Optimising land use and water allocation in intercropping systems[1]

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Abstract – The main purpose of this study is to identify the optimum allocation of limited amount of land and irrigation water across a number of alternative farm enterprises, maximising the whole-farm profitability by considering present relative prices, changes in river water availability, irrigation system efficiency and a highly variable climate. It was developed an optimisation model by using linear programming language to maximise the whole-farm profit of farm located in Wee Waa (NSW, Australia), for three different scenarios (dry, average and wet years) over two seasons. The whole-farm profit is highly sensitive to climate variability and also to prices and yields variability, especially in relation to cotton.

Keywords: Crop rotation, linear programming, profit maximization.

Otimização do uso da terra e da alocação de água em sistemas de rotação de culturas

Resumo – O principal objetivo deste estudo de caso é identificar a alocação ótima de recursos, especificamente água para irrigação e terra, entre alternativas de atividades agrícolas, visando maximizar o lucro da propriedade, considerando preços relativos, mudanças na disponibilidade de água, eficiência do sistema de irrigação e alta variabilidade climática. Foi desenvolvido um modelo de programação linear, com o objetivo de maximizar o lucro das atividades agrícolas de uma propriedade localizada em Wee Waa (NSW, Austrália), considerando três cenários (seco, médio e úmido, conforme a variabilidade do regime de chuvas) ao longo de 2 anos. O lucro total da propriedade mostrou-se altamente sensível à variabilidade climática, bem como às variações nos preços e ao rendimento produtivo das culturas, especialmente com relação ao algodão.

Palavras-chave: rotação de culturas, programação linear, maximização de lucro.

Introduction

In Australia, cotton farmers confront the challenges of drought, increased climate variability and poor business profitability, driven by low yields, low prices and increased costs. Despite profit from cotton remains better than most broad acre rainfed crops, high yielding cereals grown on limited water are providing higher profitability per mega litre of water. This is the reason why Australian growers are interested in identifying opportunities that maximise returns per mega litre by considering the crop rotations between cotton and cereal, instead of planting cotton back to back.

Because of that and considering the increased focus on more economic and environmental sustainable farm systems, there is an increased interest in building models to improve the whole-farm profitability in a sustainable way. These whole-farm models are able to predict the impacts of different scenarios not only in terms of climate variability, but also prices, yields and costs variability. Also, whole-farm models can be complemented by simple analysis or specific economic models such as that ones of Engindeniz and Tuzel (2006) or Beltrame et al. (2007), respectively. As a crop rotation system has a major impact on environment sustainability and productivity increase due to improve yields, soil characteristics, diseases control, etc., it addresses a more economic and environmental sustainable production system. Thus, the whole-farm models which include crop production must somehow include crop rotation as an important component (DETLEFSEN; JENSEN, 2007).

Optimisation models are developed to give farmers support in decision making related to what to plant, where in the farm and when, to maximise the whole-farm profitability by identifying the optimum resources allocation across a number of alternative farm enterprises in crop/grazing rotation systems. Optimisation models can be developed using linear programming (LP) language. LP is an upgrade of a linear equation system's resolution technique through a sequence of matrixes inversion, with the advantage of including an additional linear equation which represents an objective to be achieved in terms of maximisation or minimisation (CHVÁTAL, 1983).

This work was done adopting a study case of an Australian cotton/grain farming system, specifically from Wee Waa, New South Wales, but the idea can be extrapolated elsewhere. The goal is to present an optimisation methodology based on operational research, indicating the best trade-off between land and water use in this agricultural system by analysing the best net return of the whole agricultural activity throughout the years of crop rotation in a farm scale.

Methodology

The currently most used algorithm in linear programming (LP) softwares is the Simplex Method which was developed during the Second War in 1947 by a Northern American scientist staff, and has been published afterwards. However, breakthrough in terms of correlated algorithms efficiency only could be observed in the 1980's through developed studies (KAMARKAR, 1984). Nowadays, LP is broadly used around the world and can be applied for different objectives such as maximise profits, efficiency, social welfare, etc.; or minimise costs, time, losses, etc.

