BIOSYSTEMS ENGINEERING 122 (2014) 74–90

Available online at www.sciencedirect.com

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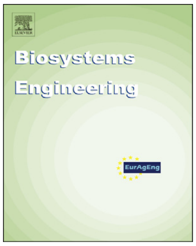

Research Paper

Drip *vs.* surface irrigation: A comparison focussing on water saving and economic returns using multicriteria analysis applied to cotton

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A R T I C L E I N F O

Article history:
Received 30 July 2013
Received in revised form
7 March 2014
Accepted 27 March 2014
Published online 23 April 2014

Keywords:
Economic water productivity
Decision support systems
Deficit irrigation
Model MIRRIG
Model SADREG
Northeast Syria

This study explores the use of drip and surface irrigation decision support systems to select among furrow, border and drip irrigation systems for cotton, considering water saving and economic priorities. Data refers to farm field observations in Northeast of Syria. Simulation of drip irrigation was performed with MIRRIG model for various alternatives: double and single row per lateral, emitter spacing of 0.5 and 0.7 m, six alternative pipe layouts and five self-compensating and non-compensating emitters. Furrow and border irrigation alternatives were designed and ranked with the SADREG model, considering lasered and non-lasered land levelling, field lengths of 50–200 m and various inflow discharges. A multi-criteria analysis approach was used to analyse and compare the alternatives based upon economic and water saving criteria. Results for surface irrigation indicate a slight advantage for long non-lasered graded furrows; non-lasered alternatives were selected due to economic considerations. For drip irrigation, the best ranking is for systems having lower costs, mainly with double rows per lateral and larger emitter spacing. Comparing surface and drip irrigation systems, despite low cost, drip alternatives may lead to 28–35% water saving relative to improved graded furrows, and increase water productivity from 0.43 kg m^{-3} to 0.61 kg m^{-3}, surface irrigation provides higher farm returns. Drip irrigation is selected only when high priority is assigned to water saving. Deficit irrigation does not change this pattern of results. Apparently, adopting drip irrigation requires appropriate economic incentives to farmers, changes in the structure of production costs and increased value of production.

1. Introduction

Cotton (*Gossypium hirsutum* L.) is a main summer crop in Syria, both in economic and social terms. Cotton uses about 20% of the irrigated area, and more than 20% of the country labour force depends upon cotton cultivation, manufacturing, marketing and other services (Al Ashkar, 2009; MAAR, 2011; Shweih, 2006). However, cotton is a high water demand crop (Chapagain, Hoekstra, Savenije, & Gautam, 2006). The

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http://dx.doi.org/10.1016/j.biosystemseng.2014.03.010

sustainability of cotton cropping is a major priority, mainly in the Northeast of Syria, where water scarcity is severe (Beaumont, 1996; Hole, 2009; Mourad & Berndtsson, 2012). Irrigation is mainly performed by traditional zigzag furrowed basin irrigation, used in 88.5% of the cotton area; pressurised systems are increasing, mainly drip irrigation. Irrigation modernisation is therefore of great importance to achieve sustainable water use (Janat & Khalout, 2011; MAAR, 2011; Sadiddin, 2009).

This study applies to Ras-El-Ain area, Northeast of Syria, Euphrates basin, which is heavily affected by water scarcity due to the drawdown of the groundwater table and the enormous decrease of the Khabour river flow to less than 10% of its former discharges (Galli, Morini, & Di Terlizzi, 2010). This relates to the recent increase of irrigation areas, mainly using groundwater in the nearby plain of Harran (Öztan & Axelrod, 2011). Modernising cotton irrigation includes achieving water saving, coping with the severe water scarcity, soil and water conservation, prevention against salinity, and the increase of farmers' economic incomes, thus contributing to the economic and social rural development (Sadiddin & Atiya, 2009). Irrigation modernisation needs identification of the most recommended solutions for increased yields and incomes as well as for water saving and water productivity (Gonçalves, Muga, Horst, & Pereira, 2011; Oweis, Farahani, & Hachum, 2011; Pereira, Cordery, & Iacovides, 2012), e.g., knowing when drip irrigation may be advantageous relative to surface irrigation. Irrigation modernisation is indeed a target of Syrian agriculture policy (Al Ashkar, 2009) and a project has been setup encouraging farmers to replace the traditional irrigation systems by modern drip irrigation and providing technical support and low-interest loans (MAAR, 2011).

Several studies have demonstrated the appropriateness of using drip irrigation for cotton in water stressed regions (e.g., Bucks, Allen, Roth, & Gardener, 1988; Dağdelen, Başal, Yılmaz, Gürbüz, & Akcay, 2009; DeTar, 2008; Karam et al., 2006; Wang et al., 2012). Several studies have been carried out in the region, which have shown a high potential for water saving and yield increase, particularly when adequate fertilisation is adopted (Farahani, Oweis, & Izzi, 2008, 2009; Hussein, Janat, & Yakoub, 2011; Janat, 2008; Oweis et al., 2011). However, studies show contradictory results in terms of deficit irrigation (DI), with some clearly considering DI less favourably (e.g., Akhtar, Tischbein, & Awan, 2013; Dağdelen et al., 2009; DeTar, 2008; Ünlü, Kanber, Koc, Tekin, & Kapur, 2011) and few reporting positive results of DI (e.g., Hussein et al., 2011). It has also been demonstrated that the modernisation of surface irrigation may lead to water saving and cotton yield improvements (Horst, Shamutalov, Gonçalves, & Pereira, 2007; Hulugalle, Weaver, & Finlay, 2010; Hunsaker, Clemmens, & Fangmeier, 1998; Smith, Raine, & Minkevich, 2005). For this reason, despite numerous studies showing advantages of drip over surface irrigation, related categorical conclusions are often not drawn. Howell, Meron, Davis, Phene, and Yamada (1987) reported that drip reduced soil evaporation in narrow rows but did not lead to significant differences from furrow irrigation when soil water was not limiting. Hodgson, Constable, Duddy, and Daniells (1990) found higher water productivity under drip and that results for furrow irrigation could achieve high performance if furrow irrigation management were to be improved through reduced "transmission losses between pump and field, by reducing runoff losses from the field, by recirculating runoff water, and by reducing waterlogging". Similarly, Bhattarai, Mchugh, Lotz, and Midmore (2006) found that advantages of drip over furrow irrigation could be obviated with improved furrow management producing faster irrigation advance and reduction of tail water. However, drip had advantages over furrow irrigation relative to off-site movement of sediments, nutrients and pesticides (Mchugh, Bhattarai, Lotz, & Midmore, 2008).

When comparing drip with furrow irrigation, the main questions refer to the performance of the irrigation systems and to irrigation scheduling (Barragan, Cots, Monserrat, Lopez, & Wu, 2010), which were the main factors considered in previous surface irrigation studies (Darouich, Gonçalves, Muga, & Pereira, 2012; Gonçalves et al., 2011). These aspects were evidenced in the study of Hunsaker et al. (1998), who reported excellent results for high frequency surface irrigation with precise level basins. Horst et al. (2007) reported the benefits of using appropriate control of furrow inflows and surge flow, and Pereira et al. (2009) referred to positive impacts of improved schedules applied to furrow systems. However, the difficulties inherent in modernising surface irrigation, mainly referring to investments in equipment, land levelling costs, insufficient training facilities and lack of support to farmers, make it relatively difficult to improve surface irrigation (Darouich et al., 2012; Gonçalves et al., 2011).

Many studies in various regions of the world have shown the advantage of replacing surface by drip irrigation of cotton. Mateos, Berengena, Orgaz, Diz, and Fereres (1991) reported both higher and lower yields from drip systems, with less water use in drip systems. Norton and Silvertooth (2001) referred to advantages for drip in terms of water use, yield and consequently water productivity in Arizona. Janat and Somi (2001) found higher yields associated with water savings of 35–55% for Syrian conditions. For Turkey, Cetin and Bilgel (2002) reported yields about 20% higher with drip irrigation than for furrow as well as higher water productivity (4.87 and 3.87 kg ha^{-1} mm^{-1} for drip and furrow, respectively). Bhattarai et al. (2006) found that drip was advantageous when deficit irrigation was applied. Ibragimov et al. (2007) reported 18–42% of irrigation water saving associated with higher yields in Central Asia. DeTar, Maas, Fitzgerald, and Shafter (2010, pp. 375–380) found no differences in yield but 1/3 less water use by drip in a sandy soil. Sankaranarayanan et al. (2011) reported advantages in water use, yield and quality of the produced cotton in favour of drip; however, they found it difficult to overcome the economic advantages of furrow irrigation, which led them to develop a low-cost drip system. Rajak, Manjunatha, Rajkumar, Hebbara, and Minhas (2006) have also shown that, though the gross income was more with drip than furrow irrigation, the net profit per unit of applied water was higher with furrow irrigation.

The review presented above shows that a main question when selecting drip or modern surface irrigation for cotton refers to making compatible two central but contradictory objectives: water saving and farm economic results. If for a water scarce region like Northeast of Syria it is essential to find irrigation solutions that lead to a reduced demand of irrigation water, it is also true that farmers would only adopt new technological solutions if these are economically viable. This type of decision problem considering contradictory criteria is appropriate to be handled with multicriteria analysis (MCA) aiming at supporting the decision maker to select the best compromise solution. MCA incorporates quantitative and qualitative information relative to various criteria and takes into account the decision maker's preferences. Various applications of MCA to irrigation have been reported, e.g., Bartolini, Gallerani, Raggi, and Viaggi (2010) evaluating expected outcomes of different water policy scenarios from the point of view of different stakeholders, Rodrigues, Paredes, Gonçalves, Alves, and Pereira (2013) comparing and ranking various drip and sprinkler systems, and Darouich et al. (2012) and Gonçalves et al. (2011) selecting surface irrigation alternative systems for cotton in Central Asia and Syria, respectively. More often MCA is incorporated in decision support system (DSS) models that integrate data, design and selection models, allowing the creation of design and/or management alternatives and their selection following appropriate criteria. Examples of software applied to cotton include models for irrigation management (Chen, Lei, Cao, & Li, 2012; Richards, Bange, & Johnston, 2008), for qualitative crop modelling (Plant, Kerby, Zelinski, & Munk, 1998) and for fertilisation options (Papadopoulos, Kalivas, & Hatzichristos, 2011). DSS for surface irrigation design have been reported by Hornbuckle, Christen, and Faulkner (2005) and Gonçalves and Pereira (2009), and for microirrigation by Pedras, Pereira, and Gonçalves (2009).

Adopting MCA and appropriate irrigation design focused on the cotton producing area of Ras-El-Ain, Northeast of Syria, where field data have been collected, it is possible to evaluate and rank alternatives for graded furrows and borders using SADREG model (Gonçalves & Pereira, 2009) as well as for drip systems using the MIRRIG model (Pedras et al., 2009). Thus, the objectives of this study are: (a) to develop appropriate sets of design alternatives for surface and drip irrigation; (b) to rank and select the best alternatives for both types of systems; (c) considering water saving and economic criteria, to use MCA to compare and rank those selected solutions assuming various weights for the diverse attributes; and (d) to analyse the results in terms of possible identification of surface and drip solutions for cotton irrigation modernisation in Northeast of Syria.

2. Material and methods

2.1. *The study area and field characteristics*

The study area is located in Ras-El-Ain district, Al Hassakeh governorate, Northeast of Syria. Ras-El-Ain is a well-known region of Mesopotamia, Euphrates basin, where groundwater is progressively declining and water scarcity is increasing (Galli et al., 2010; Hole, 2009; Öztan & Axelrod, 2011; Sadiddin, 2009). The climate is semi-arid, with an annual rainfall ranging from 160 to 350 mm and a potential evaporation of 1600–2800 mm. Air temperature often reaches 43 °C in summer and decreases to less than 4 °C in winter months. The prevailing wind blows from the west and wind speed averages 2.3 m s^{-1} during summer. Land elevation ranges from 165 to 325 m a.s.l. Further information on the area and its agriculture is provided by Galli et al. (2010).

