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DEFICIT IRRIGATION FOR CORN: A COMPARISON OF TWO METHODS

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ABSTRACT

The room for engineering aspects of water planning is increasingly limiting, which must lead to more efficient use of existing water supplies. In this study two methods of seasonal and intraseasonal approaches for deficit irrigation of corn at Bajgah, a semi-arid region, 16 km north of Shiraz, I.R. Iran were compared. In seasonal approach, time pattern distribution of applied water is not considered. Therefore, cost and benefit analysis is merely done on an annual basis. On the other hand, intraseasonal approach gains from applicability on decision making of water allocation at shorter duration of time periods. The results showed that intraseasonal method offered a higher allowable water reduction, which may lead to a more economical water use. Such comparisons have not been reported in literature up to now.

Keywords: Irrigation economics, Irrigation optimization, Seasonal and intraseasonal approaches.

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چکیده

جنبه های مهندسی برای برنامه ریزی آب که بایستی موجب مصرف کارآمد تر منابع آبی موجود شود به تدریج محدود می شود. در این پژوهش، روش های فصلی و درون فصلی برای کم آبیاری ذرت در ناحیه نیمه خشک باجگاه واقع در ۱۶ کیلومتری شمال شیراز در منطقه جنوب جمهوری اسلامی ایران مقایسه شدند. در روش فصلی، توزیع زمانی مصرف آب در دوره های مختلف رشد منظور نمی شود، بنابراین، تحلیل هزینه و درآمد تنها بر اساس نتایج سالانه انجام می شود. از طرف دیگر، در روش درون فصلی، قاعده تصمیم گیری برای اختصاص آب آبیاری در دوره های مختلف رشد به کارگرفته می شود. نتایج نشان داد که روش درون فصلی، کاهش آب مصرفی بیشتری را مجاز می داند که منجر به استفاده اقتصادی تر از آب می شود. تا کنون چنین مقایسه ای بین این دو روش گزارش نشده است.

INTRODUCTION

A major agricultural problem facing developing arid regions throughout the world is the inadequate supply of water for irrigation. Opportunities for augmenting water supply are being sharply curtailed by increasing costs of water in many developing regions. Consequently, water planning will focus less on engineering problems and more on the problems associated with the more efficient use of existing water supplies. Irrigation scheduling is commonly defined as when to irrigate and how much water to apply. Crop production is the objective of most irrigation systems. Plant water stress is often the main cause for depression of yield in semi-arid and arid regions, where the scarcity of water is dominant. Deficit irrigation is an optimization strategy under which crops are deliberately allowed to sustain some degree of water deficit and yield reduction. The fundamental goal of deficit irrigation is to increase water use efficiency, either by reducing irrigation adequacy or by eliminating the least productive irrigation at a certain crop stage. Management of deficit irrigation is fundamentally different from conventional irrigation management. Rather than minimizing crop water deficits, the irrigation manager must decide what level of deficit to allow and also recognize when that level has been reached. The potential benefits of deficit irrigation are derived from three factors:(i) reduced costs of production, (ii) greater irrigation water use efficiency, and (iii) the opportunity costs of water to be used in alternative ways. Use of the deficit irrigation concept requires an understanding of the significance of these factors. English (6) proposed a seasonal approach to deficit irrigation, which depends only on annual relationships of cost- and revenue-applied water. On the other hand, time distribution of applied water seems to play an important role in crop production, due to pronounced effects of water deficit at certain critical growth stages of crops. On the deficit irrigation issues, however, this study was conducted to make a comparison between these seasonal and intraseasonal approaches.

The Economics of Deficit Irrigation

There is a nearly linear relationship between evapotranspiration (ET) and yield, whereas a nonlinear equation governs for defining applied water-yield relationship. The latter may roughly parallel the former up to approximately 50% of full irrigation (13). At higher levels, the latter function begins to curve over, reflecting percolation and runoff losses that develop as applied water approaches full irrigation (22). If the increase in applied water is associated with higher irrigation frequencies, evaporation from wet soil surfaces will also increase (2) which may decrease the water use efficiency. Beyond the maximum yield, factors such as lodging, reduced aeration in the root zone, leaching of nutrients, and diseases associated with wet soils may reduce yield (25).

