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WATER MANAGEMENT STRATEGIES UNDER DEFICIT IRRIGATION

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1. Introduction

Water is becoming scarce, both in quantity and quality, not only in traditionally prone arid and semi-arid zones, but also in regions where rainfall is abundant. Agriculture represents the major user worldwide, and a general perception that agricultural use is often wasteful and has less value than other uses is widespread [39]. Furthermore, energy analysis of agricultural operations has shown that irrigation consumes a significant amount of energy as compared to other operations [49]. For these reasons, there is an urgent need to use water resources efficiently by enhancing crop water productivity.

Deficit irrigation (*DI*), the application of irrigation rates below the full crop evapotranspiration (*ET*), is potentially able to improve efficiency and maximize profits through a reduction in capital and operating costs. Although the *DI* concept dates back to the 1970s [11, 13, 25], and the theoretical basis and analytical frameworks for *DI* are well established [12, 13], this technique is not usually adopted as a practical alternative to full irrigation by either academics or practitioners. An obstacle is related to the need for precision irrigation required by *DI* strategies, the use of highly efficient irrigation systems, and prediction of the cost function and crop price. Considering that this knowledge spans a wide range of disciplines, from eco-physiology and plant sciences to hydrology, engineering and economics, the approach to *DI* may often be hard. Another reason for the slow progress of DI is the risk associated with the uncertainty of the knowledge required [12]. Uncertainty is associated with optimal water use estimation, e.g. lack of accuracy in crop *ET* data; no a priori information about the production function or data available only for specific locations or seasons or very few years. Generally, a priori crop production function data is missing due to a number of unpredictable factors such as climate change, irrigation system failure, germination rates, or disease impact.

Furthermore, the amount of irrigation water for certain crop yields depends on the irrigation scheduling strategy. Published results of experimental research into crop response to water and progress in hydrological and crop growth/yield models could contribute towards the application of *DI* strategies. The uncertainty discussed above implies risk. English et al. [12] suggest that simulation models could be used not only to predict optimal levels of irrigation water but also to quantify prediction uncertainties.

Finally, in the literature there is a certain amount of confusion regarding the *DI* concept and, as described in the following section, the term *DI* is used indifferently for different water management strategies.

The aim of this paper is to synthesize the basic concepts and the main techniques of *DI* and to present the main research results. The paper includes, as an example, a short description of a recent experimental research project conducted by the authors, which integrates agronomic, engineering and economic aspects of *DI* at farm level.

2. Concepts and techniques of deficit irrigation

The concept of deficit irrigation was introduced as an economic concept in the 1970s [25] and the first research appeared in the early ’80s [11, 20]. English [12, 13, 14] defines *DI* as the deliberate and systematic under-irrigation of crops to achieve, under some circumstances, the maximum attainable income for an irrigated field. Lecler [28] made the definition of English more explicit: *DI* is an optimization strategy whereby net returns are maximized by reducing the amount of irrigation water applied to a crop to a level that results in some yield reduction caused by water stress. Other authors deal with *DI* as an irrigation strategy to maximize yield with a minimum rate of water application and only deal with the physiological and agronomical

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aspects of *DI* (crop response to different irrigation regimes) without any economic evaluation.

In the latter case, it is more appropriate to use the term Regulated Deficit Irrigation (*RDI* or *CDI* - Controlled Deficit Irrigation as introduced by [13]) for irrigation strategies based only on a reduction of irrigation amounts during certain plant cycle phases [7]. Research into *RDI* could also concern the crop coefficient (K_c) in different phenological phases. This kind of study is a fundamental step (but not the only one) to implement *DI* strategies. In fact, the analyst must rely on a crop production function that links water use to crop yield in order to plan, design or manage irrigation systems under *DI*. Another strategy, initially used for grapevines [9], is Partial Root Drying (*PRD*), an irrigation technique by which half of the root zone is kept under dry soil, alternating irrigation from one half to the other.

