THE ECONOMICS OF SPRINKLER IRRIGATION UNIFORMITY FOR LETTUCE PRODUCTION WITH IN-SEASON RAINFALL

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ABSTRACT

Irrigation non-uniformity has been shown to adversely affect crop production and it is often assumed that high levels of uniformity are required to optimise economic returns. However, sprinkler irrigation systems used for lettuce production in the Lockyer Valley, Australia commonly operate with low uniformity. Despite lettuce being a relatively high value crop there appears to be little evidence that growers in this region identify low application uniformities as a constraint to either crop production or economic returns. Local relationships between marketable lettuce yield and water application for two seasons were obtained from previous field trials. These relationships were used to model the field scale crop yields and returns for irrigation systems operating with various application uniformities and under different in-season rainfalls. Implications for identifying optimum levels of irrigation system performance with in-season rainfall are discussed.

KEYWORDS: Lettuce, sprinkler, irrigation uniformity, rainfall, returns

INTRODUCTION

The shortage of water available for agriculture demands an increase in crop productivity through efficient irrigation management. The uniformity of irrigation applications plays a major role in irrigation production (Pereira et al. 2002). Higher uniformity gives lower in-field variability of crop yield (Dukes et al 2006). However, growers with low uniformity irrigation systems often irrigate more frequently or apply greater depths particularly when water prices are low (Mantovani et al. 1995). This ensures that areas receiving lower applications are adequately irrigated and can contribute to the yield. However, this occurs at the expense of higher water use (Smith and Raine 2000) and fertiliser losses which may impact negatively on the environment (Clemmens 1991). Even with high uniformity application systems, inappropriate irrigation scheduling (e.g. volume and timing) can lead to substantial yield and economic losses (Alvarez et al. 2004). The effect of low application uniformity on crop yield is also affected by environmental conditions including soil properties and in-season rainfall (Mateous et al. 1997). However, the optimal irrigation uniformity and profitability will also be a function of the cost of the various inputs (e.g. water, fertiliser) (Romero et al. 2006) and the return for the crop (Alvarez et al. 2004). Hence, there is a need to incorporate both the physical crop responses and the economic costs and benefits in analyses to identify optimal irrigation uniformity. In this paper, measured crop production functions are used to predict the yield and economic returns for different depths and uniformities of irrigation applications and for different depths of effective rainfall.

CROP PRODUCTION FUNCTIONS

Crop production functions were developed from field trials (Hussain et al. 2008) for autumn (eqns 1a & 2a) and winter (eqns 1b & 2b) lettuce grown in the Lockyer Valley, Queensland. Because of uncertainty over the yield response if excess water is applied, two different functions were applied to the data, to cover the cases where (i) a yield penalty is incurred (i.e. a quadratic production function, eqns 1 a & b) or (ii) where no yield penalty is incurred (i.e. an exponential plateau production function, eqns 2 a & b):

$$Y = -0.0025D_a^{2} + 0.8007D_a - 32.912 \quad (1a)$$

$$Y = -0.006D_a^{2} + 1.0914D_a - 26.156 \quad (1b)$$

$$Y = 32.0 - 111.2(exp(-0.02431D_a)) \quad (2a)$$

$$Y = 23.51 - 240.4(exp(-0.06296D_a)) \quad (2b)$$

Where Y is the marketable yield (t/ha) and D_a is the total seasonal water application (expressed as % of potential evapotranspiration).

CALCULATION OF FIELD SCALE YIELDS AND ECONOMIC RETURNS

Yield and economic benefits were calculated for total in-season water applications of 0.5 to 3.5 ML/ha and uniformities expressed as Christiansen Uniformity Coefficients (CU) (Christiansen 1942) ranging from 50 to 90%.