A LP model can be summarised as:

$$MaxZ = \sum_{j=1}^{n} c_j X_j \tag{1}$$

Subject to:

$$\sum_{j=1}^{n} a_{ij} X_j \leq b_i, \ \ i = 1, 2, \ldots, m \tag{2}$$

$$X_j \geq 0, \ \ j = 1, 2, \ldots, n \tag{3}$$

in which

c_j represents the j activity's gross margin.

X_j represents the j activity's level.

a_{ij} represents the each input exigency by each activity.

b_j represents the each input availability.

Equation 1 represents the objective function.

Equation 2 represents the functional constrains.

Equation 3 represents the non-negativity constrains.

The variables in a LP model cannot assume negative values, although these can be expressed as a difference between two positive variables. All involved equations must be linear, which means, all coefficients have a constant behaviour. The restrictions expressed as unequal equations allow that the whole use of resources be not mandatory and the explored level of any activity can be more than or equal zero. The LP models allow a much wider range of response by farmers in their choice of outputs and inputs than the limited number of alternatives presented in other methodologies, for example in budgeting studies. In addition, LP is a powerful optimising technique in that it selects the combination of enterprises that will maximise profits from a specified set of enterprises subject to specified resource constraints set. An added advantage of LP is that they provide dual prices information indicating the change in profit when additional units of a limited resource were made available. Thus, specifically in this case study it was developed an optimisation model, by using LP language, to maximise the whole-farm profit of a 1,348 ha farm located in Wee Waa (NSW). The necessary information to be included as the inputs in the optimisation model was collected from an interview with the farm manager. Moreover, it was collected information from QL-DPI&F and NSW-DPI&F cotton-irrigation researchers. As the whole-farm profit can be highly affected by the climate variability, the analysis was developed for three different scenarios: typically dry, average and wet years.

In addition to changes in climate, the irrigation system efficiency variability and the prices and crop yields variability may have significant effects on the farm business profitability. Thus, it was performed a sensitivity analysis on the variability of irrigation system efficiency, prices and yields to evaluate their influence on the whole-farm maximum return. The irrigation system ef-ficiency was varied from 40% to 90%; prices and yields, for each of the crops, were individually varied by ±10%, ±20%, ±30% and ±40%. The central purpose of this work is to show how the whole-farm profitability can be improved through the optimum allocation of land and water across a number of alternative farm enterprises, face on high variability of prices, yields, costs and climate condition.

The Crop Rotation Optimisation Model

The optimisation model was developed by considering five different enterprises as the objective function variables, i.e. irrigated cotton, irrigated maize, rainfed wheat, irrigated wheat (with 1 irrigation) and irrigated wheat (with 2 irrigations). In addition, it was considered two different seasons, where the first one goes from May of year 1 to February of year 2 and the second one goes from October of year 2 to April of year 3.

Variable Description:

1) Five Crops: (i = 1, 2, 3, 4, 5); where Crop 1 = Irrigated cotton; Crop 2 = Irrigated maize; Crop 3 = Rainfed wheat; Crop 4 = Irrigated wheat (1 irrigation); Crop 5 = Irrigated wheat (2 irrigations).

2) Two Seasons: (j = 1, 2): Season 1 = May year 1 – February year 2; Season 2 = October year 2 – April year 3.

The objective function is a linear equation which can represent different objectives to be achieved such as maximise profits, efficiency, social welfare, etc.; or minimise costs, time, losses, etc. Specifically in this case study the objective is to maximise the whole-farm profit so that the equation coefficients represent the gross margin ($/ha) associated to each enterprise to be implemented. The variables of interest are the area (ha) to be cultivated with each activity. Other important feature of linear programming models is related to the constraints set represented by unequal equations that allow the whole use of resources be not mandatory. In this case study the func-

tional constraints are related to water and land availability over each season, which means, the maximum area to be cultivated in each season must be smaller than the total available area and the maximum water use in each season must not be more than the available water from rain, soil moisture and irrigation system.

