Optimal irrigation scheduling for fodder crops under multiple resource constraints in an arid zone environment

Hamed Al-Dhuhli1 · Gerd H. Schmitz2 · Franz Lennartz3 · Niels Schütze2 · Jens Grundmann2 · Sebastian Kloss2 · Marcus Pistorius2

1 Ministry of Agriculture and Fisheries, Sultanate of Oman · 2 Dresden University of Technology, Germany · 3 United Arab Emirates University, Al Ain UAE

Abstract

The potential water productivity (WP) (kg/m³) of irrigation schemes in arid regions is generally rather low. Therefore we investigate the potential of optimal irrigation control and scheduling for improving water use efficiency (WUE) on the basis of open field experiments with Maize (Zea Mays) (maize sow cultivar = pioneer_3527) under micro irrigation. The trials were conducted in three replicates and a randomized complete block design at the Agricultural Research Station, Oman. We used three irrigation rates 100%, 125% of potential crop evapotranspiration (Etc, FAO) and a controlled deficit irrigation schedule (CDIS) which was based on references local soil and weather conditions and a simulation based optimization employing the APSIM-SWIM model (Keating et al. 2003) within the new evolutionary algorithm for optimal irrigation scheduling of deficit irrigation systems GET-OPTIS (Schütze et al. 2010). The results of the experiments revealed that increasing amounts of irrigation water from 100% to 125% Etc increased productivity of fresh biomass yield by 14% (from 19 to 22 ton/ha). However, the CDIS yielded superior water productivity (WP) of 5.5 kg m⁻³ of fresh biomass yield compared to 4.8 kg m⁻³ for the treatment using 125% Etc.

The results of CDIS experiment were subsequently compared to the outcome of the modeling approach. Both results agreed very well and recommend the new approach as promising tool for improving irrigation efficiency. In the next steps of this investigation we will include different irrigation water qualities (EC 1, 3 & 6 dS/m).

1. Introduction and Literature Review

Water is the limiting constraint for almost 600 million hectares of potentially suitable arable land around the globe (http://www.fao.org). The fresh water resources available for agriculture are declining quantitatively and qualitatively. E.g. for the Gulf countries it has been estimated that to the year 2030 the water requirements will increase about two times in Bahrain, Oman and Qatar and three times in Kuwait, Saudi Arabia, UAE and Yemen (Adel El-Beltagy. 2004). At the same time unsustainable practices in irrigation
will lead to increased salinization of soil, nutrient depletion and erosion. Globally, some 20% of irrigated land (450,000 km²) is salt-affected, with 2,500–5,000 tons km² of lost production every year as a result of salinity (UNEP, 2008).

To face water scarcity problems which increasingly affect the development of the arid and semiarid countries, innovative solutions for water saving irrigation techniques are needed which allow for high water use efficiencies (WUE) or water productivities (WP) like e.g. deficit irrigation strategies.

The improvement of WP requires the characterization of the relationship between irrigation practice and grain yield by e.g. crop-water production functions (CWPF) (Schütze et al. 2011a). Efforts to investigate WP are numerous and can be divided into two main groups; (a) field experiments which relate crop growth and water stress by experimental evaluation and (b) simulation-based studies, based on calibrated and validated crop growth models which are used to calculate the impacts of water stress for a range of environmental boundary conditions.

Due to the manifold of possible water stress situations and their specific impact on crop yield mere field testing of all possible combinations is difficult, complex, expensive and time-consuming (Prathapar et al. 1999). The scope of simulation-based studies ranges from field level investigations to water resources management on catchment scale using stochastic planning tools. Using the 1D mechanistic crop growth model APSIM (Keating et al. 2003) Kloss et al. (2012) investigated the performance of APSIM within the frame of a stochastic simulation-based approach on field level. They found that, based on a sound calibration, the simulations with APSIM yielded realistic results for intensely monitored field experiments.

