects was improved by using LP models to estimate on-farm benefits. This system was further improved by estimating productivity changes using LP models (Stoneham et al, 2000). The ability of LP models to account for substitution between different enterprises and to present input-output tables made them suitable for estimating productivity changes due to changes in technology.

The Victorian Department of Natural Resources and Environment (NRE) then realised the need for better-specified LP models. In the past, these models were built for other purposes such as provision of decision support for farm advisers (O'Brien, 1999; Wimalasuriya, 1999). However, the advancement of technology in spreadsheets and modelling now allows for greater flexibility.

Development of the new approach of LP modelling of a farm system that is presented in this paper arose from the need to improve productivity estimates.

What is LP Modelling?

Being developed in 1940's for military operations, LP modelling is widely used in business and commercial planning today (Dent, et al, 1986). It's one of the mathematical programming techniques that are one class of operations research. The technique can be applied to a wide range of problems with the following characteristics:

(1) A range of activities is available to choose from.
(2) Constraints prevent free selection from the range of activities.
(3) A quantifiable objective needs to be attained.

As with any other economic tool or technique, LP has its own limitations in its ability to be applied to some real world problems. These limitations arise from underlying assumptions of LP including divisibility of variables, linearity of constraints, additivity, and non-negativity of activities. However, Dent et al (1986) argues that these limitations are more perceived than real. This argument is reinforced by Pannell (1997) that in most cases, there are ways of overcoming, or at least minimising the degree of these limitations.

LP's and Productivity

NRE's economic evaluation system applied to assist resource allocation between R&D projects comprise of a qualitative and a quantitative component (Stoneham et al, 2000). The objective of resource allocation decisions is to maximise wealth, or well being, in the Victorian economy. The quantitative component attempts to measure the gross benefits derived from a research-induced technical change.

Breeding of a new wheat variety that yields more than the existing ones using the same amount of inputs, for example, would enable farmers to produce more at the same cost as before. This means the cost of producing the same output would fall. At the same time, the area under wheat may increase at the expense of some other crop if this new variety is adopted. An optimising LP model can capture this substitution effect.

Research-induced technical changes such as that given in the example above, shift the commodity supply curve downwards (Stoneham et al, 2000). Practically, this shift is found by measuring the change in productivity. Basically, a productivity change is the difference between the rate of output and input growth. Productivity change is a physical concept; it is concerned with the quantity of outputs and inputs. Wholefarm LP models are used to estimate productivity change due to research-induced technical shocks.

LP Modelling of a Farm System

The simplest way to model a farm system in LP is to determine the optimal crop (or enterprise) mix. Activities of the LP matrix would be individual crops or enterprises with their respective gross margins as the activity budgets. This method would not take any rotation effects into consideration. Unless some resource constraints such as labour, capital or machinery are put in, the LP solution would choose only the crop or the enterprise that has the highest gross margin.

The next level of complexity is for the LP to determine the optimal Crop (or Crop-Pasture) Rotation out of a pre-determined set of rotations. MIDAS models in WA (Kingwell and Pannell, 1986) and PRISM models in Victoria (O’Brien, 1999; Wimalasuriya, 1999) and NSW (Faour et. al., 1999) have been developed using this method. Rotation effects on crop yields are considered in determining the rotation gross margins. In this method, it’s possible to have rotations with different lengths in the same model.

Some examples for activities of the LP matrix in such models are Canola-Wheat-Barley; Lentils-Canola-Wheat; Canola-Wheat-Barley-Lentils; and Canola-Wheat-Barley-Lentils-Wheat. There are two major limitations in using this method to model a farm system. Firstly, the solution is confined within the restricted set of pre-determined rotations. This results in the model being unable to be used to evaluate new crop varieties and any potential rotations. Secondly, it becomes inevitable to build a completely new model for any other agroclimatic region because the crop and rotation choices may be different.

An even more complex method for modelling a farm system is for the LP to develop the optimal crop rotation, from all possible crops grown after all possible two-year paddock histories. Activities in the LP matrix in this method would be single crops, after each possible two-year history. Some examples are Wheat after Wheat-Wheat; Wheat after Wheat-Lentils; and Wheat after Wheat-Canola.

