Crop Systems & Global Change Lab
Applying Systems Theory
To Complex
Agricultural Problems

Simulating Effects of CO_2 and Drought on Potato

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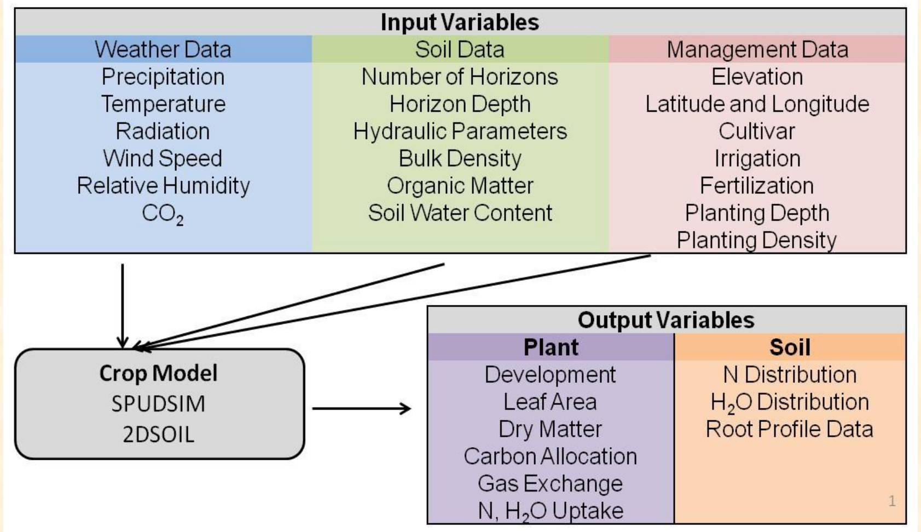
INTRODUCTION

IPCC forecasts indicate major agricultural production regions are likely to experience prolonged periods of drought. Predicting effects of elevated carbon dioxide concentration (CO_2) and water scarcity on agronomic production using crop models is vital to develop adaptation strategies and assess food security needs. Confidence in such mathematical tools is limited due to insufficient validation against appropriate experimental data sets and the type of knowledge encapsulated in the model. Process-level crop models are being developed by the USDA-ARS that incorporates the state-of-the-art with respect to modeling the soil-plant-atmosphere system at the plant level. **The present study evaluates the ability of the potato model, SPUDSIM, to predict effects of CO_2 and drought on potato using soil-plant-atmosphere research (SPAR) growth chamber data.**

SPUDSIM v.1.1

SPUDSIM incorporates similar phenological and carbon allocation routines as in SIMPOTATO (Hodges, 1992). The C++model is integrated with 2DSOIL (Timlin et al., 1996) to simulate water, solute, heat and gas movement. Root growth is simulated using a diffusive scheme in horizontal and vertical directions. Climate, soil status, management, and genetic information is processed by the model which simulates plant and soil nitrogen and water status, plant development, leaf and canopy gas exchange, dry matter production, and carbon allocation. Model outputs include hourly predictions for organ dry weights, leaf area, rates for photosynthesis, respiration, and transpiration, and 2-D root growth and soil status variables (Fig. 1).



Input Variables

Weather Data	Soil Data	Management Data
Precipitation	Number of Horizons	Elevation
Temperature	Horizon Depth	Latitude and Longitude
Radiation	Hydraulic Parameters	Cultivar
Wind Speed	Bulk Density	Irrigation
Relative Humidity	Organic Matter	Fertilization
CO_2	Soil Water Content	Planting Depth
		Planting Density

Crop Model
SPUDSIM
2DSOIL

Output Variables

Plant	Soil
Development	N Distribution
Leaf Area	H_2O Distribution
Dry Matter	Root Profile Data
Carbon Allocation	
Gas Exchange	
N, H_2O Uptake	

Fig. 1: Input and output data for SPUDSIM potato model. The model runs on an hourly time-step.

$$A_n = \min\left(W_c, W_j, W_p\right)\left(1 - \frac{\Gamma^*}{C_c}\right) - R_d$$

$$g_s = g_o + mA_n \frac{h_s}{\left(C_s / P_a\right)} f\left(\psi_l\right)$$

$$T_L = T_a + \frac{R_{abs} - \varepsilon\sigma T_a{}^4 - \lambda g_v D / P_a}{c_p\left(g_h + g_r\right) + \lambda\left(\left(de_s\left(T_a\right)/dT\right)/P_a\right)g_v}$$

Fig. 2: Coupled biochemical model for C3 photosynthesis (An), stomatal conductance (gs), and energy budget. Gs is also influenced by leaf water potential ψ.

