Modeling Reactive Nitrogen Cycling on a Forested Hillslope Using $^{15}NO_3$ and D_2O Tracers

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Abstract

Headwater forests are important sources of drinking water. They process reactive nutrients, e.g., nitrate (NO_3^-), that enter the terrestrial ecosystem through atmospheric deposition. However, some nutrients are exported downstream, where water quality degradation can occur, leading to eutrophication, algal blooms, and impacts to aquatic food webs. Nutrient export from forests is influenced by many factors, including nutrient loading rates, biological uptake, sorptive interactions in soil, denitrification, climate variability, and hydrological processes. The dynamics and relative importance of such factors are not well understood.

We propose a nutrient ($^{15}NO_3^-$) and water (D_2O) tracer addition experiment on a unique experimental hillslope (15 m long) to elucidate the biogeochemical reactions in soil at hydrologic steady-state. Transport of the $^{15}NO_3^-$ tracer relative to the D_2O tracer will provide a better understanding of how soil processes retain NO_3^- and impact export rates. Research questions include:

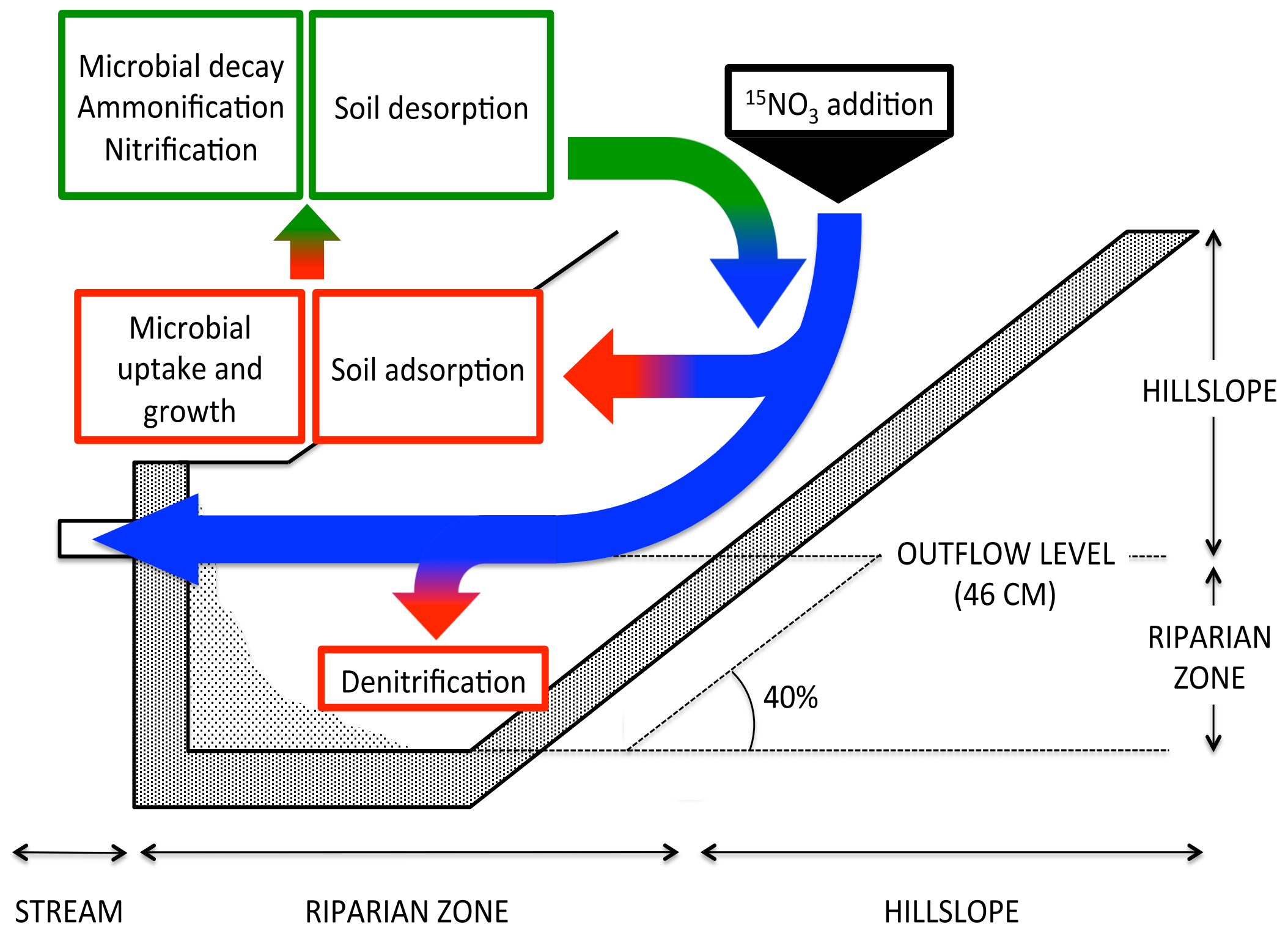
- What is the timing and quantity of NO_3^- export after a hotspot of NO_3^- is introduced on a forested hillslope?
- How much denitrification occurs and which conditions (e.g., wetting dynamics, depth to saturation, soil temperature, position on the hillslope) promote it?
- How do varying slope angle/length, nutrient loading, or climate scenarios affect NO_3^- export?
- How can the variable source area streamflow generation paradigm be updated to account for a more complex hillslope (e.g., macropore flow)?