Cotton irrigation is traditionally applied through furrowed zigzag basins, typical of the small family farms in the region. Few farmers adopt improvements in furrow and border irrigation. Zigzag basins adapt well to existing field conditions without land levelling but are labour consuming, impose limitations to mechanisation, result in relatively low distribution uniformity and often show a low beneficial water use ratio of about 50% (Darouich, Gonçalves, & Pereira, 2007; Darouich et al., 2012; Janat, 2008). The seasonal irrigation water use by traditional cotton production systems is close to 16,000 m^3 ha^{-1}, with an average yield of 4.6 t ha^{-1} (Farahani, Izzi, & Oweis, 2009; Janat, 2008; MAAR, 2011; Oweis et al., 2011). A yield increase to about 5.0 t ha^{-1} is expected if irrigation and crop practices are improved (Janat, 2008; Oweis et al., 2011). The recent increase in water scarcity has made traditional systems less sustainable because they are unable to provide for water saving. Modernised surface irrigation and drip systems have been tested in various cotton fields. However, for the majority of farmers, having limited financial resources, technology investments are limited while they aim at maximising economic incomes for family sustainability.

Main soils are loam-clay soils, with average particle size distribution of 31% sand, 31% silt and 39% clay. Soil water content at field capacity is 0.371 cm^3 cm^{-3} and is 0.232 cm^3 cm^{-3} at the wilting point, so the total available water (TAW) of 139 mm m^{-1}. The saturated hydraulic conductivity (K_s) was considered to be 3 mm h^{-1} for drip systems. The infiltration characteristics are described below and detailed in Darouich et al. (2012). Typical field sizes in Ras-El-Ain are 200 m long and 100 m wide, a longitudinal slope of 0.8% and a zero cross slope. The water is supplied from the highest part of the field and the maximum flow rate available is 40 l s^{-1}. Surface irrigation trials considered graded furrows and borders and adopted locally developed gated pipelines for farm distribution systems (Galli et al., 2010). Drip irrigation systems used locally consist of a single plant row per lateral, spaced at 0.75–0.80 m, emitter spacing of 0.30–0.60 m, and emitter discharges of 1.5–4.0 l h^{-1}. When double rows per lateral are used, lateral spacing increases to 1.40 m. In surface irrigation systems, a conventional fertilisation scheme is adopted, whereas fertigation is often used with drip irrigation. Further information is provided by Darouich et al. (2007, 2012).

The crop cycle duration is 170 days, with planting by early May. The planting density is of 71,400 plants ha^{-1}. The seasonal crop evapotranspiration (ETc) and net irrigation requirements (NIR) were assessed with the ISAREG model (Pereira, Teodoro, Rodrigues, & Teixeira, 2003). The average ETc is 934 mm and the irrigation scheduling results for full and deficit irrigation are presented in Table 1. A water-yield function $Y_a/Y_{max} = f(W_a/W_{max})$ was used to estimate crop yield as a function of the total water use during the irrigation season (Table 2). It relates the relative yield with the relative net water availability, with Y_a and Y_{max} referring to the actual and the maximum yield, respectively, which are achieved when the net applied water are W_a and W_{max}, respectively. It follows the methodology proposed by Solomon (1984) and was parameterised for both deficit and excess irrigation using regional data (Dăgdelen et al., 2009; Yazar, Sezen, & Sesveren, 2002).

Table 1 – Irrigation scheduling considering the irrigation method and full and deficit irrigation.

Irrigation method	Irrigation strategy	Number of irrigation events	Net irrigation depth per event (mm)	Net irrigation water use (mm)
Surface	Full	10	80	800
Drip	Full	32	25	800
Surface	Deficit	8	80	640
Drip	Deficit	26	25	640

Note: for double rows per lateral the same net irrigation depths as for single row per lateral were used but the time duration of irrigation was 1.21 times larger in average.

The determination of infiltration characteristics was performed through field evaluations using the methodology described by Horst, Shamutalov, Pereira, and Gonçalves (2005) and Walker and Skogerboe (1987).The typical Kostiakov infiltration curve obtained from the field observations, which was discussed by Darouich et al. (2007, 2012), is:

$$Z = 0.0118\tau^{0.3227} + 0.000167\tau \quad (1)$$

where Z is cumulative infiltration ($m^3\ m^{-1}$) and τ is infiltration opportunity time (min).

In the present case study, the yield price was 0.74 € kg^{-1}, the water cost was 0.022 € m^{-3}, the labour cost 0.8 € h^{-1} (qualified labour was 1.28 € h^{-1}) and the energy cost was 0.08 € kWh^{-1}. A period of 10 years was considered for the financial analysis and the annual interest rate was 4.0%.

2.2. *The MIRRIG model*

MIRRIG is a decision support system (DSS) aiming at design of microirrigation systems, i.e., drip and microsprinkling set systems, as well as performance analysis of field evaluated systems (Pedras & Pereira, 2009; Pedras et al., 2009). MIRRIG is composed of design and simulation models, a multicriteria analysis model and a database. The database contains updated information on emitters and pipes available in the market, as well as on crops, soils and other field data collected from systems under operation. Design alternatives refer to the layout of the pipe system, the pipe characteristics and the emitters (drippers or microsprinklers). The model includes a design module to iteratively size the pipe and emitter system, and a performance analysis module that simulates the functioning of the system and computes various indicators. These are used as attributes of the alternatives relative to the design criteria adopted for MCA. The alternative drip systems are designed taking into consideration user defined targets for the distribution uniformity. The importance of distribution uniformity on cotton yields has been analysed by Guan, Li, and Li (2013). All alternatives could be compared and ranked through multicriteria analysis with user defined weights relative to the adopted water saving and economic criteria.

Table 2 – Empirical water-yield function.

W_a/W_{max}	0.25	0.5	0.75	1.0	1.5	2.0	2.5
Y_a/Y_{max}	0.10	0.56	0.85	1.0	0.97	0.9	0.73

Note: Y_a and Y_{max} are the actual and the maximum yields, which correspond to the net applied water W_a and W_{max} respectively.

Characteristics of the simulated drip irrigation alternatives are:

- Six different layouts (L1, …, L6) whose differences refer to the number of manifolds, position of the supply inlet in the manifold and pipe lengths. Polyethylene of low density was selected for the pipe laterals, of high density for the manifolds and submains, and PVC for the mainline (Table 3); a general schematic layout is presented in Fig. 1.
- Two alternative lateral layouts: single row per lateral (SRL) and double rows per lateral (DRL). DRL reduces investment relative to SRL.
- Spacings between laterals were: 0.7 m for SRL, thus equal to row spacing, and 1.4 m for DRL, i.e., 0.8 m between paired rows and 0.6 m between rows in each pair.
- Two types of emitters were considered: non-compensating (NC) and self-compensating (SC) emitters having various discharges (1.5, 1.6, 2.7, 3.5 and 4.0 l h^{-1}): NC1.5, NC2.7, NC4.0, SC1.6 and SC3.5.
- Two emitter spacings (ES) of 0.5 and 0.7 m were considered (ES0.5 and ES0.7).

From the various combinations of features described above, a set of 120 alternatives were built with MIRRIG to be analysed and ranked; only the high ranked alternatives were compared with the high ranked surface irrigation solutions.

The fixed cost comprises pipes, emitters, pump, chemical tank and injector pump, disk filter, control and management devices, and pipe layout accessories. Accessories were considered in the range 18–22% of the fixed cost; their costs vary with the pipe layout, being higher for layouts L2 and L4 and lower for L1 (Table 3). The variable costs include the water cost and the maintenance and operation cost, which includes the energy and labour cost. Considering that the main source for water is groundwater, the well pumping cost was included in the water cost (€ m^{-3}), which was the same value for drip and surface irrigation.

2.3. *The SADREG model*

SADREG is a DSS model developed to assist designers and managers in the process of designing and planning improvements in farm surface irrigation systems (Gonçalves et al., 2011; Gonçalves & Pereira, 2009). The design component applies database information and produces a set of alternatives

Table 3 – Layout characteristics of the alternatives.

Project	Length (m)					Location of manifold supply inlet	Number of manifolds per sector	Number of laterals per manifold[a]
	Mainline	Submain	Manifold	Lateral on left	Lateral on right			
	A	B	C	D	E			
L1	110	None	50	200	None	Middle	1	72
L2	110	100	50	100	None	Edge	2	72
L3	210	None	50	100	100	Edge	1	72
L4	160	100	50	50	50	Edge	2	72
L5	210	None	100	100	None	Middle	1	144
L6	210	None	100	50	50	Edge	1	144

[a] Refers to single row per lateral, SRL.

in agreement with the user options. These alternatives are characterised by various hydraulic, economic and environmental indicators. The alternatives sharing the main characteristics are grouped in “projects” (as described by Gonçalves & Pereira, 2009) such as graded furrows (GF) and graded borders (GB) in the present application. The ranking and selection component is based on MCA.

The main steps of a SADREG application are the following:

1) Identification of field characteristics assuming a rectangular field shape (Fig. 2);
2) Input of data characterising the water supply to the field and the in-field distribution equipment used to supply water to furrows or borders;
3) Input data referring to the crop and soil characteristics (Section 2.1), including infiltration parameters;
4) Through interactive simulations with the ISAREG model (Pereira et al., 2003), definition of the crop irrigation scheduling to be used in model simulations;
5) Definition of the surface irrigation design options to be used for creating the alternatives;
6) Running the SIRMOD simulation tool (Walker, 1998), which is incorporated in SADREG, to create the desired set of surface irrigation alternatives and the respective indicators that are used as attributes for MCA;
7) Selection of the criteria and weights to be assigned to the attributes; weights are user defined according to design and management priorities;
8) Performing a pre-selection of the satisfactory alternatives, which are those having indicators above pre-defined thresholds;
9) Ranking and selection of satisfactory alternatives using MCA.

The projects considered – graded furrows (GF) and borders (GB) – were developed adopting an open tail end condition, layflat gated tubing for in-field water distribution, flat soil surface for borders and 0.70 m spacing between furrows in GF systems. Simulations were performed assuming two land levelling scenarios: without land levelling operation (identified $\mathrm{GF}_{\mathrm{NLL}}$ and $\mathrm{GB}_{\mathrm{NLL}}$), which represent reduced costs but lower irrigation uniformity; and with precise land levelling ($\mathrm{GF}_{\mathrm{LL}}$ and $\mathrm{GB}_{\mathrm{LL}}$), thus with higher investment and operation costs that provide for higher irrigation uniformity (Darouich et al., 2012). Hydraulic simulations were performed assuming a Manning roughness coefficient of 0.04 $\mathrm{m}^{1/3}\ \mathrm{s}^{-1}$ for furrows, and 0.16 $\mathrm{m}^{1/3}\ \mathrm{s}^{-1}$ for borders (Walker & Skogerboe, 1987). For both GF and GB, various alternatives were simulated in terms of inflow rates ($\mathrm{l\ s^{-1}\ furrow^{-1}}$ or $\mathrm{l\ s^{-1}\ m^{-1}}$), which in turn depend upon the number of furrows irrigated

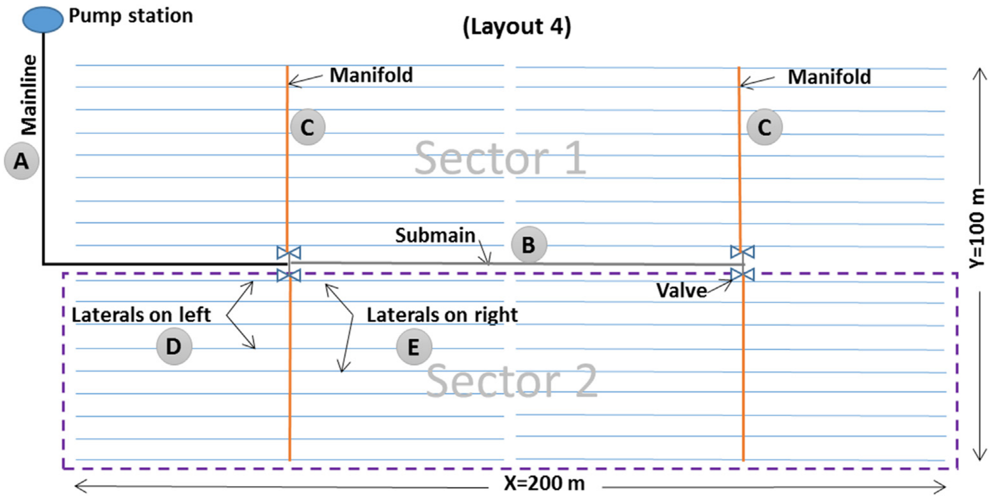

Fig. 1 – Schematic layout base of drip irrigation systems (letters A through E refer to sizes in Table 3).

