Experimentally validated mathematical modeling reveals the influence of surface rock cover on soil water availability in a semi-arid ecosystem

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Background: Plant growth in arid ecosystems is water limited. Soil water availability is determined by infiltration and runoff (during wetting events), and evapotranspiration (a drying event), which vary with soil type and landscape features. **Surface rock is a dominant and highly variable landscape feature in deserts.**

Question: How does the distribution of surface rock impact the soil water available for plants in an arid ecosystem?

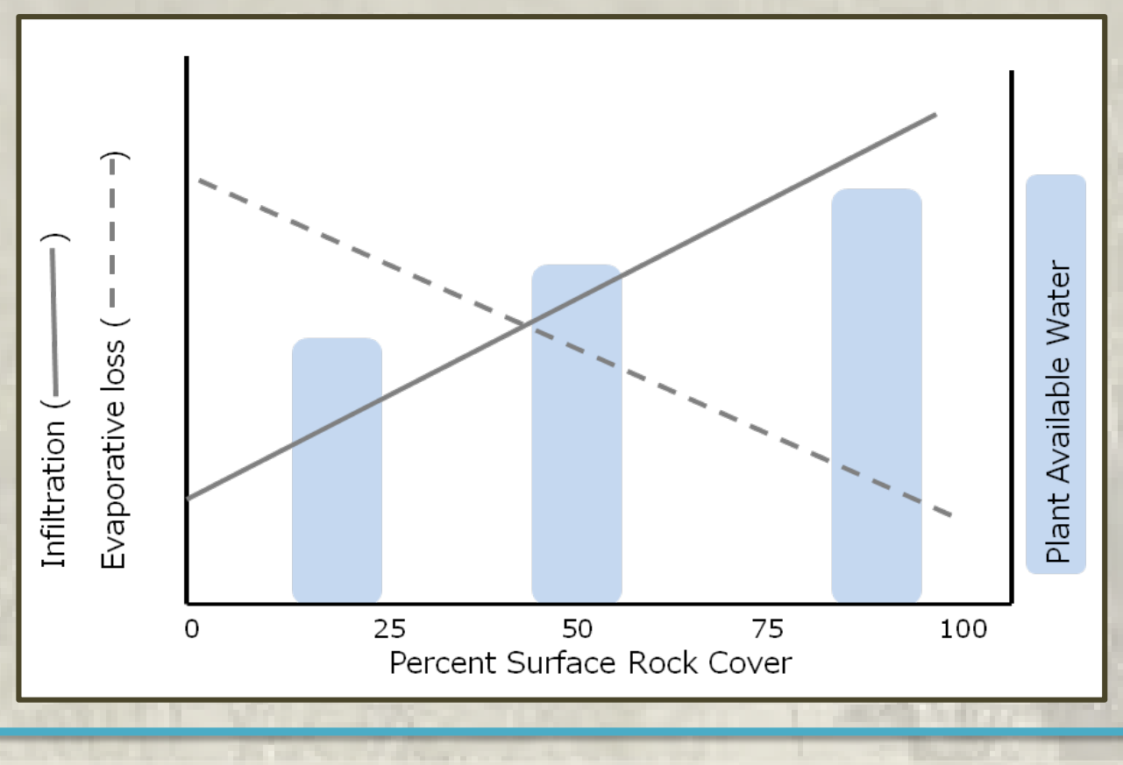


Figure 1. We expected an increase in infiltration and a reduction in evaporative loss as surface rock cover increased, resulting in more plant available water in the soil.

Previous experimental data are contradictory

- Increased rock cover can decrease runoff, increasing infiltration
- Increased rock cover can increase runoff, decreasing infiltration
- Increased rock cover can reduce evaporation, increasing water retention

Hypothesis: **Soil water content is positively related to the amount of surface rock cover** **(Figure 1).**

Building and calibrating a soil water model in Hydrus 2D

Soil box construction

- Soil collected from a known prehistoric site near Cave Creek, Arizona was used to fill a soil box 90 cm long x 40 cm wide x 25 cm deep (Figure 2).
- Soil moisture and temperature sensors were installed at 7 cm.
- Atmospheric temperature & humidity sensors were deployed at the site.