The depths applied by sprinkler irrigation have been found to be normally distributed. Hence, for each of the cases considered, the irrigation depths within the field were assumed to be normally distributed about the seasonal mean application (I_μ). The standard deviations (σ) of applied depths for each irrigation uniformity and seasonal application were calculated from the CU (Warrick 1983):

$$\sigma = (1 - \frac{CU}{100})\frac{I_\mu}{0.798} \tag{3}$$

The individual irrigation depths (I_a) over the field were expressed as a standard score (Z_a) reflecting the number of standard deviations the particular depth was from the seasonal mean depth:

$$Z_a = \frac{I_a - I_\mu}{\sigma} \tag{4}$$

This standard score was then used to calculate the probability (P) of occurrence of depths in the range Z_a to Z_{a-1} (Bluman 1997):

$$P(Z_a \text{ to } Z_{a-1}) = P(< Z_a) - P(< Z_{a-1}) \tag{5}$$

The effect of in-season rainfall was evaluated by assuming that the seasonal mean irrigation depth (I_μ) was reduced by the magnitude of the effective rainfall (R) which was varied from 25 to 75% of the potential evapo-transpiration (ET_o) for the whole season. This effective rainfall was assumed to have fallen uniformly across the field. Hence, in this analysis, the total seasonal water application (D_a) at each location within the field was calculated as:

$$D_a = I_a + R \tag{6}$$

and the probably of occurrence was again determined using equation 5 by substituting the total seasonal water application for the irrigation application. The depths applied (D_a) were then used to calculate the corresponding marketable yield using both the quadratic (i.e. declining) (eqns 1a & b) and exponential (i.e. plateau) (eqns 2 a & b) production functions. The marketable yields for each location in the field were then aggregated to determine the total yield achieved at the field scale for each irrigation uniformity and seasonal mean water application.

Gross margins were calculated using the marketable yields, assuming 12 lettuces per carton, $12 per carton gross return and that the agronomic input costs (Table 1) were the same for each irrigation system irrespective of application uniformity. The lifetime (15 year) capital and maintenance costs were estimated at $8000/ha (Australian dollars) for an irrigation system with CU of 50% and were assumed to increase by $2000/ha for each 10% increase in CU. The net economic return was calculated as the gross margin less the amortised capital and maintenance cost of the irrigation system and assuming two crops were grown each year. Additional analyses were conducted to evaluate: (a) the effect of irrigation system uniformity and seasonal depth of applications on the product price required to break-even, and (b) the sensitivity of net returns to the product price.

Table 1 Production and marketing costs used in the gross margin analysis

Production and marketing components	Cost (AUD)
Agronomic inputs (machinery, seedling, fertiliser, herbicide, insecticide, fungicide, casual labour for chipping/thinning)	$5719 / ha / crop
Irrigation water and energy	$50.00 / ML
Harvesting labour	$1.10 / carton
Packaging	$2.50 / carton
Cooling	$0.50 / carton
Freight (to Brisbane market)	$0.84 / carton
National research & marketing levy	0.5% of sale price
Agent's commission	15% of sale price
Amortised capital cost of irrigation infrastructure (dependent on system CU)	$267- $533 / crop

EFFECT OF IRRIGATION DEPTH AND UNIFORMITY ON YIELD

As expected, the yield curves presented in Figure 1 reflect the form of the individual production functions. They show that increasing the irrigation uniformity generally increases the yield for all but very low depths of application. However, the benefits obtained by improvements in irrigation system uniformity are also influenced by whether a yield penalty is incurred (ie. quadratic function) or not incurred (i.e. exponential function) when excessive water is applied.

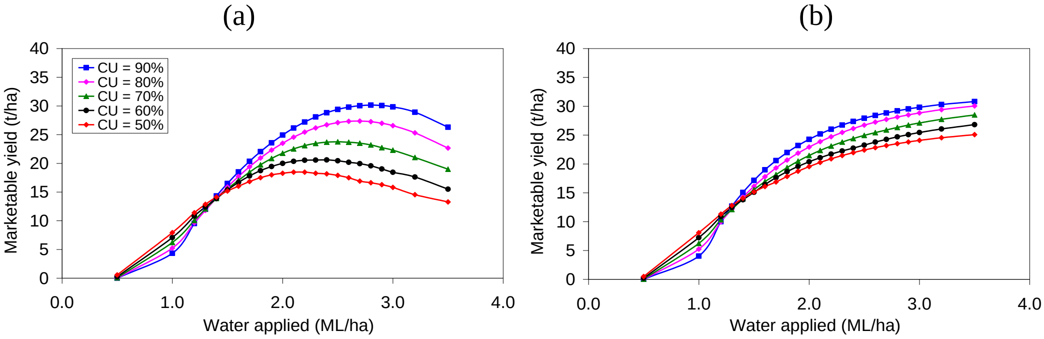

Figure 1 Effect of irrigation uniformity on the marketable yield of lettuce calculated using (a) quadratic and (b) exponential production functions from the autumn trial