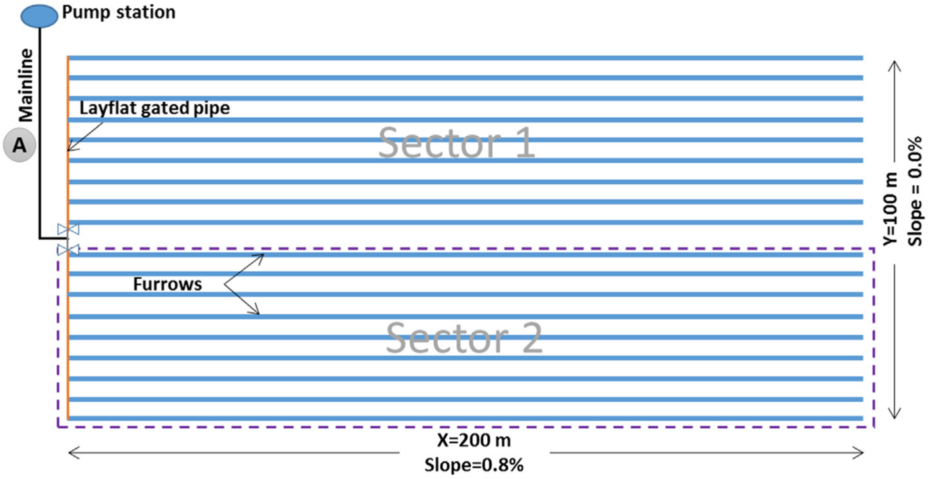

Fig. 2 – Schematic layout of graded furrows for a field of 200 m length.

simultaneously or the border width. Costs are fully described by Darouich et al. (2012).

2.4. *Multicriteria analysis (MCA)*

The evaluation and selection of the best irrigation method is performed with multicriteria analysis. The comparison between surface and drip irrigation makes evident contrasting criteria relative to economic farm returns and water saving. It is assumed that there is not a unique optimal alternative but, because MCA integrates different types of attributes on a trade-off analysis, it is possible to find the solutions that are closer to the wishes of the user (Ishizaka & Nemery, 2013; Pomerol & Romero, 2000). MCA may also support a better understanding of the environmental, economic and social impacts of irrigation while enabling satisfactory compromises between contradictory objectives.

The MCA procedure starts with the definition of the design objectives and related criteria attributes (Table 4). Attributes refer to:

1. Economic productivity and costs related to farmer economic perspectives, including economic land productivity, economic water productivity, economic water productivity ratio, fixed irrigation costs and variable irrigation costs;
2. Water saving, relative to the irrigation environmental performance including total irrigation water use, beneficial water use fraction, irrigation water productivity and non-beneficial water uses.

The criteria attributes were calculated according to the water use and productivity indicators defined by Pereira et al. (2012), which were incorporated in MIRRIG and SADREG models. These attributes are handled through appropriate linear utility functions:

$$U_j(X_j) = \alpha \cdot X_j + \beta \tag{2}$$

where x_j is the attribute value, α is the slope, negative for costs and positive for benefits, and β is the utility value for a null value of the attribute. The utility functions adopted are listed in Table 4. With this procedure, the utilities U_j for any criterion

Table 4 – Criteria attributes, utility functions and attribute weights.

Criteria attributes (x)		Symbol	Units	Utility functions	Weights (%) assigned to attributes when considering	
					Water saving	Economic returns
Economic					20	80
Economic land productivity		ELP	€ ha^{-1}	$U(\mathbf{x}) = 0.27 \times 10^{-3}\,\mathbf{x}$	5	15
Economic water productivity		EWP	€ m^{-3}	$U(\mathbf{x}) = 1.73\,\mathbf{x}$	4	15
Economic water productivity ratio		EWPR	Ratio	$U(\mathbf{x}) = 0.133\,\mathbf{x}$	5	20
Fixed irrigation costs		FIC	€ ha^{-1}	$U(\mathbf{x}) = 1 - 0.17 \times 10^{-3}\,\mathbf{x}$	3	15
Variable irrigation costs		VIC	€ ha^{-1}	$U(\mathbf{x}) = 1 - 0.17 \times 10^{-3}\,\mathbf{x}$	3	15
Water saving					80	20
Total irrigation water use		IWU	mm	$U(\mathbf{x}) = 1.67 - 1.031 \times 10^{-3}\,\mathbf{x}$	20	5
Beneficial water use fraction		BWUF	Ratio	$U(\mathbf{x}) = 1.0\,\mathbf{x}$	15	4
Irrigation water productivity		WP_{Irrig}	kg m^{-3}	$U(\mathbf{x}) = 1.27\,\mathbf{x}$	15	5
Non-beneficial water use	Irrigation tail-end runoff	IRO	mm	$U(\mathbf{x}) = 1 - 0.118 \times 10^{-2}\,\mathbf{x}$	15	3
	Irrigation deep percolation	IDP	mm	$U(\mathbf{x}) = 1 - 0.118 \times 10^{-2}\,\mathbf{x}$	15	3

j are normalised into the [0–1] interval (zero for the most adverse and 1 for the most advantageous result).

There are various methods for ranking the considered design alternatives (Mendoza & Martins, 2006; Pomerol & Romero, 2000; Yan, Huynh, Nakamori, & Murai, 2011). The Linear Weighted Sum method (Stanimirovic, Zlatanovic, & Petkovic, 2011; Takahara, Nakano, & Kijima, 1979) was applied as it has been successful in ranking surface irrigation alternatives (Gonçalves et al., 2011). It is an aggregative and fully compensatory method that leads to a unique global criterion, assuming that the decision maker aims at the optimisation of an overall utility function. The great simplicity of this method is its major advantage. For each alternative, the method allows the calculation of a global utility that represents its integrative score performance:

$$U = \sum_{j=1}^{N_c} \lambda_j U_j \tag{3}$$

where U is the global utility, scaled in the [0–1] interval; N_c is the number of criteria; λ_j is the weight assigned to the criterion j; and U_j is the utility relative to criterion j. The application of this method requires priorities to be assigned by selecting the weights λj that represent the relative importance of each criterion j from the perspective of the decision maker. Criterion weights depend on several factors including socio-cultural values, and economic and/or environmental perspectives. In this study, two priority scenarios were considered, one aimed at achieving the best water saving and the other aimed at attaining the highest farm incomes (see Table 4).

SADREG and MIRRIG produced a large set of alternatives, which were clustered in groups after the respective ranking and selection analysis. A further application of MCA to the selected drip and surface irrigation alternatives allowed the required comparison between these different systems, considering the referred criteria.

The analysis of rankings was carried out by varying progressively the weights relative to farm economics and water saving criteria, i.e., starting with a scenario where 90% of weights were assigned to farm economic criteria and 10% to water saving and ending with a last scenario where 90% of weights were assigned to water saving. The same analysis was performed for deficit irrigation.

3. Results

3.1. *Comparison of drip irrigation alternatives*

MIRRIG simulated a set of 120 alternatives for drip irrigation resulting from different combination of six system layouts (L1, …, L6), two lateral layouts (SRL and DRL), five emitters (SC1.6, SC3.5, NC1.5, NC2.7, NC4.0) and two emitters spacing of 0.5 and 0.7 m, as described in Section 2.2. Results (Fig. 3a) relative to total irrigation water use (IWU) show that lower IWU values (825–832 mm) refer to self-compensating (SC) emitters as opposed to non-compensating (NC) emitters (837–977 mm) (Fig. 3a), with the highest IWU for NC with discharge of 4.0 l h^{-1} installed in layout L1, SRL and spacing ES0.5. The difference of IWU between the two types of emitter SC and NC results from higher emitter and distribution uniformity (DU) when using SC emitters. With SC emitters, DU ranged 96–97%, while with NC emitters DU varied from 81 to 95%. Similar results have been obtained by other researchers, e.g., Yohannes and Tadesse (1998).

IWU was slightly smaller for DRL than for SRL (Fig. 3a) with 89–96% BWUF. Aujla, Thind, and Buttar (2008) also reported higher water saving when using double rows per lateral compared to single rows. Relative to emitter spacing along the lateral, it was observed that the smaller spacing of 0.5 m leads to slightly higher IWU for most of the layouts, which is in agreement with results reported by Ozbahce and Tari (2010). Grabow, Huffman, Evans, Jordan, and Nuti (2006) reported that spacing varying from 0.91 to 1.82 m did not show significant differences in yield but only very small differences in terms of WP_{irrig}, which is in agreement with our results. The variation of IWU and WP_{Irrig} values relative to the NC emitters adopted is higher for layout L1 when compared with L6 (Fig. 3), because L1 has longer laterals that favour higher head losses and lower DU for non-compensating emitters. That variation is higher for ES0.5 because head losses tend to increase when increasing the number of outlets.

As expected, WP_{Irrig} behaves in the opposite way to IWU, i.e., WP_{Irrig} is larger when IWU is smaller (Fig. 3b). Thus, WP_{Irrig} values are higher for SC emitters (0.61 kg m^{-3}) and lower for NC emitters, particularly for larger discharges and smaller spacing (0.51 kg m^{-3}). Dağdelen et al. (2009), Hussein et al. (2011), Ibragimov et al. (2007) and Sankaranarayanan et al. (2011) reported WP_{Irrig} similar values (0.56–0.85 kg m^{-3}). In agreement with the discussion above, differences in IWU and WP_{Irrig} values due to emitters spacing (0.5 *vs.* 0.7 m) are smaller for SC emitters than for NC and are also smaller for DRL lateral layouts comparatively to SRL (Fig. 3).

The economic water productivity (EWP) shows the same trend as WP_{Irrig} (Fig. 4a), with higher values (0.45 € m^{-3}) for both SC1.6 and SC3.5 emitters, and for DRL layouts. The lowest EWP is for L1, NC4.0, SRL and ES0.5.