A review of about 100 papers recently published in major international journals (most of which are cited in the References) has shown that only a few [12, 23, 24, 32, 38, 43, 44] use the English definition in its complete sense (e.g. by analysing the economics of *DI*).

2.1 *Economics of deficit irrigation*

Recognition of the following key factors is extremely important to understand the potential benefits of *DI* [12, 13, 28]: the efficiency of irrigation water decreases as the application depth increases; irrigation water application is expensive; the water saved by reducing irrigation depth may allow to extend the amount of irrigated land (opportunity cost of water); the determination of an optimal irrigation strategy depends on whether a land or water shortage is the limiting production factor.

DI increases water use efficiency for several reasons [22, 44]. Firstly, an increase in application efficiency occurs when the amount of water applied is lower than full *ET*, because (most or all of) the applied water remains in the root zone (e.g. water losses due to run-off and deep percolation are reduced). The consumption efficiency (i.e. the ratio between the amount of evapotranspired water and the amount of water in the root zone) may increase because crops are forced to extract higher water levels from the soil. Furthermore, the yield efficiency (i.e. the proportion of biomass in the harvested product) may be enhanced due to an excessive vegetative growth of some crop species (cotton and grapevines, for example) under full irrigation.

The relationship between irrigation water (w) and crop yield (y) may be generally expressed by a quadratic form equation (Figure 1),

$$y(w) = a_1 + b_1 w + c_1 w^2 \qquad (1)$$

The estimated revenue from irrigation (R), obtained by multiplying the production function by a constant (crop price, P_c), has the same form as the production function (curved line in Figure 2),

Fig. 1 - General form of crop production function.

$$R(w) = P_c \cdot y(w) \qquad (2)$$

The straight line in Figure 2 represents a possible function relating total production costs (c) to applied water:

$$c(w) = a_2 + b_2 w \qquad (3)$$

When different water depths modify both yield and crop cycle length, the cost function may be nonlinear [4, 6].

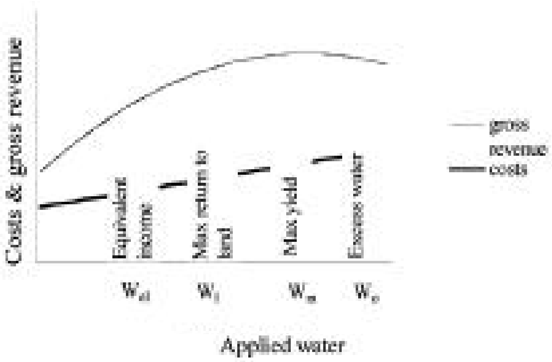

Fig. 2 - Cost and gross revenue functions versus applied water.

The vertical axis intercept, a_2, is associated with fixed costs: capital costs, taxes, insurance, fixed costs of tillage, planting, chemical use and harvesting. The slope represents the marginal variable costs of production that include variable costs of irrigation (water costs, pumping costs, labour and maintenance) and other costs based on yield variation with water use (costs associated with fertilizers, when farmers adjust them for the expected crop production, harvest costs, etc...). English et al. [12] recommend to analyse both the direct costs of irrigation and the other production costs. Incomplete cost analysis may lead to underestimation of the optimal deficit magnitude and the related potential gain in net income. The upper limit represents the maximum water delivering capacity of the system. When saved water, obtained by reducing water depths, can be used to irrigate additional land, farmers can increase their income. This potential increase represents the opportunity cost of the water. For example, 50 mm of water could be applied to 1 ha, or 25 mm could be applied to 2 ha, thus producing an increase in total profit.

If land is limited, the main concern is what irrigation depth produces the maximum difference between costs and yield return. Since the optimal level of irrigation (when land or water are limited) requires less water than the level maximizing yield, the system may have a lower capacity and lower capital costs. As shown in Figure 3, a lower cost function corresponds to a higher difference between costs and yield return (net return). Obviously, a lower system capacity represents a limitation in certain situations, for example when several crops are irrigated in rotation and deficit irrigation strategies can only be applied to some of them.

