Presentation at WG-WATS

Water and salt regulation scheme under mulched drip irrigation for cotton in arid regions

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Outline

1. Introduction
2. Field experiment
3. A numerical model of soil water and salt movement under MDI
4. Optimal irrigation schedule for cotton fields under MDI
5. Water and salt regulation scheme for cotton fields under MDI
6. Summary

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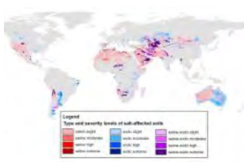
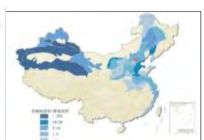
An Old Problem We Have: Salinization

Salinization is a big issue throughout the whole agricultural history worldwide.



Distribution of saline, sodic and saline-sodic soils in the world. Source: Energy Environ. Sci., 2011,4, 2669-2681



Distribution Map of Salinization Arable Land in China

"Salt remains one of the gravest threats to irrigated agriculture and food security in a world that will be striving to feed 8 to 9 billion people within 50 years" – Sandra Postel

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New Situations We Face: Water and Food Security

Water shortage pressure promotes application of water saving irrigation technologies, e.g., mulched drip irrigation (MDI) method

Water scarcity is common all over the world

- Almost all countries around 10 to 40°N, together with Western South America, South Africa, and Australia are affected by water scarcity.
- Totally, 3.6 billion people (nearly half of the global population) live in potentially water-scarce areas at least one month per year.

Source: The United Nations World Water Development Report 2018: nature-based solution for water.

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Water Saving Irrigation Technologies

Sprinkler Irrigation

Micro Sprinkler Irrigation

Drip Irrigation

Mulched Drip Irrigation

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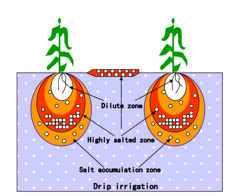
Two types of secondary salinization

(1) Secondary salinization induced by flood irrigation: too much irrigation water causes rising of water table and salt contained in the groundwater goes up and builds up at the ground surface.

(2) Secondary salinization induced by water saving irrigation: too less water is deficient to leach salt to deeper soil and groundwater. The situation is more serious for brackish water irrigation.



New Challenges for the Old Problem!

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Secondary salinization induced by water saving irrigation

Salinization in cotton fields in Northwest China (Photographed by the author)

Salt rings formed on soil surface due to evaporation of saline irrigation water from drip irrigation of grapes (Raine et al., 2007)

Salinity evolution and crop response to secondary soil salinity in two agro-climatic zones in Lebanon

Darwish T, Atallah T, Moujabber M E, et al. Salinity evolution and crop response to secondary soil salinity in two agro-climatic zones in （Darwish et a., AWM)

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Methodology

TARGET
A sustainable tool-kit to deal with both water and salinity challenges in arid areas

Field Experiments ↔ Virtual Experiments

Optimal: Irrigation schedule in grow period and flush scheme in non-grow period + Chemical ameliorants

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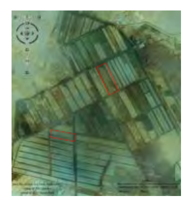
Location of Experimental Station

Northeast edge of Taklimakan Desert, belong to Bayangol Prefecture of Xinjiang Uygur Autonomous Region in northwestern China.

The experiments began from 2007



2 plots (4 ha)

Field Photo

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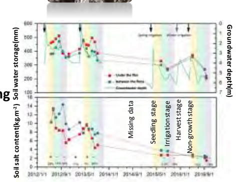
General Conditions

1. Dry climate
   - Annual mean P 60 mm, and ET_p 2788 mm
2. Favorable light and thermal conditions for cotton growth:
   - Annual mean temperature: 11.48 ℃
   - Annual total sunshine: 3036 h
3. Water table is relatively high with decreasing trend: annual variation of 1.4- 3.1m
4. Salinity condition (electrical conductivity):
   - Groundwater: 3.9 dS/m
   - Irrigation water: 0.9 dS/m

Over 50% China's cotton yield comes from Xinjiang



Dynamics of Water Table and Soil Salinity

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Mulched Drip Irrigation (MDI)

The use of **drip irrigation** in conjunction with plastic **mulch** allows one to reduce leaching of fertilizers. Using **drip irrigation** eliminates the use of flood and furrow **irrigation** that applies large quantities of water to the soil which in turn tends to leach nitrogen and other nutrients to depths below the root zone.

