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Mavuto M. Banda
University of Nebraska-Lincoln, mavuto@huskers.unl.edu

Derek M. Heeren
University of Nebraska-Lincoln, derek.heeren@unl.edu

Derrel Martin
University of Nebraska-Lincoln, derrel.martin@unl.edu

Francisco Munoz-Arriola
University of Nebraska-Lincoln, fmunoz@unl.edu

László G. Hayde
IHE Delft Institute for Water Education, l.hayde@un-ihe.org

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269.429.0300 fax 269.429.3852 hq@asabe.org www.asabe.org

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Economic Analysis of Deficit Irrigation in Sugarcane Farming: Nchalo Estate, Chikwawa District, Malawi

Mavuto M. Banda[1, 2]
Derek M. Heeren[1]
Derrel L. Martin[1]
Francisco Munoz-Arriola[1]
László G. Hayde[2]

[1] *Dept. of Biological Systems Engineering, Chase Hall, University of Nebraska-Lincoln, Lincoln, NE 68583-0730, USA*

[2] *Dept. of Water Science and Engineering, IHE Delft Institute for Water Education, Westvest 7, Delft, The Netherlands*

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ABSTRACT: Sustenance of the growing world population calls for increased agricultural production. However, this will have to be done while forecasts of water withdrawals on a global scale predict sharp increases in future demand to meet human needs. The inadequacy of irrigation water supplies has led to the need to consider deficit irrigation (DI) as a water saving strategy. DI is a deliberate under-application of water to growing crops.

In this study we carried out an economic analysis of DI in sugarcane farming with an aim of developing an understanding of the economic impact of various irrigation water management strategies. The study was undertaken at a 36.6-ha field in Nchalo sugar estate in Malawi. The AquaCrop model was used to simulate yield response of sugarcane to different water application levels. The model was calibrated and validated based on field data. The output from the simulations were used to generate a yield–water production function which was used in the economic analysis.

The study showed that DI is a viable strategy that can be used at the estate when water is limited. The optimum water-limiting irrigation depth (W_w) was 120 mm and the optimum land-limiting depth (W_l) was 1,400 mm. When available water is less than W_w, it is recommended to apply an irrigation depth of W_w on a portion of the field and leave the rest of the field in rainfed conditions, which resulted in a small increase (up to \$5,490) in the total net returns for the field. When the available water depth is greater than W_w but less than W_l, it is recommended to apply the available water depth across the whole field; this resulted in a large increase (up to \$ 208,000.) in total net returns for the field compared to applying W_l on a reduced field area.

Keywords: AquaCrop simulations, deficit irrigation, economic analysis, crop production function, water use efficiency.

Introduction

Forecasts of water withdrawals on a global scale predict sharp increases in future water demands to meet the needs of the urban, industrial, and environmental sectors (Fereres & Soriano, 2007). This is mainly due to the increasing demand for water among the competing sectors in the process of meeting the needs of the rising world population. Sustenance of the growing world population calls for an urgent need to increase agricultural production (Howell, 2001). This, however, will have to be done at a point when the portion of fresh water currently available for agriculture (72%) is decreasing (Cai & Rosegrant, 2003). The need for sustainable methods of increasing crop water productivity is gaining eminence in arid and semi-arid regions (Debaeke & Aboudrare, 2004).

Recently, there has been a shift from the emphasis on maximizing total agricultural production to the investigation of limiting factors of production systems, with much more attention being paid to the availability of either land or water (Fereres & Soriano, 2007). Scarcity is the biggest water problem worldwide, and this poses significant uncertainty about the level of water-supply for future generations (Jury & Vaux, 2005). The Scarcity of irrigation water supplies has led to the need to consider deficit irrigation as a water saving strategy (Martin, Supalla, & Hergert, 2010). In this context, deficit irrigation (DI) is widely investigated as a valuable strategy where water is the limiting factor in crop cultivation such as dry regions (English, 1990).

Deficit irrigation is defined as a deliberate under-application of water to growing crops (English, 1990). This is normally practiced where water is in limited supply, or where it is economically proven to be a viable option in order to minimize costs associated with irrigation while maximizing revenue realized from crops produced under the same practice.

Despite the advantages of deficit irrigation, there are several factors that need to be analyzed and established before deficit irrigation can be adopted as an irrigation management approach. Among other factors, deficit irrigation requires detailed analysis and in-depth understanding of how a given crop responds to water stress. This is an important step in establishing the level of water deficit that would result in maximum returns. This entails the need to develop a water-crop production function for the given crop. Establishment of the optimum level of production along the production function further means establishing the minimum amount of water that needs to be available and supplied to the growing crop when required.

There is an uncertainty associated with deficit irrigation. This generally comes in the sense that the estimation of optimum water use by using a production function requires knowledge of the yields in advance (English & Raja, 1996). However, apart from water availability, crop yields are also affected by a number of unpredictable factors such as climate, irrigation system failures, germination rates and incidence of pest and diseases. This means that the production function is an estimate of the true relationship between the amount of water applied and the yield with some degree of uncertainty. The use of the uncertain functions in the determination of the optimum levels of production implies that the resulting estimates of optimum water use will also be uncertain, and this uncertainty implies risk associated with the use of the function.

However, the risks associated with deficit irrigation do not completely preclude it as a viable irrigation water management option. Farmers, like any other business-minded people, take necessary steps to reduce or even to eliminate risks. Although farmers are likely to adjust their water use to reduce risk, they may be more willing to accept some degree of risk in exchange for potential economic gain (English, 1990). Crop yield models should be used to predict yields and to quantify the uncertainty of yield predictions. While we cannot know the true yield functions in advance, these functions can be used in estimates to develop a sense of the associated risks.

The objectives of this study were 1) to develop a sugarcane crop production function for a field site in Malawi, and 2) to ascertain whether or not deficit irrigation can be an economically viable option. Specifically, we performed an economic analysis and established the optimum water limiting and land limiting irrigation water depths and their corresponding crop yields and economic returns.

Analytical Framework

Production Function

Research has shown that there is a direct relationship between water applied to a growing crop and the resulting yield (Waller & Yitayew, 2016; Marin et al., 2017). English (1990) indicated that the relationship between the amount of water applied to a crop and the corresponding yield (crop-water production function) has a general form of a quadratic function (Equation 1). The AquaCrop model was used to establish the sugarcane crop yield response to the varying amounts of irrigation water depths at a 36.6 ha field site in the Nchalo sugar estate, Chikwawa District, Malawi. Data on climate, crop characteristics, field management practices and soil characteristics, collected from field experiments and the estate database, were used as input parameters in AquaCrop. The model was calibrated and validated based on the collected data (Banda, 2019).

$$y(w) = c_1 w^2 + b_1 w + a_1 \tag{1}$$

where y was yield (tons/ha), w represents irrigation water depth (mm), and a_1, b_1 and c_1 were constants describing the nature of the curve.

While the AquaCrop model is known for its simplicity, robustness and accuracy in simulation process (FAO, 2012), its inability to account for spatial variations within a field is one of the limitations of the model. We adopted the approach used in the work of Martin et al. (2010) as proposed by Clemmens (1992) to incorporate the concept of irrigation uniformity and the consequent variations in field conditions in the simulations. The approach uses a statistical method to partition irrigation infiltration into net irrigation and deep percolation based on a normal distribution (Figure 1). This method has an ability to predict the mean depth of application required to produce the full yield for a prescribed portion of the field if the surface water loss (runoff) is known (Martin et al., 2010). This approach takes into account the inherent variations in water application by an irrigation system. Therefore, the combination of this approach with the outstanding abilities of AquaCrop resulted in a realistic and reliable approach in running crop simulations.

The coefficient of uniformity (CU) established from catch can tests was used to determine the distribution of infiltration and the partitioning of water between the adequately irrigated area and inadequately irrigated portions of the field for each of the irrigation depths. With the established distribution, the yield realized from each of the areas (adequately and inadequately irrigated areas) were established from the AquaCrop model.