The main influences of the emitter spacing and lateral layouts refer to the fixed investment cost (FIC). DRL with 0.7 m emitter spacing have values for FIC 11–16% lower than SRL for the same emitter spacing and layout (Fig. 4b). Aujla et al. (2008) reported that double rows per lateral led to a reduction in costs of up to 50% due to a smaller number of laterals required. FIC is also higher for SC emitters, which are more expensive than NC ones. The highest FIC (>3150 € ha^{-1}) was for NC4.0 and SC3.5 for SRL and ES0.5, while the lowest FIC (<1450 € ha^{-1}) was for NC2.7 for DRL and ES0.7. The economic water productivity ratio EWPR, representing the yield value per unit cost of production, varies contrarily to FIC (Fig. 4c). The economic results are closely related to the emitter type (SC emitters having larger costs than NC ones), emitter spacing (with high costs for the smaller spacing), and lateral layout (with lower costs for the double rows per lateral). Apparently, the design of layouts has less influence. However, the emitter type plays an important role in irrigation performance: self-compensating emitters, mainly the SC1.6, appear as the best solutions in terms of water saving; by contrast, the non-compensating emitters, particularly the NC2.7, appear to be the best from an economic perspective. The emitter spacing of 0.5 m is more costly than that of 0.7 m and favour

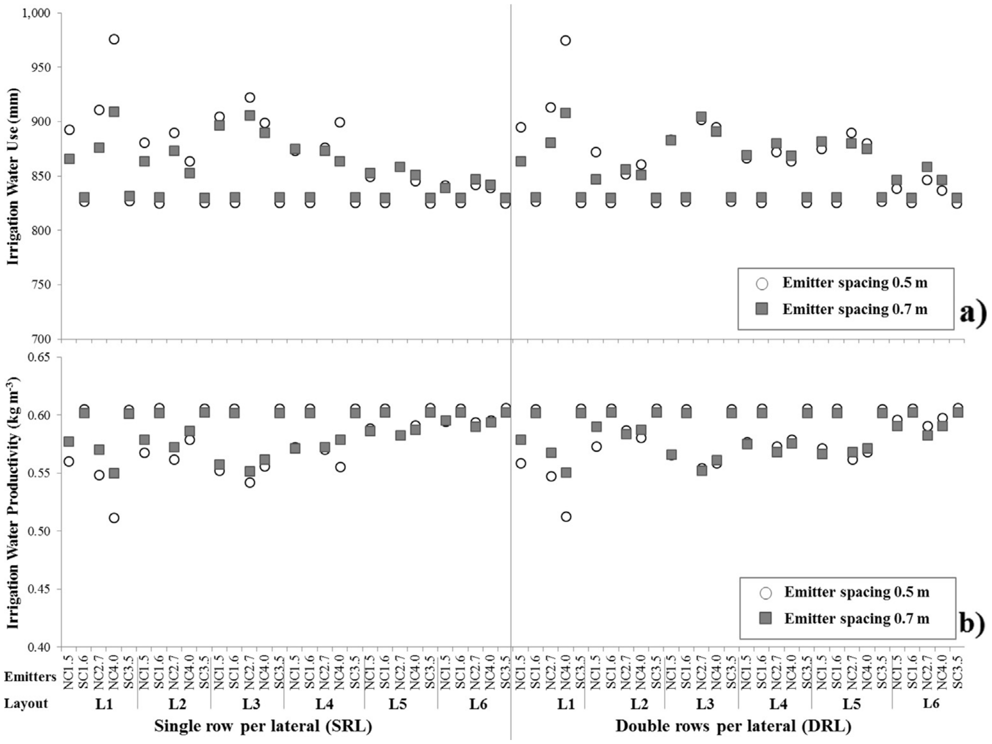

Fig. 3 – Comparing irrigation water use (a) and irrigation water productivity (b) for single and double rows per lateral (SRL and DRL), various layouts (L1 to L6) with self-compensating (SC1.6 and SC3.5) and non-compensating emitters (NC1.5, NC2.7 and NC4.0), and two emitter spacings.

higher IWU, thus lower WP_{irrig}. Relative to the lateral layouts, DRL appears to be better than SRL in terms of costs and water use, as also reported by Aujla et al. (2008) and Grabow et al. (2006). The layouts for lateral zero slope (L5, L6) produce lower pressure variation and higher DU. The layouts where laterals are in agreement with slope favour longer pipes and smaller head losses, while other layouts require higher pressure head and result more costly. Thus, the best layouts in terms of water saving and economic results are L2 and L6, while the worst is L1.

3.2. *Comparison of surface irrigation alternatives*

SADREG simulated 64 surface irrigation design alternatives, mainly border *vs.* furrow systems with and without precise laser land levelling (LL and NLL). The alternatives with higher performance are presented in Fig. 5, where they are compared using the utilities relative to the indicators IWU, EWP, BWUF and EWPR. Results show that land levelling has a direct impact on irrigation performance, mainly the irrigation uniformity, so that LL leads to high utility values for IWU, EWP and BWUF, i.e., land levelling favours a reduced IWU and higher EWP and BWUF. A similar conclusion was reported by Darouich et al. (2012) and Gonçalves et al. (2011) who explained that land levelling improves irrigation performance and favours water saving but associated costs lead to less good economic results. Thus, land levelling leads to higher production costs and to reducing EWPR (Fig. 5b). Therefore, a compromise between these two contradictory effects of LL has to be sought depending upon the field topography and unevenness, the impacts on distribution uniformity and the respective costs. The relatively high cost of land levelling implies that the NLL alternatives are likely to be more appropriate when a priority is assigned to economic results, whereas a high utility would correspond to LL alternatives when the priority is assigned to water saving.

Results for graded furrows appear to be slightly better than those for graded borders when comparing the utilities for EWP and EWPR (Fig. 5). Global utilities are higher for small discharges with furrows and for larger discharges with borders (Fig. 6) as already reported by Darouich et al. (2012). In fact, the irrigation performance depends greatly upon the appropriateness of discharges and cut-off time. Considering this fact, to avoid biasing the comparison among alternatives, the equipment for control of inflow rates was similar for all alternatives.

Differences are small when comparing field lengths of 100 and 200 m, which indicates adequate adaptability to predominant local conditions. However, the soil type and field slope influence this selection. Horst et al. (2007) reported that the best results were achieved for long furrows of 320 m, an inflow rate of 2.4 $l\ s^{-1}$ and a furrow spacing of 0.9 m. However, for different slopes and infiltration characteristics of soils, lengths and discharges need to be different (Gonçalves & Pereira, 2009; Hunsaker et al., 1998; Walker & Skogerboe, 1987).

3.3. *Comparing and ranking drip* vs. *surface irrigation alternatives*

The comparison and ranking of drip *vs.* surface irrigation alternatives was performed after ranking and then selecting the best alternatives for each system as analysed in the previous

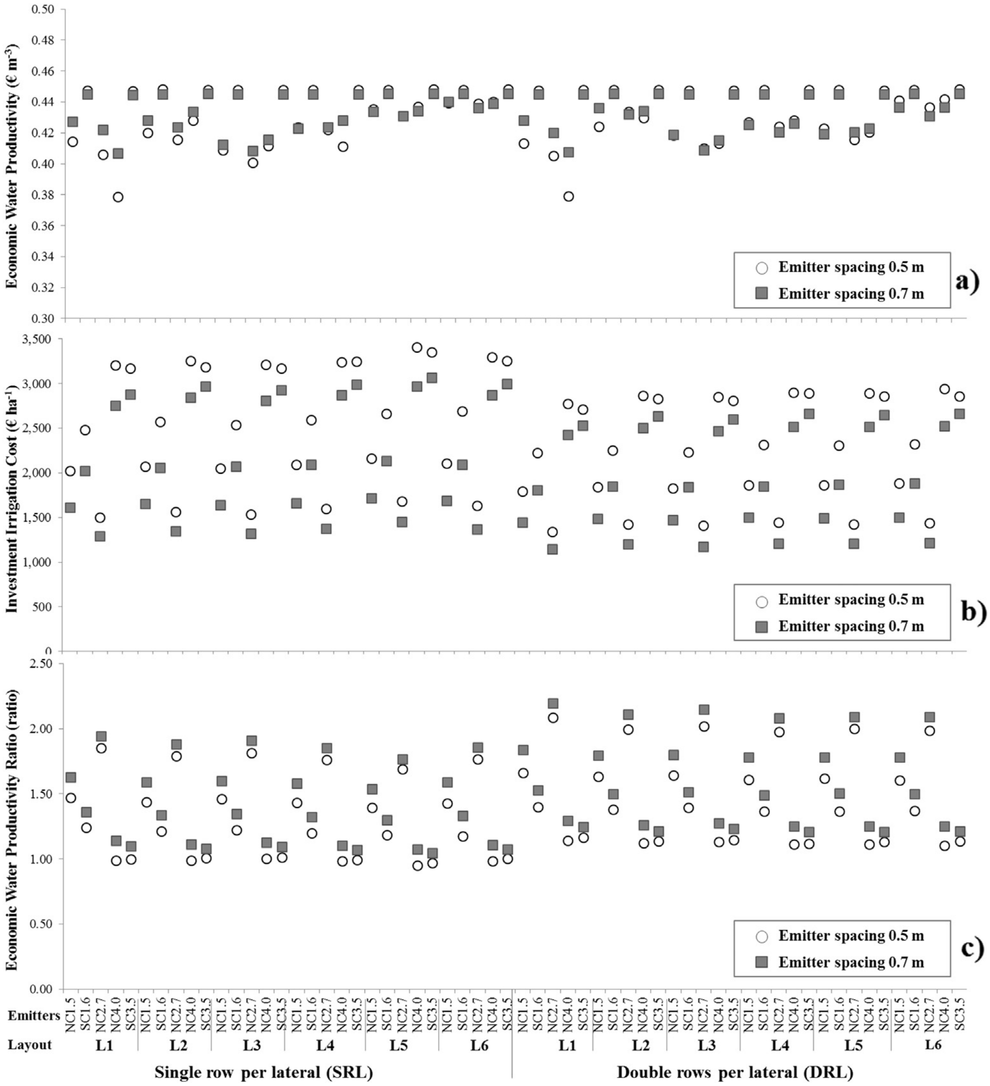

Fig. 4 – Comparing economic water productivity (a), investment costs (b), and economic water productivity ratio (c) for single and double rows per lateral (SRL and DRL), various layouts (L1–L6) with self-compensating (SC1.6 and SC3.5) and non-compensating emitters (NC1.5, NC2.7 and NC4.0), and two emitter spacings.

Sections. The traditional surface irrigation system was considered as reference. The attributes for comparison include IWU, NBWU, and WP_{Irrig} as described in Section 2.4 and Table 4. IWU and WP_{Irrig} show contrasting results when comparing drip with surface irrigation (Fig. 7). Drip irrigation requires less water use, about 350–700 mm less than surface irrigation, thus providing for higher water productivity, which exceeds that of surface irrigation by 0.13–0.29 kg m^{-3}. These results are similar to those presented by Cetin and Bilgel (2002), Ibragimov et al. (2007) and Sankaranarayanan et al. (2011), who reported differences of 0.11, 0.27 and 0.15 kg m^{-3} respectively. Non-beneficial water use (NBWU) in surface irrigation is much higher than for drip, respectively 450 and 50 mm for surface and drip. A large part of NBWU in surface irrigation consists of runoff, that can be reused but with additional costs. Deep percolation may also not be lost if not degraded and available for later reuse after reaching the groundwater. Moreover, deep percolation has a beneficial "service" of salt leaching, favouring the utility of surface irrigation in areas where salinity control is a must (Pereira et al., 2012). Nevertheless, when the available water for irrigation is very limited, the water saving achieved by drip irrigation favours the selection of this method aiming at water saving and considering leaching requirements. Differences in NBWU between surface and drip irrigation are the main causes for the respective differences in IWU and WP_{Irrig}. All selected solutions for graded borders imply land levelling. By contrast, various solutions for graded furrows did not include LL; when LL is considered then NBWU and IWU decrease. Apparently, the length of the fields has a smaller influence on IWU, NBWU and WP_{Irrig}. In contrast with the varied responses of these indicators to various surface irrigation characteristics, the variation of these attributes for the various selected drip alternatives are very small. Summarising, Fig. 7 shows that drip irrigation provides for lower IWU and NBWU than surface irrigation and higher water productivity.