In a similar manner, total cost-applied water relationship (total cost=fixed cost+variable cost; see Eq. [8], referred to latter) has a linear nature, but revenue-applied water relationship (revenue=gross profit) is nonlinear in nature. Profit-applied water relationship (profit=revenue-total cost) has usually a distinct maximum. Depth of applied water associated to this point, W_m, represents the yield at maximum irrigation level. Applying more water will reduce the profit, as the cost and revenue curves converge. Also, profit diminishes as depth of applied water is short of W_m .

Two different situations may be distinguished. If land is limited while the water supplies are not, maximum economic efficiency occurs when the cost of an additional unit of water just equals the value of the resulting increment of yield. However, the associated water depth, W_1, is less than W_m. The second situation depicts the limitation of water supplies. In this case, water saved by deficit irrigation could be used to irrigate a competing crop in a mixed crop system. The potential increase in farm income that would result is an opportunity cost associated with water. Under such circumstances, farm profits will be maximized by reducing the amount of water applied per unit of land and increasing the amount of land under irrigation until the marginal profit per hectare, multiplied by the number of hectares irrigated, just equals the total profit per hectare (6). This optimum point is associated with a water depth of w_w.

Yield functions, in particular, tend to be quite uncertain (7). It is difficult to estimate spray losses, deep percolation and runoff, particularly when the variability of the weather, soil topography, uneven storage of water in the root zone, and crop are considered. The applied water-crop yield relationship is therefore uncertain, and that uncertainty implies economic risk. English (5) concluded that some farmers would select water use strategies that may be very different from profit maximizing strategies in order to reduce risk.

The effects of water deficits at certain critical growth stages can be quite pronounced (4) which is not considered in English's (6) approach. The latter implies that when seasonal irrigation water for a crop is decreased, such a decrease is propagated just uniformly through all irrigation events with a similar rate, which may not be the optimum allocation of water. To incorporate uneven irrigation scheduling, the dated water production functions needs to be fully defined.

MATHEMTICAL OPTIMIZATION

Researchers have derived algorithms for optimum water use for a single crop or field (3, 6, 9, 10). Two different approaches are considered here:

Seasonal Approach

In this approach, English (6) derived the following formulas for water-not limiting and water-limiting conditions, respectively:

$P_c\ \partial Y/\partial W=\partial C/\partial W$ **[1]**

$W(P_c\partial Y/\partial W-\partial C/\partial W)=P_cY-C$ **[2a]**

where P_c is price per unit of crop, *W* is depth of applied water, and *Y* and *C* are yield and total production costs, respectively, per unit of land, while both are definite functions of applied water.

Eq. [1] is an expression of an axiom of economics: the optimum occurs at the point where the marginal cost of production equals the value of the marginal product. The left-hand side of Eq. [1] is an expression for the value of the marginal product, while the right-hand side is the marginal cost. This enlightens a fact that the optimum water use will occur at the point where the slopes of the two curves of gross revenue and total cost are equal, when land is the limiting factor.

The economic relationship of Eq. [2b] is somewhat different. This equation can be rewritten as follows (6):

$-A\partial i_1(w)/\partial w=i_1(w)\partial A/\partial w$ **[2b]**

where $i_1(w)$ is net income per hectare as a function of water use, and A is the irrigated area ($A=W_t/w$, where W_T is total available water supply, and w is water applied per unit of land). Suppose water use is reduced by a small amount on all fields of a farm, and the water thus saved is used to irrigate an additional increment of land. The expression on the left side of Eq. [2b] would then represent the cumulative reduction in income from all of the originally irrigated land, while the right-hand side is the income derived from irrigating the additional increment of land. When these quantities balance, the optimum level of water use has been reached.