Objective Function:

$$Max\sum_{i=1}^{5}\sum_{j=1}^{2}G_{ij}X_{ij}$$

i = crop

j = season

G = gross margin ($/ha)

X = area (ha)

Subjected to the following constraints:

1) Land restriction:

Season 1: $\sum_{i=1}^{5}X_{i1} \leq A$

Season 2: $\sum_{i=1}^{5}X_{i2} \leq A$

A = Area

2) Area balance each season:

Season 1: $\sum_{i=1}^{5}X_{i1} - TA = 0$

Season 2: $\sum_{i=1}^{5}X_{i2} - TA = 0$

TA = Total area

3) Water restriction:

Season 1: $\sum_{i=1}^{5}W_{i1}X_{i1} \leq W$

Season 2: $\sum_{i=1}^{5}W_{i2}X_{i2} \leq W$

W_{i1} = Water consumed per crop i, during the cycle, on season 1; W_{i2} = Water consumed per crop i, during the cycle, on season 2; W = Total water availability during each season.

4) Non-negativity restrictions:

$X_{ij} \geq 0$

i = 1, 2, 3, 4, 5

j = 1, 2

After developing the optimisation model the next step should be apply it based on empirical data set in order to verify its practical applicability. Thus, the methodology was empirically tested based on a data set collected from an interview with the studied farm's manager as showed in the next section.

Data set considered for the case study

The case study was developed based on an interview with the farm manager of a grain-cotton irrigation farm system located in Wee Waa, NSW. In addition to the farm manager, it was collected information from QLD-DPI&F and NSW-DPI&F cotton-irrigation expertises. The studied farm business has a total area of 1,348 ha with a soil type of 250 mm under full Plant Available Water Capacity (PAWC). The analysis was developed under three different scenarios: Table 1) Dry year: low water availability from soil + rainfall and irrigation; Table 2) Average year: plenty of water availability; Table 3) Wet year: high water availability. Two seasons were considered into the model: (1) Season 1: From May to February (sow wheat in May or maize in August) and (2) Season 2: From October to April (sow cotton in October). It was assumed a fallow efficiency of 30%; and 125 mm 50% PAWC over the dry year scenario, 188 mm 75% PAWC over the average year scenario and 250 mm 100% PAWC over the wet year scenario.

The sources of irrigation water were river or bore. Therefore, the costs of irrigation were different for the different scenarios i.e. the dryer the season, the lower the river allocation and, as a consequence, the higher the allocation cost. The three tables below summarise the variables and assumed values used to calculate gross mar-

Table 1. Inputs to the optimisation model: dry year.[1]

Variables	Irrigated cotton	Irrigated maize	Rainfed wheat	Wheat 1 irrigation	Wheat 2 irrigations
1) Price ($/t)	$458	$250	$200	$200	$200
2) Yield (bales/ha or t/ha)	9	10	2	5	7
3) Variable cost[2] ($/ha)	$2,100	$749	$465	$550	$590
4) Water cost ($/ML water)	$66.67	$66.67	–	$66.67	$66.67
5) Water delivered to the crop (ML/ha.year)	7	7	–	1.5	3
6) Irrigation cost ($/ha)	$467	$467	$0	$100	$200
7) Gross margin ($/ha)	$1,457	$1,210	-$65	$337	$601
8) Gross margin ($/ML)	$208	$173	$0	$224	$200

[1] Data collected from the farm manager.

[2] Variable cost source = DPI (NSW) / Farm Enterprise Budget Series – Northern Zone/2005–2006.

Table 2. Inputs to the optimisation model: average year.[1]

Variables	Irrigated cotton	Irrigated maize	Rainfed wheat	Wheat 1 irrigation	Wheat 2 irrigations
1) Price ($/t)	$458	$200	$200	$200	$200
2) Yield (bales/ha or t/ha)	10	11.25	3	6	8
3) Variable cost[2] ($/ha)	$2,100	$749	$465	$550	$590
4) Water cost ($/ML water)	$46.42	$46.42	–	$46.42	$46.42
5) Water delivered to the crop (ML/ha.year)	6	6	–	1.5	2.5
6) Irrigation cost ($/ha)	$278	$278	$0	$70	$116
7) Gross margin ($/ha)	$2,160	$1,190	$35	$604	$897
8) Gross margin ($/ML)	$360	$198	$0	$402	$359

[1] Data collected from the farm manager.