This is an unrestricted approach where new crop varieties and potential rotations can be evaluated. The newly developed Victorian Wimmera Rotation Model was built using this innovative approach.

The Major Assumptions in Modelling Rotations

Two of the major assumptions considered in modelling rotations in either of the last two methods above, are as follows:

1) The same rotation would occur in the farm, at least 2 years more than a single complete cycle.
2) In any given year, the total cropping area would be equally divided into each segment of the rotation.

Eg: Rotation Canola-Wheat-Barley-Lentils (Ca-Wh-Bl-Lt)

On a 1,000 ha farm in any given year: 250 ha under Ca after Bl-Lt,
250 ha under Wh after Lt-Ca,
250 ha under Bl after Ca-Wh,
250 ha under Lt after Wh-Bl.

In large cropping farms such as those in Western Australia, there could be different rotations practiced on different parts of land within the same farm, due to variations in soil and land type. However, this type of variation within farms is less apparent in the southeastern parts of Australia except in the Mallee region.

The New Wimmera Rotation Model

The farming system modelled is continuous cropping on the Grey Cracking Clay soils of the Wimmera region of northwestern Victoria. A continuous cropping rotation is generally repeated for two to three cycles until some paddocks start showing signs of problems such as weed control. These paddocks are then rested for a year under a green manure crop, a legume pasture or a fallow. The model is presently calibrated to Murtoa, receiving an average rainfall of 400 mm/annum (280 mm growing season rainfall).

Crops considered are Wheat (Wh), Barley (Bl), Field Peas (Fp), Lentils (Lt) and Canola (Ca). The three important crop types for the Mediterranean regions are cereals, pulses and oilseeds. Once a model is developed with one or two crops in each category, these could easily be replaced with any other crop belonging to the same category.

The LP Matrix

Following is a summary of the activities of the LP matrix:

No. of crops	5
No. of 2-year histories	25
No. of options (each year) (Each crop after each history)	125 (5 x 25)
Maximum length of rotation	6 years
No. of Activities	750 (125 x 6)

“Transfer Rows” are used to transfer the 2nd crop of the history and the crop selected in the current year as the two-year history in the following year. For example, if the selected option in the 1st year is Lt after Wh-Bl, a History of Bl-Lt will be transferred to the 2nd year. These history transfers will occur from Years 1 to 2, 2 to 3, 3 to 4, 4 to 5, 5 to 6 and 6 back to 1. Therefore, the model will develop a rotation by choosing a single option for each year, so that the 6 selected options would form a continuous rotation that maximises total rotation gross margin. Activity budgets contain the gross margin of each crop after each history.

The objective function to be maximised by this LP model is the total rotation gross margin. This depends on the gross margins of all crops of the rotation chosen. Gross margin of a crop depends on its yield, price and input cost. Yield and the rate of nitrogen fertiliser applied for the same crop may differ depending on the paddock history. Unless these differences are considered in calculating the gross margins, an LP model would choose only the most profitable crop for all the years of the rotation.

Length of the rotation

In this new Wimmera Rotation Model, it’s possible to choose between 3, 4, 5 and 6 years as the length of the rotation. This is done by selecting “option buttons”, which are assigned to macros for changing the formulas in the LP matrix. There’s also a button assigned to a macro for optimising the model automatically under each length of the rotation and pasting the solution into a table.

Crop Yields and Paddock Histories

The gross margin of a crop may vary due to the differences in its expected yield depending on the paddock history. Expected yield of wheat for example, should be higher after a pulse crop than after a cereal crop, due to disease break and nitrogen fixation. Data on how different paddock histories affect the yield of a crop are generally not available.

However, farm advisers who work closely with farmers and farmer groups possess a significant understanding in this regard. This understanding can be supplemented by the experience of researchers involved in breeding and rotation research.

Several group discussions were facilitated among a group of extension staff from the target region. It was decided to consider the crop yields, management level and input use among the top 20% to 30% of farmers in the region. When it comes to using the model for evaluating any regional issues, these crop yields are brought down to district averages.

First of all for each crop, a potential yield for an average rainfall year that could be obtained after the best paddock history for that crop was finalised during the discussions. In order to link these yields to rainfall, potential “water use efficiencies” (French and Schultz, 1984) were estimated using the fixed evaporation losses as shown in van Rees and Ridge (1994). Crop yield data from research station trials as well as from top farmers in the region together with corresponding growing season rainfall (April to October) were considered in these estimations.