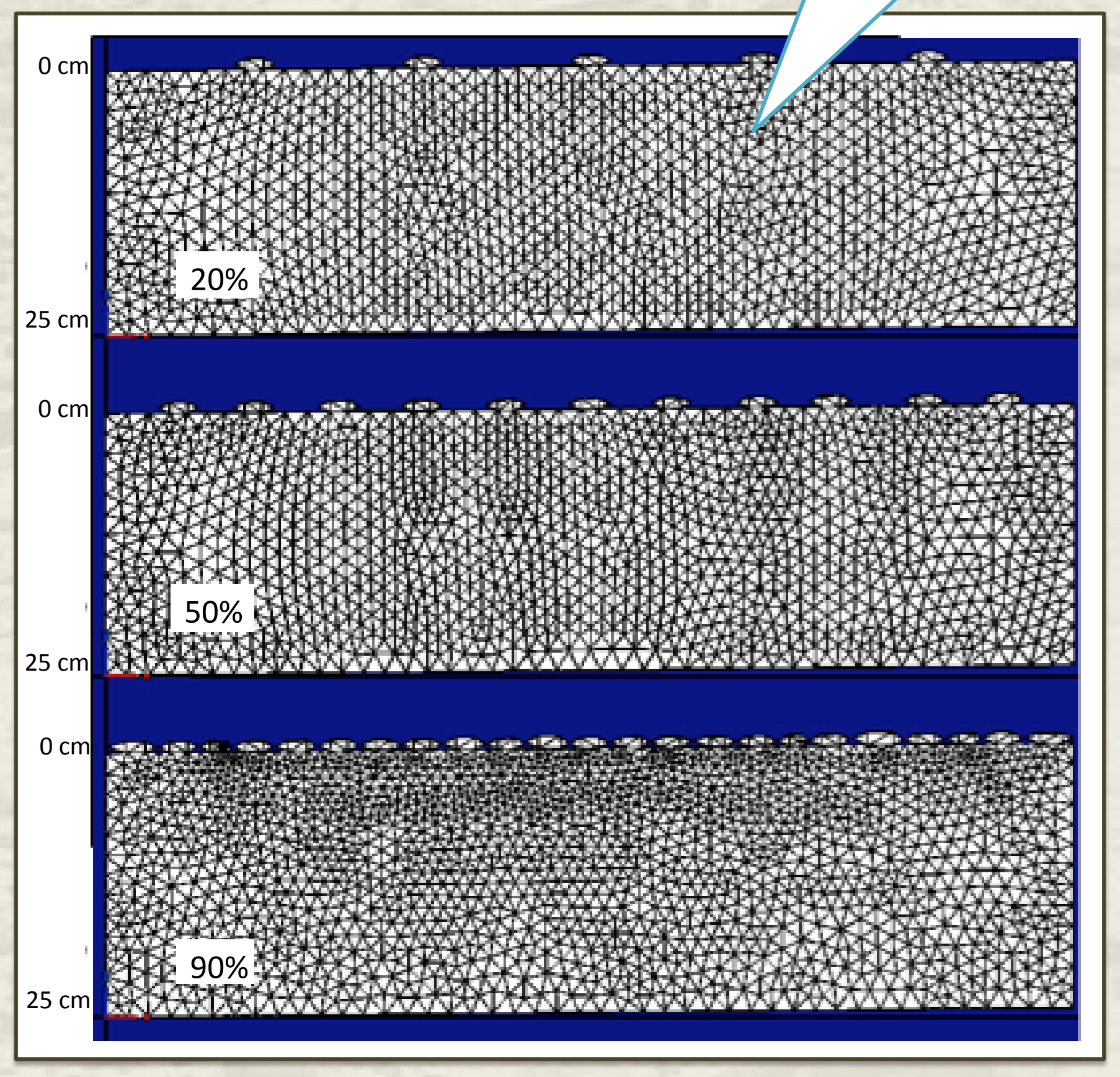
Model construction in Hydrus 2D

- The geometry of the model was built to match the soil box.
- Rock cover (0%, 2%, 50%, and 90% cover) was simulated by building impervious structures on the soil surface (Figure 3).
- Soil parameters and environmental variables for model input are listed in Table 1.