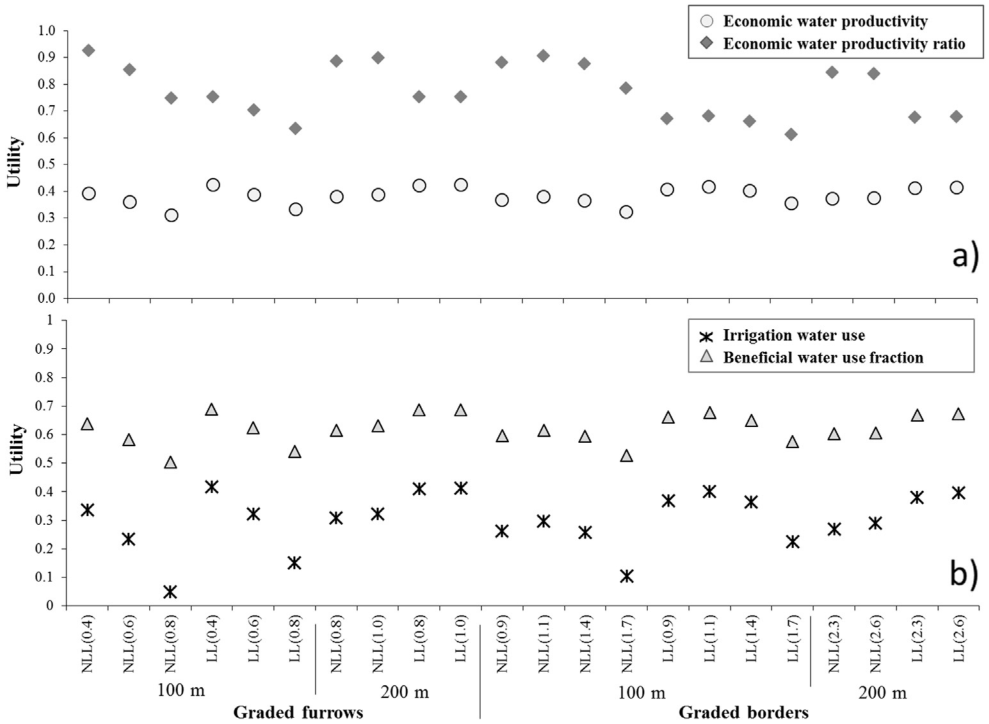

Fig. 5 – Comparing the utilities relative to: a) economic water productivity and the economic water productivity ratio, and b) irrigation water use and beneficial water use fraction for graded furrows and borders with lasered and non-lasered land (LL and NLL), field lengths of 100 and 200 m, and various inflow rates (l s^{-1} $furrow^{-1}$ or l s^{-1} m^{-1}).

Economic attributes – fixed investment costs (FIC), variable irrigation costs (VIC) and EWPR – are analysed in Fig. 8 when comparing drip and surface irrigation systems. The investment costs are much higher for drip than for surface irrigation, however depending on various design factors analysed in Section 3.1. The investment cost for drip systems varies from 1313 to 2320 € ha^{-1}, with higher values when selecting SC emitters, resulting in FIC that is much higher than for surface irrigation. The annuity relative to investment costs represents 24–53% of the average farmers' gross income of 3700 € ha^{-1}, which is quite high and explains why farmers have kept surface irrigation until now. These results are in line with those reported by MunlaHasan (2007) who showed that furrow irrigation has the lowest cost and highest farmer return, with drip irrigation providing for economic results 25–45% smaller than surface irrigation. By contrast, differences in annual maintenance and operation costs are not very different when comparing drip with NLL systems; however, investment

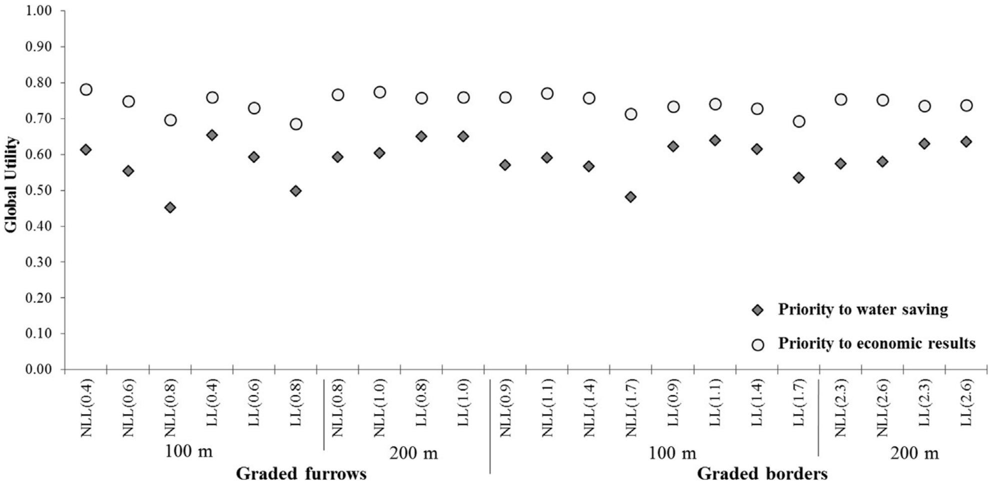

Fig. 6 – Comparing the global utilities of graded furrows and borders when the priority is assigned to economic returns or to water saving considering lasered and non-lasered land (LL and NLL), field lengths of 100 and 200 m, and various inflow rates (l s^{-1} $furrow^{-1}$ or l s^{-1} m^{-1}).

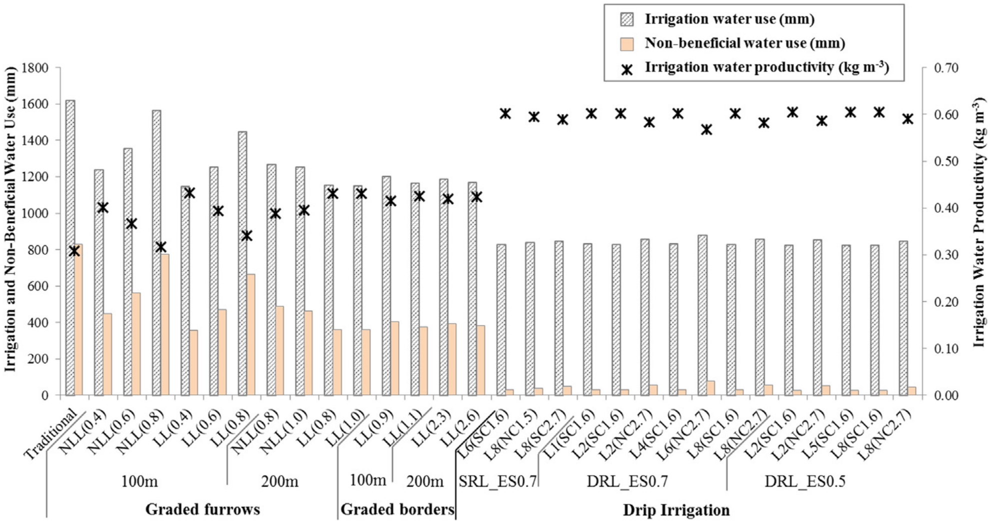

Fig. 7 – Comparing irrigation water use, non-beneficial water use and irrigation water productivity for drip systems with single and double rows per lateral (SRL and DRL), various layouts (L1–L6) with self-compensating (SC1.6) and non-compensating emitters (NC1.5, NC2.7), and two emitter spacings, and for graded furrows and borders with lasered and non-lasered land (LL and NLL), field lengths of 100 and 200 m, and various inflow rates (l s^{-1} furrow^{-1} or l s^{-1} m^{-1}).

annuity and maintenance costs for laser levelling are relatively important and related VIC exceed those costs for drip; moreover VIC for LL systems exceed those for NLL systems by about 120–165 € ha^{-1}. The EWPR ratio (see Fig. 8) expresses an enormous disparity between economic results obtained for these two irrigation methods, with EWPR ranging from 1.3 to 2.2 for drip systems, and from 4.9 to 7.1 for surface irrigation. Similar results were reported by Rajak et al. (2006) who reported that the gross benefit–cost ratio was lower for drip irrigation than for furrow irrigation due to higher initial cost incurred in drip irrigation. Results in Fig. 8 show that decisions behind selecting drip systems to replace surface irrigation is mainly an investment decision, which is sensitive to the water cost and availability, labour cost and availability, yield commodity prices and credit facilities.

Two prioritisation schemes are considered following the differences observed comparing surface and drip irrigation systems: to assign priority to water saving or to economic returns of irrigation (see Table 4). Therefore it is appropriate to compare the global utilities of the selected alternatives when assigning the priority to economic results or to water saving. Results show (Fig. 9) that the global utility relative to the surface irrigation is greater than that for drip relative to economic results and vice-versa for water saving, which is in

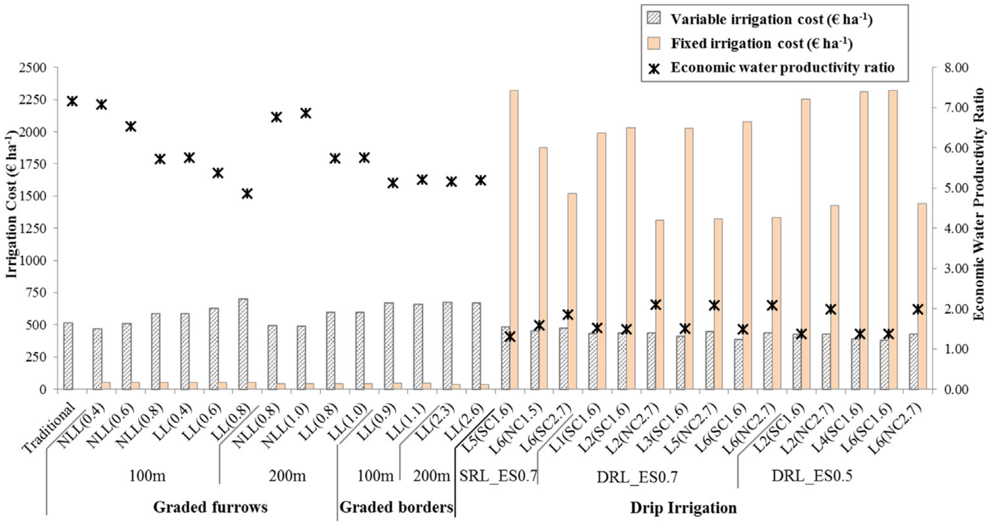

Fig. 8 – Comparing investment costs, variable costs and the economic water productivity ratio for drip systems with single and double rows per lateral (SRL and DRL), various layouts (L1–L6) with self-compensating (SC1.6) and non-compensating emitters (NC1.5, NC2.7), and two emitters spacings, and for graded furrows and borders with lasered and non-lasered land (LL and NLL), field lengths of 100 and 200 m, and various inflow rates (l s^{-1} furrow^{-1} or l s^{-1} m^{-1}).

