Closed Water Loop in Greenhouses: Effect of Water Quality and Value of Produce

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Abstract

An increasing fraction of protected cultivations is on systems where drain water is recollected and re-used for irrigation (closed systems). Such systems have a direct reward for growers in saving on fertilizers (and water) costs and in a higher value of the product, caused by a better control of the root environment. In view of the benefit of the prevention of leaching of chemicals in the environment, the application of closed irrigation systems is being increasingly made compulsory.

However, when irrigation water contains non-nutrient salts, such salts will accumulate in the closed loop. Since a high salt concentration is known to cause yield loss (though the effect is specie-specific), first or later salts will have to be leached out, by draining the loop. Indeed, even in Holland (where environmental rules are possibly the strictest) growers are allowed to leach the system whenever a specie-specific ceiling of sodium concentration is reached. It can be shown that in a crop cycle, the fraction of water that is leached is nearly proportional to the ratio between the concentration of the critical salt of the irrigation water and the concentration at which the system is leached.

In principle, therefore, the "optimal" EC-ceiling can be calculated, that balances marginal costs of water and fertilizers with marginal yield loss. By using a number of yield response curves, in a couple of different cases (Holland and Mediterranean basin), we show that, with realistic prices both of resources and of produce, the optimal EC is very near to the value that ensures maximal yield. That is, there is no advantage to the grower in maintaining a closed loop whenever the quality of irrigation water is poor.

Therefore, closed systems are financially viable only in two cases: a. in regions with good water or b. with high-value crops that offset the costs of ensuring good water (such as rain collection or desalinization). We will show that the latter is the case in most protected cultivation in Europe. On the other hand, there is no way that low-value crops in poor-water-quality regions may still be profitable under stricter environmental rules. This means that local authorities, seriously planning to enforce such rules, should either provide incentives for growers to switch to less sensitive or more valuable combinations of crops, or contemplate developing other economic activities than agriculture.

INTRODUCTION

The fraction of greenhouse crops that is being cultivated in substrates is increasing also in regions where greenhouses are typically rather low-investment. The reason is that the increased amount of control that such systems allow, usually results in higher productions, with a higher uniformity and quality, so that returns justify the larger investment required. Caballero and de Miguel (2002), for instance, made a compelling comparison of return of soil-less sweet pepper vs traditional cultivation in the region of Almeria.

Besides, soilless systems have the advantage that, with a relatively small additional expense, drain water can be recollected and re-used, with saving of both water

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and fertilizers. This is the reason why most soil-less systems in Holland were "re-circulating" long before it became official environmental policy. Such "closed" growing systems are seen as the solution both to the environmental problems caused by leaching of fertilizers, and to the scarcity of water in many regions.

However, when the irrigation water contains non-nutrient salts (sodium chloride is the most common case), such salts will accumulate in the closed loop. Since a high salt concentration is known to cause yield loss (though the effect is specie-specific), at some time salts will have to be leached out, by [partly] draining the loop. In Holland, for instance, growers are allowed to leach the system whenever a specie-specific ceiling of sodium concentration is reached. The Dutch decree about leaching in glasshouse horticulture (Dutch government, 1994, revised 2002), that was emanated in the framework of a law preventing pollution of surface water, is a complex set of rules about conditions for leaching; maximal allowed water gift; conditions for compulsory rain collection basin and its size and management.

Since water use and leaching pollution are very strictly related, an increasingly fashionable line of thought (for instance: OECD, 1999; European commission, 2000) is that the solution to both scarcity and environmental problems caused by over-irrigation, is to price irrigation water in such a way that saving water through closed systems and/or using water of lesser quality becomes optimal economic policy for growers. In this paper we analyze the feasibility of such an approach, in view of information collected and generated in the framework of a project co-financed by the European Union (HORTIMED, ICA3-1999-0009), aimed at methods for saving water in Mediterranean Horticulture.