The optimum water depth level will be the one that allows maximum profit per water unit or per land unit, depending on whether water or land is the limiting factor.

English [13] identified the following five optimum levels of applied water, which provide maximum food production or profit with a limited availability of resources (e.g., land or water):

a) level at which crop yield per unit of land is maximized, W_m

b) level at which net income per unit of land is maximized, W_l

c) level at which net income per unit of water is maximized, W_w

d) level at which net income equals that at full irrigation when land is limited, W_{el}

e) level at which net income equals that at full irrigation when water is limited, W_{ew}

At the W_m level (see figure 2), the application of additional water does not increase yield, thus the marginal water use efficiency is zero. Marginal water use efficiency increases as water depth decreases.

Profit per unit of land reaches its maximum when the level of applied water is W_l; at this point the cost line slope equals that of the revenue line and the net income per unit of water (difference between revenue and cost) is maximum. Within the range between W_l and W_m growers may benefit from cost reductions. If additional land can be irrigated, the optimal water use strategy to maximize profit could be to irrigate below W_l, indicated as the W_{el} level. At optimal levels W_{el} (land-limiting case) and W_{ew} (water-limiting case) the vertical difference between the revenue and cost lines equals that at level W_m. Within the range between W_{el}, for the land-limiting case, or W_{ew}, for the water-limiting case, and W_m (named range of profitable deficits) the net income associated with the level of deficit is at least as great as it is at full irrigation.

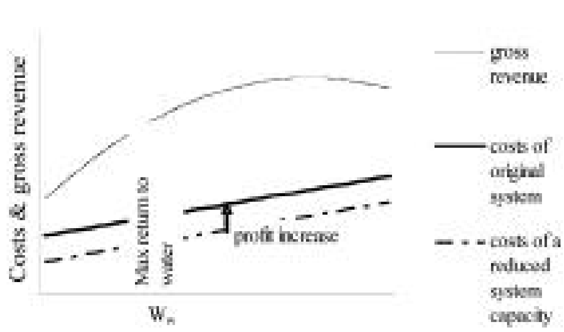

Fig. 3 - Effects of reduced system capacity

English [13] derived general expressions to estimate the above-mentioned optimal application levels. Assuming that the production function has a quadratic polynomial form (see eq. 1) and the cost function has a linear form (see eq. 3), the author proposed the following explicit expressions (eq. 4 to eq. 10) for W_m, W_l, W_w, W_{el} and W_{ew}.

$$W_m = -\frac{b_1}{2c_1} \tag{4}$$

$$W_l = \frac{b_2 - P_c b_1}{2P_c c_1} \tag{5}$$

$$W_w = \left(\frac{P_c \cdot a_1 - a_2}{P_c \cdot c_1}\right)^{1/2} \tag{6}$$

$$W_{el} = \left(\frac{b_2 - P_c b_1 + Z_1}{2P_c c_1}\right) \tag{7}$$

with

$$Z_1 = \left[\left(P_c b_1 - b_2\right) - 4P_c c_1 \cdot \left(\frac{P_c b_1^2}{4c_1} - \frac{b_1 b_2}{2c_1}\right)\right]^{1/2} \tag{8}$$

$$W_{ew} = \frac{-Z_2 + \left[Z_2^2 - 4P_c c_1 \left(P_c a_1 - a_2\right)\right]^{1/2}}{2P_c c_1} \tag{9}$$

with

$$Z_2 = \frac{P_c b_1^2 - 4a_2 c_1 + 4P_c a_1 c_1}{2b_1} \tag{10}$$

Furthermore, equations (12) to (17) can be used when both the production (see eq. 1) and cost (eq. 11) functions have a quadratic form [4].