Intraseasonal Approach

A dated water production function with all variables other than water held at a constant level can be written as $Y=g[f_t(w_t)]$ where Y is the crop yield, w_t is the amount of water applied at stage t, and f and g are some arbitrary functions. Modeling of crop-water production functions requires a theoretical framework concerning the relationships between the soil, irrigation water, and crop response. Detailed reviews of crop-water production function studies and the underlying theoretical frameworks can be found in Vaux and Pruitt (28). Nearly all crop-water production functions are derived in the developed countries. Transferring such functions from developed to developing countries is not simple and needs many subtle points to be considered (24). However, changing applied water (as an independent variable) to either soil moisture or evapotranspiration provides some degrees of site transferability. From the viewpoint of Soltani *et al.* (24), for the more immediate run, the evapotranspiration model developed by FAO (4) seems promising. These authors proposed that the Jensen's equation (16) is also suitable, as far as transferability is concerned. This equation is as follows:

$$Y_a/Y_p=\Pi i\ (ET_a/ET_p)^{\lambda}{}_i \qquad [3]$$

where Y is yield, λ is yield sensitivity index, a and p indices are denoting actual and potential conditions, respectively, and i is an index of growth stage. Multiplicative form for crop water production function (e.g. Eq.[3]) is claimed by some authors (e.g. 11, 12, 20). On the other hand, others defend an additive approach (8, 14, 26). Although it is not known in advance which form is more correct, the major drawback of the additive forms is that they can not predict the plant death as a result of zero crop evapotranspiration at some definite growth stages, while the other form can do. Despite the popularity of such models (4, 16) for irrigation scheduling (27), they have some limitations, particularly when used in developing countries. Two major limitations are that, in relating empirical yield to ET, all other factors are assumed to be non-limiting and all climatic and management variables are assumed to be reflected in the estimated value of potential yield achievable under potential management practice (24).

Nairizi and Rydzewski (21) and Meyer *et al.* (19) approximated the ET_a (Eq.[3]) by applied water (W_a). In this case, partial irrigation in arid and semi-arid regions may lead to a different result only for the first irrigation (at the beginning of the growing season), since the soil water reserve may supply some water for plant needs. However, in succeeding irrigations, the readily available soil water is depleted before each partial irrigation is applied and W_a is considered as the amount of applied water. For a deficit irrigation, the total seasonal irrigation requirement (ΣET_p) is reduced by a fraction of x ($\lambda<1$). So the total seasonal water that can be allocated to specific crop would be:

$$\Sigma(Wa)=(1-x).\ \Sigma(ET_p) \qquad [4]$$

It is consistent to impose some logical bounds to each Wa as follows:

$$0\leq= Wa<=ET_p \qquad [5]$$

Equation [3] depicts an optimization model which Eqs. [4] and [5] form its constraints. This model is a nonlinear one. and its solution can be found in any optimization textbook (e.g. 17). Ghahraman and Sepaskhah (9) addressed the details of solution by Lagrangian multiplier for winter wheat and spring barley.

English (6) used mathematical approach for optimum level of water depth under a water limiting condition in a seasonal model (Eq.[2]). However, such an approach is needed for intraseasonal model, based on economical analysis.

The relative yield decreases according to x values, but the total area farmed can be increased by a factor of 1/(1-x). Therefore, the relative net benefit (Z) of a farm (whole farm profit under deficit irrigation divided by unit area farm profit under full irrigation) will change as follows:

$$Z=[(B/C)(Y/Y_p)-1]/\{(1-x)[(B/C)-1]\} \qquad [6]$$

For a fixed amount of revenue and cost (B and C, respectively) for a specific crop in a specific region, Z is a function of x. Deficit irrigation can be prescribed in a domain for x as far as Z>1. The assumptions in this analysis are: (1) there is no interaction between stages of growth, and the analysis is applicable to determinate crops; (2) irrigation water can be applied at any moment on request; (3) rainfall during the growing season is

negligible; and (4) deficit irrigation just decreases the quantity of yield, its quality is either unaffected or it does not change the sale price.