[2] Variable cost source = DPI (NSW) / Farm Enterprise Budget Series – Northern Zone/2005–2006.

Table 3. Inputs to the optimisation model: wet year.[1]

Variables	Irrigated cotton	Irrigated maize	Rainfed wheat	Wheat 1 irrigation	Wheat 2 irrigations
1) Price ($/t)	$458	$180	$200	$200	$200
2) Yield (b/ha or t/ha)	8.5	12.5	3.8	7.5	8.0
3) Variable cost[2] ($/ha)	$2,100	$749	$465	$550	$590
4) Water cost ($/ML water)	$40	$40	–	$40	$40
5) Water delivered to the crop (ML/ha.year)	4.5	4.5	–	1.25	2
6) Irrigation cost ($/ha)	$180	$180	$0	$50	$80
7) Gross margin ($/ha)	$1,584	$1,304	$295	$947	$921
8) Gross margin ($/ML)	$352	$290	$0	$757	$460

[1] Data collected from the farm manager.

[2] Variable cost source = DPI (NSW) / Farm Enterprise Budget Series – Northern Zone/2005–2006.

gins ($/ha; inputs in the Optimisation Model) for each crop over dry, average and wet years, respectively. The considered crops are irrigated cotton, irrigated maize, rainfed wheat and wheat with one and two irrigations.

Information about rainfall (mm) in Wee Waa, over the considered periods (Seasons 1 and 2), was collected from SILO (JEFFREY et al., 2001) to the last 100 years. The rainfall pattern was considered different among the scenarios, which means, across the 100 observations for each season, the lower, the average and the higher values were associated to dry, average and wet scenarios, respectively, as showed in Table 4. According to the farm manager's information, the water availability to irrigation per season would be considered in each scenario as: (i) Dry year: 2,000 ML (from Bore) + 1,000 ML (from River) = 3,000 ML; (ii) Average year: 2,000 ML (from Bore) + 3,300 ML (from River) = 5,300 ML; and (iii) Wet year: 2,000 ML (from Bore) + 5,000 ML (from River) = 7,000 ML.

The total water availability (including both, from irrigation and from soil + rainfall) considered per season, in each scenario, is described in the Table 5 and Table 6, and the water allocation cost was considered different among the three scenarios, as showed in Table 7.

Results and discussion

The optimum use of land across different crop options, in order to maximise the whole-farm profit, over a two-year period, subject to water constraints and taking in account the present relative prices for cotton, maize and wheat is summarised in Table 8. In a typical dry year, for the first season, the maximum profit was obtained from planting 652 ha of irrigated maize, whereas for the second season the maximum profit was obtained from planting 611 ha of irrigated cotton. The same interpretation can be done for typically average and wet years. By adopting such strategies, the whole-farm profits were $ 1,679,209; $ 3,483,832 and $ 3,893,024 over dry, average and wet years, respectively.

Table 4. Rainfall pattern (mm) in Wee Waa, NSW, Australia.

Scenario	Season 1 Rainfall from May to February	Season 2 Rainfall from October to April
Dry year	355 mm	276 mm
Average year	473 mm	363 mm
Wet year	648 mm	512 mm

Source: Jeffrey et al. (2001).

Table 5. Total water availability over Season 1.

Season	(I) Irrigation[1] (ML/ Season)	(II) Soil + rainfall (ML/ Season)	(I + II) Total (ML/ Season)
Dry	2,100 ML	3,114 ML	5,214 ML
Average	3,710 ML	4,448 ML	8,158 ML
Wet	4,900 ML	5,985 ML	10,885 ML

[1] It was assumed an irrigation efficiency of 70% so that the irrigation water availability was multiplied per 0.7.

Table 6. Total water availability over Season 2.