Relevant modeling components:

1) Coupled leaf-level biochemical, stomatal conductance, and energy balance models (Fig. 2) are used to estimate gas exchange as influenced by CO_2, T, VPD, PAR, SRAD, WIND, and other variables
2) Leaf-level results are scaled to canopy utilizing sunlit-shaded leaf fractions
3) Water stress (a) reduces stomatal conductance (Figs. 2 and 3) and leaf expansion rate via leaf water potential and (b) increases carbon allocation from shoot to root

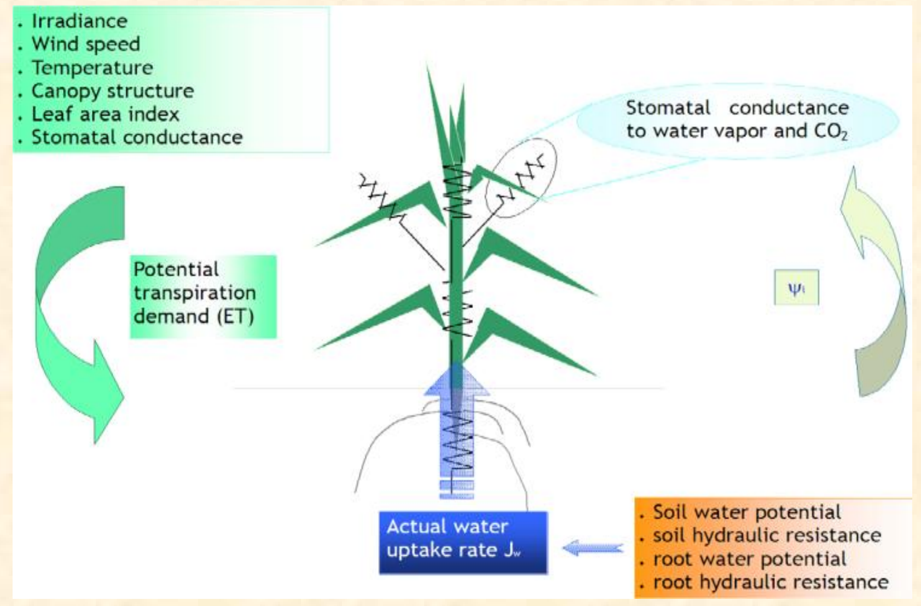


Fig. 3: Potential transpiration is affected by atmospheric conditions and stomatal conductance. Actual water uptake is determined in 2DSOIL by soil moisture and soil-plant-atmosphere-hydraulic conductivity. Leaf water potential is used as a hydraulic signal between soil and plant and 'regulate's stomatal conductance in the coupled leaf model.

EXPERIMENTAL DATA

Experiments conducted in 12 Soil-Plant-Atmosphere-Research (SPAR) chambers located at USDA-ARS facilities in Beltsville, Maryland. SPAR chambers (Fig. 4) provided precise control and monitoring of T, CO_2, RH, and irrigation. Whole plant net carbon exchange rates are calculated at 30-sec intervals and evapotranspiration rates at 15-min intervals over the course of the study. Each chamber has a 1 m^2 plant production area and 1 m^3 'soilbin'. Irrigation is provided via a micro-fertigation system and water content monitored using TDR probes.

Relevant protocols:

- Two 6-SPAR chamber experiments at 370 (ambient) and 740 (elevated) μmol mol^{-1} CO_2 were conducted.
- A 16h 23°C day / 8h 18°C night thermoperiod was used for all chambers.
- A 75% sand / 25% vermiculite mix was used with time release fertilizer.
- *Solanum tuberosum* cv Kennebec seed tubers were used (12 plants m^{-2}).
- Water stress was imposed by varying daily irrigation (H_2O) amount to each chamber.
- The amount of H_2O was provided to each SPAR chamber according to 90, 75, 50, 25 and 10% of the daily water uptake measured from the control chamber (100%) at either CO_2 concentration

Fig. 4: Left – SPAR facility; Middle – potato plants 30 days after emergence; Right – soilbin compartment

Experimental Outcomes to Note:

- Total biomass was linearly correlated with H_2O treatment.
- More biomass was fixed for elevated versus ambient CO_2 at well-watered treatments, but not always at less irrigated chambers.
- Drought increased partitioning to tubers and this was enhanced under elevated CO_2.
- Below ground : above ground dry matter ratios declined with H_2O and were influenced by growth CO_2.
- WUE was higher for elevated versus ambient CO_2 at most treatment levels.