MATERIALS AND METHODS

Let's assume we deal with a crop that in optimal conditions generates a gross return Y (€ m^{-2} year^{-1}), and that return decreases by a fraction a, for each dS/m that the salinity EC in the root zone environment increases.

$$Gross\ return = Y(1 - aEC) \qquad \text{€ m}^{-2}\ \text{y}^{-1} \qquad (1)$$

Obviously, in a closed system fed with saline irrigation water, water use exceeds potential evaporation (ETP), since the water has to be periodically refreshed, as quantified by Carmassi et al., 2003. Stanghellini & Kempkes, 2004, have shown that if irrigation water has as salt concentration EC_{in}, actual water use W depend from the average EC one wants to maintain in the system according to:

$$W = \frac{EC - 0.5EC_{in}}{EC - EC_{in}} ETP \qquad \text{m}^3\ \text{m}^{-2}\ \text{y} \qquad (2)$$

Obviously, the potential yield, Y and ETP are typical of the crop, and a is a measure of the crop sensitivity to salinity (the higher is a, the faster is yield loss with salinity). Now, let's assume that irrigation water has a price structure that encourages use of saline water, in particular that: (see Fig. 1)

$$water\ price = \max\left(0.1, P\exp(-b \cdot EC_{in})\right) \qquad \text{€ m}^{-3} \qquad (3)$$

where b is a parameter giving the "steepness" of the price decrease with salinity (Fig. 1). Please observe that water of poorer quality carries a hidden cost that is the cost of fertilizers that are expelled with leaching. Accounting for this would simply result in a somewhat less steep trend than the "bare" cost. Therefore, in the following we will regard b as a parameter incorporating both water and fertilizers cost.

Finally, let's assume that all other production costs are independent of the salinity of the irrigation water. A smart grower chooses the EC_{in} of the irrigation water and the mean EC to maintain in the root zone (that is, in fact, water use) in a way that his profit is the maximum possible. Considering only irrigation costs, that is:

$$Y(1 - a \cdot EC) - \frac{EC - 0.5EC_{in}}{EC - EC_{in}} ETP \cdot P \exp(-b \cdot EC_{in}) \Rightarrow \max \qquad € \text{ m}^{-2} \text{ y}^{-1} \quad (4)$$

The equation above cannot be solved in an analytical fashion. It is possible, however, to explore under which conditions the parameters of the price structure would ensure that it makes economic sense to use irrigation water with an EC_{in} larger than zero. One can show that all possible solutions to eq(4) depend similarly from the ratio:

$$k = \frac{aY}{P \cdot ETP} \qquad \text{m dS}^{-1} \quad (5)$$

that is, the ratio between loss of return for each dS/m increase in salinity in the root zone and the "potential irrigation costs", that is the costs when using irrigation water of good quality.

For instance, a reasonable return for Dutch glasshouses is about 50 € m^{-2} y^{-1} (Agri-Holland, 2004; CBS, 2004) whereas for unheated plastic houses in the Mediterranean basin it is 10 € m^{-2} y^{-1} (Caballero & De Miguel, 2002). Sonneveld (2000) has tabulated yield decrease with salinity for a number of greenhouse crops, ranging from 2-3% for tomato and carnation; 5-6% for sweet pepper, cucumber and rose to 10% for gerbera and most pot plants. At the lower end of the range we can add cherry tomato with a yield loss of less than 1% (in view of the quality-premium in price). Potential evaporation is about 1 m^3 m^{-2} y^{-1} in all cases, since heating in Dutch greenhouses, and winter cultivation cycle (and whitewashing) in the Mediterranean, tend to offset differences in climatic potential evaporation. Table 1 shows the corresponding values of k, with a number of possible potential irrigation costs.

Figure 2 shows the net income for a grower (eq(4), only irrigation costs are deduced from return), for all sensible combinations of salinity of the irrigation water and water use, for various combinations of k (0.5, 1 and 2 from top to bottom) and two different price structures of the irrigation water (exponents used are as in Fig. 1). The white area represents all cases with incomes less than 90% of the theoretical maximum (that is, irrigation costs and yield loss exceed together 10% of possible income), and each contour line is 2% of it. The star gives the approximate position of the economically optimal combination.

RESULTS

What Figure 2 shows is that in the measure that k increases (top to bottom), the range of economically sensible salinities of irrigation water shifts towards a higher quality of the water, and that this trend is independent from the price structure of the irrigation water (left and right panels). Indeed, it can be shown that:

$$EC_{in,optimal} \approx \frac{0.5}{k} = 0.5 \frac{P \cdot ETP}{aY} \qquad \text{dS m}^{-1} \quad (6)$$

So that for k around 2 (or larger), "optimal EC_{in}" would be 0.25 dS/m (2 mmol_{Na} l^{-1}) or less, which is a water quality many would dream of. Even with $k < 2$, in order to ensure that it is sensible to use saline irrigation water, water cost has to drop very fast with quality. Otherwise the slightly higher cost of good water is always worthwhile. Please observe that left panel of Fig. 2 assumes the price evolution represented by the three steepest lines of Fig. 1, whereas the right panel is calculated with the gentlest one. The consequence of a fast decreasing price is that there is little restraint with respect to quantity used. Observe that the economic optimum on the left hand side of Figure 2 is always around 2.5 ETP, which is a leaching fraction of 60%, in the common definition of the latter as the ratio of amount of water leached to quantity of water applied.