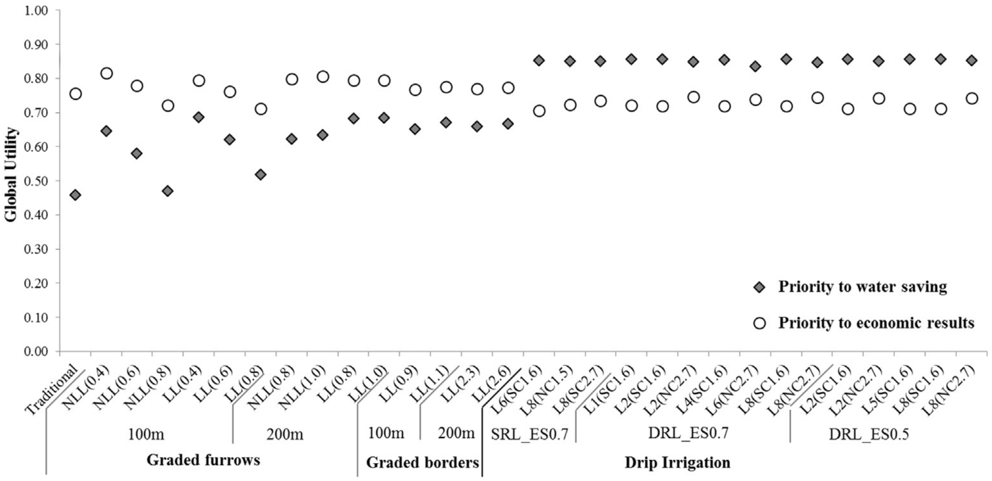

Fig. 9 – Comparing global utilities when the priority is assigned to economic returns or to water saving referring to graded furrows and borders and to drip systems with single and double rows per lateral (SRL and DRL).

agreement with the analysis performed above concerning Figs. 7 and 8. It should be noted (Fig. 9) that the traditional system has a utility similar to those of modernised systems when prioritising economic results but quite low when the priority is water saving, i.e., the traditional system is not a feasible and sustainable solution to cope with water scarcity because it has very high water use (Fig. 7). Summarising, results in Fig. 9 show that when prioritising water saving the advantage is for drip systems, while if economic results are prioritised the advantage goes to surface irrigation.

Following the results analysed before, the retained drip and surface irrigation systems were ranked assuming various prioritisation schemes, W1 to W6, with W1 corresponding to assign 90% of weights (see Table 4) to economic results and 10% to water saving while for W6 only 10% of weights were assigned to economic results and 90% to water saving. Results in Table 5 show that surface irrigation is dominant until 40% of weights are assigned to economic returns to farmers (scenario W3) and that drip is selected when weights assigned to water saving represent 50% or more of total weights. The first ranked for W1 through W3 are non-levelled graded furrows with controlled discharges while laser levelling has a lower preference. When drip is ranked first, the double rows per lateral layout is always selected. Non-compensating emitters are selected when drip starts to be first ranked (W4), but SC emitters become the choice when higher priority is assigned to water saving (W6). Overall, results in Table 5 represent an evolution in adoption of technologies, which are progressively more demanding mainly in terms of investment costs.

These results must be interpreted from a policy and decision making perspective: if policy and decision makers define water saving as the priority then they have to create technical and financial solutions that support farmers adoption of improved systems because the farmers economic perspectives favour the adoption of improved surface irrigation without laser levelling i.e., just adopting low cost technology. However, farmers also need technical support to successfully adopt such improvements (Galli et al., 2010).

Table 5 – Ranking of the alternative solutions for various weighting scenarios W1 (highest weights assigned to economic issues) through W6 (highest weights assigned to water saving) when full irrigation is considered.

Rank	Weighting scenarios, with progressively decreasing weights to economic issues and increasing weights to water saving					
	W1(10–90)	W2(30–70)	W3(40–60)	W4(50–50)	W5(70–30)	W6(90–10)
1	GFNLL100(0.4)	GFNLL100(0.4)	GFNLL100(0.4)	DRL0.5L6(NC2.7)	DRL0.7L6(SC1.6)	DRL0.5L2(SC1.6)
2	GFNLL200(1.0)	GFNLL200(1.0)	DRL0.7L2(NC2.7)	DRL0.7L2(NC2.7)	DRL0.5L6(NC2.7)	DRL0.5L6(SC1.6)
3	GFNLL200(0.8)	GFLL100(0.4)	GFLL100(0.4)	DRL0.7L6(SC1.6)	DRL0.7L2(SC1.6)	DRL0.7L6(SC1.6)
4	GFLL100(0.4)	GFLL200(1.0)	GFLL200(1.0)	DRL0.7L2(SC1.6)	DRL0.5L2(SC1.6)	DRL0.7L2(SC1.6)
5	GFLL200(1.0)	GFLL200(0.8)	DRL0.5L6(NC2.7)	DRL0.5L2(SC1.6)	DRL0.5L6(SC1.6)	DRL0.5L6(NC2.7)
6	GFLL200(0.8)	GFNLL200(0.8)	GFLL200(0.8)	DRL0.5L6(SC1.6)	DRL0.7L2(NC2.7)	DRL0.7L2(NC2.7)
7	DRL0.7L2(NC2.7)	DRL0.7L2(NC2.7)	GFNLL200(1.0)	GFLL100(0.4)	GFLL100(0.4)	GFLL100(0.4)
8	DRL0.5L6(NC2.7)	DRL0.5L6NC2.7)	GFNLL200(0.8)	GFLL200(1.0)	GFLL200(1.0)	GFLL200(1.0)
9	DRL0.7L6(SC1.6)	DRL0.7L6(SC1.6)	DRL0.7L6(SC1.6)	GFLL200(0.8)	GFLL200(0.8)	GFLL200(0.8)
10	DRL0.7L2(SC1.6)	DRL0.7L2(SC1.6)	DRL0.7L2(SC1.6)	GFNLL100(0.4)	GFNLL100(0.4)	GFNLL100(0.4)
11	DRL0.5L2(SC1.6)	DRL0.5L2(SC1.6)	DRL0.5L2(SC1.6)	GFNLL200(1.0)	GFNLL200(1.0)	GFNLL200(1.0)
12	DRL0.5L6(SC1.6)	DRL0.5L6(SC1.6)	DRL0.5L6(SC1.6)	GFNLL200(0.8)	GFNLL200(0.8)	GFNLL200(0.8)

NOTE: GF refer to graded furrows and DRL to double plant rows per drip lateral line.

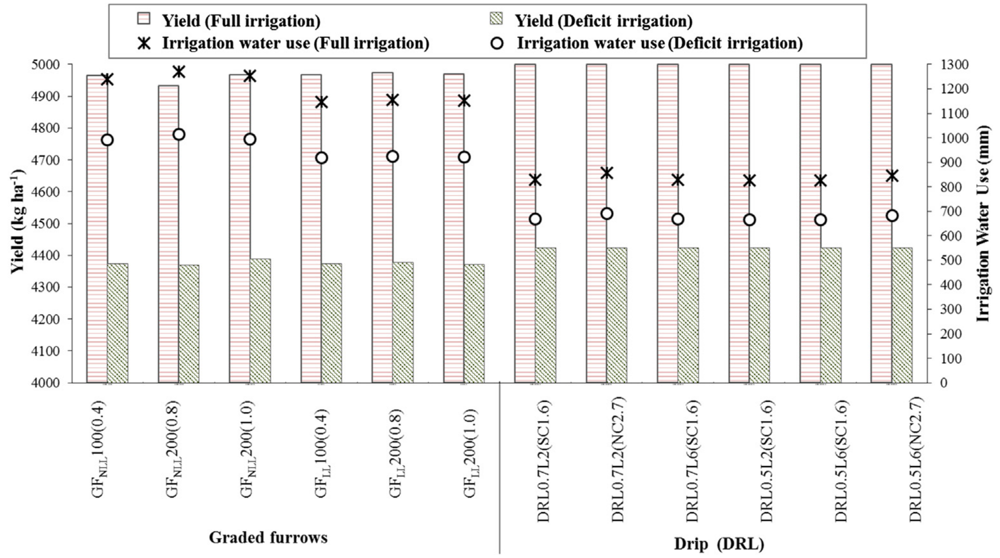

Fig. 10 – Comparing yields and irrigation water use for drip systems having double rows per lateral and for graded furrows with lasered and non-lasered land (LL and NLL) considering full and deficit irrigation.

3.4. *Deficit irrigation impact on ranking the alternatives*

The comparison between the 12 selected drip and surface irrigation alternatives when adopting deficit irrigation was performed considering an irrigation depth of 640 mm, i.e., a reduction of 20% relative to full irrigation (800 mm). This decrease in water availability impacts the actual evapotranspiration and yield (Table 2). Selected results are presented in Fig. 10 where yields and water use are compared for full and deficit irrigation (FI and DI). A yield reduction of 11–12% was estimated for both surface and drip systems when adopting DI. Ünlü et al. (2011) reported that reducing irrigation by 22% produced a yield loss of 11%, which is a result similar to ours. Akhtar et al. (2013) reported a lower impact on yields, reducing the yield by 14% when the water supply is decreased by 40%. Dağdelen et al. (2009) also reported lower yield impacts of DI. Results in Fig. 10 show that DI has lower impacts on yields when drip irrigation is adopted. This relates to the lower non-beneficial water use with drip and to the better placement of the irrigation water in the root zone.

Figure 11 presents the difference in IWU, BWUF, WP_{Irrig} and ELP utility values relative to the 12 retained surface and drip irrigation systems when changing from FI to DI. All utility values increase except the economic land productivity, which decreases due to yield reduction. IWU and BWUF increase because they reflect a decrease in water use, and WP_{Irrig}, also increases, because the yield decrease is proportionally smaller than the water use decrease. Drip and

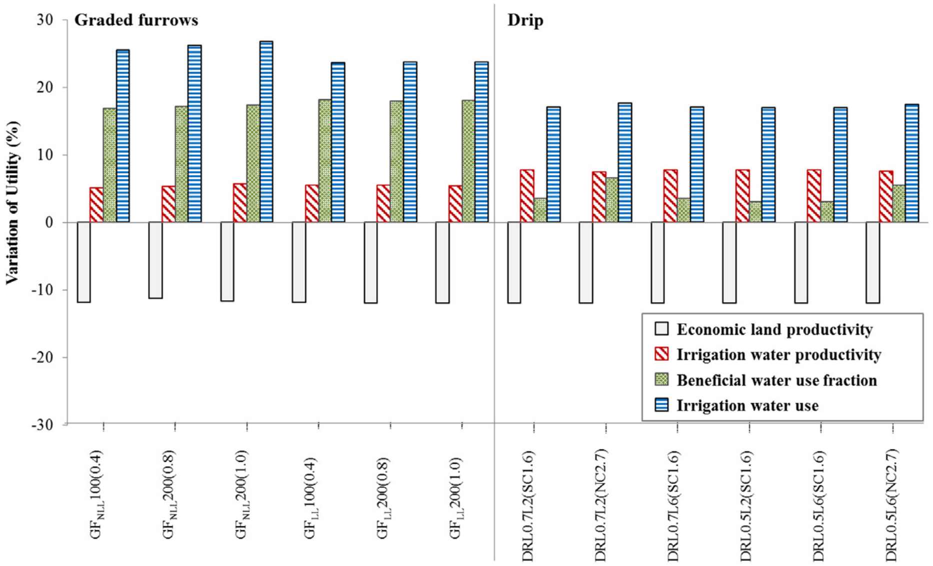

Fig. 11 – Differences of the utilities relative to economic water productivity (ELP), water productivity of the irrigation water (WP_{Irrig}), beneficial water use fraction (BWUF) and irrigation water use (IWU) when considering full and deficit irrigation for drip and graded furrows systems.

Table 6 – Ranking of the alternative solutions for various weighting scenarios W1 (highest weights assigned to economic issues) through W6 (highest weights assigned to water saving) when deficit irrigation is adopted, the drip alternatives is for double rows per lateral, DRL and emitters spacing 0.5 and 0.7 m.