SIMULATION PROTOCOLS

(1) SPUDSIM was calibration was based on the ambient CO_2 x 100% irrigation irrigation. **No other modifications or calibrations were applied for any of the other 11 model runs.**

(2) Inputs for each model-run (i.e. one simulation per chamber) used the uniquely measured environmental, irrigation data, and specific harvest data associated with each chamber.

(3) Nitrogen was added as solid amendment and in liquid fertilizer and was thus a confounding effect. The ability to simulate nitrogen stress (or excess) was therefore included in all model-runs.

RESULTS

DRY MATTER

Observed and simulated end-of-season dry matter is shown for ambient (left) and elevated (right) CO_2 model runs (Fig. 5). Model predictions were within two standard-errors for all chambers. However, simulated carbon allocation among above and below ground organs did not always correspond to observed relationships. For example, harvest index did not reflect the higher partitioning of CHO to tubers as H_2O decreased, particularly for elevated CO_2 (Table 1). Below ground : above ground dry matter ratios did respond to H_2O, but not to the observed extent (Table 2).

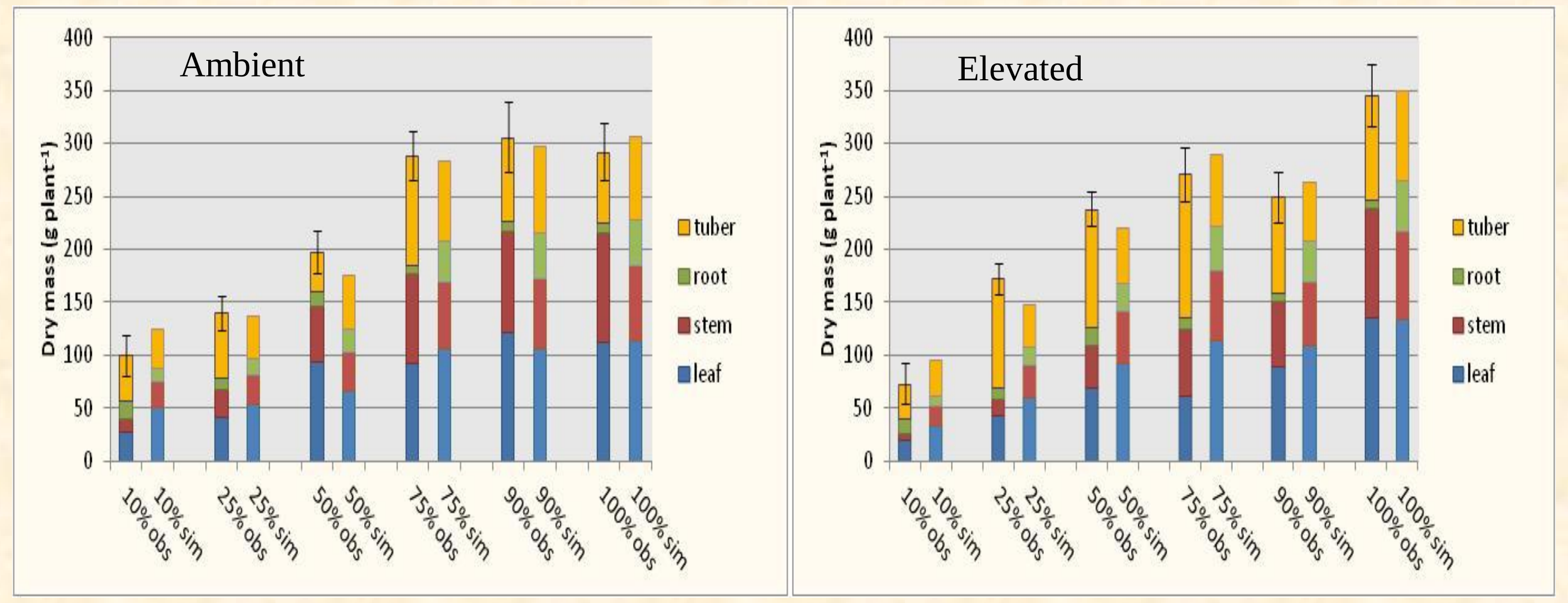


Fig. 5: Observed and simulated dry matter at six different irrigation levels for ambient (left) and elevated (right) CO_2 treatments. Single standard errors are shown.

Table 1: Observed and simulated harvest index (yield : total biomass).

	Harvest Index			
	Ambient		Elevated	
H_2O (%)	obs	sim	obs	sim
100	0.23	0.26	0.29	0.24
90	0.26	0.28	0.36	0.21
75	0.37	0.26	0.50	0.23
50	0.19	0.27	0.47	0.23
25	0.44	0.28	0.59	0.27