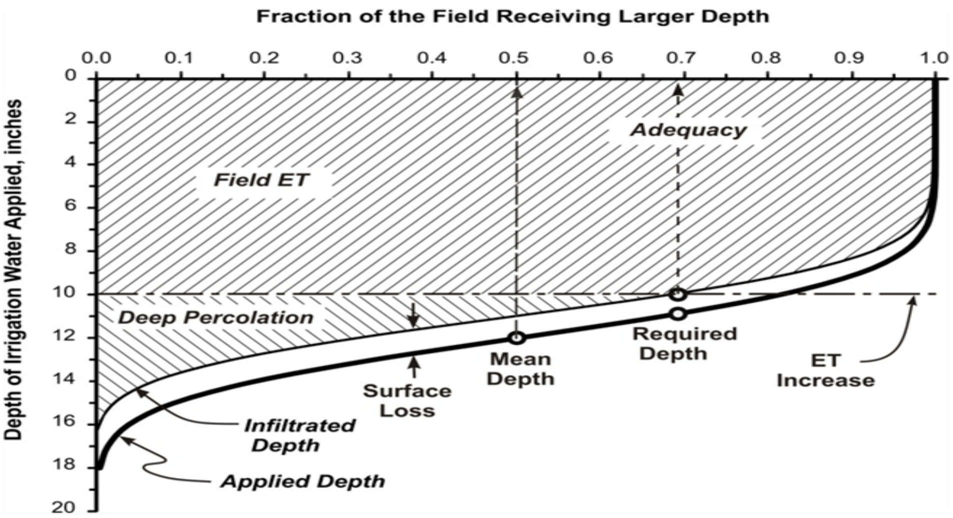

Figure 1: Partitioning of irrigation infiltration using normal distribution function – courtesy of Martin et al., (2010).

A general relationship of crop yield as a function of water depth shows that an increase in amount of water applied to a growing crop leads to increase in yield. However, as shown earlier on, this relationship is not linear. A closer look at the crop production function would show that the curve is made up of three distinct regions (Figure 2): (i) region of increasing marginal output (yield), (ii) a region of decreasing marginal yield and (iii) a region of diminishing total yield.

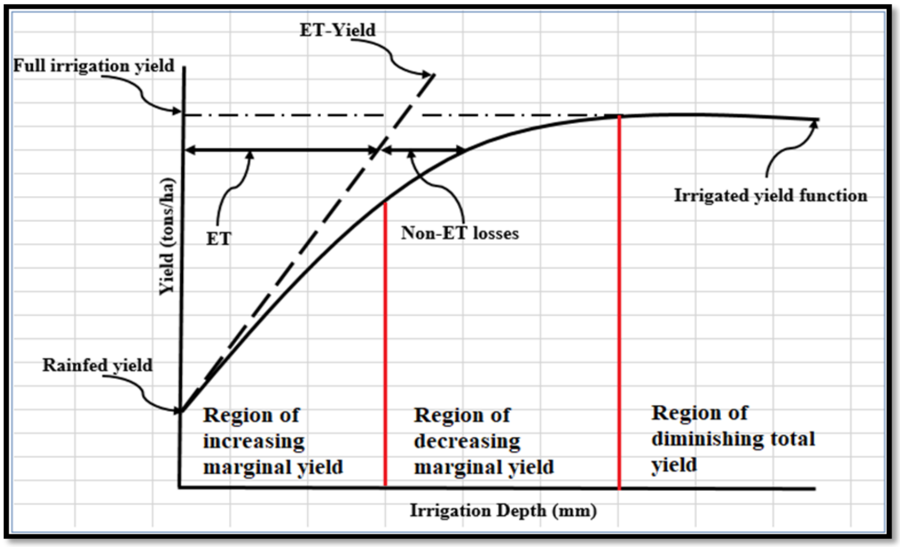

Figure 2: General elements of a crop production function.

Production under the region of increasing marginal yield is characterized by increasing yield output per additional unit of water. An additional unit of water would yield a higher marginal unit of crop yield. Under this region almost all the water applied is used to produce yield, resulting in a linear relationship between the water applied and the yield realized (Martin et al., 2010). Production under the region of decreasing marginal yield results in a smaller marginal yield. There are high non-ET water losses in this region. The yield increases at a decreasing rate with each additional unit of water applied leading to a non-linear relationship between the yield and applied water.

Further addition of water beyond the region of decreasing marginal yield results in waterlogging conditions which are detrimental to yield production. The marginal yield decrease leads to a decrease in total yield. Increment of an input variable (water) to a crop beyond a certain limit, while holding the other factors of production constant, generally triggers the law of diminishing returns. This means that with a continued addition of the variable input (water) to the fixed resource (crop), a point would be reached where further increase in water applications would not give any increment in the yield. This realization helped in the establishment of a realistic production function in this exercise: a parabolic relationship was used until the maximum yield was reach, and after this point the yield was held constant.

A series of simulations were performed with irrigation depth increments of 1 mm per irrigation event in AquaCrop. The simulations were discontinued when further increments in irrigation depth did not result in increase in yield. The relationship of water and sugarcane crop yields were plotted to generate a crop-water production function (Figure 3). With an assumption that irrigation water application follows a normal distribution function, the incorporation of the CU in the simulations accounted for variation of irrigation system performance in water application (Figure 3). This approach meant that the final production function was a representation of the yield response to water under averaged field conditions (Martin et al., 2010).

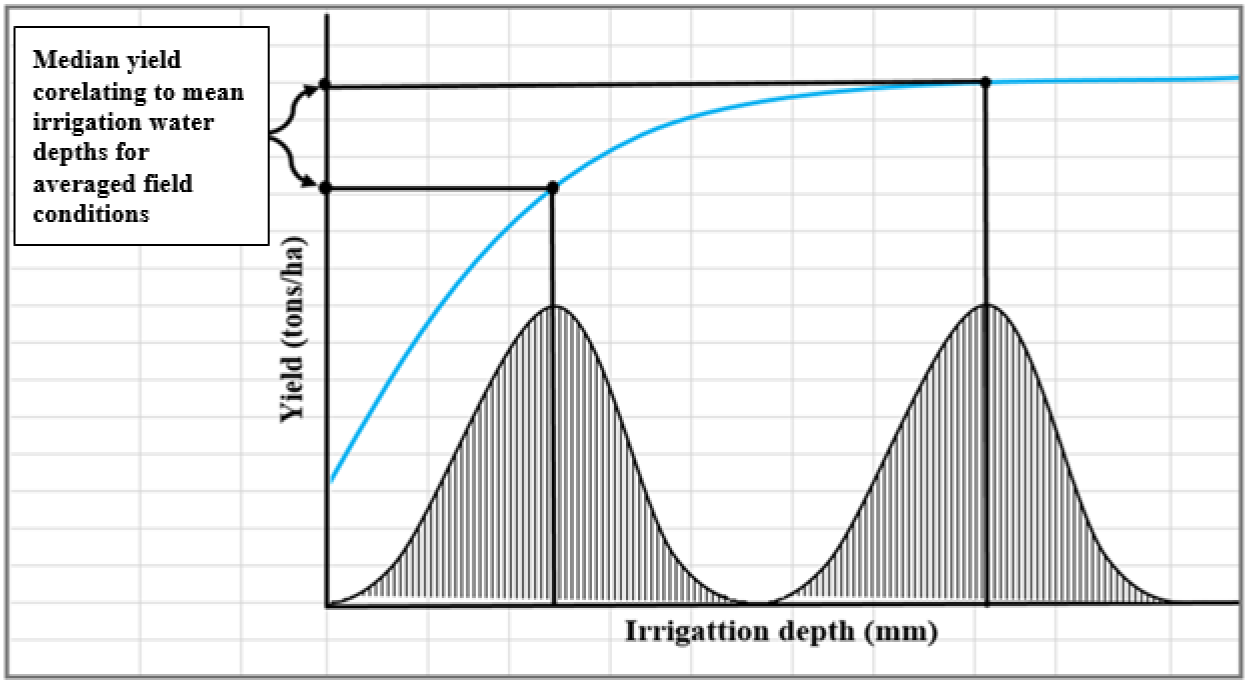

Figure 3: Crop water production function for a point in the field (blue curve). For a given irrigation event, the spatial distribution of irrigation depths was assumed to be a normal distribution around the mean irrigation depth. Average yield for the whole field was estimated to be the average of the yields associated with deciles of irrigation depth.

Economic Analysis

The relationship between an input and output in a production system has economic implications. The understanding of such relationships is paramount in efficient allocation of production inputs. The recent diminishing trends of water resources calls for an in-depth understanding of crop yield response to water. This is why a crop-water production function is an important decision-making tool to the water resources and irrigation system managers.