Study Location and Crop Specifications

The theory presented was applied for corn (*Zea mays* L.) at Bajgah, 16 km north of shiraz (Fars province, I.R. Iran) at 29° 31′ N and 52 ° 35′ E, and 1810 m elevation. Malek (18) has classified the climate of the study area as semi-arid. The chronology of the various growth stages and yield response factors of corn were reported by Honar and Sepaskhah (15) and are shown in Table 1. A line source sprinkler irrigation experiment was managed by Sepaskhah *et al.* (23) to measure Y_a/Y_p at various water reduction fractions. The water requirement of this crop was estimated by the Penman-Monteith method (1) and modified crop factors, K_c, (2) and the results are given in Table 1.

Table 1. Some characteristics of corn at Bajgah.

Physiological stage	λ	ET_P, mm
Establishment	0.01	71.4
Early vegetation	1.42	248.1
Late vegetation	5.81	178.7
Flowering	0.99	314.0
Yield formation	0.05	23.4

RESULTS AND DISCUSSION

Seasonal Approach

A regression line was fitted to measured yields Y (t ha^{-1}) and applied seasonal irrigation water W (cm), the result of which is as follows (the data are from 15):

$$Y=127.6-8.7*W+0.207*W^2-0.002*W^3+6.85*10^{-6}*W^4-2.81*10^{-41}*W^5 \qquad [7]$$

In spite of high correlation (R^2, coefficient of determination, =0.916, n=19), the measured points are highly scattered around the best-fit curve (Fig. 1). Total cost (C, Rls ha^{-1}) of production is composed of two items of fixed costs and variable costs. Based on a local survey, the fixed cost amounts to

1266970 Rls ha^{-1} (8000 Rls equal one US Dollar). So, based on a cost of water of 15.55 Rls/m^{-3}, the total cost-applied water relationship may be written as:

$C= 1266970+1555*W$ [8]

The mild slope of this line is mainly due to low irrigation water costs. The derivative of Eq. [7] was set equal to zero. Therefore, W_m was determined to be 77 cm. Applying Eqs. [1] and [2] combined with yield and cost functions (Eqs. [7] and [8], respectively), W_l=76.8 cm and W_w=73.3 cm would result. The latter figure means that under limited water supply, a 4.8% reduction in the amount of applied water is an optimum policy. A conclusion can be made from these figures that due to low irrigation water costs, the values of W_w and W_l are close to each other. Meanwhile, the finding of $W_w < W_l$ seems reasonable. Some important factors such as similarities of derived applied irrigation waters by the two different procedures, the highly scattered measured points (Fig. 1), high sensitivity of corn to water deficit (Table 1), and high dependence of corn yield to applied water lead to a conclusion that by seasonal approach, deficit irrigation may be a questionable practice.

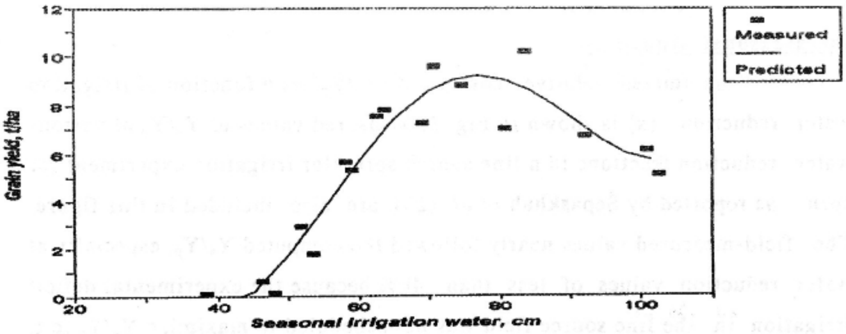

Fig. 1. Variability of yield as a function of seasonal irrigation water.

On the other hand, if cost of water increases, the optimum irrigation depth would change accordingly. For water costs of 20, 100, 200 and 500 Rls m^{-3} the optimum seasonal irrigation depths were 73.38, 73.94, 74.62, and 76.78 cm. It is observed that water cost and optimum irrigation water are in phase with each other. However, the variation in optimum amount of water is not significant. A graphical representation of net benefit (profit) and seasonal

irrigation water based on different costs of water is presented in Fig. 2. The plotted curves in this figure were drawn through computation, not by direct shift. Therefore, it is concluded that with increasing cost of water there will be less chance for prescribing deficit irrigation, as far as a seasonal approach is concerned.