Model calibration in Hydrus 2D

- The soil box experienced experimentally simulated rainfall events and drying periods under 0%, 20%, 50% and 90% cover.
- Volumetric water content (ϴ) was continuously monitored in the soil box via sensors.
- Simulations in Hydrus 2D were run to match soil box experiments.
- Model output (volumetric water content at 7 cm) was compared to soil box sensor data in a Nash Sutcliffe efficiency (NSE) goodness-of-fit test. **The goodness-of-fit was > 80% for all rock cover treatments.**

Figure 2. Soil box under 20% cover



The nodes in the soil profile are generated by the model to create the experimental "mesh".

Figure 3. "Rocks" are added to the base model in Hydrus 2D to increase surface cover. The rocks are separate entities with different material properties than the base soil profile.

Experimentally derived parameters		*Mathematically derived parameters*	
Soil properties			
Bulk Density	1.51 g/cm^3	α: 1° conductivity function coefficient	0.039
Θ_r: Residual Water Content	0.059 cm^3/cm^3	n: 2° conductivity function coefficient	1.44
Θ_s: Saturated Water Content	0.32 cm^3/cm^3	K: Hydraulic conductivity	12.45 cm/day
Environmental variables			
Air Temperature	Relative Humidity	Potential Evaporation	

Table 1. Input parameters for the Hydrus 2D model.