Unmanned Tractor (from news.ifeng.com)

Advantages of MDI

1. Saving water: irrigating root only
2. Increasing yield: precise irrigation and favorite temperature in spring
3. Saving labor: installation of MDI system and irrigation are automatic

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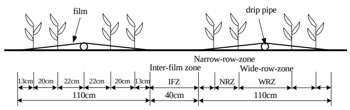
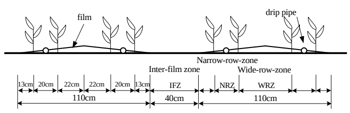
Layout of Pipe & Film & Cotton



One pipe, one film and four rows of cotton arrangement (OPA)



Two pipe, one film and four rows of cotton arrangement (TPA)

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Facilities and Instruments


Pond


Pond for Saline water irrigation


Windbreak


Drainage canal




Laboratory

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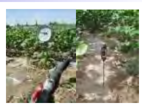
Facilities and Instruments


Observation Well


Weather station


Hydra Probe


Drip pipe and valve


Crop growing


Root


Cotton yield

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Facilities and Instruments


Flux tower


CO_2/H_2O Open Path Gas Analyzer
Sonic anemometer


PAR and Net radiation sensor

The **eddy covariance** technique is a key atmospheric measurement technique to measure and calculate vertical turbulent fluxes (H_2O and CO_2) within atmospheric boundary layers.

(from Wikipedia)

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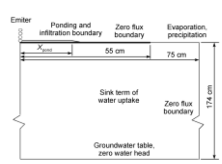
A numerical model of soil water and salt movement under MDI

A numerical model has been developed for water and salt movement under MDI conditions, which has higher accuracy and calculation efficiency.



Moving ponded area boundary: drip irrigation will pond soil surface close to dripper, and the ponded area will expand gradually when drip irrigation begins

$$C(h)\frac{\partial h}{\partial t}=\frac{\partial}{\partial x}\left[K(h)\frac{\partial h}{\partial x}\right]+\frac{\partial}{\partial z}\left[K(h)\frac{\partial h}{\partial z}\right]-\frac{\partial K(h)}{\partial z}-S_w$$ Richards equation

$$\frac{\partial s}{\partial t}=\frac{\partial}{\partial x}\left(D_{sh,x}\frac{\partial c}{\partial x}-q_x\cdot c\right)+\frac{\partial}{\partial z}\left(D_{sh,z}\frac{\partial c}{\partial z}-q_z\cdot c\right)+F\cdot c+G$$ ADE equation

$$\begin{cases} h(x,0,t)=h_a, & 0\le x\le X_{pond}(t) \\ \int_0^{X_{pond}(t)} q_{v,T,x}dx=Q(t) & \\ q_{v,T,x}=P(t)-E_a(t), & X_{pond}(t)<x\le X \end{cases}$$ Upper boundary condition

The left and right boundaries are zero flux boundaries and the lower boundary is the fixed water head boundary

Tian et al., Science China, 2011

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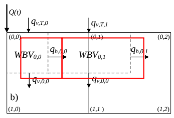
A numerical model of soil water and salt movement under MDI

✓ Moving ponded area boundaries are treated by combining water balance and flux methods.

The surface saturation infiltration flux is computed by **the flux method**

$$\Delta\theta_{0,j} = \theta_s - \theta_{0,j}$$

$$q_{v,T,j} = \frac{\Delta\theta_{0,j}}{\Delta t} \cdot ED_0 + q_{v,0,j} - \left(q_{h,0,j} - q_{h,0,j-1}\right) \cdot \frac{ED_0}{EW_j}$$



The number of surface saturation nodal points PJ is computed by the mass balance equation

$$\sum_{j=0}^{PJ-1}\left(q_{v,T,j} \cdot EW_j\right) \le Q(t) < \sum_{j=0}^{PJ}\left(q_{v,T,j} \cdot EW_j\right)$$

✓ **Infiltration flux of first non-saturated nodal point is calculated as**
✓ **Infiltration flux is zero for other non-saturated nodal points**
✓ **To ensure water balance and flux accuracy for boundary nodes**

$$q_{v,T,PJ} = \frac{Q(t) - \sum_{j=0}^{PJ-1}\left(q_{v,T,j} \cdot EW_j\right)}{EW_{PJ}}$$

Tian et al., Science China, 2011

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A numerical model of soil water and salt movement under MDI

✓ The **two-dimensional Richards Equation** and **the Advection-Dispersion Equation (ADE) / solute-transport equation** are used to describe **the movement of water and salt** in the soil. The Richards Equation and the ADE Equation, partial differential equations, are made spatially-discrete to yield ordinary differential equations (ODEs). Backward differentiation formula, aided by a solver called CVODE, are used to solve these resultant ODEs. **The model has a high computational efficiency and robust numerical stability.**

Theoretical Validation: extreme case - ponded infiltration into dry soil

Soil type	Initial soil moisture	Initial water head/cm	Simulation length/h	Time consumption/s	Relative error /%
Sand	0.028	-1500	1	**2**	**0.13**
Loam	0.11	-15000	10	**1**	**0.18**
Clay	0.224	-15000	50	**1**	**0.27**

Ponded infiltration into dry soil: soil moisture experiences very strong dynamics, which challenges numerical stability and computational efficiency.