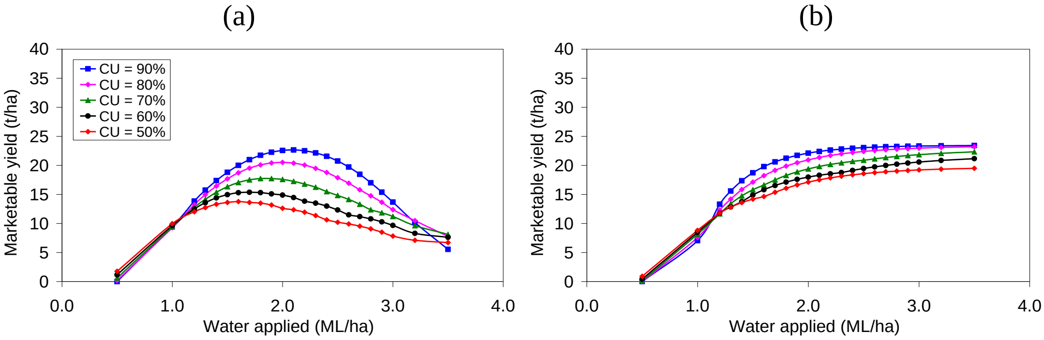

Figure 2 Effect of irrigation uniformity on the marketable yield of lettuce calculated using (a) quadratic and (b) exponential production functions from the winter trial

Where a quadratic production function is used (Figures 1a & 2a), the application depth at which maximum yield occurs increases as uniformity increases, that is, between 1.6 and 2.0 ML/ha for CU of 50% depending on the season, increasing to between 2.0 and 2.6 ML/ha for CU of 90%. The yield benefit associated with higher uniformity is greatest (up to 10 t/ha) when the depth applied is close to the crop water requirement (in this case ~ 2 to 3 ML/ha depending on the season**)**. However, the benefits associated with increasing uniformity are substantially smaller when either higher or lower volumes are applied.

There is little or no yield difference between the different uniformities when the depth applied is less than 1.2 ML/ha. At these low application depths, a low uniformity may even result in higher yields than a high uniformity. In these cases, the high spatial variability in the water applied using the low uniformity irrigation system results in at least some (small) areas of the field receiving a water application which produces marketable product while the high uniformity has all areas of the field failing to produce any marketable product.

Where an exponential (i.e. yield plateau) production function is used (Figures 1b & 2b), there is no yield benefit associated with increasing the uniformity when the depth applied is less than 1.2 ML/ha and the benefit is relatively small (<5 t/ha) at higher application depths. In general, the same yield can be achieved by either increasing the application system uniformity from 50% to 90% or by applying an additional irrigation depth of 1.0 to 1.4 ML/ha.

EFFECT OF IRRIGATION DEPTH AND UNIFORMITY ON NET ECONOMIC RETURN

Net economic returns (Figures 3 & 4) were primarily influenced by the marketable yield (Figures 1 & 2). Hence, returns generally increased with improvements in irrigation system uniformity. However, the magnitude of benefit was a function of both the season and the total water applied.

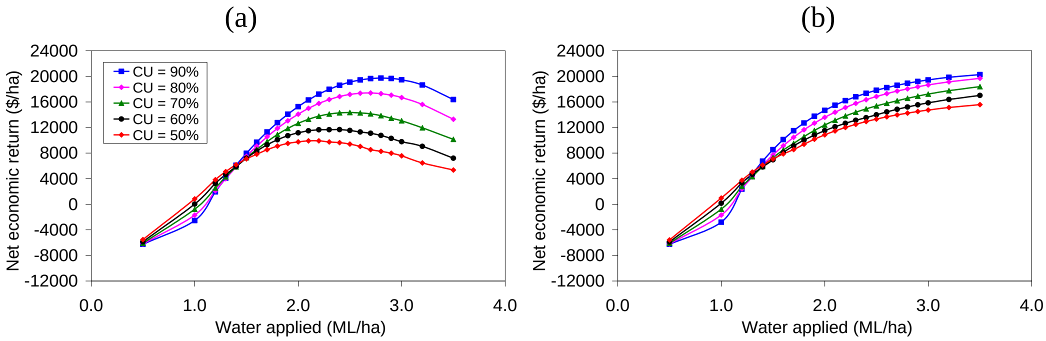

Figure 3 Effect of irrigation uniformity on the net economic return calculated using (a) quadratic and (b) exponential yield production functions from the autumn trial