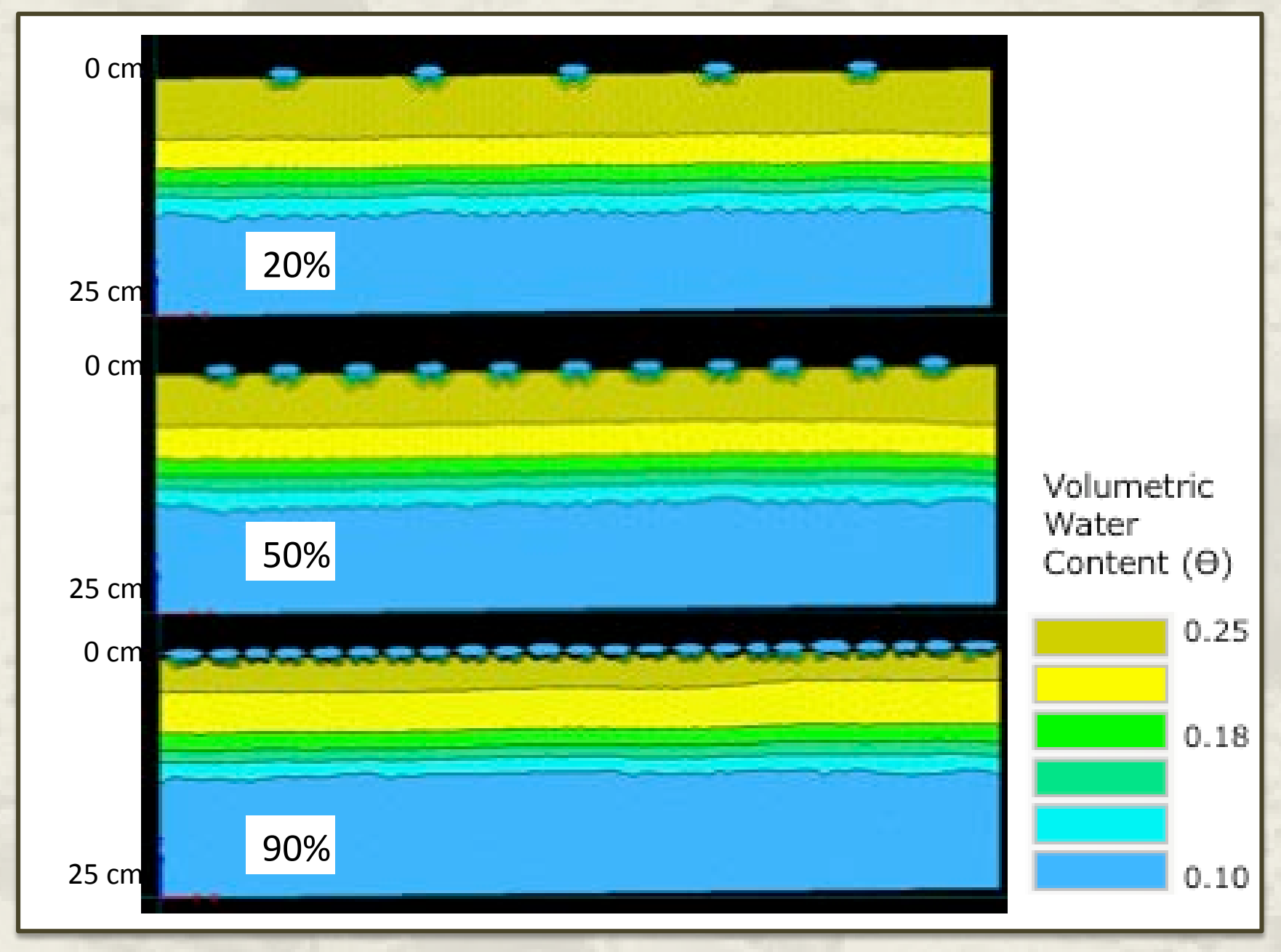


Figure 4. Screenshots showing the treatment models during a wetting simulation at10 hours.

Testing the hypothesis using an experimentally calibrated model

Simulations were run in Hydrus 2D to test the wetting and drying of the soil profile separately (Figure 4 shows an example of wetting simulations). **Except for surface rock cover, initial conditions were identical for each rock cover treatment.** Table 2 shows a summary of simulated events and model variables.

Test	Simulation	Output Variables
The effect of rock cover on infiltration of water into the soil	Precipitation event	Time to runoff (sec)
		Depth of wetting front (cm)
		Total runoff (cm$^{3)}$
		Total infiltration (cm^3)
The effect of rock cover on retention of water in the soil	Drying event	VWC at 7 cm (cm^3/cm^3)
		Total evaporation (cm^3)
		Evaporation rate (cm^3/day)

Table 2. Hydrus 2D experiments and associated output variables used for analysis.

Surface rock cover affects infiltration and evaporation of soil water in an experimentally calibrated Hydrus 2D model

Wetting: infiltration of simulated precipitation

- The percent of infiltrated rainfall is greatest for **20%** and **50%** rock cover (Figure 5a).
- The wetting front following a precipitation event is deeper under **20%** and **50%** rock cover than it is for 0% or 90% cover (Figure 5b).