Economists and finance managers are more interested in the relationship between the cost associated with using a given unit of water and the revenue (return) realized from the same. Economists strive to understand the costs, revenue and output behavior in response to changes in inputs in a given production system. It is only when such a relationship is established and understood that well informed and economically sound decisions about the production can be made. Therefore, attention was shifted from the yield and water depth relationship to understanding the revenue, cost and water depth relationship in this section.

The AquaCrop model gives yield response to water in dry weight basis while the estate records its yield in wet (fresh) weight. Further, AquaCrop does not give the amount of sugar that could be recovered from the harvested sugarcane. While agronomists are concerned with the sugarcane yield, to the economists and the factory managers the sucrose recoveries from the sugarcane are of importance. The conversion from one form of yield to another required knowledge of the moisture and sucrose content of the sugarcane when harvested. The data on yield, sucrose recoveries and moisture content were also collected from the estate database (Table 1) to aid in the conversion from one form of yield to another. FAO (2012) indicated that typically mature sugarcane stalk consists of water, fiber, sucrose and impurities in the proportions of about 70%, 15%, 13% and 2% respectively. We found the collected data in much agreement with the findings of the FAO (2012).

Table 1: Sugarcane crop yield parameters.

Season	**Sucrose recovery (%)**	**Moisture content (%)**	**Fresh cane yield (tons/ha)**	**Dry cane yield (tons/ha)**	**Sugar yield (tons/ha)**
2007/2008	14.6	69.7	130.29	39.09	19.02
2008/2009	13.6	68.7	139.65	41.90	19.06
2009/2010	13.5	70.0	151.95	45.59	20.44
2010/2011	14.2	69.6	121.59	36.48	17.23
2011/2012	13.1	71.2	130.21	39.06	17.12
2012/2013	13.1	70.3	137.28	41.18	18.00
2013/2014	12.2	71.6	129.94	38.98	15.89
2014/2015	13.8	69.4	112.87	33.86	15.58
2015/2016	12.2	71.4	110.04	33.01	13.39
2017/2018	14.0	69.4	153.33	46.00	21.47
Mean	**13.4**	**70.1**	**131.72**	**39.52**	**17.72**

Revenue and Cost Functions

The revenue realized from the sugarcane crop is simply the product of the yield and the selling price. As established earlier on, holding other factors equal, the amount of yield realized depends on the amount of water applied (Equation 1). This means that the revenue realized from a given amount of water is the product of the crop-water production function and unit selling price of the yield (Equation 2). Thus, the relationship between irrigation water use and gross income will have the same general shape and form as the crop-water production curve.

$$R(w) = Pc * y(w) = Pc * (c_1 w^2 + b_1 w + a_1) \tag{2}$$

where R was the gross revenue (\$/ha) as a function of water (w) applied and Pc was the selling price (\$/ton) of the sugar yield produced from a given amount of water and the other parameters are as defined in Equation 1. In this research, the currency was the U.S. Dollar (\$). The yield parameters (especially the average sugar recovery %) given in Table 1 were used for the conversion of sugarcane yield to sugar yield.

On the other hand, the cost function relating irrigation-related production costs to the amount of applied water is a fairly straight line (Equation 3) whose lower limit (the vertical intercept) represents fixed costs (a combined cost of insurance and capital costs). The slope of the linear function represents the marginal variable costs of production associated with electricity bills, labor, and maintenance; its upper limit will give an indication of the maximum system design cost (English & Raja, 1996).

$$c(w) = b_2 w + a_2 \tag{3}$$

where c was the cost ($/ha) associated with pumping w (mm) amount of water, b_2 was the marginal variable cost ($/mm/ha) and a_2 was the fixed costs ($/ha) of the irrigation system. Other costs of production not associated with irrigation were not included since the objective was to quantify the impact of irrigation management on net returns rather than the magnitude of net returns. If these costs were included, they would be a fixed cost added to a_2.

The net irrigated return (NIR) was determined from the difference between the total gross revenue generated from a given water depth and the irrigation related costs associated with the same (the difference of Equation 2 and Equation 3). The average net return (ANR; Martin et al., 2017) above rain-fed conditions, per unit of irrigation water, was determined by dividing the difference between the rain-fed net revenue ($NR_{rain\text{-}fed}$) and the NIR by the corresponding irrigation water depth (w) as represented by Equation 4:

$$ANR = \frac{(NIR - NR_{rain-fed})}{w} \tag{4}$$

where ANR was the average net return above rain-fed conditions per volume of irrigation ($/ha-mm), w was the depth of irrigation water (mm), NIR was the irrigated net return ($/ha) associated with w, and $NR_{rain\text{-}fed}$ was the net return for the best rain-fed alternative ($/ha). Note that one ha-mm is the volume of water that would cover one ha of land to a depth of one mm.

Optimum Land- and Water-Limiting Irrigation Depths

The optimum water limiting irrigation depth is the water depth at which the ANR per unit of irrigation is the maximum. At this point, the net return (profits) on irrigation is maximized. Graphically the optimum water limiting depth of irrigation was determined by plotting the ANR on a graph of NIR, with the maximum ANR occurring when ANR is tangent to the NIR curve. Numerically, the optimum water limiting depth was approximated by using Equation 5 (English & Raja, 1996):

$$W_w = \sqrt{\frac{P_c a_1 - a_2}{P_c c_1}} \tag{5}$$

where P_c, a_1, a_2 and c_1 were parameters as defined in Equations 1, 2 and 3, and W_w was the optimum water application level in a water-limiting case.

The optimum land-limiting irrigation depth was graphically established by observing the point at which the revenue function transitioned from decreasing marginal returns to diminishing total returns. Numerically this point was established by finding the water depth which gave the highest difference between the gross return and the irrigation cost, resulting in Equation 6:

$$W_l = \frac{(b_2 - b_1 P_c)}{2 P_c c_1} \tag{6}$$

where W_l was the optimum land-limiting depth (mm), and b_1, b_2, c_1 and P_c were parameters as defined in Equations 1, 2 and 3.

Maximizing Net Return under Different Water Availability Scenarios

Different water availability scenarios were examined to establish the water application depth that maximizes returns under each scenario. Three water availability scenarios were created and tested (Figure 4); (i) water depth less than W_w, (ii) water depth less than the W_l but greater than W_w, and (iii) water depth more than the W_l.

Under each scenario the total net return (NR_{total}) realized from irrigating the whole field area with the available irrigation water depth was compared to the total net return realized from applying full irrigation (when the available irrigation water is more than the optimum deficit irrigation depth) or optimum deficit irrigation depth (when the available irrigation water depth is less than the optimum deficit irrigation depth) to a reduced field area (Figure 5).

The NR_{total} was determined as the sum of total net returns realized from rain-fed area and irrigated area at the given irrigation depth (Martin et al., 2017). This was calculated by Equation 7:

$$NR_{total} = A_{rain-fed} * NR_{rain-fed} + A_{irrig} * NIR \tag{7}$$

where NR_{total} was the total net returns for the field (\$), $NR_{rain-fed}$ was rain-fed net return (\$/ha), NIR was net irrigation return (\$/ha), A_{irrig} was the sugarcane crop area (ha) cultivated under irrigation, and $A_{rain-fed}$ was the sugarcane crop area (ha) under rain-fed cultivation. The total area of the field site was 36.6 ha.