Season	(I) Irrigation[1] (ML/ Season)	(II) Soil + rainfall (ML/ Season)	(I + II) Total (ML/ Season)
Dry	2,100 ML	2,790 ML	4,890 ML
Average	3,710 ML	4,004 ML	7,714 ML
Wet	4,900 ML	5,446 ML	10,346 ML

[1] It was assumed an irrigation efficiency of 70% so that the irrigation water availability was multiplied per 0.7.

Table 7. Water allocation cost[1].

Season	Allocation	Average cost
Dry	67% from Bore / 33% from River	$67/ML
Average	38% from Bore / 62% from River	$46/ML
Wet	29% from Bore / 71% from River	$40/ML

[1] River = $ 20/ML; Bore = $ 90/ML.

Table 8. Optimum crop allocation over seasons 1 and 2 for dry, average and wet years.

Scenario	Season 1	Season 2
Dry year	652 ha of irrigated maize	611 ha of irrigated cotton
Average year	473 ha of irrigated maize	990 ha to irrigated cotton
	875 ha of wheat with 2 irrigations	
Wet year	1,348 ha of irrigated maize	1,348 ha to irrigated cotton

Once maize is priced internally in the Australian market, its price is highly affected by different climate conditions, being relatively low in wet seasons and raising gradually from wet to dry seasons. Alternatively, cotton and wheat prices are not affected by climate conditions, where the former is determined in the international market, whereas the latter usually does not change due to contracted prices. Despite maize being more water exigent than wheat, throughout dry years it is interesting to plant only maize in season 1 instead of doing wheat. As maize not only has a higher yield but also has a higher price, in comparison to wheat, maize gross margin is approximately twice as higher than that of wheat. Consequently, to plant only maize is economically more interesting for typically erratic rain years.

According to the farm manager's information, the maize and wheat prices are roughly the same if the scenario is considered average. However, the maize gross margin is still higher than that of wheat in that case due to the higher maize yield. In that context, there is reasonable water availability for planting and the most appropriated strategy in terms of profit maximisation would be to plant a larger area of wheat, given that its water consume is approximately 40% lower than that for maize. It is important to consider that throughout the average situation maize gross margin is no longer twice as higher than that of wheat, decreasing for 33% higher. By considering the wet scenario, despite maize price being lower than wheat price, the maize gross margin is still higher than that to wheat, in approximately 42%. Once in a typically wet year there is plenty of available water, the economically most interesting strategy would be to plant only irrigated maize during the first season instead of planting irrigated wheat in a part of the area.

Other interesting information from a linear programming resolution is the dual price, which represents the objective function value variation (whole-farm profit in this specific case) due to a unitary variation in a binding constrain value. Only binding constraints have a dual price value, and for those nonbindings, the dual price is zero, as summarised in Table 9. For example, for the dry scenario, the land constraints were nonbinding, whereas the water constraints were binding in both, seasons 1 and 2. In that case, if one extra ML of water per hectare were made available,

Table 9. Dual price analysis to water and land restrictions.

Restrictions	Dry year Dual price ($)	Average year Dual price ($)	Wet year Dual price ($)
Land season 1	0.00	408.66	1,304.00
Land season 2	0.00	0.00	1,584.00
Water season 1	151.25	97.66	0.00
Water season 2	182.13	276.92	0.00

the whole-farm profit could be increased in $151 and $182, over seasons 1 and 2, respectively. So, these values are the maximum amount the farm would be willing to pay for one additional ML of water per hectare.

As over the average scenario there was reasonable water availability for planting and wheat is less exigent in water when compared with cotton and maize, for the first season, when the optimum strategy was to plant 65% of the total area with wheat and 35% with maize, both constraints (land and water) were binding. In this case, if one extra hectare or one extra ML of water per hectare were made available, the whole-farm profit could be increased in $408 and $97, respectively. For the second season, only the water availability was a binding constraint and if one extra ML of water per hectare were made available, the farm profit could be increased in $276. As cotton has a high water exigency over its cycle, the optimum strategy was to plant 73% of the total area with cotton so that the land availability was not a binding constraint.

