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AquaCrop, the FAO simulation model for crop water productivity, irrigation management and hydrologic assessment

Theodore C. HSIAO
Dept. of Land, Air and Water Resources
University of California
Davis
USA

Lee HENG
Joint FAO/IAEA Div.of Nuclear Techniques in Food and Agric.
aEA
 Vienna
 Austria
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Theodore C. HSIAO¹ and Lee HENG²

¹ Dept. of Land, Air and Water Resources, Univ. of California, Davis, USA

² Joint FAO/IAEA Div. of Nuclear Techniques in Food and Agric., IAEA, Vienna, Austria

To download AquaCrop: WWW.fao.org/nr/water/aquacrop.html

ICTP-IAEA Conference, Trieste, May, 2011
Globally, water is a finite resource

Demand and competition for water is increasing

- Rising world population
- Improved living conditions
- Increasing recreational use
- Shifting to diets higher in animal products

Water use is highly unequal among nations

Example in the Mediterranean countries

- Rising world population
- Improved living conditions
- Increasing recreational use
- Shifting to diets higher in animal products

Source: A. A. A. O. 1996 (1)
Where there is rain, there is food production

NDVI—indicator of green biomass, May 2005
To ameliorate the problem of water scarcity for agriculture, need to quantify water availability and use for food production, and seek improvements in water use efficiency through management changes.

AquaCrop is designed by FAO with those purposes in mind for the potential use to:

- Improve irrigation management by reducing water use while maintaining crop productivity, i.e., improve water use efficiency
- Quantify crop ET and production from field to landscape scale in the hydrological analysis of water resources
- Develop water production functions for economical analysis to optimize water use and farm income
- Predict crop water use and productivity for climate change scenarios
AquaCrop Conceptual Framework | Crop and Climate

- Phenology
- Canopy Cover
  - Leaf expansion
  - Senescence
  - Canopy Cover
- Biomass
- HI
- Yield
- Rooting depth
- Climate, weather
- $T$ (°C)
- $ET_o$
- $E_{soil}$
- $Tr$
- WP
- $CO_2$
- $g_s$
Soil water (and salt) balance

Infiltration

Redistribution

Uptake

capillary rise

deep percolation

Leaf expansion

Senescence

WP

HI

Ta

Ks

Rain

Runoff

Irrig.

Texture 1

Texture 2

Texture ...

Ksat

FC

PWP
Stresses

1. Ks for leaf expansion, maize
2. Ks for stomata, maize
3. Ks for senescence, maize
4. WP
5. HI

Leaf expansion

\( g_s \)

Senescence

\[ K_s \]

Water stress

\[ \text{WP} \]

\[ \text{HI} \]
Key steps of AquaCrop

• Uses growing degree day as driver (can switch to calendar time)
• Calculates canopy cover (CC) first, daily, and not use LAI
• Transpiration is calculated from CC, daily ET₀ and a crop coef. for full CC, but with empirical adjustment for daily integral and for interrow advection
• Soil evaporation is calculated from CC, daily ET₀ based on Stage 1 & 2 drying, and ET is obtained as the sum
• Water productivity normalized for atmosphere evaporative demand & CO₂, a constant, is used to convert transpiration to biomass production, daily
• Yield is calculated from biomass and harvest index (HI)
• HI is assumed to increase from anthesis onward, linearly after a lag phase
• Water stress is dependent on fractional depletion of available soil water, via several water stress functions, each with its own sensitivity threshold
• The stress functions are: leaf growth, stomata, early canopy senescence, and changes in HI
• Impact of transpiration rate on plant water status are indirectly accounted for by adjusting the sensitivity thresholds according to the daily ET₀
Canopy cover (CC) follows the exponential growth during the first half of its development (Eq. 1), and an exponential decay during the second half of its development (Eq. 2)

\[
CC = CC_o e^{CGC \cdot t} \quad (1)
\]
• AquaCrop calculates soil evaporation ($E_{\text{soil}}$) and crop transpiration ($Tr$) separately.
• Canopy cover (CC) is calculated first as it affects the separation between $E_{\text{soil}}$ and $Tr$.
• Initial canopy cover ($CC_0$) is calculated from plant density and CC per seedling.