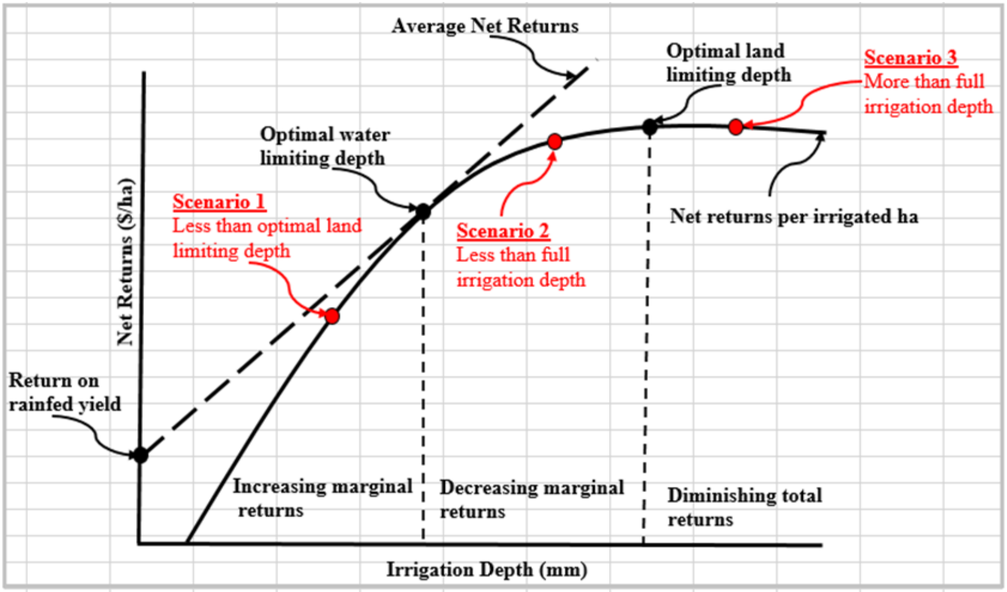

Figure 4: Water availability scenarios under consideration.

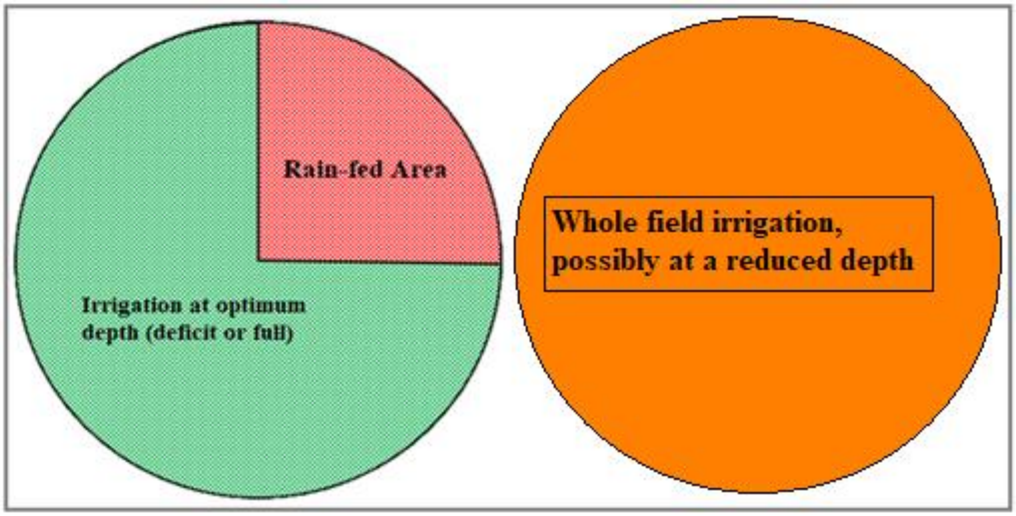

Figure 5: Irrigation water partitioning.

Results

Production Function

The initial AquaCrop simulation of the sugarcane crop growth and development, with irrigation depths between 1 and 1,200 mm and applying 16 mm per irrigation event, resulted in the production function (Figure 6). Any point in the field that received an irrigation depth of 992 mm or more would yield a maximum of 40.7 tons/ha dry yield (Figure 6). The rain-fed yield was established to be 9.92 tons/ha.

The distribution of the applied water (based on the CU) in the adequately and inadequately irrigated areas of the field were also established as in Figure 7. The yield realized for the respective water depth in each of the adequately and inadequately irrigated areas were as presented in Table 2, with the average yield correlating to an average irrigation depth being determined as the average of the yields from each decile of irrigation depth (Figure 3).

The incorporation of the system performance (CU) resulted in the production function in Figure 8. The averaged irrigation system performance achieved the same maximum yield (40.1 tons/ha) at an average depth of 1,500 mm. A parabolic equation was fit to the generated data for both cases. Specifically, yield in relation to irrigation water depth at a given point in the field is described by Equation 8, and Equation 9 describes the production function for average field conditions:

$$y = -0.00003w^2 + 0.0608w + 9.919 \tag{8}$$

$$y = -0.00002w^2 + 0.05w + 10.5 \tag{9}$$

where *y* was the sugarcane yield (tons/ha) as function of irrigation water depth *w* (mm). For this situation, the production function accounting for the uniformity of the irrigation system (Figure 8) was different from the production function for a point in the field (Figure 6), particularly in terms of the amount of irrigation required to achieve a maximum yield. Equation 8 holds as long as the irrigation water depth does not exceed 992 mm; Equation 9 reaches a maximum at 1,500 mm, after which the yield is constant.

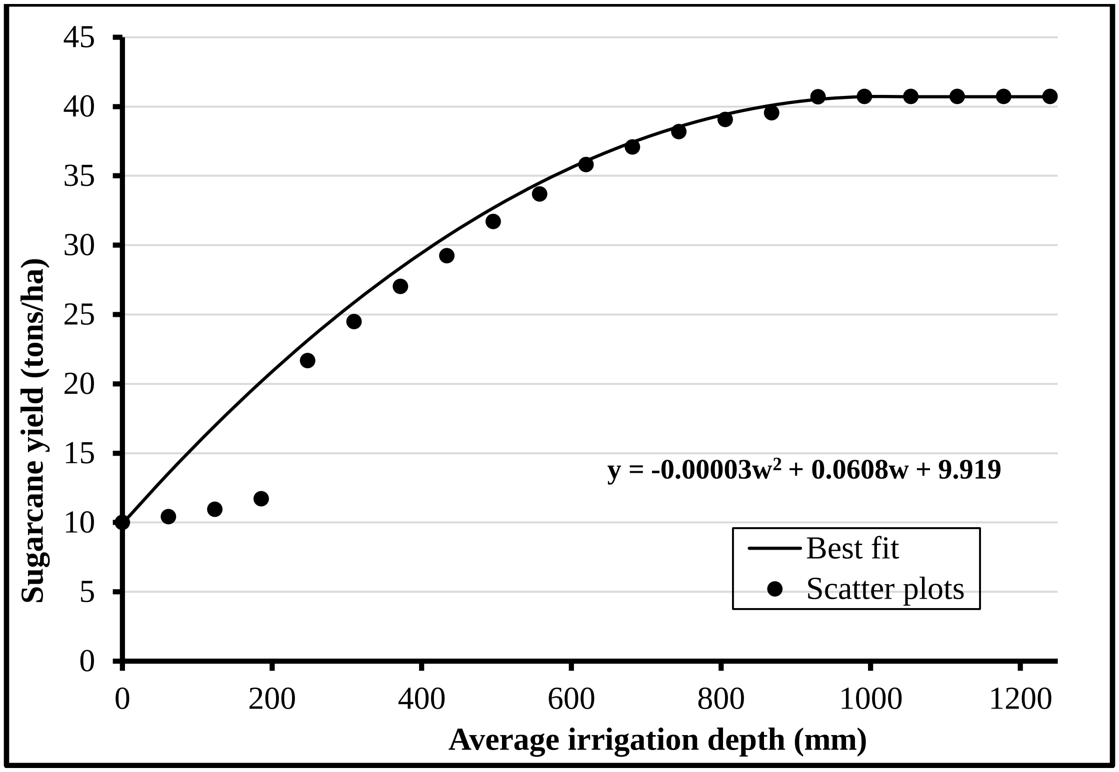

Figure 6: Production function at a point in the field.