$$c(w) = a_2 + b_2 w + c_2 w^2 \tag{11}$$

$$W_l = -\frac{b_2 - P_c b_1}{2\left(P_c c_1 - c_2\right)} \tag{12}$$

$$W_w = \left(\frac{P_c a_1 - a_2}{P_c c_1 - c_2}\right)^{1/2} \tag{13}$$

$$W_{el} = \left(\frac{b_1 - P_c b_1 + Z_1}{2\left(P_c c_1 - c_2\right)}\right) \tag{14}$$

with

$$Z_1 = \left[\left(P_c b_1 - b_2\right) - 4\left(P_c c_1 - c_2\right)\left(\frac{b_1\left(P_c b_1 - b_2\right)}{2c_1} - \frac{b_1^2\left(P_c c_1 - c_2\right)}{4c_1^2}\right)\right]^{1/2} \tag{15}$$

$$W_{ew} = \frac{-Z_2 + \left[Z_2^2 - 4\left(P_c a_1 - a_2\right)\left(P_c c_1 - c_2\right)\right]^{1/2}}{2\left(P_c c_1 - c_2\right)} \tag{16}$$

$$Z_2 = \frac{4\left(P_c a_1 - a_2\right)c_1^2 + b_1^2\left(P_c c_1 - c_2\right)}{2b_1 c_1} \tag{17}$$

The range of profitable deficits (e.g. the range between W_m, the yield maximizing level, and W_{el} or W_{ew}, the levels of *DI* where net income will at least equal that at full irrigation) is a qualitative indication of potential risk. The narrower the range of profitable deficits, the higher the risk of error and reductions in income. In the scientific works on *DI* [among others: 12, 13, 23, 30, 39, 41, 42, 44] the authors analysed the potential benefits of *DI* and the range of profitable deficits in different contexts: wheat in North-Western USA, cotton in California, maize in Zimbabwe, winter broccoli, carrot, rape and cabbage in Botswana, barley and sorghum in Iran, almond orchards in South-Eastern Spain. The main results (see Table 1) showed optimal net return with a deficit of 15-59%.

Author	Year	Region	Strategy	Crop	Main effects
[13]	1996	NW USA, California, Zimbabwe	DI	wheat, cotton, maize	optimal net return with 15-59% deficit
[27]	2000	Botswana	DI	broccoli, carrot, rape, cabbage	optimal net return with 20% deficit
[16]	2003b	Spain	CDI	garlic	negative effects in the bulbification and ripening stages
[17]	2003a	Spain		beet	no effects on total production and industrial quality index
[60].	2003	Japan	RDI	potato	decrease in tuber quantity, some positive effects on tuber quality
[32]	2004	Turkey	PRD	greenhous e tomato	10-27% additional marketable yield over DI
[52]	2004	Iran	DI	barley, sorghum, maize	optimal net return with 0.6 irrigation efficiency
[9]	2005	New Zealand	PRD	pepper	no effect on total dry mass, significant water savings
[20]	2005	Spain	RDI	peach	no effects on fruit production
[58]	2005	Morocco	PRD+RDI	bean	decrease in leaf water potential, shoot and pod biomass
[50]	2006	Spain	DI	almond	45% of water saved using RDI with a maximum production reduction of 17%
[35]	2006	Denmark	PRD+RDI	potato	increase in biomass allocation to root; decrease in leaf area; 37% water saved
[56]	2006	Thailand	PRD+RDI	mango	decrease in yield, increase in fruit size and edible fraction
[59]	2006	Uzbekista n	DI	bean, green gram	Water use efficiency (WUE) increase for green gram and constant for bean
[61]	2006	China	RDI	spring wheat	increase in yield, biomass, harvest index and WUE
[2]	2007	Ethiopia	RDI	onion	6-13% increase in WUE
[53]	2007	Denmark	PRD	potato	30% of water saved maintaining tuber yield, 61% increase in WUE

TABLE 1 - Review of the main Deficit Irrigation strategies in the literature.