For the wet scenario, when there was plenty of available water, only the land availability was a binding constraint for both seasons. If one extra hectare were made available, the profit could be increased in $ 1,304 and $ 1,584, over the seasons 1 and 2, respectively. Changes in ir-

rigation system efficiency can have significant effects on the farm business viability so that it was performed a sensitivity analysis on irrigation system efficiency to evaluate its influence on maximum farm profit. The irrigation system efficiency was varied from 40% to 90%, by assuming 70% as the most likely efficiency. Figure 1 shows the maximum return (over a two-year period) variation for different irrigation system efficiency values over dry, average and wet years, through a variation index around 70% efficiency (70% = 100). It can be observed that the maximum return is more sensitive to the irrigation system efficiency over dry years and it gets gradually less sensitive from average to wet years. In a typically dry year the production system is highly dependent of irrigation so that especially for the dry scenario the whole-farm profit is highly sensitive to the irrigation system efficiency.

Figure 2a shows a variation index of maximum farm profit for each change in price (or yield) over the dry scenario, where values above 100 indicate higher profitability and values below 100 indicate lower profitability, in relation to the most likely profitability (when considering the most likely price and the most likely yield). Figure 2b and Figure 2c present similar information for the average and wet scenarios, respectively. Cotton has a high production cost, a high price and a high gross margin ($/ha) when
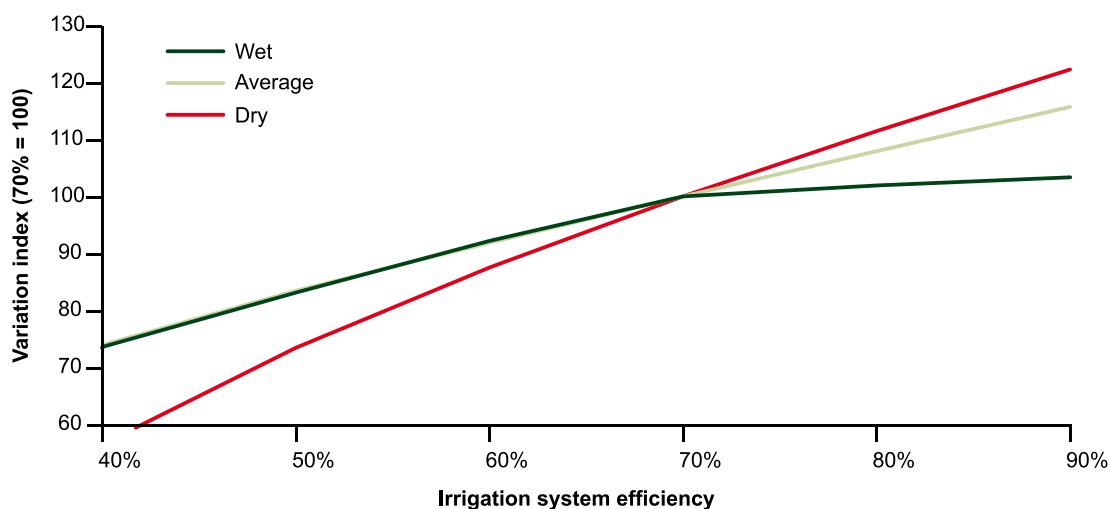