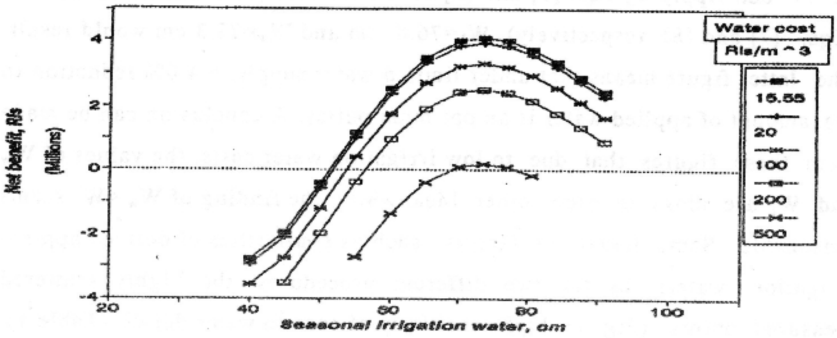

Fig. 2. Variabillity of net benefit with different seasonal irrigation water and water cost.

Intraseasonal Approach

The maximized relative corn yield (Y_a/Y_p) as a function of irrigation water reduction (x) is shown in Fig. 3. Measured values of Y_a/Y_p at various water reduction fractions in a line source sprinkler irrigation experiment for corn, as reported by Sepaskhah *et al.* (23), are also included in this figure. The field-measured values nearly followed the computed Y_a/Y_p, especially at water reduction values of less than 40% because the experimental deficit irrigation in the line source field was not scheduled to maximize Y_a/Y_p (c.f. Fig. 4). The field measured values at the right of the line source experiment, however, deviate more from the calculated curve (Fig. 3) which may be attributed to the wind distorting phenomena.

The relative net benefit (Z) as a function of water reduction (x) and various values of revenue to cost ratio (B/C) are shown in Fig. 5. Although a B/C ratio of greater than two may be unrealistic in real conditions, but it is probable to occur at low water costs (Table 2). It is concluded that at B/C ratio of 2, about 9% water reduction is allowed which results in no loss in

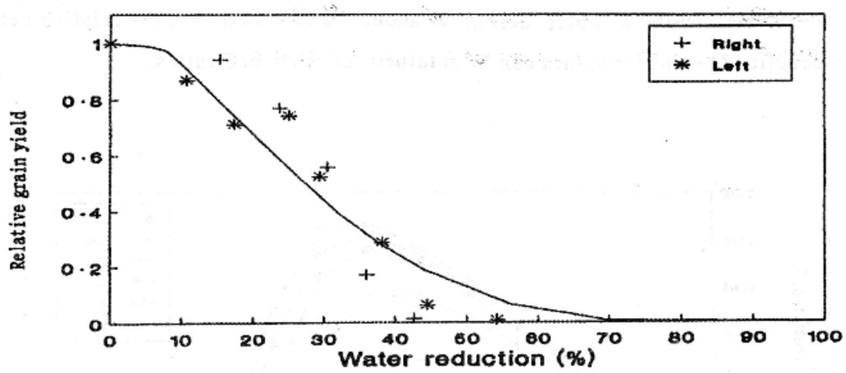

Fig. 3. Maximized relative grain yield of corn at different water reductions. Measured points are from Sepaskhah *et al.* (23).