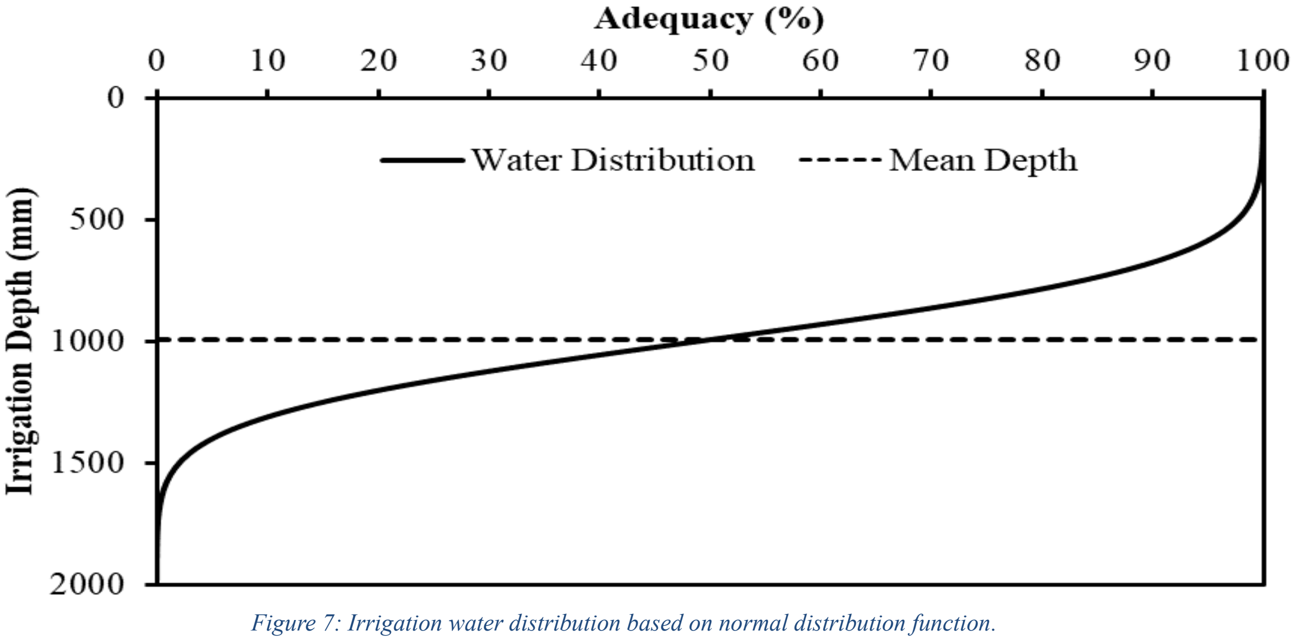

Figure 7: Irrigation water distribution based on normal distribution function.

Table 2: Water and yield distribution accounting for irrigation uniformity.

CU = 80%		**Irrigation water depth (mm) and corresponding yield (tons/ha) for each decile**																		
Mean Depth	**Standard dev. Depth**	**0.1**	**yield**	**0.2**	**yield**	**0.3**	**yield**	**0.4**	**yield**	**0.5**	**yield**	**0.6**	**yield**	**0.7**	**yield**	**0.8**	**yield**	**0.9**	**yield**	**Mean yield**
0	0	0	9.92	0	9.92	0	9.92	0	9.92	0	9.92	0	9.92	0	9.92	0	9.92	0	9.92	9.92
62	16	42	12.42	49	12.82	54	13.11	58	13.35	62	13.57	66	13.80	70	14.04	75	14.31	82	14.70	13.57
120	30	81	14.67	95	15.41	104	15.93	112	16.37	120	16.78	128	17.19	136	17.62	145	18.12	159	18.80	16.77
178	45	121	16.83	140	17.87	155	18.60	167	19.22	178	19.79	189	20.35	201	20.95	216	21.63	235	22.56	19.76
179	45	122	16.86	141	17.91	155	18.65	168	19.27	179	19.84	190	20.41	203	21.00	217	21.69	236	22.62	19.80
292	73	198	20.79	230	22.34	254	23.41	273	24.30	292	25.11	311	25.91	330	26.73	354	27.67	386	28.91	25.02
296	74	201	20.92	234	22.48	257	23.57	277	24.47	296	25.29	315	26.09	335	26.92	358	27.86	391	29.11	25.19
348	87	236	22.61	275	24.35	302	25.56	326	26.55	348	27.44	370	28.31	394	29.21	421	30.21	460	31.53	27.31
356	89	242	22.86	281	24.63	309	25.85	333	26.85	356	27.76	379	28.64	403	29.54	431	30.55	470	31.88	27.62
458	115	311	25.92	361	27.97	398	29.36	429	30.48	458	31.47	487	32.42	518	33.37	555	34.41	605	35.72	31.24
479	120	325	26.52	378	28.61	416	30.02	449	31.16	479	32.16	509	33.11	542	34.06	580	35.09	633	36.38	31.90
563	141	382	28.77	444	31.01	489	32.48	527	33.64	563	34.64	599	35.57	637	36.48	682	37.43	744	38.55	34.28
609	153	413	29.93	481	32.21	529	33.69	570	34.84	609	35.82	648	36.71	689	37.57	737	38.44	805	39.42	35.40
662	166	449	31.18	522	33.49	575	34.96	620	36.08	662	37.02	704	37.85	749	38.63	802	39.38	875	40.15	36.53
737	185	500	32.83	582	35.13	640	36.55	690	37.59	737	38.43	784	39.14	834	39.76	892	40.29	974	40.68	37.82
794	199	539	33.97	627	36.24	690	37.58	744	38.54	794	39.28	844	39.87	898	40.33	961	40.64	1049	40.71	38.57
893	224	606	35.75	705	37.87	776	39.03	836	39.78	893	40.29	950	40.60	1010	40.71	1081	40.71	1180	40.71	39.49
895	224	608	35.78	706	37.89	777	39.05	838	39.80	895	40.30	952	40.61	1013	40.71	1084	40.71	1182	40.71	39.51
970	243	658	36.95	765	38.88	843	39.85	908	40.39	970	40.67	1032	40.71	1097	40.71	1175	40.71	1282	40.71	39.95
992	249	673	37.26	783	39.13	862	40.03	929	40.51	992	40.71	1055	40.71	1122	40.71	1201	40.71	1311	40.71	40.05
1000	251	679	37.37	789	39.22	869	40.10	937	40.55	1000	40.71	1063	40.71	1131	40.71	1211	40.71	1321	40.71	40.09
1200	301	815	39.54	947	40.59	1042	40.71	1124	40.71	1200	40.71	1276	40.71	1358	40.71	1453	40.71	1585	40.71	40.57
1400	351	950	40.61	1105	40.71	1216	40.71	1311	40.71	1400	40.71	1489	40.71	1584	40.71	1695	40.71	1850	40.71	40.70
1500	376	1018	40.71	1184	40.71	1303	40.71	1405	40.71	1500	40.71	1595	40.71	1697	40.71	1816	40.71	1982	40.71	40.71

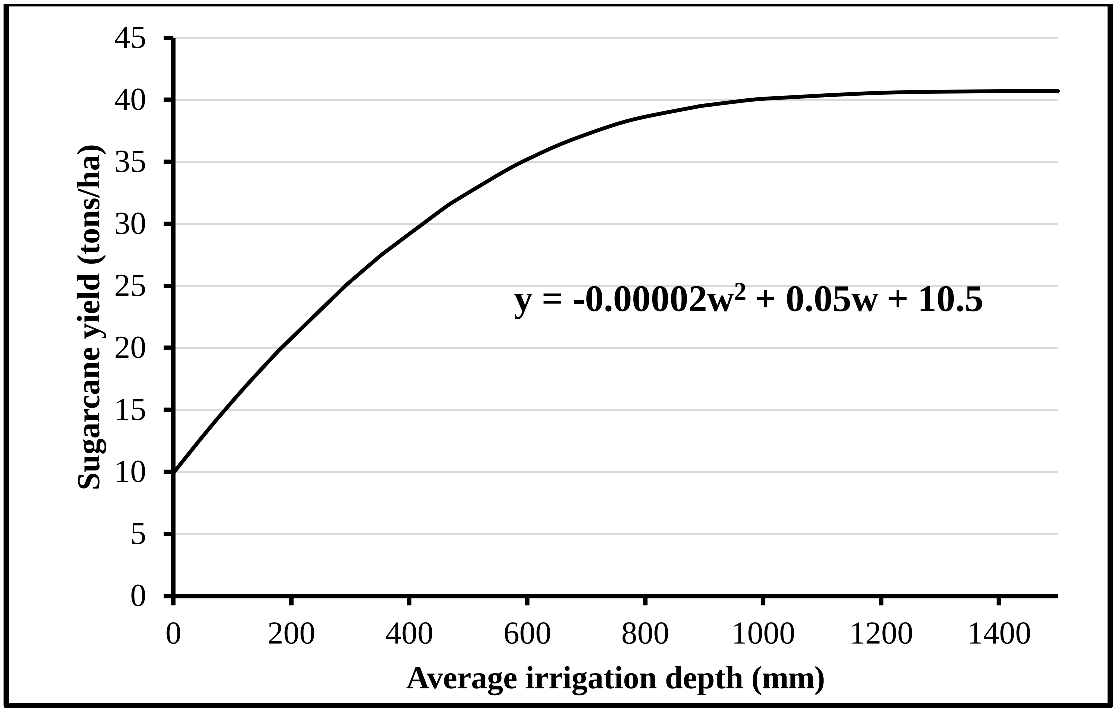

Figure 8: Production function for averaged irrigation system performance.