2.2 *Regulated deficit irrigation (RDI) and Partial root drying (PRD)*

Regulated Deficit Irrigation (*RDI*) uses water stress to control vegetative and reproductive growth and it generally imposes water deficits during crop growing phases that are not yield reducing [2, 7, 17, 18, 27]. Precision irrigation strategies, e.g. microirrigation, are paramount for a successful application of *RDI*, as well as timing control and soil water level monitoring. This practice has been adopted successfully for tree crops and mainly for grape [19, 33], peach [7], pear [36] and almond [42] production. Among herbaceous crops, *RDI* has been applied to cotton [47], garlic [16] sugar beet [15, 35] and tomatoes [21]. The reviewed literature (see Table 1) evidenced some relevant factors (both positive and negative) affecting the choice of RDI: it admits furrow irrigation; it controls vegetative growth; fruit size and quality can be achieved; positive effects mainly on grape and wine quality were achieved; it causes potential yield losses; it permits water savings; soil water monitoring is recommended.

In Partial Root Drying (*PRD*), a percentage of crop evapotranspiration is applied to alternate plant sides, allowing part of the root system to be in contact with wet soil. In the literature (see Table 1) *PRD* allows an increase in water use efficiency and a decrease in vegetative vigour without significant reductions in crop yield [9, 10, 29, 30, 34]. The beneficial effects of *PRD* are hypothesised to be due to a reduction in stomatal conductance and growth by chemical signals, possibly abscissic acid (*ABA*) synthesized by roots and transported to the leaves in the transpiration stream [31].

The main factors that may affect the choice of *PRD* are the following: drip irrigation is preferred; alternate row furrow irrigation is possible; no effects on fruit size; vegetative growth can be controlled; positive effects on crop quality; significant water savings; significant cost increase due to doubling laterals in cases where it is not necessary for technical reasons; soil water monitoring is recommended.

3. Application of an integrated agro-economic approach to DI on lettuce crops in Sicily (Italy)

3.1 *Methodology*

In the experiment, the effect of four different irrigation levels on the marketable yield and economic return of summer-growth lettuce was evaluated [5, 6]. The field trial was carried out in a randomized design experiment using *Lactuca sativa L.* (*Batavia rossa* variety *Emini)* during two consecutive summer crop production cycles (2005 and 2006). The experimental site is located in Biancavilla, a small village in Eastern Sicily (latitude 34°93' N, longitude 15°80' W and altitude 500 m above sea level). The lettuce crop was planted at a spacing of 0.25 m x 0.25 m in an area of about 400 m^2; each experiment consisted of four irrigation levels (125%, 100%, 75% and 50% of actual evapotranspiration, ET_a) with four replications. The crop was irrigated by a surface drip irrigation system with polyethylene pipes 16 mm in diameter with in-line labyrinth drippers (discharge rate of 2 or 4 l h^{-1} at a pressure of 101.2 kPa). At the beginning of each experiment, system emission uniformity (*EU*) was determined according to [26], showing values higher than 90%. At the end of the crop growth cycle marketable plants from each treatment plot and replication were weighed and the production loss percentages were evaluated.

Actual evapotranspiration (ET_a, mm/d) was estimated by combining pan evaporation measures (eq. 18) and the Penman-Monteith approach (eq. 19).

$$ET_{0-PAN} = E_{PAN} \times K_p \quad (18)$$

$$ET_{0-PM} = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (19)$$

The coefficient K_p was calculated with an equation from Allen et al., (1998) [1].

Following the Bouchet approach [3, 37], on days when the crop is well watered the evapotranspiration rates (potential, crop and actual) are almost equal. When the soil dries off, the plants begin to show some stress and ET_a drops below ET_{0-PM} by an amount equal to ET_{0-PAN}-ET_{0-PM}.

$$ET_a = ET_{0-PM} - (ET_{0-PAN} - ET_{0-PM}) \quad \text{if} \quad ET_{0-PAN} \geq ET_{0-PM} \quad (20)$$

$$ET_a = ET_{0-PM} \quad \text{if} \quad ET_{0-PAN} < ET_{0-PM} \quad (21)$$

The use of the Priestley and Taylor (1972) equation, instead of eq. 19, represents a valid alternative to determine reliable values of the reference evapotranspiration rate [37].