Rank	Weighting scenarios, with progressively decreasing weights to economic issues and increasing weights to water saving					
	W1(10–90)	W2(30–70)	W3(40–60)	W4(50–50)	W5(70–30)	W6(90–10)
1	GFNLL100(0.4)	GFNLL100(0.4)	GFNLL100(0.4)	DRL0.7L2(NC2.7)	DRL0.5L6(NC2.7)	DRL0.5L2(SC1.6)
2	GFNLL200(1.0)	GFNLL200(1.0)	GFNLL200(1.0)	DRL0.5L6(NC2.7)	DRL0.7L2(NC2.7)	DRL0.5L6(SC1.6)
3	GFNLL200(0.8)	GFNLL200(0.8)	GFNLL200(0.8)	DRL0.7L2(SC1.6)	DRL0.7L2(SC1.6)	DRL0.7L2(SC1.6)
4	GFLL100(0.4)	GFLL100(0.4)	GFLL100(0.4)	DRL0.7L6(SC1.6)	DRL0.7L6(SC1.6)	DRL0.7L6(SC1.6)
5	GFLL200(1.0)	GFLL200(1.0)	GFLL200(1.0)	DRL0.5L2(SC1.6)	DRL0.5L2(SC1.6)	DRL0.5L6(NC2.7)
6	GFLL200(0.8)	GFLL200(0.8)	GFLL200(0.8)	DRL0.5L6(SC1.6)	DRL0.5L6(SC1.6)	DRL0.7L2(NC2.7)
7	DRL0.7L2(NC2.7)	DRL0.7L2(NC2.7)	DRL0.7L2(NC2.7)	GFLL100(0.4)	GFLL100(0.4)	GFLL100(0.4)
8	DRL0.5L6(NC2.7)	DRL0.5L6(NC2.7)	DRL0.5L6(NC2.7)	GFLL200(1.0)	GFLL200(1.0)	GFLL200(1.0)
9	DRL0.7L2(SC1.6)	DRL0.7L2(SC1.6)	DRL0.7L2(SC1.6)	GFLL200(0.8)	GFLL200(0.8)	GFLL200(0.8)
10	DRL0.7L6(SC1.6)	DRL0.7L6(SC1.6)	DRL0.7L6(SC1.6)	GFNLL100(0.4)	GFNLL100(0.4)	GFNLL100(0.4)
11	DRL0.5L2(SC1.6)	DRL0.5L2(SC1.6)	DRL0.5L2(SC1.6)	GFNLL200(1.0)	GFNLL200(1.0)	GFNLL200(1.0)
12	DRL0.5L6(SC1.6)	DRL0.5L6(SC1.6)	DRL0.5L6(SC1.6)	GFNLL200(0.8)	GFNLL200(0.8)	GFNLL200(0.8)

NOTE: GF refer to graded furrows and DRL to double plant rows per drip lateral line.

surface irrigation behave differently as shown in Fig. 11 and as analysed before. It is noticeable that the increase in the utility of IWU and BWUF are greater for GF than for drip systems, which is explained by a better use of soil water when less irrigation is applied. DI could be advantageous if the decrease of farmer income is smaller than the decrease in production costs. However, DI implies an additional risk that leads farmers to adopt DI only as a response to water availability constraints.

A ranking analysis similar to that in Table 5 is presented in Table 6 for the same 12 drip and graded furrow systems. Results show with evidence that if economic results are prioritised (W1–W3), the first 6 ranked solutions refer to non-levelled graded furrows with appropriate control of inflow rates; by contrast, if priorities are assigned to water saving (W4–W6) then drip systems are selected adopting double rows per lateral. Self-compensating emitters are selected when weights assigned to water saving increase replacing the non-compensating ones, which are less expensive. Results for DI confirm that if policy and decision makers define water saving as a priority, then it is required to create technical and financial solutions that support farmer's adoption of improved systems since economic results favour the adoption of improved surface irrigation without precision land levelling.

4. Conclusions

This study aimed to develop, compare and rank various alternatives for cotton irrigation using modern surface and drip systems in Ras-El-Ain, Northeast of Syria. Two main criteria were considered: water saving and economic return to farmers. Design solutions for surface irrigation were developed and selected with the DSS model SADREG, and those for drip with the DSS model MIRRIG. Multicriteria analysis was used, adopting the same attributes for both types of systems.

Data analysis has shown that drip irrigation uses less water than surface irrigation, thus the irrigation water productivity is larger for drip systems by 0.13–0.29 kg m^{-3} depending on various systems characteristics. The economic attributes revealed an investment cost for the drip systems of 1313–2320 € ha^{-1}, which is much higher than investments in equipment for surface systems and represents 24–53% of the total annual income. Variable costs are not very different among irrigation methods. The economic water productivity ratio ranged from 1.3 to 2.1 for drip systems and up to 4.9–7.1 for surface irrigation, thus indicating an enormous economic gap between both types of systems.

When ranking the best design solutions relative to drip and surface irrigation, the high ranked solutions refer to non-levelled graded furrows when the priority is assigned to economic results, while if the priority is assigned to water saving the first ranked solutions are for drip systems adopting double rows per lateral. Results for deficit irrigation do not change the main rankings but suggest that drip may be more appropriate for water saving because it is able to reduce negative impacts on yields. Results indicate that if decision and policy makers wish to achieve water saving policies and practices, it will be necessary to adopt financial and technical support to farmers because related solutions are contrary to those providing good economic returns to farmers.

Acknowledgements

This study is part of the project PTDC/AGR-AAM/105432/2008 funded by the Foundation for Science and Technology (FCT), Portugal. Field work was funded by CIHEAM/IAM, Bari, Italy, and the Italian Cooperation. The first author thanks FCT for the fellowship SFRH/BD/60516/2009. The review and suggestions by Dr. Gonçalo C. Rodrigues are acknowledged.

REFERENCES

Akhtar, F., Tischbein, B., & Awan, U. K. (2013). Optimizing deficit irrigation scheduling under shallow groundwater conditions in lower reaches of Amu Darya river basin. *Water Resources Management*, 1–14.

Al Ashkar, H. A. K. (2009). The evolution of cotton policies in Syria. *International Journal of Life Sciences, 1*, 123–131.

Aujla, M. S., Thind, H. S., & Buttar, G. S. (2008). Response of normally sown and paired sown cotton to various quantities of water applied through drip system. *Irrigation Science, 26*, 357–366.

Barragan, J., Cots, L., Monserrat, J., Lopez, R., & Wu, I. P. (2010). Water distribution uniformity and scheduling in micro-irrigation systems for water saving and environmental protection. *Biosystems Engineering, 107*(3), 202–211.

Bartolini, F., Gallerani, V., Raggi, M., & Viaggi, D. (2010). Water management and irrigated agriculture in Italy: multicriteria analysis of alternative policy scenarios. *Water Policy, 12*, 135–147.

Beaumont, P. (1996). Agricultural and environmental changes in the upper Euphrates catchment of Turkey and Syria and their political and economic implications. *Applied Geography, 16*(2), 137–157.

Bhattarai, S. P., Mchugh, A. D., Lotz, G., & Midmore, D. J. (2006). The response of cotton to subsurface drip and furrow irrigation in a vertisol. *Experimental Agriculture, 42*(1), 29–49.

Bucks, D. A., Allen, S. G., Roth, R. L., & Gardener, B. R. (1988). Short staple cotton under micro- and level-basin irrigation methods. *Irrigation Science, 9*(3), 161–176.

Cetin, O., & Bilgel, L. (2002). Effects of different irrigation methods on shedding and yield of cotton. *Agricultural Water Management, 54*(1), 1–15.

Chapagain, A. K., Hoekstra, A. Y., Savenije, H. H. G., & Gautam, R. (2006). The water footprint of cotton consumption: an assessment of the impact of worldwide consumption of cotton products on the water resources in the cotton producing countries. *Ecological Economics, 60*, 186–203.

Chen, D. C., Lei, X. Y., Cao, W., & Li, Y. (2012). Design and implementation of an irrigation decision support system for cotton in Xinjiang, China. *Sensor Letters, 10*(1–2), 459–464 (6).

Dağdelen, N., Başal, H., Yılmaz, E., Gürbüz, T., & Akcay, S. (2009). Different drip irrigation regimes affect cotton yield, water use efficiency and fiber quality in western Turkey. *Agricultural Water Management, 96*(1), 111–120.

Darouich, H., Gonçalves, J. M., & Pereira, L. S. (2007). Water saving scenarios for cotton under surface irrigation: analysis with the DSS SADREG. In N. Lamaddalena, C. Boglioti, M. Todorovic, & A. Scardigno (Eds.), *Options Mediterranéennes, Série B: Vol. 56 I. Water saving in Mediterranean agriculture & future research needs (Proc. Int. Conf., WASAMED project, Valenzano, Feb. 2007)* (pp. 381–396).

Darouich, H., Gonçalves, J. M., Muga, A., & Pereira, L. S. (2012). Water saving vs. farm economics in cotton surface irrigation: an application of multicriteria analysis. *Agricultural Water Management, 115*, 223–231.

DeTar, W. R. (2008). Yield and growth characteristics for cotton under various irrigation regimes on sandy soil. *Agricultural Water Management, 95*, 69–76.

DeTar, W. R., Maas, S. J., Fitzgerald, G. J., & Shafter, C. A. (2010). *Drip vs furrow irrigation of cotton on sandy soil with 1/4 mile runs – Includes: Yield monitoring, remote sensing, and electronic soil survey* (Vol. 1). Cotton Economics Research Institute. URI http://hdl.handle.net/2346/1699.

Farahani, H. J., Oweis, T. Y., & Izzi, G. (2008). Crop coefficient for drip-irrigated cotton in a Mediterranean environment. *Irrigation Science, 26*(5), 375–383.

Farahani, H. J., Izzi, G., & Oweis, T. Y. (2009). Parameterization and evaluation of the AquaCrop Model for full and deficit irrigated cotton. *Agronomy Journal, 101*(3), 469–476.

Galli, D., Morini, C., & Di Terlizzi, B. (2010). *Sustainable crop management model in Syrian strategic crops. The experience of the cooperation project rationalization of Ras El Ain irrigation systems.* Montpellier: ISDA. http://hal.archives-ouvertes.fr/docs/00/52/20/55/PDF/Galli_Sustainable.pdf.

Gonçalves, J. M., & Pereira, L. S. (2009). Decision support system for surface irrigation design. *Irrigation and Drainage Engineering, 135*(3), 343–356.

Gonçalves, J. M., Muga, A. P., Horst, M. G., & Pereira, L. S. (2011). Furrow irrigation design with multicriteria analysis. *Biosystems Engineering, 109*(4), 266–275.

Grabow, G. L., Huffman, R. L., Evans, R. O., Jordan, D. L., & Nuti, R. C. (2006). Water distribution from a subsurface drip irrigation system and dripline spacing effect on cotton yield and water use efficiency in a coastal plain soil. *Transactions of the ASAE, 49*(6), 1823–1835.

Guan, H., Li, J., & Li, Y. (2013). Effects of drip system uniformity and irrigation amount on cotton yield and quality under arid conditions. *Agricultural Water Management, 124*, 37–51.

Hodgson, A. S., Constable, G. A., Duddy, G. R., & Daniells, I. G. (1990). A comparison of drip and furrow irrigated cotton on a cracking clay soil. *Irrigation Science, 11*, 143–148.

Hole, F. (2009). Drivers of unsustainable land use in the semi-arid Khabour River Basin, Syria. *Geographical Research, 47*(1), 4–14.

Hornbuckle, J. W., Christen, E. W., & Faulkner, R. D. (2005). Use of SIRMOD as a quasi real time surface irrigation decision support system. In A. Zerger, & R. M. Argent (Eds.), *MODSIM 2005. International congress on modelling and simulation, modelling and simulation society of Australia and New Zealand* (pp. 217–223).

Horst, M. G., Shamutalov, S. S., Pereira, L. S., & Gonçalves, J. M. (2005). Field assessment of the water saving potential with furrow irrigation in Fergana, Aral Sea basin. *Agricultural Water Management, 77*(1), 210–231.

Horst, M. G., Shamutalov, Sh. Sh., Gonçalves, J. M., & Pereira, L. S. (2007). Assessing impacts of surge-flow irrigation on water saving and productivity of cotton. *Agricultural Water Management, 87*(2), 115–127.

Howell, T. A., Meron, M., Davis, K. R., Phene, C. J., & Yamada, H. (1987). Water management of trickle and furrow irrigated narrow row cotton in the San Joaquin Valley. *Applied Engineering in Agriculture, 3*(2), 222–227.