10	0.42	0.28	0.46	0.35

Table 2: Observed and simulated ratios of below to above ground dry matter.

	Below Ground:Shoot			
	Ambient		Elevated	
H_2O (%)	obs	sim	obs	sim
100	0.35	0.66	0.45	0.61
90	0.41	0.72	0.65	0.56
75	0.63	0.67	1.17	0.61
50	0.34	0.69	1.16	0.56
25	1.04	0.68	1.91	0.64
10	1.45	0.63	1.84	0.85

DAILY GAS EXCHANGE

An example of daily canopy net photosynthetic and transpiration rates is shown for the 75% H_2O treatment for both CO_2 levels (Fig. 6). Simulated values for seasonal assimilation (Table 3) and transpiration (Table 4) followed the same patterns as observed data with few exceptions, Daily fluctuations (Fig. 6) are a result of variations in solar radiation, irrigation events, and plant canopy bulk leaf water potential, itself a function of plant and soil water status. As compared with observed data, the model tends to over-respond to soil water status, particularly towards the middle and end of the season when the soil media water content is depleted.

Table 3: Observed and simulated seasonal net assimilation (production area basis)

	Seasonal Net Assimilation (mol CO_2 m^{-2})					
	Ambient			Elevated		
H_2O (%)	obs	sim	% err	obs	sim	% err
100	116	121	4	161	138	-14
90	128	115	-11	108	99	-8
75	121	111	-8	125	114	-9
50	88	72	-18	100	88	-12
25	53	54	2	97	58	-40
10	28	48	71	34	36	8

Table 4: Observed and simulated seasonal water uptake (production area basis)

	Seasonal Water Use (L m^{-2})					
	Ambient			Elevated		
H_2O (%)	obs	sim	% err	obs	sim	% err
100	702	681	-3	649	764	18
90	673	816	21	556	551	-1
75	541	689	27	471	606	29
50	332	396	19	378	339	-10
25	238	218	-8	218	212	-3
10	192	141	-27	125	135	8