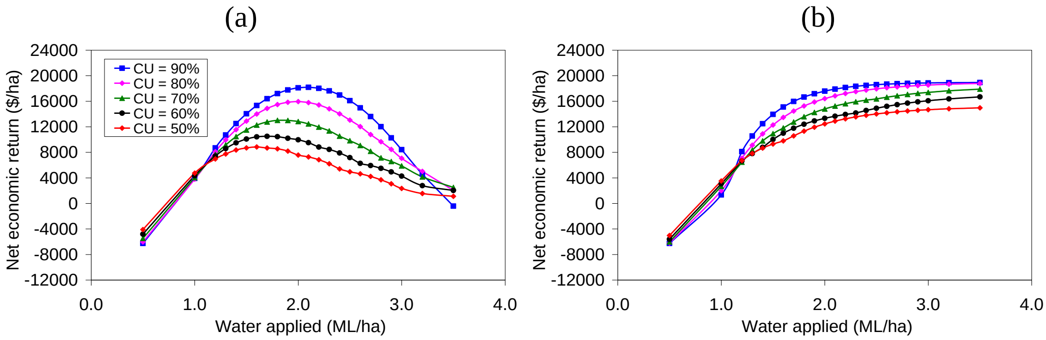

Figure 4 Effect of irrigation uniformity on the net economic return calculated using (a) quadratic and (b) exponential yield production functions from the winter trial

Where a quadratic crop production response was assumed (Figures 3a and 4a), the economic benefits are maximised when the volume of water applied is close to the maximum yield potential (e.g. ~2.25 ML/ha). In this case, the net return can be increased by up to $11000/ha by improving the CU from 50% to 90%. However, the economic benefits are smaller when an exponential crop production response is assumed. There were also differences between the two seasons in the optimal water application range required to maximise benefits when the exponential production function was used. For the first season (Figure 3b), returns increased with increasing water application and were approximately $4000/ha when 2 to 3 ML/ha was applied. For the winter season (Figure 4b), the maximum difference between the returns for CU of 50% and CU of 90% (approximately $5000/ha) occurred when ~1.8 ML/ha of irrigation water was applied.

For both seasons and irrespective of which crop production function was used, there was little difference in economic returns as a result of uniformity when less than 1.5 ML/ha was applied. Indeed, applications of ~ 1 ML/ha during the first season demonstrate slightly higher returns from the low uniformity systems compared to the higher uniformities (Figures 3 a & b). The range of seasonal application depths over which substantial differences in economic returns are obtained due to application uniformity differences is narrow (generally between 1.5 and 2.5 ML/ha). This means that the benefits of application system improvement may be small if the total seasonal water application is outside of this range (e.g. due to inappropriate irrigation scheduling). It is also likely that even when the total seasonal water application is within the range for maximising returns the use of inappropriate irrigation timing or application depths for individual events would also reduce the magnitude of the benefit. In that case, fields with higher uniformity of applications would suffer proportionally greater production losses than those with low uniformity thus reducing the net return observed due to improvements in the application uniformity.

INVESTING IN SYSTEM IMPROVEMENT OR INCREASED APPLICATION DEPTHS

Depending on the depth of water applied and the crop production function used, it is possible to obtain the same economic return (per unit area) by either increasing the irrigation uniformity (i.e. incurring a higher capital cost) or by increasing the depth of water applied (i.e. incurring a higher operating cost). Where the crop has an exponential growth response to water (e.g. Figures 3b and 4b) or sub-optimal irrigation application volumes have been applied (Figures 3a and 4a), the increase in the operating cost associated with higher water application (generally $\leq$ 1.5 ML/ha) is relatively small compared to the cost of the application system upgrade. In this case, there is little incentive for growers to invest in improved application system uniformity. Hence, the incentive for growers to invest in improving irrigation performance is greatest where the crop has a quadratic production response to water and appropriate irrigation scheduling techniques have been used to maximise production.