During the monitoring periods soil water samples were collected near the emitter at 0.20, 0.40 and 0.60 m from the soil surface and gravimetric water analyses were carried out in order to reveal any reduction in soil water content. A spatial description of plant growth was determined by i*n situ* measurements of leaf area index (*LAI*) using a LICOR ® LAI-2000 portable canopy digital analyzer.

Economic factors concerning gross return (eq. 2) and total costs (eq. 3) were assessed to test the viability of deficit irrigation criteria. Net return was calculated by subtracting total cost from gross revenue. The five levels of optimal applied water described in Section 2.1 (W_m, W_l, W_w, W_{el} W_{ew}) were evaluated (see eq. 4 to eq. 10 for linear cost function and eq. 12 to eq. 17 for quadratic cost function).

3.2 *Results and discussion*

The total irrigation water applied to the field was: 76, 113, 146, 175 mm (in 2005) and 68, 96, 120, 150 mm (in 2006) for the 50%, 75%, 100% and 125% treatments respectively.

Lettuce crop water needs were underestimated using the ET_a-based approach. In fact, the maximum yield values were for the 125% ET_a treatment (corresponding to almost 100% ET_{0-PM}). The ratio between the total water received by the crop (*IW* 125%) and ET_{0-PM} was almost equal to 1 (as specified in *FAO* publications). Leaf area index (*LAI*) values and soil water contents at selected field locations confirmed some water stress during the middle-end crop growth phases [6].

The average lettuce weight MW (equal to about 0.55 kg in 2005 and 0.53 kg in 2006) was influenced by the different rates of applied irrigation water (Table 2). The maximum marketable yields were about 55 t ha^{-1} in 2005 and 51 t ha^{-1} in 2006; these values, corresponding to about 180 mm, were recorded in the 125% treatment plots (100% ET_{0-PM}). Compared to the maximum, the marketable yield decreased by about 6, 12 and 24% in 2005 and 7, 14 and 30% in 2006, for the 100%, 75% and 50% treatments respectively. Mean plant weight decreased by about 5, 8 and 18% in 2005, and 7, 14 and 32% in 2006. Non-marketable yield increased with an increase in water deficit levels, but the differences between the treatments were not significant.

The regression coefficient values (R^2) show strong polynomial relationships between marketable yield (TMY, t ha^{-1}) and total water received (*TW*, mm, which includes rainfall) for both 2005 (eq. 22) and 2006 (eq. 23):

$$TMY = -0.00054TW^2 + 0.2653TW + 25.369 \quad R^2 = 0.996 \quad (22)$$

$$TMY = -0.0015TW^2 + 0.6136TW - 8.6849 \quad R^2 = 0.996 \quad (22)$$

Following the curves of eqs. (22) and (23), maximum lettuce yield would have been obtained up to approximately 250 mm and 200 mm (W_m) during 2005 and 2006 respectively, with corresponding production values of about 57.9 and 54.0 t ha^{-1}. These yield values would have been obtained by increasing irrigation rates by about 40% in 2005 and 12% in 2006 with respect to 100% ET_{0-PM} replenishment. The corresponding increases in crop yield would have been less than 5%.

The best sustained cost (C, Euro ha^{-1}) curve form resulted in quadratic and linear curves in 2005 and 2006 respectively:

$$C = 0.0121TW^2 - 2.5453TW + 14083 \quad R^2 = 0.999 \quad (24)$$

$$C = 1.2189TW + 13960 \quad R^2 = 0.998 \quad (25)$$

Table 3 lists the optimal levels of applied water as proposed by English (1990) and English and Raja (1996). In the land-limiting case, the estimated optimal economic levels were quite similar to optimal agronomic levels.