Figure 1. Sensitivity of maximum return to changes in irrigation system efficiency during dry, average and wet seasons.
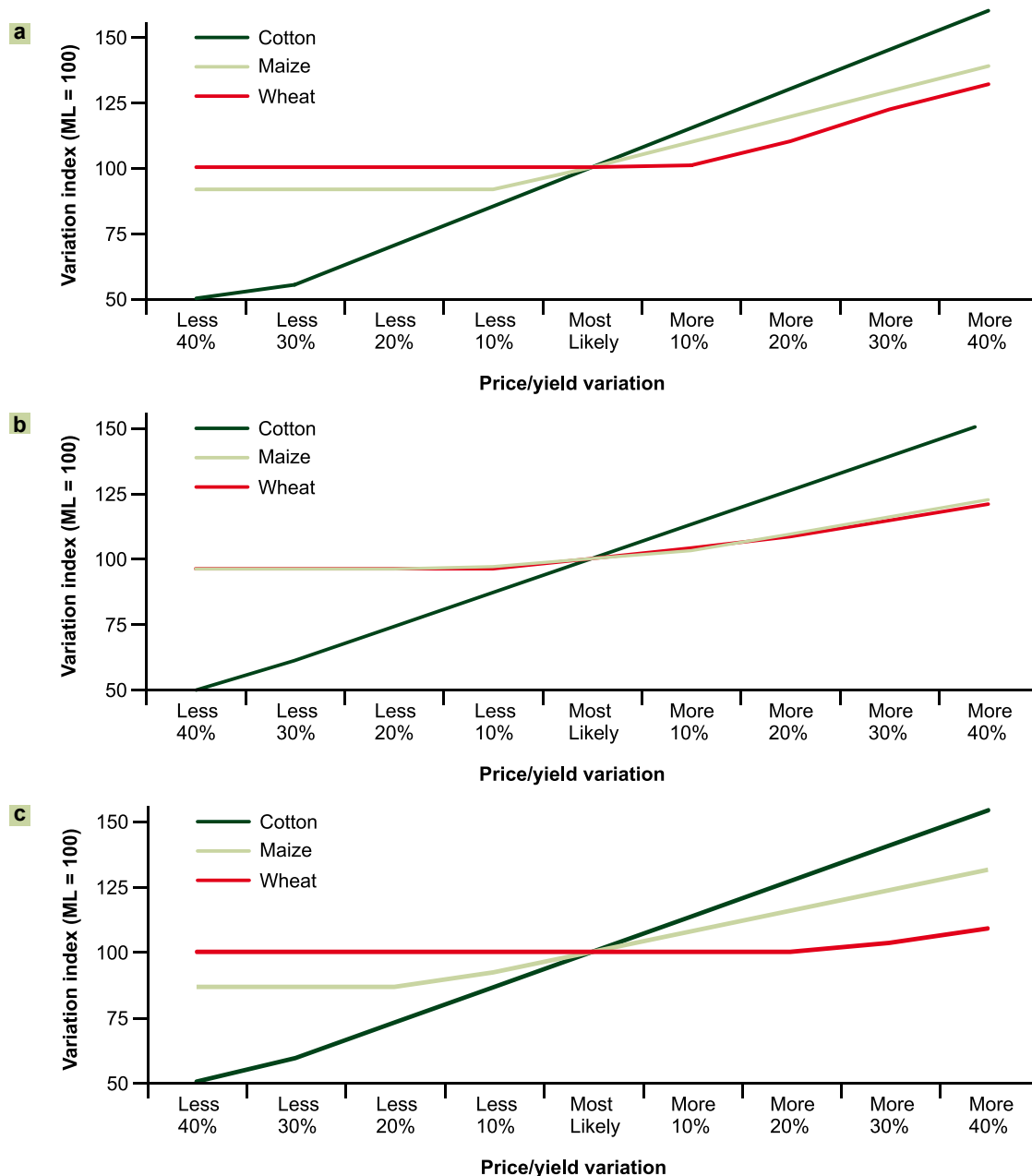
Figure 2. a) Sensitivity of maximum return to changes in prices (or yields) during dry years; b) Sensitivity of maximum return to changes in prices (or yields) during average years; and c) Sensitivity of maximum return to changes in prices (or yields) during wet years.

compared with other crops so that it can contribute considerably to improve the whole-farm profitability. Consequently, the maximum return to be achieved is highly sensitive to variations in cotton price (or yield). As cotton is priced externally, in the international market, and also is highly exigent in water over its cycle, it addresses a risky production system in relation to climate and market variability. Economic sustainability means to increase profitability and to decrease the variability of profitability throughout the time. From the economic point of view, the more diversified a business is the less risky it is in terms of profitability's variability. If a problem with

some specific activity comes, for example a crop disease, the whole-farm profitability is not highly affected because there are other activities being conducted at the same time. Moreover, when adopting a crop rotation system, the whole-farm profitability can be improved by deciding what to plant, where in the farm and when, according markets forces (present relative prices of crops) and resources availability.