\[ CC = CC_o e^{CGC \cdot t} \quad (1) \]
\[ CC = CC_x - (CC_x - CC_o) \cdot e^{-CGC \cdot t} \quad (2) \]
CC simulation using the same CGC and initial CC per seedling

Hsiao et al. unpublished
Water Productivity (WP)

\[
WP = \frac{\text{Biomass}}{\sum T_c}\quad (\text{g m}^{-2} \text{ mm}^{-1})
\]

\[
WP^* = \frac{\text{Biomass}}{\sum \left( \frac{T_c}{ET_0} \right)}\quad \text{CO}_2(2000)\quad (\text{g m}^{-2})
\]

Graphs showing the relationship between biomass and \(\sum T_c\) (mm x 1000) for different crops like Sorghum, Sunflower, Chickpea, and Wheat. Another graph illustrating the relationship between biomass and \(\sum \left( \frac{T_c}{ET_0} \right)\).
General features

- **AquaCrop** is explicit and mostly intuitive, and maintains an optimum balance between simplicity, accuracy and robustness.

- **AquaCrop** differs from other models for being water-driven, and for its relatively small number of parameters.

- **AquaCrop** is aimed at practical end-users, as those in farmers and irrigation associations, extension services, governmental agencies and NGOs, for devising water management and saving strategies.

- **AquaCrop** is also aimed at planners and economists who need estimates of production for given amounts of water.

- **AquaCrop** is suitable for perspective studies (e.g., different irrigation strategies, climate change scenarios).
How does AquaCrop perform?

Example of application to maize
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>For maize</strong></td>
<td></td>
</tr>
<tr>
<td>Canopy</td>
<td></td>
</tr>
<tr>
<td>Initial canopy cover per seedling (cm²)</td>
<td>6.5</td>
</tr>
<tr>
<td>Canopy growth coefficient (% of existing canopy)</td>
<td>16</td>
</tr>
<tr>
<td>Maximum canopy cover (plant density dependent)</td>
<td>--</td>
</tr>
<tr>
<td>Canopy decline coefficient (% per day)</td>
<td>14</td>
</tr>
<tr>
<td>Root system</td>
<td></td>
</tr>
<tr>
<td>Average deepening rate (optimal soil conditions, cm/day)</td>
<td>2.4</td>
</tr>
<tr>
<td>Transpiration</td>
<td></td>
</tr>
<tr>
<td>Crop coefficient for transpiration (full canopy)</td>
<td>1.03</td>
</tr>
<tr>
<td>Decline in green canopy activity with age (% per day)</td>
<td>0.3</td>
</tr>
<tr>
<td>Production</td>
<td></td>
</tr>
<tr>
<td>Normalized WP (optimal conditions, year 2000, g m²)</td>
<td>33.0</td>
</tr>
<tr>
<td>Reference HI (%)</td>
<td>48</td>
</tr>
</tbody>
</table>
Plant stress parameters, basic, wide applicability
Also considered as conservative (constant) parameters

For maize

$K_s$ function for leaf expansion (canopy growth)
- $p$ upper for leaf expansion
  - 0.18
- $p$ lower
  - 0.76
- Curve shape
  - +3

$K_s$ function for stomata (canopy transpiration)
- $p$ upper
  - 0.76
- Curve shape
  - +6

$K_s$ function for acceleration of canopy senescence
- $p$ upper
  - 0.78
- Curve shape
  - +3

Stress effects on HI
- Positive effects of stress inhibition of leaf growth
- Negative effects of stress inhibition of stomata

Stress effects on WP*
- 0
Parameters specific to each location & season

- Daily weather ($E_{T_o}$, rainfall, and temperature)
- Soil water characteristics of depth layers
- Initial soil water content of depth layers
- Rooting depth as affected by restrictive soil layers
- Irrigation schedule (time and amount)
- % of soil surface wetted by irrigation
- Plant density
- Crop phenology (cultivar specific), including flowering, senescence start, and physiological maturity time
1974 Experiment