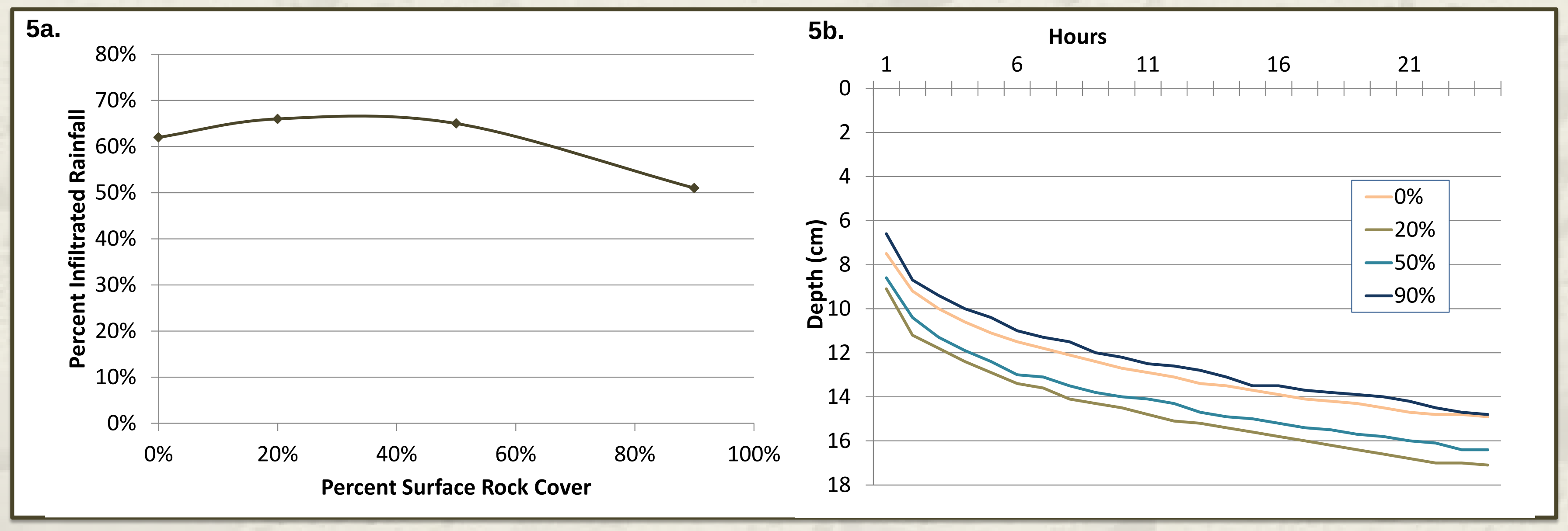
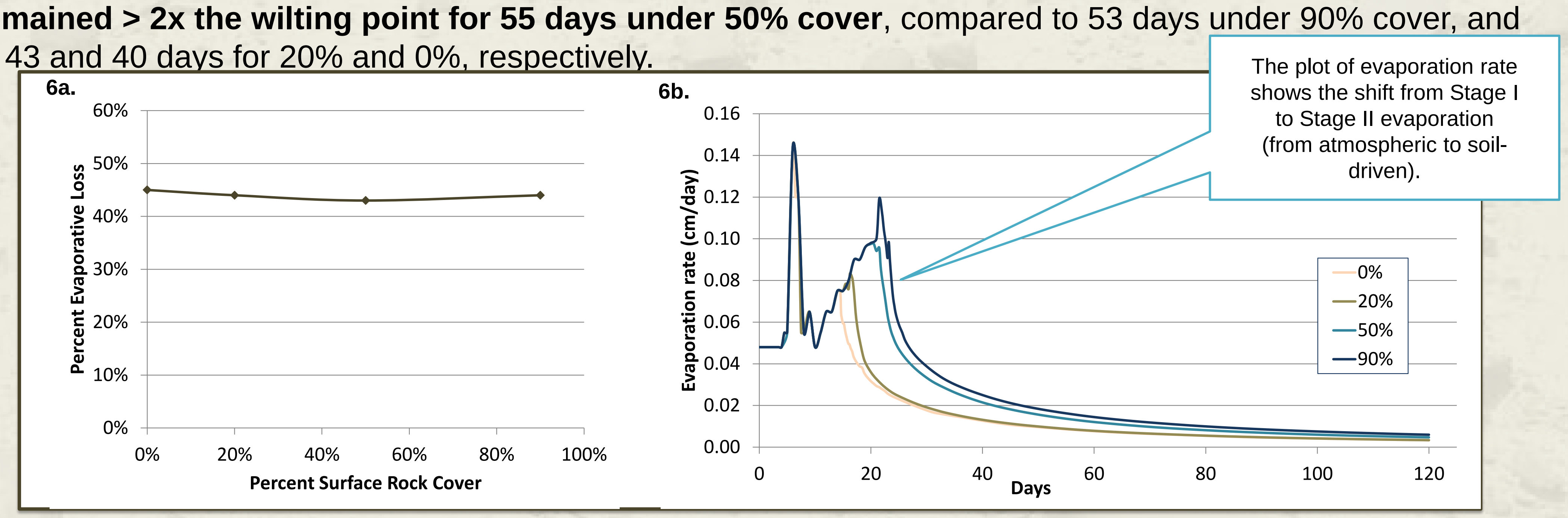


Figure 5. Results of wetting simulations (2cm/hr for 1 hr): More water infiltrates and moves deeper in the soil under moderate rock cover.

Drying: evaporation of soil water

- Evaporative soil loss is lowest under 50% cover and highest with 0% cover (Figure 6a).
- The length of Stage I evaporation is positively related to rock cover (Figure 6b).
- **ϴ remained > 2x the wilting point for 55 days under 50% cover**, compared to 53 days under 90% cover, and only 43 and 40 days for 20% and 0%, respectively.