Figure 1  Framework for generating crop water production functions (Schütze and Schmitz 2010).
In this study we evaluated the performance of different irrigation experiments with respect to their WP. The experiments were conducted on a research farm in Al-Batinah region Oman with the irrigation treatments of 100%, 125% ETc and a controlled deficit irrigation schedule (CDIS) which was based on a simulation based optimization approach employing the APSIM-SWIM model (Keating et al. 2003) together with a new evolutionary algorithm for optimal irrigation scheduling of deficit irrigation systems GET-OPTIS (Schütze et al. 2010, Schütze et al. 2011b). Figure 1 shows the framework that we used to generate the crop water production functions (CWPF) for the local soil and climatic conditions.

2. Experimental Setup, Data and Methods

2.1. Study site description

The experiment was conducted in the Directorate General of Agricultural and Livestock Research in Rumais, Sultanate of Oman (latitude 23.6° N, longitude 58.0° E at 24 m above MSL). The experimental site is located in semiarid climate with a mean annual precipitation of 100 mm. The soil properties for the experimental site are presented in Table 1.

Table 1: The experimental site's soil properties at Rumais, Sultanate of Oman with van Genuchten/Mualem parameters. $\theta_s$ and $\theta_r$ (cm$^3$ cm$^{-3}$) are saturated and residual water content, $\alpha$ (cm$^{-1}$) and $n$ are empirical parameters determining the shape of the retention curve, $K_s$ (cm h$^{-1}$) is saturated conductivity, and $i$ is a pore connection parameter.

<table>
<thead>
<tr>
<th>Soil layer (cm)</th>
<th>Clay (%)</th>
<th>Silt (%)</th>
<th>Sand (%)</th>
<th>$\theta_s$</th>
<th>$\theta_r$</th>
<th>$\alpha$ (cm$^{-1}$)</th>
<th>$n$</th>
<th>$K_s$ (cm h$^{-1}$)</th>
<th>$i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-15</td>
<td>7</td>
<td>7</td>
<td>85</td>
<td>0.32</td>
<td>0.058</td>
<td>0.036</td>
<td>1.2</td>
<td>5.4</td>
<td>0.5</td>
</tr>
<tr>
<td>15-35</td>
<td>7</td>
<td>9</td>
<td>84</td>
<td>0.32</td>
<td>0.058</td>
<td>0.036</td>
<td>1.2</td>
<td>4.8</td>
<td>0.5</td>
</tr>
<tr>
<td>35-75</td>
<td>10</td>
<td>12</td>
<td>77</td>
<td>0.28</td>
<td>0.1</td>
<td>0.036</td>
<td>1.3</td>
<td>5.4</td>
<td>0.5</td>
</tr>
<tr>
<td>75-200</td>
<td>7</td>
<td>7</td>
<td>85</td>
<td>0.32</td>
<td>0.058</td>
<td>0.036</td>
<td>1.2</td>
<td>5.4</td>
<td>0.5</td>
</tr>
</tbody>
</table>

2.2. Experimental treatments and design

The experiment consisted of two main investigation factors; irrigation water quality (electrical conductivity of 1, 3 & 6 dS/m) and three irrigation rates 100% [W2], 125% [W3] of ETc and a controlled deficit irrigation schedule (CDIS) [W1] which was based on references local soil and weather conditions and a simulation based optimization employing the APSIM-SWIM model within the new evolutionary algorithm for optimal irrigation scheduling of deficit irrigation systems (GET-OPTIS framework). The two factors were replicated 3 times in a split block design as shown in Figure 2. Total numbers of
plots were 27 (3 x 3 x 3 = 27). Area of each plot area was 14 m² (3.5 x 4 m). The plots were 0.5 meters apart from each other and 1 m was kept between the replicate.

**Experimental design**

![Experimental design diagram]

*Figure 2* The experimental design. (Red boxes indicate the plot with TDR and pF meter sensors).

### 2.3. Seeding, fertilizing and the irrigation system

Maize (Pioneer_3527) was planted for grain on 29 November 2011 and harvested on 24 March 2012. It was sown with a row spacing of 0.5 m and the seeds were planted 25 cm apart along eight rows. The planting density was 9.7 plants m⁻². The surface drip irrigation system (DI) with an emitter spacing of 50 cm was installed with two drip tubes for one plant row resulting in an emitter spacing of 0.25 m. The emitter flow rate was 4.2 L h⁻¹ at a pressure of 1 bar with dripper uniformity of 92%. Plants that were irrigated based on Class-A Pan evaporation measurements (W2) and (W3), were irrigated every two days. Water meters were used to measure the applied amount of irrigation.