Summarising the results, in a typically dry year, the maximum farm profitability was obtained with a combination of 65% of the farm area to irrigated maize, during the first season, and 45% to irrigated cotton, during the second season. In average years, the optimum strategy would be to plant 65% of the farm area with wheat with 2 irrigations and 35% with irrigated maize, during the first season, and 73% with irrigated cotton, during the second season. In a typically wet year, the optimum allocation would be to plant 100% of the area with irrigated maize, during the first season, and 100% with irrigated cotton, during the second season. By adopting such strategies, the maximum profits, over a two-year period, were $1,679,209; $3,483,832 and $3,893,024 for dry, average and wet years, respectively.

The scenarios evaluated here were considered realistic and the outcomes indicate that the whole-farm profitability can be improved by adjusting the farm business strategy i.e. optimising the land use among a number of alternative irrigated crop options, according to seasonal conditions and water availability to irrigation. As the maximum return is highly sensitive to irrigation system efficiency, especially during dry years, it is important to work towards improve it. A suggestion would be changing from furrow irrigation systems to pressurised ones, given that the latter are usually more efficient. However, before making a decision it would be necessary to evaluate the economic viability and also the associated risks. Therefore, for future studies it would be interesting to include similar evaluations to that one developed by Qureshi et al. (2001), who compared different irrigation technology systems for farms located in north Queensland, in order to identify the economic viability and the main implications in terms of investment decision when changing from furrow to pivot systems.

The results also indicate the need for a more accurate study to better capture the dynamics and complexities of the studied farm in terms of the optimal allocation of competing resources i.e. water, land, finances, productivity and labour. Additional interviews with some farm managers to ask more specific information and also other methodologies, such as non-linear programming (GHAHRAMAN; SEPASKHAH, 2004), multi-objective optimisation techniques (FLORENTINO et al., 2008), evolutionary algorithms, etc., could be used for that purpose. Once the whole-farm profit is highly sensitive to climate variability and also to prices and yields variability, especially in relation to cotton, it would be interesting for future studies to use stochastic procedures as done by Ganji et al. (2006) to introduce risk analysis into the model in relation to prices, yields and climate variability, regardless of the pragmatic separation of the conditions in wet, average or dry years. Therefore, it is important to consider that optimisation models can be used to identify the optimum allocation of water and land use in irrigated agriculture, though the analysis needs to be complemented with an evaluation of business viability and cash flow. This is because of the main input variable in the optimisation model is the gross margin ($/ha) of each farm activity, which excludes the opportunity cost of money (interest rate), and the fixed costs i.e. the value of the land/improvements, buildings, machinery and agricultural wares.

The best trade-off between water and land use will carry to the preconised, necessary and so mentioned sustainable irrigation. Therefore, as adequate knowledge already exists for implementing strategies to achieve sustainable irrigation (OSTER; WICHELNS, 2003) and following the approach of Hellegers (2006), although conciliating economic analysis in irrigation with aspects of environment dynamics and people income distribution, being this essentially political,

the economic interpretation performs a crucial role not only because of providing the basis of decision support or understanding the gross margins and financial losses of agricultural systems, but also in terms of the comprehension of the interactions of the mentioned elements, given that incorporates criteria of water use and contributes to promote social welfare, which is the final target of public policies (i.e., agricultural policies).

Conclusions

In a typically dry year, the maximum farm profitability was obtained with a combination of 65% of the farm area to irrigated maize, during the first season, and 45% to irrigated cotton, during the second season. In average years, the optimum strategy would be to plant 65% of the farm area with wheat with two irrigations and 35% with irrigated maize, during the first season, and 73% with irrigated cotton, during the second season. In a typically wet year, the optimum allocation would be to plant 100% of the area with irrigated maize, during the first season, and 100% with irrigated cotton, during the second season.

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