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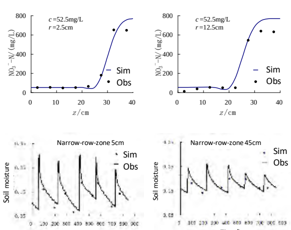
A numerical model of soil water and salt movement under MDI

✓ **Validation by laboratory experiments**

Soil salinity

Soil moisture



The laboratory data is from lab experiment

The laboratory data is from Li et al. (2003)

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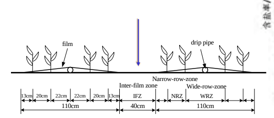
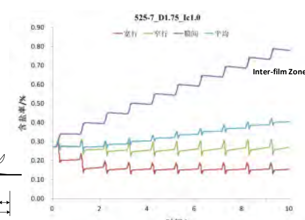
Simulation for long term dynamics of soil salinity

10-year long term simulation for cotton field under MDI shows the salt accumulation in inter-film zone.





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The optimal irrigation schedule for cotton fields under MDI

✓ **Determination of an optimal irrigation schedule based on the integrated index of water and salt stresses**

- **Experiment data: There exists a optimal interval for a specific drip system; Irrigation interval ↗, Soil moisture ↘, Salt content ↘**
- **Deduction: Constant irrigation amount; Irrigation interval ↗, Water stress ↗, Salt stress ↘**
- **Conclusion: Water-salt stress**

Field evidence

Treatment	375-3.5	375-7	375-10.5
Seed cotton yield/(kg/hm^2)	4530	**4995**	4755
Volumetric moisture content	0.18	0.13	0.09
Salt content/%	0.3	0.13	0.08

Apply the new concept to optimize irrigation schedule

1. **Both soil matrix potential and solution potential are considered**
2. **Soil root model**
3. **Maximize water use efficiency**

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The optimal irrigation schedule for cotton fields under MDI

Soil type, soil and water salinity condition impact the optimal irrigation interval!

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The optimal irrigation schedule for cotton fields under MDI

✓ The optimal irrigation schedule for cotton fields under mulched drip irrigation

With the aid of a large amount of **experimental data** and **numerical simulations**, an optimal irrigation schedule was then developed for **different water and soil conditions**.

- In mildly-salinized cotton fields, the recommended amount of irrigation water is **3900-4500 m³/ha**;
- For moderately- to severely-salinized cotton fields, the recommended amount of irrigation water is **4350-4800 m³/ha**;
- The optimal irrigation interval varies according to the soil type: **3 days for sandy soils** and **11 days for clay soils**. For **sandy loam soil**, the schedule is adjusted according to the emitter flux rate --- when the flux rate is under 3 L/h, irrigation is done every 5 days, while when it is **over 3 L/h**, the irrigation is done **every 7 days**.

Technical specification of water and salt regulation of mulched drip irrigation in salinized cotton fields (DB65/T 3269-2011).

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The optimal irrigation schedule for cotton fields under MDI

Technical specification of water and salt regulation of mulched drip irrigation in salinized cotton fields (DB65/T 3269-2011).


DB65
新疆维吾尔自治区地方标准
盐渍化区域棉花膜下滴灌水盐调控
技术规程

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Water and salt regulation scheme in cotton field under MDI

1. **Water and salt distribution and movement patterns in cotton fields under MDI based on 300,000 soil samples**
   - ✓ Soil water and salt re-distribution pattern during cotton growth period
   - ✓ Salt accumulation pattern during non-growth period
   - ✓ Soil water and salt re-distribution pattern under winter/spring flush
   - ✓ Crop coefficients of cotton under MDI
   - ✓ Soil water and salt movement with application of chemical ameliorant
   - ✓ Dynamics of wetting front
   - ✓ Optimal water amount and timing for winter flush

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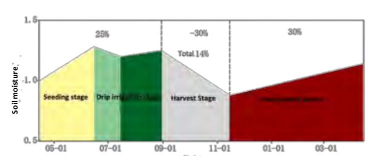
Water and salt regulation scheme in cotton field under MDI

E.g., Soil salt accumulation pattern under multi-year MDI practice

- ✓ In the root layer, soil salt will accumulate significantly during seedling period, accumulate slightly during drip irrigation period, decrease significantly during harvest period, accumulate greatly during non-growth period
- ✓ Without flush practices, soil salinity will accumulate by 14% annually, and it will be greater than some threshold values for cotton after 5-8 years.