DISCUSSION

We have seen that whenever *k* is large enough (that is, the potential loss of return caused by salinity is large with respect to the "potential" irrigation costs), there is no way that it could be profitable for a grower to use irrigation water of lower quality. That is, it is always cheaper to "clean" the water beforehand, f.i. with a on-site reverse osmosis plant. Obviously, higher potential irrigation costs make the value of *k* smaller, so that, for instance, optimal management of a closed-loop tomato crop in Holland would require good irrigation water if its price were 0.5 € m^{-3}, but not if its price were 1 € m^{-3} (Table 1). Even then, a more sensitive crop such as roses or sweet pepper would require clean water, except with such unreasonable prices as to exceed costs of on-site desalinization (estimated at about 1 € m^{-3}).

Lower-value (and lower investment) crops could be more reasonably cultivated in closed loops fed with irrigation water of poor quality. How poor, however, can be debated, as eq(6) shows. Indeed, looking at the *k* values in Tab. 1, one can see that, except for cherry tomatoes, optimal salinity of irrigation water would be at most 1 dS/m (8 $\mathrm{mmol_{Na}\ l^{-1}}$), and then only if its cost were negligible. Even then, actual water use would be more than twice ETP (a leaching fraction around 60%), which seems to be a poor definition of a closed system.

Therefore, incentives to apply water of low quality may well decrease pressure on good water resources, but may significantly improve pollution caused by leaching. Implicitly, this is acknowledged by the Dutch regulations. Indeed, after allowing for (quite benevolent) specie-specific ceilings on sodium concentration in the closed loop, above which leaching is permitted, there are limits on the amount of irrigation that may be applied yearly (Table 2). Since such limits are quite difficult to enforce, an additional item in the regulation is a detailed list of conditions that make (or not) a rain collection basin compulsory. In this respect, Holland has the obvious advantage of equilibrium between rainfall and potential evaporation, and a rather even distribution of rainfall (Fig. 3). However, the shallowness of the ground water table makes it impossible to dig deep basins, which, in turn, increases occupation of [expensive] and potentially produc-tive soil surface. Indeed, calculations of integral costs of rain basins (KWIN, 2003) show that in some cases cost of storage per cubic meter may exceed cost of desalinization.

Our thesis is that all these rules could be more effectively substituted by demanding proof that enough water of good quality is available (be it rain or desalinated water) before approval of a greenhouse business. Once (expensive) good water is available, it simply makes economic sense not to leach. There is at least one consortium of 4 growers in Holland, whose water provision is ensured by the local (private) water utility, through a combination of on-site rain collection and reverse-osmosis desalinization (and des-infection) of surface water. The price they pay for the water is 0.9 € m^{-3}, due to fall to 0.8 € m^{-3} when purchase exceeds an agreed level. Full ownership of the installations will transfer to the consortium after 10 years and there have been no subsidies, except a small one from the municipality for "landscaping" the rain collection basin.

A similar lesson can be drawn for semi-arid regions where greenhouses are presently expanding: the one way to prevent leaching is to have good water (Pardossi et al., 2004). Closed systems in greenhouses are the vegetable production system with the highest economic water use efficiency by far (Stanghellini et al., 2003) and thus can afford a relatively expensive irrigation water (Table 3). Expansion of such systems should, therefore, be welcomed, particularly in semi-arid regions.

CONCLUSION

Economically optimal management of most closed-loop crops in greenhouses requires irrigation water of good quality. A price structure of irrigation water that shifts the economic optimum towards poorer irrigation water has the consequence that the irrigation loop cannot be closed. In view of the environmental impact, it would be advisable for irrigation and local authorities in horticultural areas either to provide good water at a high price or to consider subsidizing investment costs of on-site desalinization plants, rather than stimulating use of poor quality water, or attempting to prevent pollution through regulation that may be both un-economical and un-enforceable.

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Tables

Table 1. Value of the ratio k for a number of typical greenhouse crops and costs of irrigation. The differences in potential return for the same crop refer to the growing system: it has been assumed that return in high investment glasshouses is fivefold the return in simple plastic houses. Shaded are the combinations with k>2.