The soil surface was leveled and chemical fertilizer was applied before sowing with 100 kg ha⁻¹ P₂O₅ (200 kg/ha triple super phosphate) and 50 kg ha⁻¹ K₂O (100 kg ha⁻¹ potassium sulphate) for grain. The plants were fertilized by 150 kg/ha nitrogen (326 kg ha⁻¹ Urea) in three split doses as follows: ¼ before sowing, ½ one month after germination and ¼ at flag leaf stage. The fertilizers were applied manually at 8-10 cm distance from
the plants. Necessary preventive measures were taken to protect plants from pests, diseases and birds during the growth period. The plants were kept under an agril cover for the first two weeks.

2.4. Data collection during the experiment
Meteorological data were obtained from a meteorological station on the site. Hourly data were obtained for maximum and minimum temperature, radiation, wind speed and relative humidity. Soil samples were obtained before planting (pre trial) and at the harvesting day (post trial). These soil samples were analyzed for 1:5 ECe. Time domain reflectometry (TDR) probe (used to measure soil water content, Campbell Scientific, USA) and a pF-Meter (measurement range of about pF 0 to 7) next to each other as one sensor pair were installed at four different soil depths (10, 20, 50 and 100 cm) in 6 plots at the second replication (Figure 2). Soil tensions and soil water contents were observed by TDR probes and pF-Meters every 15 minutes as shown in Figure 3.

![Figure 3](image-url)

Figure 3  
TDR probes and pF-Meters data for W1 treatment for different depths.

At each development stage three plants at each plot were randomly selected and recorded for plant height, number of leafs, leaf length and leaf width. Furthermore, a height classification work with dripper discharge test and soil samples was conducted due to the observation of the present of variation in the plant height within the replicates, treatments and within each plot, the entire field plants were classified according to their height on 23 January 2012 (for 3672 plants). In addition, the LAI data were collected on 18 January and 12 March 2012.

At the harvesting day, the green forage yield and plant parameters were recorded for each plot separately. In addition, at each plots in that day five plants were randomly selected and recorded for plant height, number of leafs, leaf length and leaf width.
Furthermore, wet and dry matter weight for leaves, stem, cob and seeds were recorded for each selected plant in each plot.

2.5. Model based optimal scheduling of the deficit irrigation treatment

The SVAT crop model APSIM (the Agricultural Production System Simulator) (Keating et al. 2003) was set up for maize (which was sown at a crop density of 9.7 (plants/m²) and row spacing of 0.5 m). Simulation was set to start 7 days prior to crop sowing in order to allow the model to properly simulate a bare soil water balance.

For the soil water balance, APSIM-SWIM is designed to run within APSIM and calculate all flows of water and nutrients through and out of soil for a given simulation. It is used based on a numerical solution of the Richards’ equation combined with the convection-dispersion equation to model solute movement. These flows include infiltration, runoff, plant uptakes, movement through soil, etc and related nutrient flows. The SWIMv2 that was used is a one-dimensional model and does not consider lateral flow or horizontal heterogeneity.

The optimization technique GET-OPTIS was applied with the calibrated APSIM-SWIM model, to determine the optimal irrigation scheduling and control. The optimization run was set to start one month after the sowing day. The optimization results were used to calculate the potential yield and WP.
3. Results

3.1. Harvested yield measurements

![Figure 4](image1.png)

**Figure 4**  Fig 4: The average of plant total height (cm), fresh weight biomass (g) and dry weight biomass (g) from five plants randomly selected at each plot out of three replications for W1, W2 and W3 treatments with S1 water salinity.

3.2. Crop yields and water productivity

The results of the experiments revealed that increasing the amounts of irrigation water from 100% [W2] to 125% Etc [W3] increased productivity of fresh biomass yield by 14% (from 19 to 22 ton ha⁻¹). Meanwhile, the CDIS [W1] increased productivity of fresh biomass yield by 4% in comparison to 100% Etc respectively (Figures 4 and 5). However, the CDIS proved superior with (WP) of 5.5 kg m⁻³ of compare to 5.2 and 4.8 kg m⁻³ for the treatment of 100% and to 125% ETC respectively as shown in Figure 5.