Where there is sufficient irrigation water available, it is the uniformity of applications which limits the maximum yield and net returns achieved (Figure 3a). However, under these conditions, the net return from both the existing and improved applications systems is positive and the difference in net return simply represents a foregone “opportunity cost”.

When the volume of water available on-farm is limited but additional water is available for purchase off-farm, the difference in the gross margin between the current irrigation system uniformity and the target irrigation system uniformity provides a measure of the price which growers could pay to obtain additional water rather than invest in application system improvements. On-farm irrigation infrastructure is generally regarded as a depreciating asset while purchased water is generally considered an appreciating asset. It is this difference in long term investment perspective which many growers use to justify investment in the purchase of additional water rather than irrigation system upgrades.

Under water limited conditions where additional off-farm water is unable to be purchased, failure to improve the application system uniformity results in a “real” decrease in total farm scale net return either by reducing the yield per unit area (i.e. reducing water application per unit area) or by reducing the area available for production (i.e. maintain water application rate per unit area). Hence, improvements in irrigation uniformity provide an opportunity to potentially increase or maintain field production and net return with the available water. This confirms anecdotal observations of grower behaviour in the Lockyer Valley which suggest that lettuce growers are much more likely to invest in irrigation system upgrades when they are experiencing limitations in water availability and are unable to purchase additional water.

Growers who improve irrigation uniformity under conditions of limited water availability often seek guidance on whether to (a) maintain their production per unit area and use any water savings to increase the area planted or (b) maintain their application rates to maximise the production per unit area. The nature of the net economic return functions (eg. Figures 3 and 4) suggest that the optimal strategy for a particular grower will be dependent on the shape of the production function and the seasonal depth of water applied (i.e. where the grower is operating on the curve). An example of a comparative analysis conducted using the quadratic production function (Figure 3) and assuming that the grower has been applying 2 ML/ha is shown in Table 2. In this case, the grower would be significantly better off by maintaining the current rate of water application on the same area after improving the irrigation system uniformity.

Table 2 Comparison of economic returns with improved irrigation system uniformity where the same total water volume (2 ML) is applied either to (a) a larger area maintaining crop yield per unit area or (b) the same area producing an increased yield per unit area.

Option A: Increase production by applying water volume to larger area		**Option B: Increase production by applying water volume to same area**	
Water used at CU of 50% (ML/ha)	2.0	Water used at CU of 50% (ML/ha)	2.0
Water used at CU of 90% (ML/ha)	1.6	Water used at CU of 90% (ML/ha)	2.0
Reduction in water at CU of 90% (ML/ha)	0.4	Net return for CU of 50% ($/ha)	$9,750
Extra area irrigated at CU of 90%	25%	Net return for CU of 90% ($/ha)	$15,259
Increase in net economic returns	**25%**	**Increase in net economic returns**	**56.5%**

EFFECT OF PRODUCT PRICE ON NET RETURNS

The price for the product has a substantial effect on the net economic return and the incentive for improving irrigation application system uniformity (Figure 5). The difference in maximum net return between systems with a CU of 50% and CU of 90% increased from ~$4000/ha (Figure 5a) to ~$16,000/ha (Figure 5b) as the lettuce price increased from $8 to $16/carton. This confirms that the economic benefits of irrigation system upgrades are larger with higher prices. However, at higher prices it is also possible to achieve positive net returns with low uniformity and across a wide range of irrigation application depths (i.e. with poor irrigation scheduling). Hence, while the potential gains are larger with higher prices, this is only a forgone opportunity cost for growers with lower performing irrigation systems and may not be a key driver of system upgrades.