Crop	**Potential return ($€\ m^{-2}\ y^{-1}$)**	**Salinity Yield Decrease SYD, % $(dS/m)^{-1}$**	**P·ETP** ($€\ m^{-2}\ y^{-1}$)		
			0.5	*1*	*1.5*
Cherry tomato	10	1	0.2	0.1	0.07
Tomato, carnation	10	3	0.6	0.3	0.2
Sweet pepper, rose	10	5	1	0.5	0.33
Cherry tomato	50	1	1	0.5	0.33
Gerbera, pot plants	10	10	2	1	0.67
Tomato, carnation	50	3	3	1.5	1
Sweet pepper, rose	50	5	5	2.5	1.67
Gerbera, pot plants	50	10	10	5	3.33

Table 2. For each crop indicated in the first column: sodium concentration (crop specific) that has to be reached in a closed loop before leaching is allowed and maximum permitted yearly irrigation application.

Crop	**Ceiling Na concentration mmol l^{-1}**	**Maximal application mm y^{-1}**
Tomato	8	1140
Sweet pepper; cucumber; eggplant; melon; squash (zucchini); beans	6	1140
Lettuce	5	860
Rose; gerbera; carnation, amaryllis	4	1140
Strawberry	3	860
Anthurium, lilium, bouvardia, iris	3	1140
Orchid	0	1140
Others	5	1000

Table 3. Average productivity (income per unit applied) of irrigation water in open field and greenhouse vegetable production in the region of Almeria (column 2); "social efficiency" (mean water use for man-hour), column 3; and break-even price of water, that is the price that would cancel out the net income of growers (Colino & Martinez, 2002).

	Productivity €/m^3	**m^3/man-hour**	**Break-even price of water €/m^3**
Open field vegetables	1.60	11.5	0.9
Greenhouse vegetables	6.12	4.2	3.7

Figures

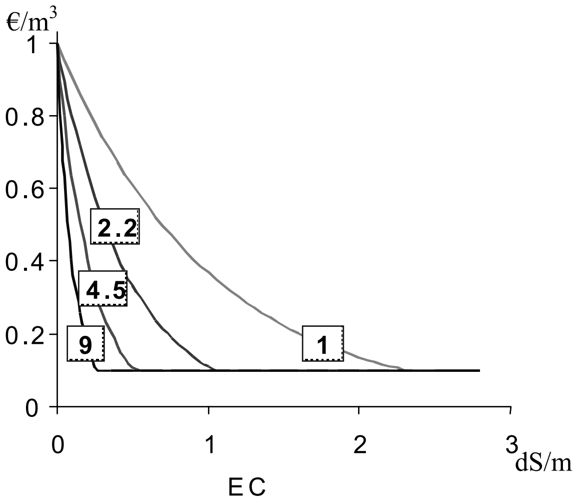


Fig. 1. Hypothetical evolution of cost of irrigation water, eq(3) with P = 1 € m^{-3}, and four different exponents, as indicated. Cost of irrigation is assumed to have a lower limit of 0.1 € m^{-3}, in view of investment, maintenance and pumping expenses.