The plot of evaporation rate shows the shift from Stage I to Stage II evaporation (from atmospheric to soil-driven).

Figure 6. Results of drying simulations (initial ϴ = 0.225): Total evaporation is reduced under moderate rock cover. Greater rock cover increases the number of days the soil experiences potential evaporation rate.

Plant available water is greater under moderate surface rock cover than under very high or very low cover.

- Surface rock cover slows runoff of precipitation and allows for greater infiltration.
- Under very high cover, soil surface area is greatly reduced and runoff increases, reversing the positive relationship between infiltration and rock cover.
- Under very high cover, the soil surface remains wet and extends Stage 1 evaporation, which increases the net evaporative loss.

Conflicting results from previous field experiments measuring infiltration in aridland soils may be a result of differences in the extent of rock cover.

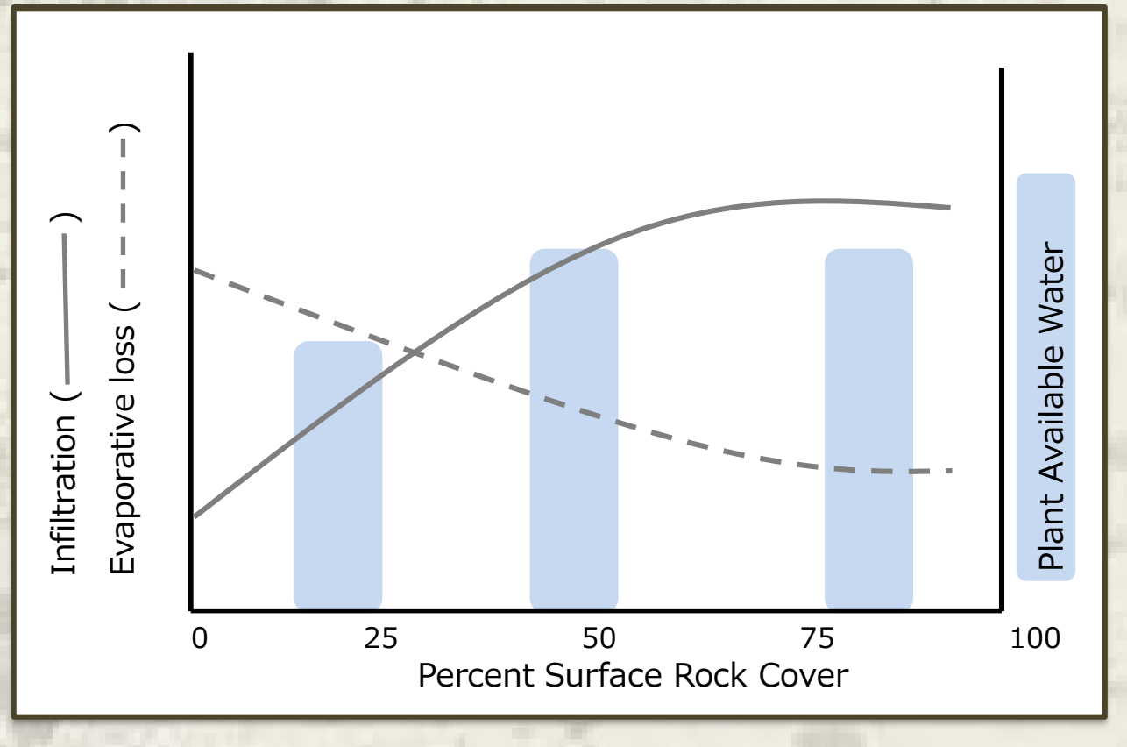


Figure 7. Contrary to our expectations, the relationship between plant available water and surface rock cover is complex. Our results suggest a threshold where infiltration is highest and evaporative loss is lowest.

Our calibrated Hydrus 2D model will be used to investigate further questions about the effects of surface rock cover.

- Do data collected under test plots instrumented in the field corroborate our results?
- How sensitive is the relationship between rock cover and soil water to the proportion of sand, silt and clay in the soil?
- Did the manipulation of surface rocks by prehistoric cultures result in rock cover distribution that could significantly influence plant available water in the soil?

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