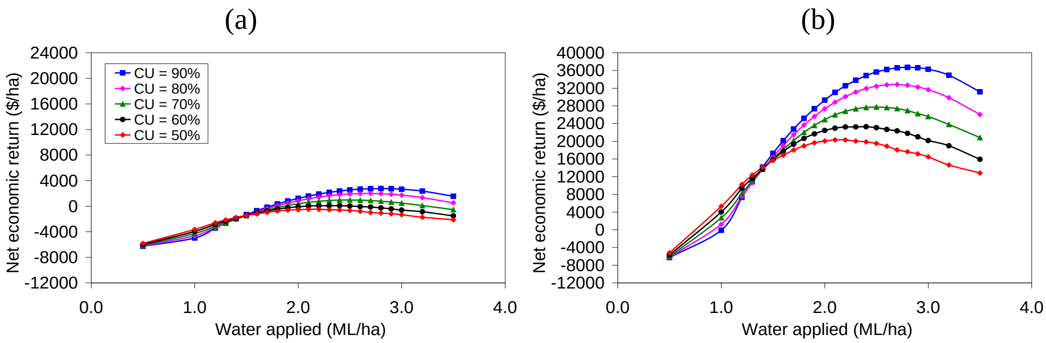

Figure 5 Net economic returns for lettuce price of (a) $8, and (b) $16 per carton (using the quadratic production function from the autumn trial)

At low product prices (e.g. $8/carton, Figure 5a), it is difficult to achieve a positive net economic return if CU ≤ 60%. However, application systems with CU of 70% are able to achieve small positive net returns and the range of water application depths over which a positive return can be achieved increases with irrigation uniformity (i.e. 1.9 – 3.2 ML/ha for CU of 70%; >1.8 ML/ha for CU of 90%). Hence, assuming access to capital is not constraining, low product prices may be expected to encourage upgrades of irrigation systems which have low uniformities.

The product price and uniformity of the irrigation applications also affect the depth of irrigation required to be applied to break-even (Figure 6). For application depths in the optimal production range (i.e. 2 to 3 ML/ha), application systems with a low uniformity have a higher break-even price (~$8.4/carton) than those with high uniformity (~$7.4/carton).

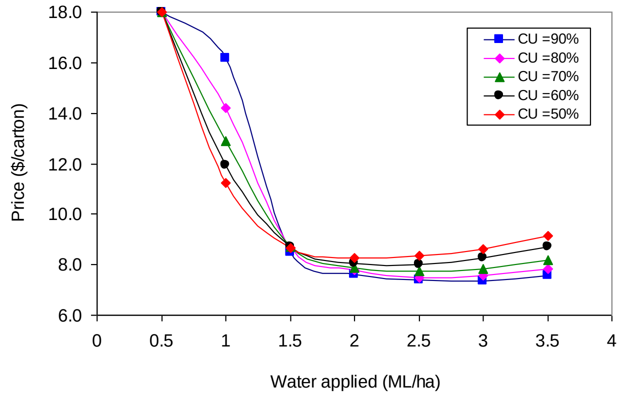

Figure 6 Effect of irrigation system uniformity and water application on the break-even lettuce price (using the quadratic production function from the autumn trial)

EFFECT OF IN-SEASON RAINFALL ON NET ECONOMIC RETURNS

The presence of in-season rainfall serves to increase the effective uniformity of seasonal water applications. Hence, it substantially reduces the effect that poor irrigation uniformity has on both yield and net return (Figure 7). Increasing the amount of rainfall increases the net returns for all levels of uniformity but the increase is larger for low CU compared to high CU systems.