Seasonal accumulation patterns of salt in root layer of cotton under MDI

Hongchang H U , Fuqiang T , .et al,Journal of Hydraulic Engineering, 2015

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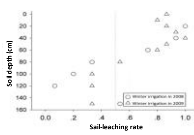
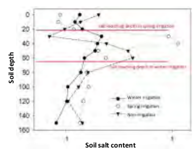
Water and salt regulation scheme in cotton field under MDI

E.g., Salt leaching effects by winter flush and spring flush

- ✓ Salt control: effective leaching depth is 60 cm for winter practice, while it is only 20 cm for spring practice
- ✓ Moisture conservation: more efficient for winter flush just implementing before soil freezing, which can provide water for crop during the next spring when soil thawing
- ✓ Winter flushing is a better choice, which requires higher water resources regulation capacity



Salt leaching with winter flush practice



Comparison of salt leaching between winter and spring flush

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Water and salt regulation scheme in cotton field under MDI

✓ **A holistic scheme of water&salt regulation for MDI cotton fields has been developed by integrating growth-period irrigation, non-growth-period flush & chemical ameliorant.**

- ☐ **Optimal styles of cotton planting and drip pipe arrangement according to soil type and degree of salinization**
  - Mild salinization conditions:
    - **Loamy soil**: a single film per every 4 planting rows with one drip pipe per film
    - **Sandy soil**: a single film per 4 or 6 planting rows with two drip pipes per film
  - Moderate to severe salinization conditions: a single film per every 4 or 6 planting rows with one drip pipe per film
- ☐ **Winter flush scheme**
  - Mild to average salinization: winter irrigation once **every 2 to 3 years**
  - Moderate to severe salinization: **annual** winter irrigation
  - Amount: **2250 m³ - 3000 m³/ha**
- ☐ **Salt control at the seedling stage**
  - Moderate to severe salinization levels or poor soil moisture conditions: Dripping-before-seeding method
  - Quota: **675 m³ - 900 m³ / ha**
- ☐ **Application of chemical ameliorants to improve soil texture**
  - The beginning and ending periods of each irrigation cycle
  - Calcium solution concentration: **2000 mg/L**

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How does the innovation save water

- ❖ **During the growth period: Based on the optimizing irrigation system, water saving can be realized by improving the utilization efficiency of irrigation water.**
- ❖ **During the non-growth period: Based on the proposed flush irrigation scheme, yearly flush irrigation can be replaced by a multi-year flush irrigation scheme, and the flush irrigation quota can also be reduced compared to traditional methods. In this way, the water amount used for salt-leaching is reduced.**
- ❖ **Additional water savings can be realized by the reducing the amount of salt-leaching water through the application of chemical ameliorants.**

Compared to traditional irrigation methods, about 25% less water is required with the proposed water and salt regulation scheme. Also, the cotton yield can be increased by 17% with controlled soil salinity.

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Summary

1. **Mulched drip irrigation has great advantages: saving water, increasing yield, reducing labor input, etc.**
2. **However, it might also cause secondary salinization in the root zone, which occurred in Israel, Egypt, USA, Lebanon and other places (Burt et al., 2003, Feng et al., 2005, Christen et al., 2007, Darwish et al., 2005; Chen et al., 2010).**
3. **Proper design of drip irrigation system and schedule can provide a favorite moisture and salinity condition for crop growth**
4. **Non-growth flush is necessary for salinity control and winter flush performs better than spring flush.**

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Further expansion of the innovation

As one of the major agricultural technologies for saving water and increasing crop yields, drip irrigation technology has been applied on a large scale in the northwestern and northeastern regions of China. And it's also in strong demand among the countries of Central Asia. The resulting technology has wide application prospects. China and Central Asia have more than 70 million ha of cotton. It is estimated that promoting the application of this technology can generate each year more than 7 billion US Dollars and save 17.5 billion m3 in water resources. It also plays a very important role in regional economies, social development and poverty reduction.

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Thank you for your attention!

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