Hulugalle, N. R., Weaver, T. B., & Finlay, L. A. (2010). Soil water storage and drainage under cotton-based cropping systems in a furrow-irrigated Vertisol. *Agricultural Water Management, 97*, 1703–1710.

Hunsaker, D. J., Clemmens, A. J., & Fangmeier, D. D. (1998). Cotton response to high frequency surface irrigation. *Agricultural Water Management, 37*, 55–74.

Hussein, F., Janat, M., & Yakoub, A. (2011). Assessment of yield and water use efficiency of drip-irrigated cotton (*Gossypium Hirsutum* L.) as affected by deficit irrigation. *Turkish Journal of Agriculture, 35*, 611–621.

Ibragimov, N., Evett, S. R., Esanbekov, Y., Kamilov, B. S., Mirzaev, L., & Lamers, J. P. A. (2007). Water use efficiency of irrigated cotton in Uzbekistan under drip and furrow irrigation. *Agricultural Water Management, 90*(1), 112–120.

Ishizaka, A., & Nemery, P. (2013). *Multi-criteria decision analysis: Methods and software*. John Wiley & Sons, Inc, ISBN 978-1-1199-7407-9.

Janat, M. (2008). Response of cotton to irrigation methods and nitrogen fertilization: yield components, water-use efficiency, nitrogen uptake, and recovery. *Communications in Soil Science and Plant Analysis, 39*(15–16), 2282–2302.

Janat, M., & Somi, G. (2001). Performance of cotton crop grown under surface irrigation and drip fertigation. I. Seed cotton yield, dry matter production, and lint properties. *Communications in Soil Science and Plant Analysis, 32*, 3045–3061.

Janat, M., & Khalout, A. R. (2011). Evaluation of drip-irrigated cotton grown under different plant population densities and two irrigation regimes. *Communications in Soil Science and Plant Analysis, 42*(6), 741–752.

Karam, F., Lahoud, F., Masaad, R., Daccache, A., Mounzer, O., & Rouphael, Y. (2006). Water use and lint yield response of drip irrigated cotton to the length of irrigation season. *Agricultural Water Management, 85*(3), 287–295.

MAAR. (2011). *Land use balance*. Damascus: Department of Statistics and Planning. Ministry of Agriculture and Agrarian Reform (in Arabic).

Mateos, L., Berengena, J., Orgaz, F., Diz, J., & Fereres, E. (1991). A comparison between drip and furrow irrigation in cotton at two levels of water supply. *Agricultural Water Management, 19*(4), 313–324.

Mchugh, A. D., Bhattarai, S., Lotz, G., & Midmore, D. J. (2008). Effects of subsurface drip irrigation rates and furrow irrigation for cotton grown on a vertisol on off-site movement of sediments, nutrients and pesticides. *Agronomy for Sustainable Development, 28*(4), 507–519.

Mendoza, G. A., & Martins, H. (2006). Multi-criteria decision analysis in natural resource management: a critical review of methods and new modelling paradigms. *Forest Ecology and Management, 230*, 1–22.

Mourad, K. A., & Berndtsson, R. (2012). Water status in the Syrian water basins. *Open Journal of Modern Hydrology, 2*, 15–20.

MunlaHasan, A. (2007). *Water use efficiency in Syrian agriculture*. Working Paper No. 26, NAPC, Project GCP/SYR/006/ITA, Damascus.

Norton, E. R., & Silvertooth, J. C. (2001). Evaluation of a drip vs. furrow irrigated cotton production system. In Jeff Silvertooth (Ed.), *2001 Arizona cotton report*. The University of Arizona, College of Agriculture and Life Sciences. http://ag.arizona.edu/pubs/crops/az1224/.

Oweis, T. Y., Farahani, H. J., & Hachum, A. Y. (2011). Evapotranspiration and water use of full and deficit irrigated cotton in the Mediterranean environment in northern Syria. *Agricultural Water Management, 98*(8), 1239–1248.

Ozbahce, A., & Tari, A. F. (2010). Effects of different emitter space and water stress on yield and quality of processing tomato under semi-arid climate conditions. *Agricultural Water Management, 97*(9), 1405–1410.

Öztan, M., & Axelrod, M. (2011). Sustainable transboundary groundwater management under shifting political scenarios: the Ceylanpinar Aquifer and Turkey–Syria relations. *Water International, 36*(5), 671–685.

Papadopoulos, A., Kalivas, D., & Hatzichristos, T. (2011). Decision support system for nitrogen fertilization using fuzzy theory. *Computers and Electronics in Agriculture, 78*(2), 130–139.

Pedras, C. M. G., & Pereira, L. S. (2009). Multicriteria analysis for design of microirrigation systems. Application and sensitivity analysis. *Agricultural Water Management, 96*(4), 702–710.

Pedras, C. M. G., Pereira, L. S., & Gonçalves, J. M. (2009). MIRRIG: a decision support system for design and evaluation of microirrigation systems. *Agricultural Water Management, 96*(4), 691–701.

Pereira, L. S., Teodoro, P. R., Rodrigues, P. N., & Teixeira, J. L. (2003). Irrigation scheduling simulation: the model ISAREG. In G. Rossi, A. Cancelliere, L. S. Pereira, T. Y. Oweis, M. Shatanawi, & A. Zairi (Eds.), *Tools for drought mitigation in Mediterranean regions* (pp. 161–180). Dordrecht: Kluwer.

Pereira, L. S., Paredes, P., Cholpankulov, E. D., Inchenkova, O. P., Teodoro, P. R., & Horst, M. G. (2009). Irrigation scheduling strategies for cotton to cope with water scarcity in the Fergana Valley, Central Asia. *Agricultural Water Management, 96*(5), 723–735.

Pereira, L. S., Cordery, I., & Iacovides, I. (2012). Improved indicators of water use performance and productivity for sustainable water conservation and saving. *Agricultural Water Management, 108*, 39–51.

Plant, R. E., Kerby, T. A., Zelinski, L. J., & Munk, D. S. (1998). A qualitative simulation model for cotton growth and development. *Computers and Electronics in Agriculture, 20*(2), 165–183.

Pomerol, J. C., & Romero, S. B. (2000). *Multicriterion decision in management: Principles and practice*. Netherlands: Kluwer Academic Publishers.

Rajak, D., Manjunatha, M. V., Rajkumar, G. R., Hebbara, M., & Minhas, P. S. (2006). Comparative effects of drip and furrow irrigation on the yield and water productivity of cotton (*Gossypium hirsutum* L.) in a saline and waterlogged vertisol. *Agricultural Water Management, 83*(1), 30–36.

Richards, Q. D., Bange, M. P., & Johnston, S. B. (2008). HydroLOGIC: an irrigation management system for Australian cotton. *Agricultural Systems, 98*(1), 40–49.

Rodrigues, G. C., Paredes, P., Gonçalves, J. M., Alves, I., & Pereira, L. S. (2013). Comparing sprinkler and drip irrigation systems for full and deficit irrigated maize using multicriteria analysis and simulation modelling: ranking for water saving vs. farm economic returns. *Agricultural Water Management, 126*, 85–96.

Sadiddin, A. (2009). *The foreseen impact of the recent policy reforms and other scenarios on water use in Syrian Arab Republic: The case of Al-Khabour Basin*. Working Paper No. 46. Damascus: NAPC.

Sadiddin, A., & Atiya, B. (2009). *Analysis of agricultural production for selected crops: Wheat, cotton and barley*. Working Paper No. 44. Damascus: NAPC.

Sankaranarayanan, K., Nalayini, P., Sabesh, M., Rani, S. U., Nachane, R. P., & Gopalakrishnan, N. (2011). *Low cost drip – Cost effective and precision irrigation tool in Bt cotton*. Technical bulletin No.1. Coimbatore: Central Institute for Cotton Research Regional Station.

Shweih, R. (2006). *Comparative advantages of cotton commodity chain*. Working Paper No 21. Damascus: National Agricultural Policy Centre (NAPC).

Smith, R. J., Raine, S. R., & Minkevich, J. (2005). Irrigation application efficiency and deep drainage potential under surface irrigated cotton. *Agricultural Water Management, 71*(2), 117–130.

Solomon, K. H. (1984). Yield related interpretations of irrigation uniformity and efficiency measures. *Irrigation Science, 5*(3), 161–172.

Stanimirovic, I. P., Zlatanovic, M. L., & Petkovic, M. D. (2011). On the linear weighted sum method for multi-objective optimization. *Facta Acta Universitatis, 26*, 49–63.

Takahara, Y., Nakano, B., & Kijima, K. (1979). Characterization of the linear weighted sum decision principle. *Information Sciences, 19*, 199–228.

Ünlü, M., Kanber, R., Koc, D. L., Tekin, S., & Kapur, B. (2011). Effects of deficit irrigation on the yield and yield components of drip irrigated cotton in a Mediterranean environment. *Agricultural Water Management, 98*(4), 597–605.

Walker, W. R. (1998). *SIRMOD – Surface irrigation modeling software*. Logan: Utah State University.

Walker, W. R., & Skogerboe, G. (1987). *Surface irrigation: Theory and practice*. Englewood Cliffs, New Jersey: Prentice-Hall, Inc.

Wang, R., Kang, Y., Wan, S., Hu, W., Liu, S., Jiang, S., et al. (2012). Influence of different amounts of irrigation water on salt leaching and cotton growth under drip irrigation in an arid and saline area. *Agricultural Water Management, 110*, 109–117.

Yan, H. B., Huynh, V. N., Nakamori, Y., & Murai, T. (2011). On prioritized weighted aggregation in multi-criteria decision making. *Expert Systems with Applications, 38*, 812–823.

Yazar, A., Sezen, S. M., & Sesveren, S. (2002). LEPA and trickle irrigation of cotton in the Southeast Anatolia Project (GAP) area in Turkey. *Agricultural Water Management, 54*(3), 189–203.

Yohannes, F., & Tadesse, T. (1998). Effect of drip and furrow irrigation and plant spacing on yield of tomato at Dire Dawa, Ethiopia. *Agricultural Water Management*, 35(3), 201–207.

Glossary

BWUF: beneficial water use fraction (ratio)
DI: deficit irrigation
DSS: decision support system
DRL: double rows per lateral
ELP: economic land productivity (€ ha^{-1})
ES: emitter spacing (m)
ETc: actual evapotranspiration (mm)
EWP: economic water productivity (€ m^{-3})
EWPR: economic water productivity ratio
FI: full irrigation
FIC: fixed irrigation costs (€ ha^{-1})
GB: graded border
GF: graded furrow
IWU: total irrigation water use (mm)
IDP: irrigation deep percolation (mm)
IRO: irrigation runoff (mm)
Ks: hydraulic conductivity (mm h^{-1})
L1, …, L6: layout 1, 2 …, 6
LL: laser levelled land
MCA: multicriteria analysis
NC: non-compensate emitter
N_c: number of criteria
NBWU: non-beneficial water use (mm)
NLL: non-laser levelled land
SC: self-compensating emitter
SRL: single row per lateral
TAW: total water available (mm m^{-1})
U_j: utility for criteria, j
$U_j(x_j)$: utility for criteria's attribute, x_j
U: global utility
VIC: variable irrigation costs (€ ha^{-1})
Wi: weighting scenarios ($i = 1, \ldots, 7$)
W_a: actual water applied (mm)
W_{max}: maximum water required (mm)
WP_{Irrig}: irrigation water productivity (kg m^{-3})
x_i: criteria's attribute
Y_a: actual yield (kg ha^{-1})
Y_{max}: maximum yield (kg ha^{-1})
Z: cumulative infiltration (m^3 m^{-1})

Greek symbols

α: graph slope of utility function
β: origin intercept of the utility function
λ_j: weight of criteria j
τ: infiltration opportunity time (min)