Potential WUE (kg/ha/mm) = Potential yield (t/ha) x 1,000 (kg/t) / WU (mm)
Where;
WUE: Water Use Efficiency
WU: Water Use
WU = GSR – Evaporation losses
Where;
GSR: Growing Season Rainfall (cumulative rainfall from April to October; van Rees and Ridge, 1994)

GSR for Northern part of Victoria is approximately, 65-70% of the annual rainfall. The percentage increases when the annual rainfall becomes higher than average.

Potential water use efficiency (WUE) and evaporation losses for each crop for the Wimmera region are shown in Table 1. These figures are used in the model to arrive at potential crop yields for a given rainfall. The next step during the discussions with extension staff was to develop the expected differences in crop yields depending on the paddock history of the rotation. Experience shows that a paddock history of two previous years is long enough to capture a significant amount of this yield variation.

Crop	**Potential WUE**	**Evaporation losses**
	(Kg/ha/mm)	(mm)
Wheat	15	110
Barley	15	90
Field Peas	10	130
Lentils	9.5	130
Canola	8.5	110

Table 1: Potential water use efficiencies (WUE) and evaporation losses for the crops in the Wimmera Rotation Model.

Weed, disease, nitrogen and moisture status that could be expected as results of each two-year paddock history were considered in developing percentages by which the potential yield of each crop would be reduced.

Expected Yield = Potential Yield - % Weed Effect - % Disease Effect - % Nitrogen Effect - % Moisture Effect

Crop inputs were considered to be of the standard recommended rates as in the regional gross margin book (O'Brien, 1998), except for nitrogen fertiliser. The rate of application of urea for cereals immediately following canola was considered to be higher and that after pulses to be lower than the standard rate.

These discussions with local extension staff from the target region during the model development resulted in a sense of ownership of the model and credibility in its results.

Testing and Validating Model Results

Conducting model runs with a wider group of extension and research scientists from the region further refined these crop yields in various rotations. Some of the model results however, challenged the traditional wisdom of scientists. Traditionally, scientists believed that canola in these Wimmera continuous cropping rotations should always follow a pulse crop. But, the model results don't show a significant difference in profitability of a rotation with canola following a pulse crop and a similar rotation with a pulse crop following canola.

It was also highlighted during these validation sessions that there could be differences between what's happening on farms in the region and what's biologically possible to achieve. Barley for example, normally yields more than wheat if the same paddock and cultural conditions are provided. However, farmers in the region generally achieve lower yields for barley than for wheat because they don't provide optimal conditions when barley is grown.

According to local experience in the region, there are three reasons for not providing optimal conditions for barley. The most important reason is that farmers consider barley as a low return crop because they aren't sure of obtaining the malting quality. Yield penalty for planting later in the season is more profound with wheat than with barley, therefore farmers sow barley once they've finished sowing all other crops most of the time. The third reason is the concern of barley being downgraded to feed grade by having a higher protein content if soil nitrogen is high.

Some Results of Model Applications

A sensitivity analysis was performed with the Wimmera Rotation Model to determine the sensitivity of the optimal rotation and the total farm gross margin to a 10% increase in the market price of each crop (Table 2). Length of the rotation modelled was five years. The base rotation was Canola-Lentils-Wheat-Canola-Wheat with a rotation gross margin of $287/ha.

Crop	**Price Increase**	**Rotation**	**Increase in Gross Margin**
		Base Rotation: *Ca-Lt-Wh-Ca-Wh*	
Wheat	10%	No change	7%
Barley	10%	Ca-Lt-Bl-Ca-Bl	4%
Field Peas *	10%	No change	0%
Field Peas *	20%	Ca-Lt-Ca-Fp-Wh	2%
Lentils	10%	No change	4%
Canola	10%	No change	7%

Wh: Wheat; Bl: Barley; Fp: Field Peas; Lt: Lentils; Ca: Canola

* Field Peas wasn't included in the optimal rotation until its price was increased by 20%.

Table 2: Sensitivity of the optimal rotation and the total farm gross margin to a price increase of each crop.