In the water deficit case (if land is abundant), the optimal irrigation strategy was that of under-irrigation by 49% ET_{0-PM} and 90% ET_{0-PM}, thus obtaining water savings of about 51% in 2005 and 10% in 2006. Deficit irrigation ranges, at least as profitable as full irrigation, were 17-49% ET_{0-PM} and 71-90% ET_{0-PM} in 2005 and 2006 respectively; within the described

		TMY (t ha⁻¹)		N-TMY (%)		MW (g)	
Year	Treatment	Mean	σ	Mean	σ	Mean	σ
2005	125%	55.3 (a)	4.8	4.4 (a)	2.3	547 (a)	50.5
	100%	52.1 (a,b)	3.3	4.9 (a)	3.1	518 (a)	59.2
	75%	48.8 (b)	6.6	8.5 (a)	4.6	504 (a,b)	70.5
	50%	42.3 (c)	3.0	10.3 (a)	5.5	446 (b)	35.1
2006	125%	51.2 (a)	3.3	6.7 (a)	2.6	526 (a)	33.5
	100%	48.1 (a,b)	2.3	6.6 (a)	3.9	487 (a,b)	25.5
	75%	44.6 (b,c)	4.4	7.1 (a)	8.8	453 (b)	44.6
	50%	35.4 (c)	6.1	6.8 (a)	3.9	358 (c)	62.0

Numbers followed by different letters are statistically different ($P<0.05$); the comparison is between lines; σ = standard deviation

TABLE 2 - Statistics of yield parameters for different treatments.

2005			2006		
IW (mm)	Net economic returns		IW (mm)	Net economic returns	
	to land (€ ha⁻¹)	to water (€ mm⁻¹)		to land (€ ha⁻¹)	to water (€ mm⁻¹)
245	13000	53.10	199	10470	52.67
242	13020	54.55	198	10470	52.90
86	7130	79.22	158	9280	59.00
240	13000	56.00	197	10470	53.12
30	1760	53.10	125	6560	52.67

TABLE 3 - Optimal levels of irrigation water and net economic returns.

ranges the grower must define the most appropriate irrigation strategy for optimal water use. The differences between 2005 and 2006 were mainly related to the lower production yields in 2006 due to the sub-optimal climatic conditions (lower air temperature). Obviously, the economic results obtained from the study for the optimal water irrigation levels are related to the market trend in the study area.

4. Conclusion

Deficit irrigation is an optimization strategy whereby net returns are maximized by reducing the amount of irrigation water and crops are deliberately allowed to sustain some degree of water deficit and yield reduction. This technique is not usually adopted as a practical alternative to full irrigation by either academics or practitioners due to several obstacles. In particular, it involves the use of precision irrigation; the required knowledge spans over a wide range of disciplines; the strategy involves risks associated with the uncertainty of the required knowledge; it is necessary to persuade farmers and irrigation practitioners not only of the economic value of *DI* but also of its practicability.

Furthermore, there is a certain amount of confusion regarding the *DI* concept. A review of about 100 papers dealing with *DI* recently published in major international journals has shown that only a few papers use the concept of *DI* in its complete sense (e.g. analysing both the agronomic and economic aspects of *DI*). A number of papers only deal with the physiological and agronomical aspects of *DI* (crop response to different irrigation regimes) without any economic evaluation. Other publications concern Regulated Deficit Irrigation (*RDI*, or Controlled Deficit Irrigation, *CDI*), a strategy based only on a reduction of irrigation during certain plant cycle phases, and Partial Root Drying (*PRD*), a technique in which a percentage of crop *ET* is applied to alternating plant sides.

The review of the experimental research shows quite positive effects from *DI* applications. The positive effects are mostly evidenced when the economics of *DI* is included in the research approach. The applications present a wide survey of the agronomic effects of *DI*. Generally, total fresh mass and total production are reduced under *DI*, whereas the effects on dry matter and product quality are positive, mainly in crops for which excessive soil water availability significantly influences the size, colour or composition of fruit (grape, tomato, mango, etc.). The economic convenience of *DI* therefore also depends on the type of crop.