Production Function Discussion

At the given coefficient of uniformity and desired average net irrigation depth, increase in adequacy resulted in application of more water than the required depth. The difference in water depth applied between the adequately irrigated and the stressed area, which is determined by the CU of the system, has a major impact on the amount of water that needs to be applied to meet the crop water needs. The CU affects how much water should be applied to achieve the required average net irrigation depth. In an irrigation system with low CU, for example, the need to ensure that the stressed area also gets close to the optimum water depth would result in applying more water than required in the adequately irrigated area (Table 2). The application of more water than required is likely to result in water logging and large water losses due to deep percolation and surface runoff in the adequately irrigated area. The water logging conditions may result in significant yield loss in the adequately irrigated area as well. This suggests that improving system water distribution efficiency could be key to improving water productivity.

Beyond 992 mm further increments in water depth did not result in any increments in yield (Figures 7 and 8 and Table 2). This depth resulted in the maximum field yield of 40.7 tons/ha for the point in the field and 40.1 tons/ha for the averaged field conditions. The rain-fed yield of 9.92 tons/ha was realized from a total rainfall of 651 mm. The amount of rain-fed yield realized largely depends on the planting date, distribution, timing and amount of rainfall received over the period after the planting of the crop. Although it would be logical to time the planting date of the sugarcane in a manner that takes full advantage of the rainfall (December, January and February) in this area, field observations have shown that sugarcane crop planted in these months is poorly established (poor germination percentage, less vigor and requires a lot of attention to establish the cane).

Again, it has to be noted that Nchalo estate is in a flood prone area, thus planting is always planned to ensure that the crop should be fully grown and established by the time a possible flooding event hits the estate. Further, the nature of the harvesting and haulage system dictates the timing of planting dates. Farm managers always plan their planting to ensure that the cane is harvested during the dry period. Harvesting and hauling sugarcane during the wet period not only makes it easy for the haulage trucks to get stuck, it also leads to enormous sugarcane losses due to poor handling. Often times, sugarcane hauled during the wet periods results in low quality sugar and poor sucrose recoveries due to difficulties in haulage logistics that lead delayed sugarcane delivery to factory for processing.

Economic Analysis

As observed in the above section, the field produces a maximum average sugarcane yield of 40.7 tons/ha, and an equivalent sugar yield of 18.2 tons/ha (Figure 9). Incorporating the sucrose recovery data and the moisture content of the sugarcane into Equation 1 resulted in Equation 10 (the sugar production function) which describes the relationship between the sugar yield and irrigation water depth.

$$y_s = -0.00000893w^2 + 0.0223w + 4.69 \tag{10}$$

where y_s was the sugar yield (tons/ha) with respect to the irrigation water depth w (mm).

Further mathematical operation on Equation 10, with incorporation of the sugar selling price, resulted in Equation 11 (revenue function as presented in Equation 2). The estate sells the produced sugar at an average of 1,103 $/ton. Equation 11 describes the relationship between the revenue and amount of irrigation water applied.

$$R(w) = -0.00995w^2 + 24.63w + 5171.65 \tag{11}$$

where R was the revenue ($/ha) realized from application of w (mm) of irrigation water depth. The maximum gross return was 20,100 $/ha (Figure 10), which was produced with 1,500 mm of irrigation water. Since the rain-fed condition didn't have any costs associated with irrigation, the $NR_{rain\text{-}fed} = R(0)$ = 5172 $/ha.

The costs of irrigation for the whole field included variable costs of $5.16/mm and a fixed cost of $5,490. The cost function (Equation 12) was generated by transforming the cost data into a mathematical function per unit area in the form of Equation 3. Equation 12 describes the relationship between the cost of irrigation ($0.141/mm per ha) in relation to the amount of water pumped and applied to the field, with a fixed cost of 150 $/ha:

$$C(w) = 0.141w + 150 \tag{12}$$

where C was the cost of irrigation ($/ha) as a function of irrigation water depth w (mm).

The revenue and cost functions were used in the generation of a function for NIR (Equation 13). Subsequently, a line representing the ANR (Equation 14) was superimposed on top of the NIR function, with the maximum ANR occurring when the ANR line was tangent to the NIR function.

$$NIR = -0.00995w^2 + 24.489w + 5021.65 \tag{13}$$

$$y = ANR * w + 5171.65 \tag{14}$$

where NIR was the net irrigation return ($/ha), w was the irrigation water depth (mm), ANR was the average net return (26.717 $/ha-mm), and y was the line representing ANR. The field produced a maximum NIR of 19,700 $/ha (Figure 10). This net return does not include other costs of production (not associated with irrigation) since the objective was to quantify the change in net return resulting from various irrigation management strategies. The maximum ANR was 26.72 \$/ha-mm of irrigation water applied, which occurred when ANR was equal to the slope of the NIR curve (Figure 11). It is noted that the ANR depends the net return of the best rain-fed alternative ($NR_{rain\text{-}fed}$), which is where the ANR line intercepts the y-axis. At the estate, rain-fed production is limited to sugarcane for practical considerations. If a different crop was considered that was more profitable under rain-fed conditions, this would result in a higher $NR_{rain\text{-}fed}$, a lower ANR, and a higher W_w (Figure 4).

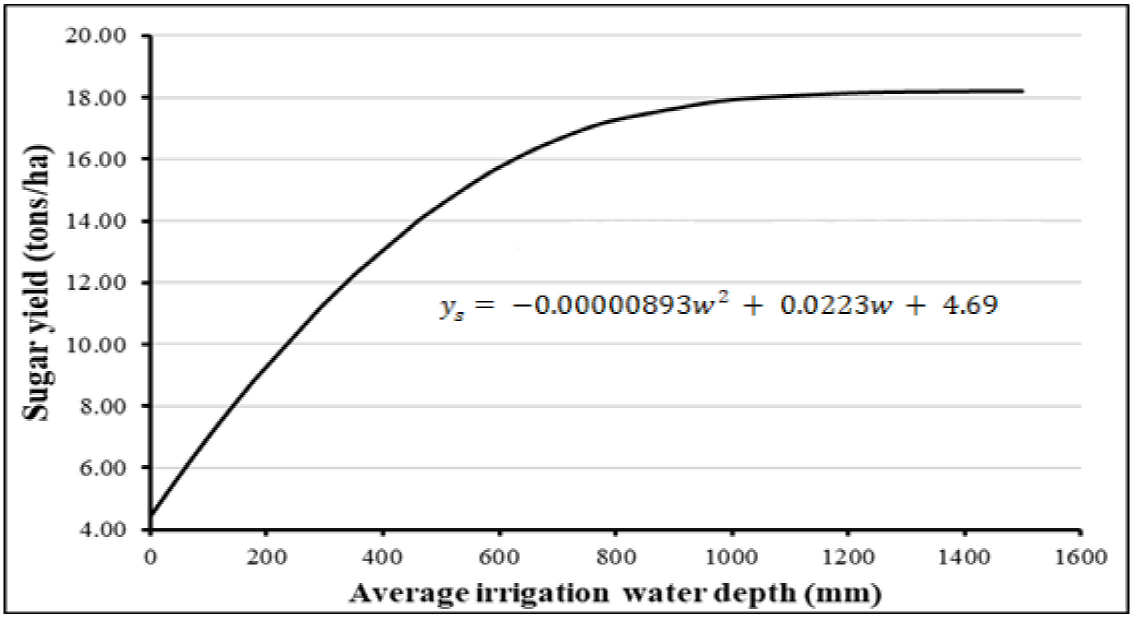

Figure 9: Sugar production function.