The optimal rotation is sensitive to a price increase of 10% for barley, and of 20% for field peas. The largest increase in gross margin resulted from price increases in wheat and canola. When the barley price was increased, barley replaced all wheat in the new rotation, however, the gross margin only increased by 4%, which is also similar to lentils.

Another analysis was performed using the Wimmera Rotation Model to determine the impact of a 10% increase in yield of each crop (keeping the input use constant) on the optimal rotation, the total farm gross margin and the productivity (Table 3). Each crop was analysed individually.

The productivity improvement was estimated using the following method. The wholefarm LP model was initially optimised (the base run) using the standard crop yields of the model as the "without" technical change scenario. Then, the model was optimised with the increased yield for each crop as "with" technical change scenarios. Productivity change was measured after each test run by measuring the changes in the quantity of inputs and outputs between the "with" and "without" technical change scenarios.

Crop	**Yield Increase**	**Rotation**	**Resulted Increase in**	
			Gross Margin	**Productivity**
		Base Rotation: *Ca-Lt-Wh-Ca-Wh*		
Wheat	10%	No change	6%	3.5%
Barley	10%	Ca-Lt-Bl-Ca-Bl	3%	0.8%
Field Peas *	10%	No change	0%	0%
Field Peas *	15%	Ca-Lt-Ca-Fp-Wh	0.1%	0.9%
Lentils	10%	No change	4%	2.5%
Canola	10%	No change	6%	4%

Wh: Wheat; Bl: Barley; Fp: Field Peas; Lt: Lentils; Ca: Canola

Table 3: Impact of a price increase of each crop on the optimal rotation, the total farm gross margin and the productivity.

There was no change in the rotation for yield increases in wheat, lentils and canola. This occurred because they were already in the base rotation. If the yield increase is significant enough to overcome the agronomic restrictions there is a change in the rotation.

An increase in barley yield resulted in a new rotation because of its competitiveness with wheat. They are very similar crops. Field peas require a significant increase in yield to replace one of the crops that are already in the base rotation.

It must be kept in mind that if there were changes in commodity prices and technical changes the rotations that may result would be significantly different. This style of LP allows multiple changes to be explored among all possible rotations.

Input-output summary table for wheat in the above analysis is presented in the Appendix, together with a list of all inputs considered in measuring productivity change for each crop. The column "t-1" is the "without" scenario while "t" is the "with" scenario.

Conclusions

Although the LP matrix looks complicated and huge with 750 activities and 218 constraints, it's fairly straightforward to model all theoretically possible rotation options using the approach presented in this paper. A major proportion of the constraints is simply to transfer the paddock histories between years so that the model will develop the optimal cropping rotation.

This is an innovative, unrestricted approach to model wholefarm systems. Once the LP matrix and the data entry spreadsheet are developed with any five crops, this type of a model can be used for any geographical region by replacing the crops, and their yields, prices and inputs.

The only major work necessary before the model can be used for a new agro-climatic region is the development of expected crop yields after each two-year paddock history. Group facilitation skills, a brief understanding of rotational effects on crop yields and a commitment to obtain active participation of local extension and research scientists are important in undertaking this task.

The ability of wholefarm LP models to account for substitution between different enterprises makes them a powerful tool for estimating productivity changes due to research-induced technical shocks. The conventional method of wholefarm modelling with a pre-determined, restricted set of cropping rotations confines the solution to be within this set. The unrestricted method of modelling all theoretically possible rotation options presented in this paper overcomes this limitation.

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APPENDIX

Input-Output Summary Table for Wheat in Measuring the Productivity Increase due to a 10% Increase in its Yield, and a List of Inputs Considered for Each Crop in these Productivity Estimates

	t-1	t	percent growth
inputs	100	100	0
outputs	100	103.4468	3.446816
PRODUCTIVITY (percent)			3.446816

Inputs:

Fertiliser 1
Fertiliser 2
Fertiliser 3
Fertiliser 4
Herbicide 1
Herbicide 2
Herbicide 3
Herbicide 4
Insecticide 1
Insecticide 2
Fungicide 1
Fungicide 2
Land Preparation 1
Land Preparation 2
Sowing
Harvesting
Fertiliser Application
Herbicide Application 1
Herbicide Application 2
Insecticide Application
Fungicide Application