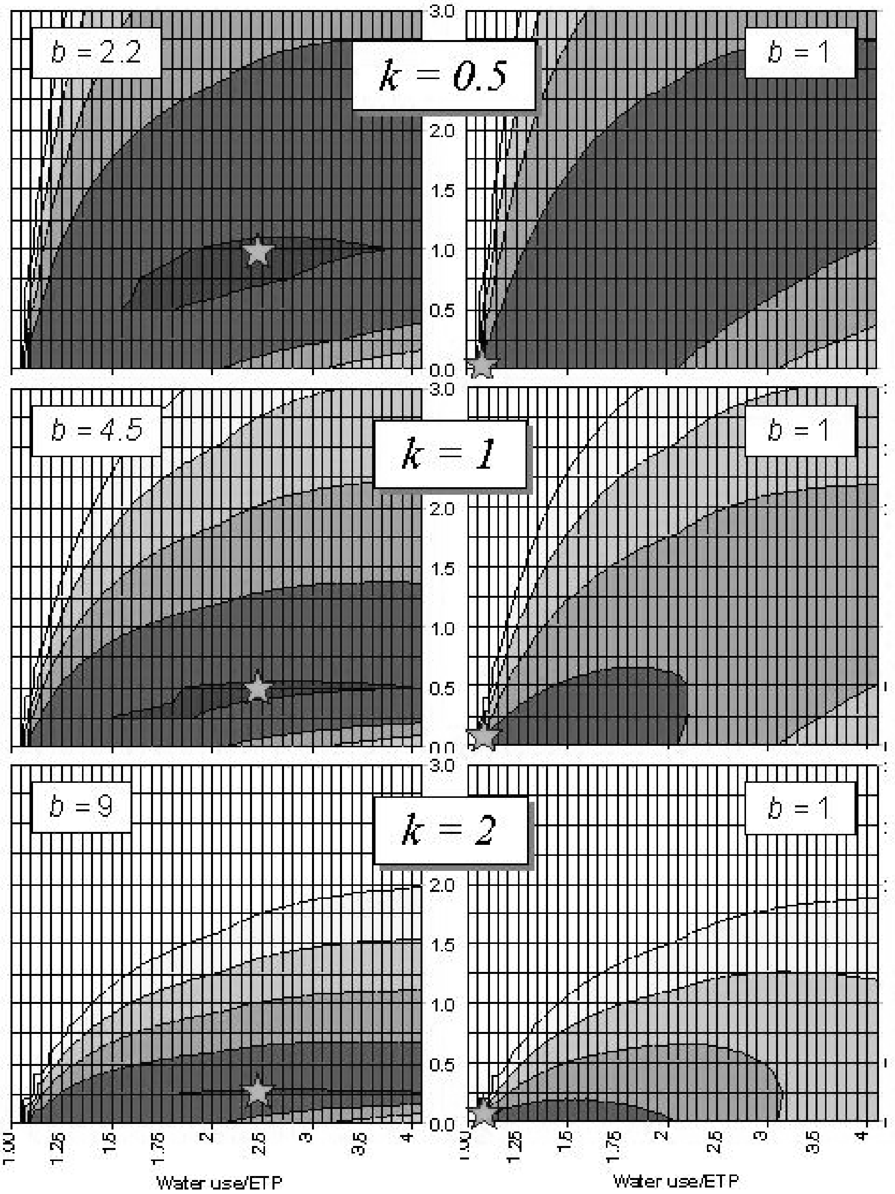
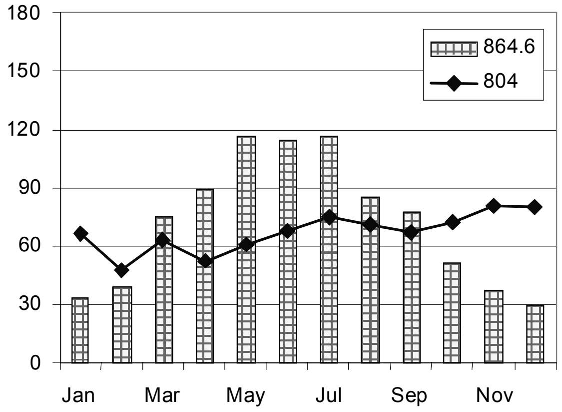


Fig. 2. Net income (only irrigation costs are deduced from return) for a grower for all sensible combinations of salinity of the irrigation water (EC_{in}, dS/m, y-axis) and water use (as multiple of potential transpiration, x-axis), under various conditions. From top to bottom: k is respectively 0.5; 1 and 2. In the panels on the left-hand side the exponent b of eq(3), that is the price structure, is selected in order to maximize optimal EC_{in} (b=2.2; 4.5 and 9, from top to bottom), whereas on the right hand size optimal water use is minimized (b=1). The white area represents all cases with incomes less than 90% of the theoretical maximum, and each contour line is 2% of it. The star gives the approximate position of the economically optimal combination. 1 dS/m is about 8.5 mmol/l Na.



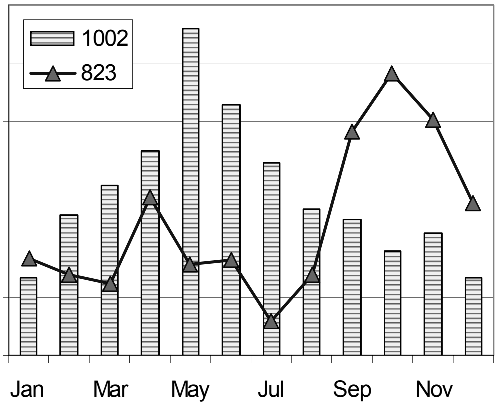


Fig. 3. Monthly rainfall (line) and water use of greenhouse roses (bars) in Holland left and the Versilia (Lucca) region of Italy (right). The numbers are the yearly totals. Roses greenhouses are whitewashed in Versilia from June to August. From Kempkes & Stanghellini, 2001.