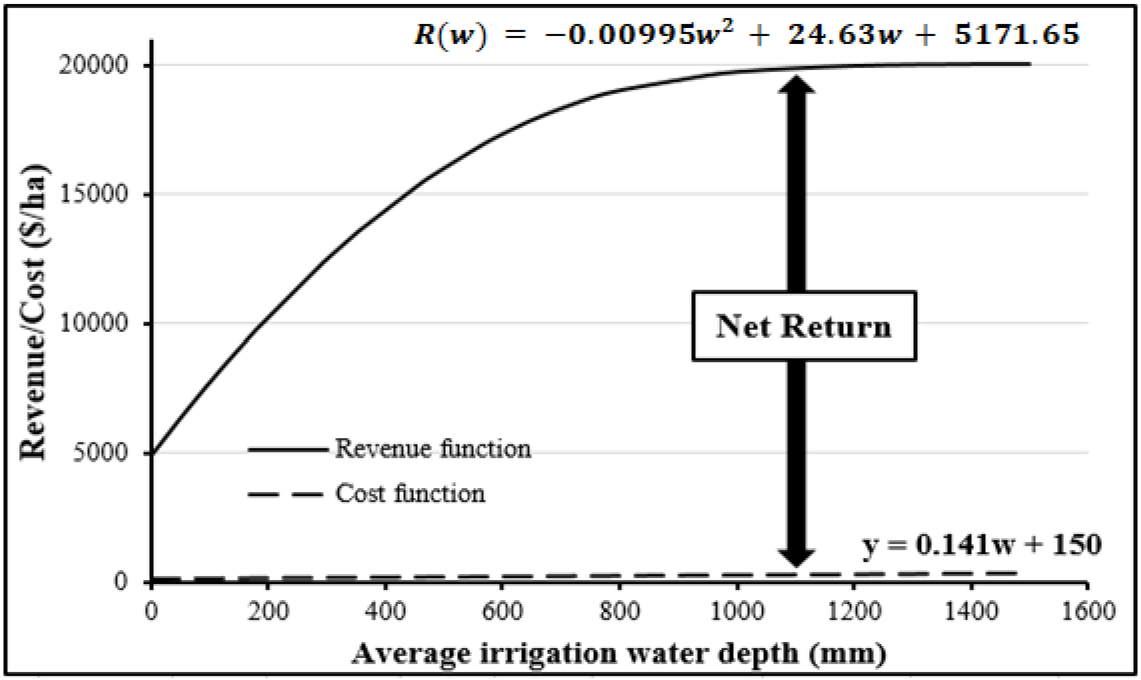

Figure 10: Revenue and cost functions.

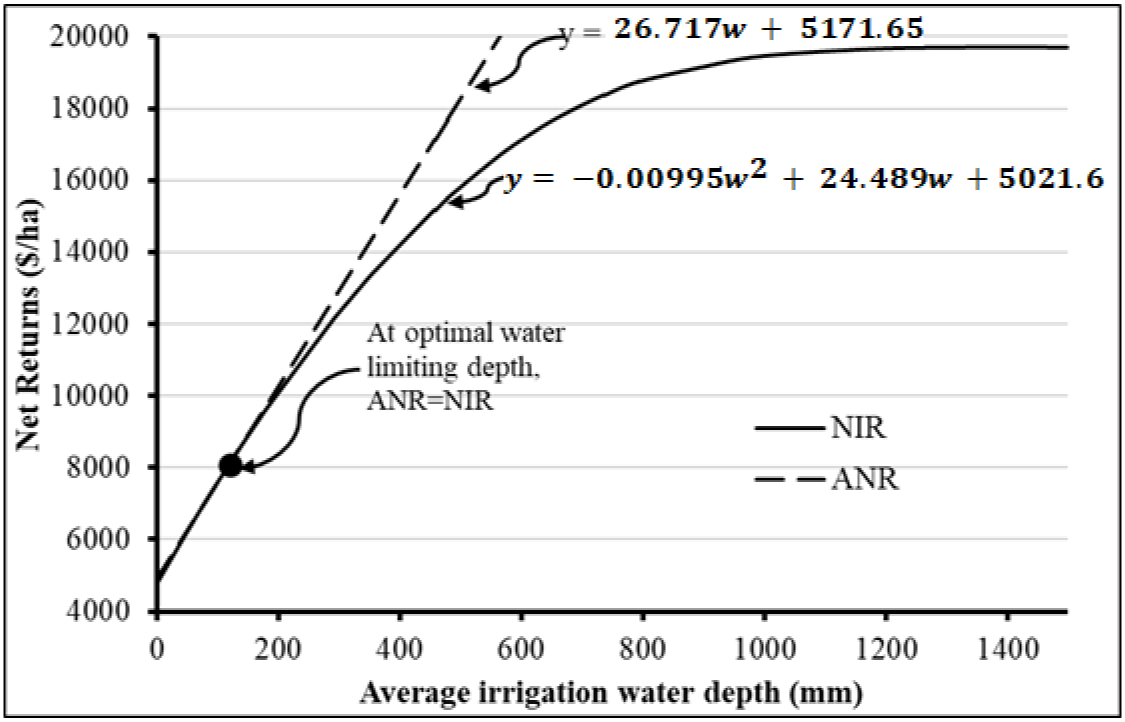

Figure 11: Net irrigation return (NIR) and average net return (ANR) on irrigation.

The maximum net return on irrigation of 19,700 $/ha was achieved when 1,400 mm of irrigation water was applied (Figure 12). This means that when water was not limited in availability (land limiting case), applying 1,400 mm of irrigation water would maximize the total return. The average return above rain-fed conditions per mm of water (ANR) was the maximum when 120 mm (W_w) was applied (Figure 12). This means that when water is the limiting factor of production (water available is less than W_w), applying 120 mm of irrigation on a fraction of the field area would maximize the ANR, maximizing the total net return. This W_w, however, is practically too low to be used on real irrigation system operation at the estate considering that no estate record on water availability had shown such a low level. However, this is still useful as a threshold to determine which water availability scenario the field is in (water depth less than W_w or water depth greater than W_w but less than the W_l) to determine the optimal DI strategy.

The situation analysis of the possible water availability options showed that when the amount of water available was less than W_w (120 mm), the best irrigation option was to irrigate part of the field with W_w and to leave the other portion as rain-fed. When the available water depth was more than W_w but less than W_l, irrigating the whole field area with the available water depth showed to be the best option (in contrast to irrigating W_l on only a portion of the field) (Figure13). When the available water depth is more than W_l, the best option would be to irrigate with a depth of W_l in order to maximize net revenue (not using all of the available water).

Further, it was also established that the cost (in returns) of applying the alternative option rather than the best option when the available water depth is less than W_w was up to $5,490 (Figure 13). It was also found that, when the available water depth was greater than W_w but less than W_l, up to $208,000 was the total foregone returns for following the alternative option (irrigating a portion of the field with W_l) compared to the recommended strategy (applying the available water on the whole field) (Figure 13).