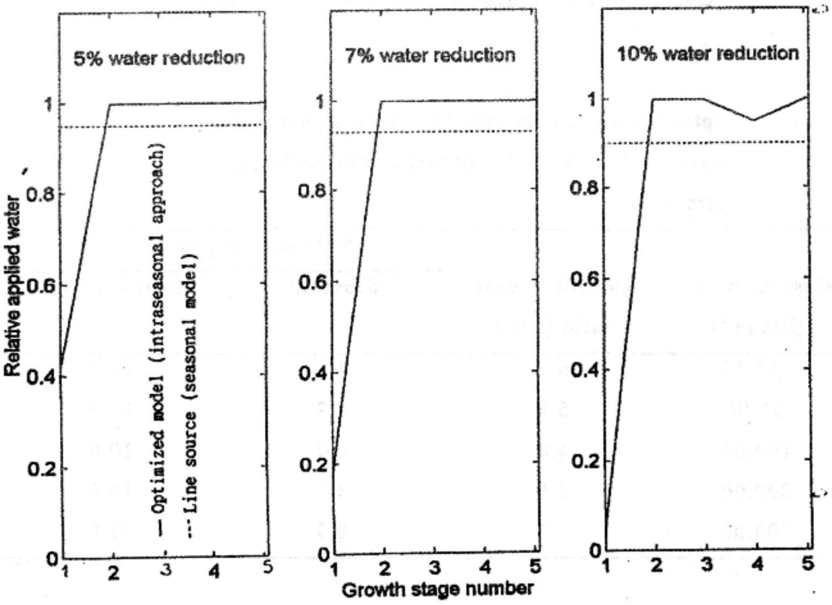

Fig. 4. Relative applied water at different corn growth stages (Table 1) and under two methods of intraseasonal and seasonal (line source).

net benefit (deficit irrigation can be prescribed economically in a domain of $0 \leq x \leq 9\%$), while a water deficit of about 7% can maximize the relative net benefit (Z). Similar values can be obtained for other B/C ratios.

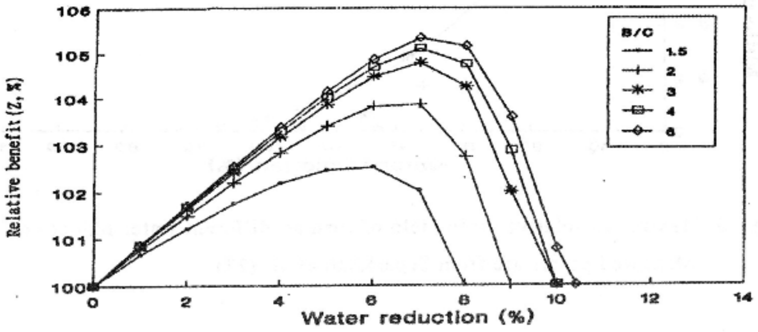

Fig. 5. Relative net benefit at different water reductions and B/C ratios.

Table 2. optimum water reduction (%) for seasonal and maximum allowable water deficit (%) for intraseasonal method and at different water prices.

Cost of water (Rls m^{-3})	Benefit to cost ratio (B/C)	Method of approach	
		Seasonal	Intraseasonal
15.55	6.1	4.8	10.5
20.00	5.9	4.7	10.5
100.00	4.0	4.0	10.0
200.00	2.9	3.1	10.0
500.00	1.6	0.3	8.1

CONCLUSIONS

Table 2 shows the optimum water reductions under seasonal approach and the maximum allowable water deficit under intraseasonal approach at different water prices. This table shows that the figures differ by more than two fold. As cost of water increases, however, the differences become more noticeable. Although intraseasonal approach is relatively insensitive to water cost changes (about 30% for water cost of 15.55 to 500 Rls m^{-3}), but this is not the case for the other approach. In fact, the seasonal approach presents a drastic change in optimum water reduction as the water cost increases from 15.55 to 500 Rls m^{-3}.

It seems that due to the fact that the two methods differ in theoretical aspects, the results show that there is a remarkable difference (more than two fold) between the results of allowable water reduction obtained by these two scenarios for corn. Such a finding had not been reported elsewhere, and so it is the main contribution of this paper. As corn is a highly water sensitive crop (Table 1), the allowable water reductions for both methods are low (Table 2). This result seems reasonable under field conditions. But, the more clear conclusion on the selection of the best method can be made after more data are analyzed for various crops, climates and economical conditions.

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