RESULTS

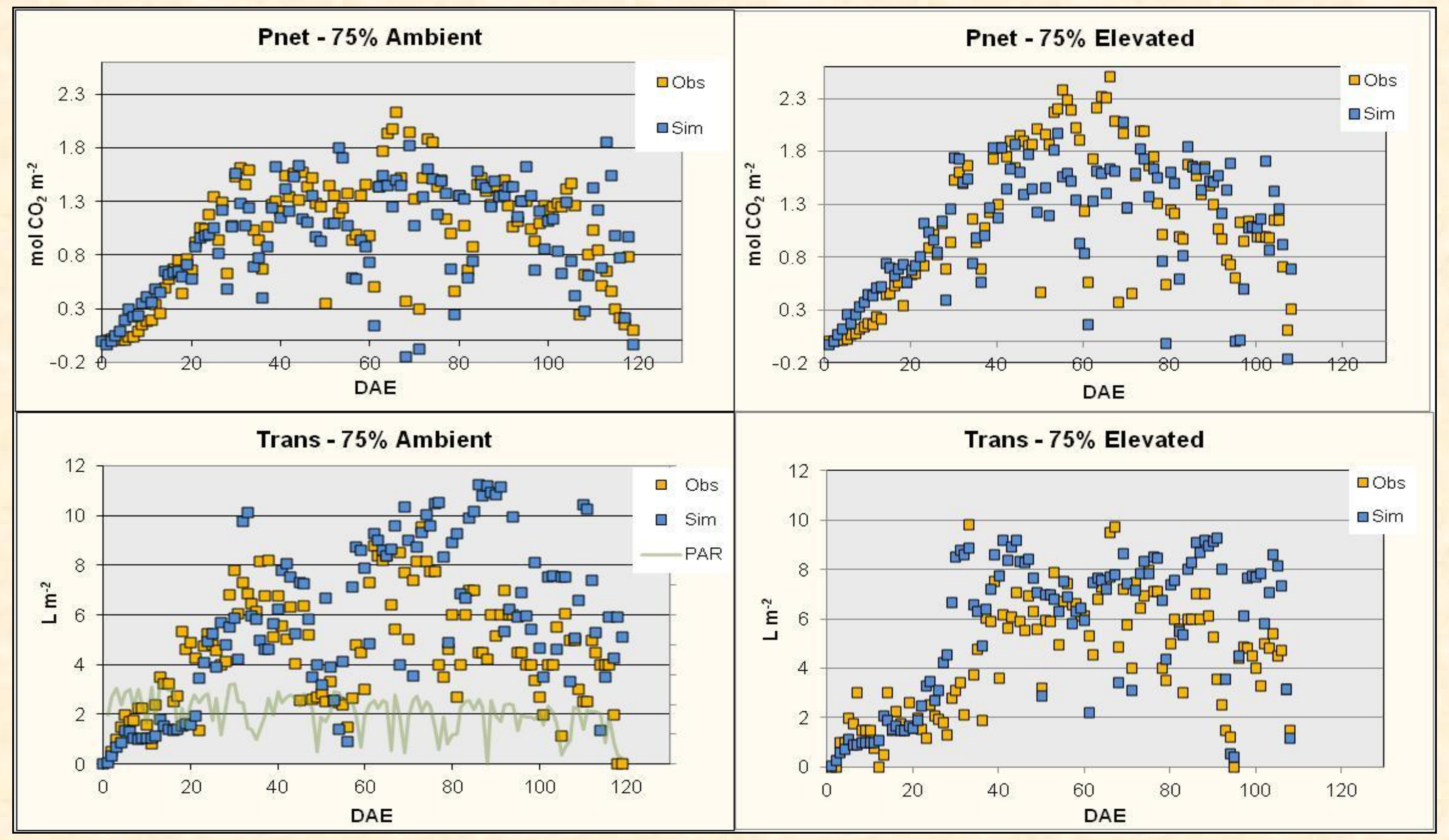


Fig. 6: Observed and simulated daily net assimilation rates (top) and transpiration rates (bottom) for ambient (left) and elevated (right) CO_2 chambers at 75% irrigation.

WUE

In the observed and modeled case, elevated CO_2 grown plants did not always use less water (Table 4), but due to higher biomass production, WUE values were usually higher as compared to the corresponding ambient CO_2 x H_2O treatment. Simulated WUE followed expected trends, increasing with drought and CO_2 concentration (Table 5).

Table 5: Observed & simulated WUE

	WUE (g d.m. L^{-1})			
	Ambient		Elevated	
H_2O (%)	obs	sim	obs	sim
100	5.0	5.4	6.4	5.5
90	5.5	4.4	5.4	5.8
75	6.2	5.0	6.9	5.9
50	7.2	5.6	7.6	8.0
25	7.1	8.0	9.5	8.6
10	6.2	11.3	7.0	8.7

DISCUSSION

Using just a single calibration 'point', the SPUDSIM model was able to realistically respond to a wide range of irrigation treatments at two different CO_2 levels with respect to total dry matter production, net assimilation rates, and water use. Where the model appeared to be deficient was in simulating the observed shifts in carbon allocation from haulm to the tubers as H_2O decreased, particularly when compared with the elevated CO_2 responses. Future research is focused on quantifying how these shifts in priority for CHO can be modeled in a mechanistic fashion. Overall, the results suggest SPUDSIM can accurately respond to future CO_2 and drought scenarios.

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