The description of recent trials conducted by the authors in Sicily (Italy), is an example of experimental research integrating the agronomic, engineering and economic aspects of *DI* at a farm level.

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SUMMARY

Deficit irrigation (*DI*) is an optimization strategy whereby net returns are maximized by reducing the amount of irrigation water; crops are deliberated allowed to sustain some degree of water deficit and yield reduction. Although the *DI* strategy dates back to the 1970s, this technique is not usually adopted as a practical alternative to full irrigation by either academics or practitioners. Furthermore, there is a certain amount of confusion regarding its concept. In fact, a review of recent literature dealing with *DI* has shown that only a few papers use the concept of *DI* in its complete sense (e.g. both the agronomic and economic aspects). A number of papers only deal with the physiological and agronomical aspects of *DI* or concern techniques such as Regulated Deficit Irrigation (*RDI*) and Partial Root Drying (*PRD*). The paper includes two main parts: i) a review of the principal water management strategies under deficit conditions (e.g. conventional *DI, RDI* and *PRD*); and ii) a description of a recent experimental research conducted by the authors in Sicily (Italy) that integrates agronomic, engineering and economic aspects of *DI* at farm level. Most of the literature reviewed here showed, in general, quite positive effects from *DI* application, mostly evidenced when the economics of *DI* is included in the research approach. With regard to the agronomic effects, total fresh mass and total production is generally reduced under *DI*, whereas the effects on dry matter and product quality are positive, mainly in crops for which excessive soil water availability can cause significant reductions in fruit size, colour or composition (grapes, tomatoes, mangos, etc.). The experimental trial on a lettuce crop in Sicily, during 2005 and 2006, shows that the highest mean marketable yield of lettuce (55.3 t ha^{-1} in 2005 and 51.9 t ha^{-1} in 2006) was recorded in plots which received 100% of ET_{0-PM} (reference evapotranspiration by the Penman-Monteith method) applied water. In the land-limiting case, the estimated optimal economic levels were quite similar to the optimal agronomic levels. In the water-limiting case *DI* ranges, at least as profitable as full irrigation, were of 17-49% ET_{0-PM} and of 71-90% ET_{0-PM} in 2005 and 2006 respectively.

Key words:
Deficit irrigation, Economics of deficit irrigation, Evapotranspiration, Yield production features.

Notation

a_1, b_1, c_1 = coefficients of the crop production curve
a_2, b_2, c_2 = coefficients of the cost function curve
C= sustained cost
$c(w)$ = cost function
CDI = controlled deficit irrigation
Δ = slope of the saturation vapour pressure curve
DI = deficit irrigation
E_{PAN} = pan evaporation
e_s-e_a = vapour pressure deficit
ET_a = actual evapotranspiration
ET_{0-PAN} = reference evapotranspiration by pan evaporation
ET_{0-PM} = reference evapotranspiration by Penman-Monteith (PM) approach
EU = emission uniformity
G = soil heat flux density
γ= psychrometric constant
IW = irrigation water
K_c = crop coefficient
K_p = pan evaporation coefficient
LAI = leaf area index
MW = mean weight
N-TMY = no-marketable yield
P = probability level
P_c = prize per unit of weight
PRD = partial root drying
R^2 = regression coefficient
RDI = regulated deficit irrigation
R_n = net radiation
$R(w)$ = revenue per hectare
σ= standard deviation
T = daily mean air temperature
TMY = total marketable yield
TW = Total water received
u_2 = wind speed
w = depth of applied water
W = mean applied water
W_{el} = level of applied water at which net income equals that at full irrigation when land is limiting
W_{ew} = level of applied water at which net income equals that at full irrigation when water is limiting
W_l = level at which net income per unit of land is maximised
W_m = level at which crop yield per unit of land is maximised
W_w = level at which net income per unit of water is maximised
WUE = water use efficiency
$y(w)$ = crop production function