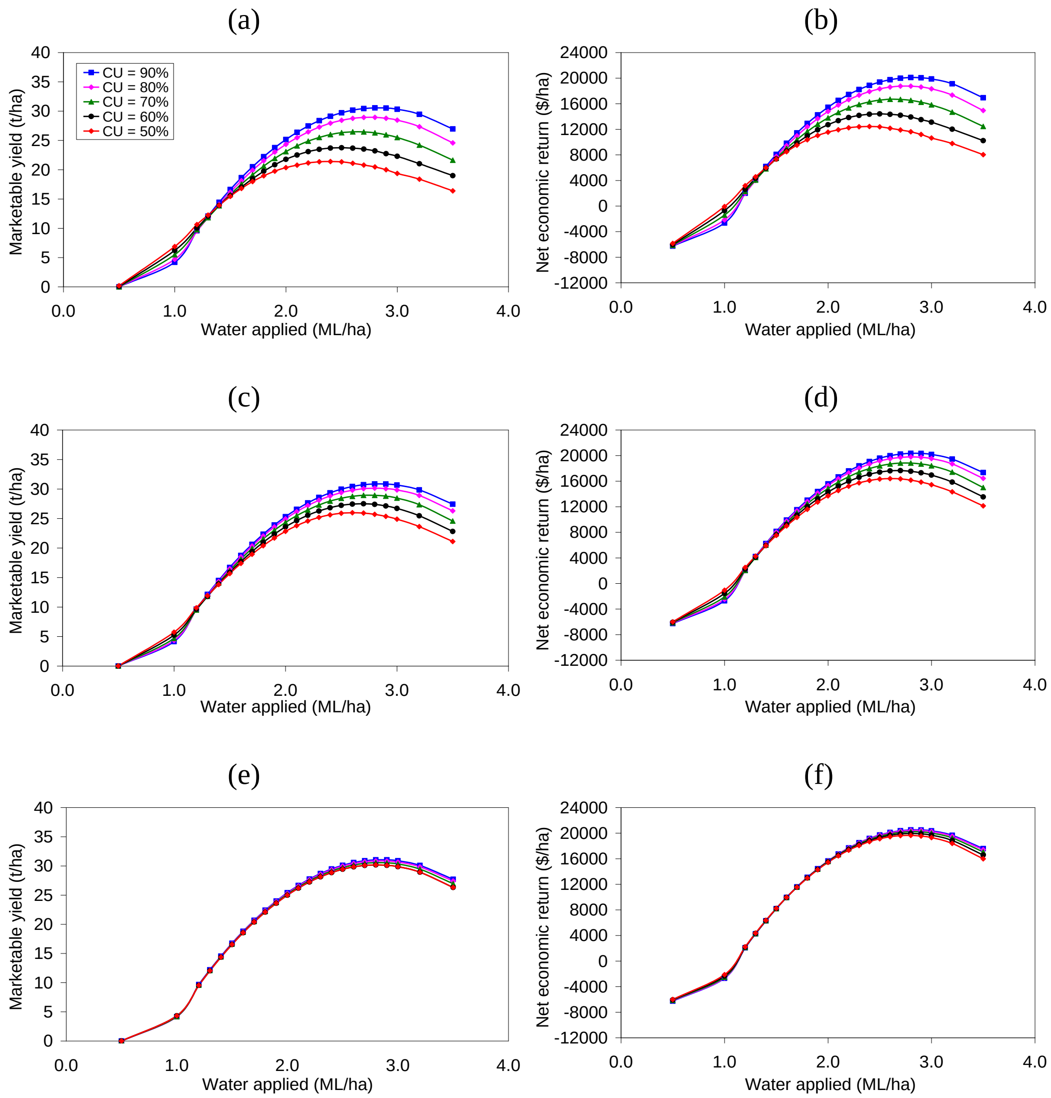

Figure 7 Marketable yield and net economic return for (a & b) 25%, (c & d) 50% and (e & f) 75% in-season rainfall, respectively (using the quadratic production function from the autumn trial)

For example, where 2.5 ML/ha was applied, the net return during a season where half of the water application was rainfall (Figure 7d) was 74% higher for an irrigation CU of 50% but only 2.6% for a CU of 90% when compared to the net return for a season with no rainfall (Figure 3a). Where 75% of the mean seasonal water application is rainfall, there was no discernable difference between the net economic returns for different uniformities irrespective of the depth of water applied (Figure 7f).

CONCLUSIONS

Net economic returns are primarily influenced by marketable yields for lettuce producers in the Lockyer Valley. Returns can generally be increased with improvements in irrigation uniformity but the magnitude of the benefit is dependent on the season, nature of the crop production response and the total water applied. The benefits of system improvement are maximised when the crop has a quadratic production function and appropriate irrigation scheduling is used. However, where the crop has an exponential production function or inappropriate scheduling is used then the gains may be small or negative. Similarly, the presence of in-season rainfall reduces the marginal benefit of irrigation system improvement. The benefits of system improvement are negligible where effective rainfall meets 50% or more of the crop water requirements. The incentive for irrigation system improvement is greatest when water is limited and unable to be purchased. Periods of low product price also encourage irrigation system improvements as non-uniform systems have a higher break–even price and require increased management (e.g. scheduling) to remain viable.

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