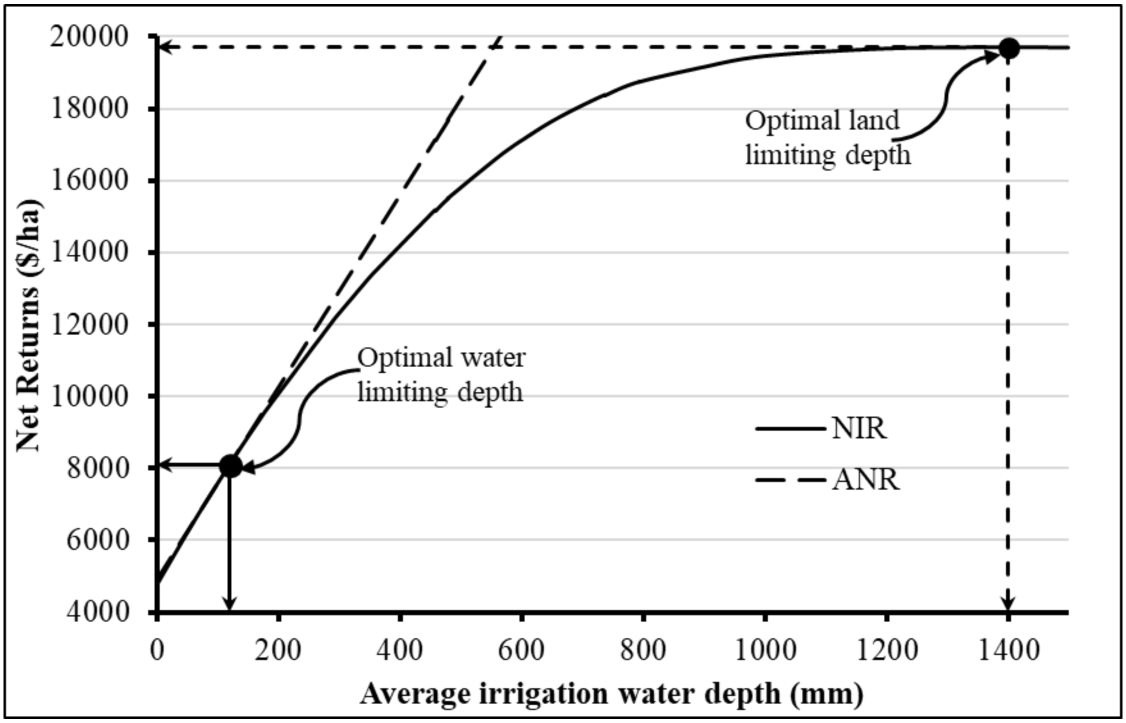

Figure 12: Optimum water limiting and land limiting irrigation depths.

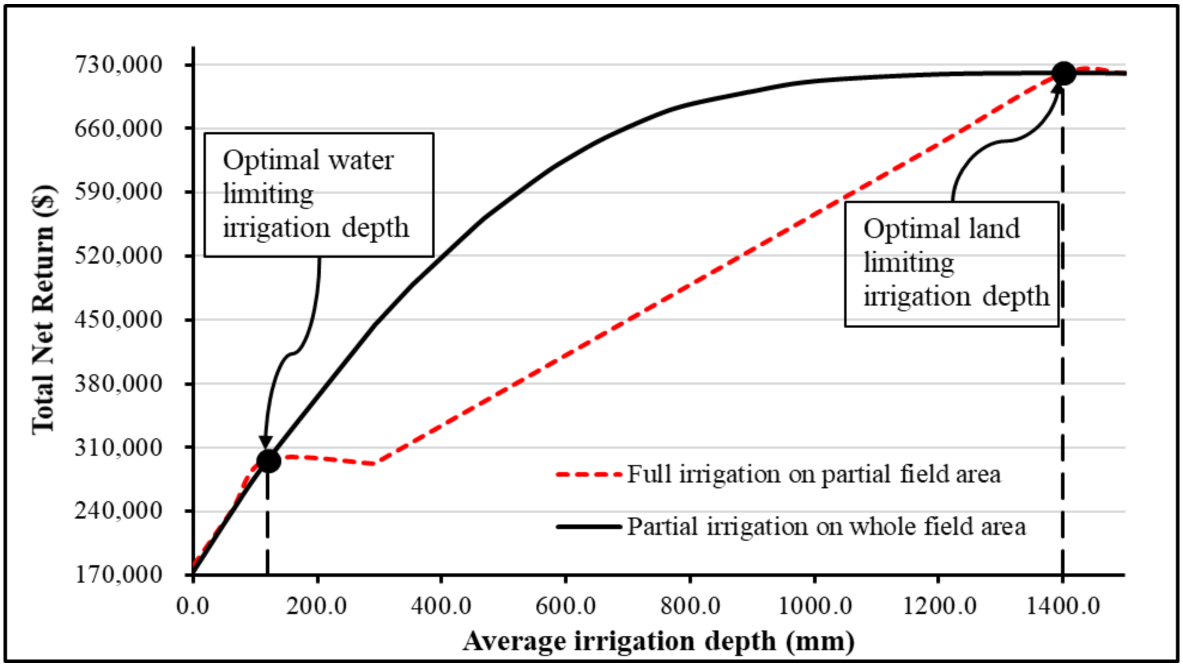

Figure 13: Net revenue for the whole field under different water availability possibilities.

Economic Analysis Discussion

A maximum net return of 19,700 \$/ha was realized at an irrigation depth of 1,400 mm (W_l). The sugar yield achieved (17.2 tons/ha) at this depth was not the maximum yield possible (17.7 tons/ha). However, the maximum sugar yield was achieved with a higher irrigation water depth (1,500 mm) with a lower net return of 19,690 \$/ha. While the yield increase with respect to the amount of water is at a decreasing rate in this region of the graph, the increase in cost of irrigation is in a linear relationship with respect to amount of water applied. While the cost of irrigation increased by a margin of \$164.7, there was no marginal sugar yield increase as a result of increasing the water depth from 1,400 mm to 1,500 mm. This explains the difference in net returns between the two irrigation depths.

The W_w was established to be 120 mm, resulting in a net return of 8,090 \$/ha. While the variable cost of water is 0.141 \$/ha-mm (0.014 $\$/m^3$), the ANR was 26.72 \$/ha-mm at W_w and was 10.58 \$/ha-mm at W_l. This illustrates why it is economically sound to apply an irrigation depth of W_w on a portion of the field when water supply is less than W_w. Although the W_w has the maximum ANR, it is only beneficial to irrigate at a depth of W_w when the available irrigation water is less than W_w. The irrigation records at the estate showed that at no point in time under consideration was the available irrigation water less than 120 mm. It is should be important to note that this depth should be regarded as a threshold for decision making.

Whether or not to irrigate the whole field with partial irrigation depth or irrigating part of the field area at full irrigation depth depends on the available water depth. When the available water depth is less than W_w (120 mm), irrigating part of the field at a depth of W_w and leaving the rest of the area under rain-fed farming is the best option. The W_w is a transition point between the region of increasing ANR and the region of decreasing ANR on water on the crop-water production function. The maximum return on every water droplet is achieved at W_w. This explains why irrigating part of the field at W_w (which maximizes return on a fixed amount of water) while leaving the rest of the field area under rain-fed is the best economic reason when the available irrigation water is less than W_w.

However, the situation is different when the available water is more than W_w but less than W_l. Production in this case falls in the region of decreasing marginal returns with the lowest return on the applied water occurring at W_l. This means that any water depth less than W_l would result in a higher return on the water applied (higher ANR) than the return at W_l (lower ANR). This explains why, in this scenario (available water is more than W_w but less than W_l), it makes economic sense to irrigate the whole field at the available water depth rather than irrigation a portion of the field at W_l and leaving the rest of the area in rainfed conditions.

If the irrigation depth is greater than W_l, both irrigation alternatives resulted in the same net returns. Either way, water above W_l is not utilized well because it is decreasing total net return. As noted earlier, additional water beyond the yield maximizing irrigation water depth did not result in any yield increase. However, the cost of irrigation keeps increasing, which is the reason why the total net returns are diminishing under this region.

These results emanate from the observations from the irrigation data over the past ten years. However, it has to be borne in mind that there were a number of assumptions that guided the study, especially running the simulations in the AquaCrop model. For example, some of the major assumptions included that there were no nutrient deficiency at any stage of the crop's growth and development cycle; and that the crop did not face any competition for nutrients, sunlight and oxygen/carbon dioxide due to weed infestation. It is important to note as well that, as far as the assumptions made in this case were reasonable, it would be important to confirm the validity of such assumptions with field tests if there would be need to upscale the study.

Conclusion

The study has shown that the estate can use deficit irrigation (DI) to manage irrigation and water allocation within a field depending on water availability. The optimum water-limiting irrigation depth (W_w) was 120 mm and the optimum land-limiting depth (W_l) was 1,400 mm. When available water is less than W_w, it is recommended to apply an irrigation depth of W_w on a portion of the field and leave the rest of the field in rainfed conditions, which resulted in a relatively small increase (up to $ 5,490) in the total net returns for the field. However, it was also noted that this may not be a significant difference in total net returns, and it is unlikely that available water will be less than 120 mm. A more likely scenario would be that the available water depth would be greater than W_w but less than W_l; in this scenario it is recommended to apply the available water depth across the whole field. This resulted in a large increase (up to $208,000 in this research) in total net returns for the field compared to applying W_l on a reduced field area and leaving the rest of the field in rainfed conditions. When the available water depth is more than W_l, the best option would be to irrigate the whole field with a depth of W_l in order to maximize net revenue (not using all of the available water).

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