![Figure 5](image2.png)

**Figure 5**  Fresh biomass yield (ton ha⁻¹) on the left and water productivity (kg m⁻³) on the right, out from three replications for W1, W2 and W3.
3.3. Simulation runs for calibration soil water contents

The simulated soil water contents showed mostly a fit agreement with the observed data for treatment W1 as shown for the different depths in Figure 6:

![Figure 6](image.png)

The reason for the low fit at the beginning of the simulation is probably due to cover management that is used to protect the seed from birds for the first 12 days after the seeding, which could affect the soil evapotranspiration. The reason for the low fit at the end of the simulation is due to a leaching event at the end of the experiment, which was not included as a simulation input.

Meanwhile, the simulation run showed a good fit for the plant data compared to the observed experiment data as shown in the Table 2.
3.4. Optimized irrigation scheduling and control
The optimization technique GET-OPTIS was applied with the calibrated APSIM-SWIM model, to determine the optimal irrigation scheduling. The optimization run was set to start one month after the sowing day. The optimization results were used to calculate the potential yield and WP. The maximum water productivity (high productive + deficit irrigation systems) was achieved at about 400 mm water application as shown in Figure 7.

![Figure 7](image)

**Figure 7**  The calculated potential yield (grain dry yield weight in kg ha⁻¹) vs. potential water productivity (kg m⁻³) from the irrigation scheduling and control optimization run according to water application depths from 200 mm to 500 mm with an increment of 20 mm.

4. Summary and Conclusion
In this study, an open field experiment was conducted with maize under a micro irrigation system using different treatments for water quantity and quality. The impact on crop yield was calculated by the new evolutionary algorithm GET-OPTIS for optimal irrigation scheduling of deficit irrigation systems together with the SVAT-model APSIM.
The simulated results match very well with the observations and the results with the new optimization strategy showed a high potential to increase irrigation efficiency. Optimal irrigation schedules were determined and considerable irrigation water savings were feasible, the optimized irrigation schedule would highly increase WP compared to the current practice. The model output for the optimal irrigation schedule (380 mm for the present study case) is similar to the applied controlled deficit irrigation schedule (CDIS) treatment which was based on references local soil and weather conditions and APSIM-SWIM model within the evolutionary algorithm GET-OPTIS framework, it also agree with those appearing in the literature, evidencing the robustness of this methodology for simulating the behavior of maize crops under such arid zone climatic condition.

The study showed to what extent modeling efforts can contribute to the permanent reduction of irrigation water use. The new evolutionary algorithm GET-OPTIS for optimal irrigation scheduling of deficit irrigation systems together with the SVAT-model APSIM, that was calibrated by field experiment where observed weather and soil input data were used, showed plausible results for potential yields and a high potential increase in the irrigation efficiency. Within this study, APSIM confirms to be a promising model within the OCCASION optimization framework. Nevertheless, further investigations are still necessary to validate and generalize the results.

In the next steps of this investigation, we will include different irrigation water qualities (EC 1, 3 & 6 dS/m), bearing in mind that APSIM is 1 dimensional model and the side salt accumulation is not considered within its application. Furthermore, this study could also be used for further investigation of the impact of climate change on potential yield using the OCCASION optimization framework.
References


German National Committee for the
International Hydrological Programme (IHP) of UNESCO and the
Hydrology and Water Resources Programme (HWRP) of WMO
Koblenz 2013

©IHP/HWRP Secretariat
Federal Institute of Hydrology
Am Mainzer Tor 1
50068 Koblenz · Germany

Telefon: +49 (0)261 / 1306 - 54 35
Telefax: +49 (0)261 / 1306 - 54 22

www.ihp-germany.de

DOI: 10.5675/ICWRER_2013

Disclaimer
Any papers included in these proceedings reflect the personal opinion of the authors. The publisher does not accept any liability for the correctness, accuracy or completeness of the information or for the observance of the private rights of any third parties. Any papers submitted by the authors do not necessarily reflect the editors’ opinion; their publication does not constitute any evaluation by the editors.