Treatments:
- Irrigated (I)
- Rainfed (NI)
- Irrig. day 55 onward (I55)

- Early senescence of NI fairly well simulated
- Biomass time course and difference fairly well simulated
- Effects of early stress and late irrigation fairly well simulated

<table>
<thead>
<tr>
<th>Biomass</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>24.3</td>
</tr>
<tr>
<td>NI</td>
<td>16.8</td>
</tr>
<tr>
<td>I55</td>
<td>21.2</td>
</tr>
</tbody>
</table>

White—measured
Blue—simulated
1990 Experiment

Treatments:
- Irrigated (I)
- Late dry (LD, dry day 56 on)

- Canopy decline of LD under-simulated slightly
- Reduced late biomass accumulation of LD well simulated

<table>
<thead>
<tr>
<th></th>
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<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>26.9</td>
<td>12.0</td>
</tr>
<tr>
<td>LD</td>
<td>22.7</td>
<td>10.1</td>
</tr>
</tbody>
</table>

White—measured
Blue—simulated
1994 Experiment

Treatments:
Irrigated (I)
Limited irrig. (LI)

- Effects of irrigation in delaying senescence well simulated
- Recovery in biomass growth upon irrigation simulated

<table>
<thead>
<tr>
<th></th>
<th>Biomass</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>27.6</td>
<td>12.7</td>
</tr>
<tr>
<td>LI</td>
<td>22.2</td>
<td>10.2</td>
</tr>
</tbody>
</table>

White—measured
Blue—simulated
1994 irrigated

Limited irrigation

T(\text{act})
Max=10 \text{ mm/d}

CC (%)
Max=98%
Range of 6 different years in Davis simulated (same basic parameters)

- Three different cultivars
- Planting dates: May 14 to June 16
- Time to maturity: 118 to 138 days
- Substantial range of evaporative conditions
- Variety of watering regimes:
  - Rainfed
  - No irrigation first half of season
  - No irrigation last half of season
  - Limited irrigation in mid season
  - Fully irrigated

![Graph of ETo, 15-day running mean for 1974 and 1990](image)

• Bushland Texas—high wind and very high $ET_o$
  soil water holding capacity = 15%

• Gainsville Florida—sandy soil and humid, low $ET_o$
  soil water holding capacity = 5 to 10%

• Zaragoza Spain—sandy loam and 3 irrigation regimes
  soil water holding capacity = 17 to 20%

All using same conservative parameters as Davis

Coefficients of efficiency for the simulations was 0.9 or higher for the large majorities of the test cases
So far AquaCrop has been parameterized for only a number of crops:

Available now:
- Maize
- Cotton
- Wheat (mild winter)
- Paddy rice
- Soybean
- Sunflower
- Sugar beet
- Quinoa
- Potato

Working on:
- Sorghum
- Tomato
- Sugar cane
- Barley

Next to do:
- Wheat (cold winter)
- Alfalfa
• Need to make canopy growth coefficient (CGC) more sensitive to water stress  
• Need to make transpiration less sensitive  
• Need to make the HI vs. DAP function a curve instead of straight line  

Potato  
Davis 80  

Full irrig.  

65% irrig.  

24% irrig.
What about potato water use, simulated?

- Water balance is simulated OK in this case
- Hard to find data where ET, CC or LAI, and biomass are sampled over the season, along with detailed weather data
Data desired for parameterization and testing

- Daily weather (rainfall, radiation, temperature, humidity, and wind)
- Soil water characteristics of depth layers
- Initial soil water content of depth layers
- Irrigation schedule (time and amount)
- Soil water content at different times
- Plant density
- Canopy cover (CC from LAI) progression with time
- Rooting depth at different times
- Transpiration (or ET) as function of time
- Biomass at different times and final harvest
- Yield

Most experiments not provide all desired data
Have to test various aspects separately
Now demonstration of model use

www.fao.org/nr/water