Approach

Labeled nitrate ($^{15}NO_3^-$) and water (D_2O) addition

1. Use model (HYDRUS) to guide experimental design
   1. Calibrate and parameterize 2-D Richards equation numerical model HYDRUS using data from water retention curves
      1. Historical data
      2. New data by repeating drainage experiment in Hewlett and Hibbert (1963)
   2. Simulate irrigation, drainage, and solute transport

2. Introduce tracers
   1. Irrigate soil model to steady state with water quantity and quality similar to local throughfall
   2. Add labeled $^{15}NO_3^-$ and D_2O to the surface of the soil model at an upslope position
   3. Continue irrigation until tracers are captured in the outflow
   4. Sample soil solution throughout hillslope and at outlet for $^{15}NO_3^-$, D_2O, dissolved organic carbon, pH, and major ions
   5. Compare transport times of $^{15}NO_3^-$ and D_2O; create a nitrogen mass balance
   6. Calibrate HYDRUS model with new data and perform additional virtual experiments to evaluate sensitivity under variable slope angle/length, nutrient loading, and climate scenarios



Microbial decay
Ammonification
Nitrification

Soil desorption

$^{15}NO_3$ addition

Microbial uptake and growth

Soil adsorption

Denitrification

Figure 1. The black box represents the $^{15}NO_3^-$ addition; the blue arrow represents conservative transport of $^{15}NO_3^-$; red boxes represent possible $^{15}NO_3^-$ sinks; green boxes represent possible $^{15}NO_3^-$ mobilization.

Experimental Hillslope Description and Preparation

Figure 2 (below). Experimental hillslope soil model at Coweeta Hydrologic Laboratory, USDA Forest Service, Southern Research Station, Otto, NC. The model was originally used to develop the Variable Source Area theory to explain subsurface runoff in hillslope hydrology (Hewlett and Hibbert 1967).

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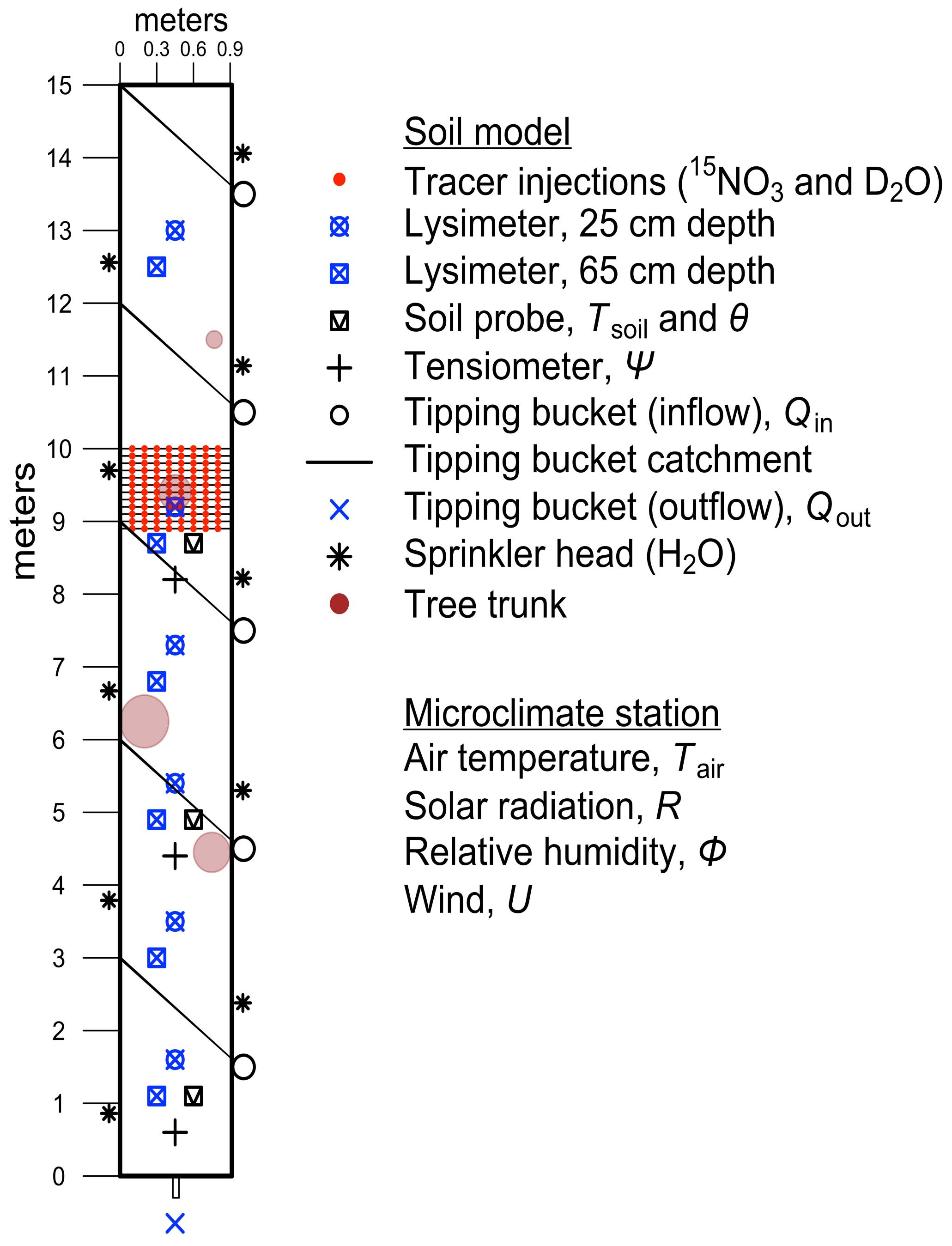
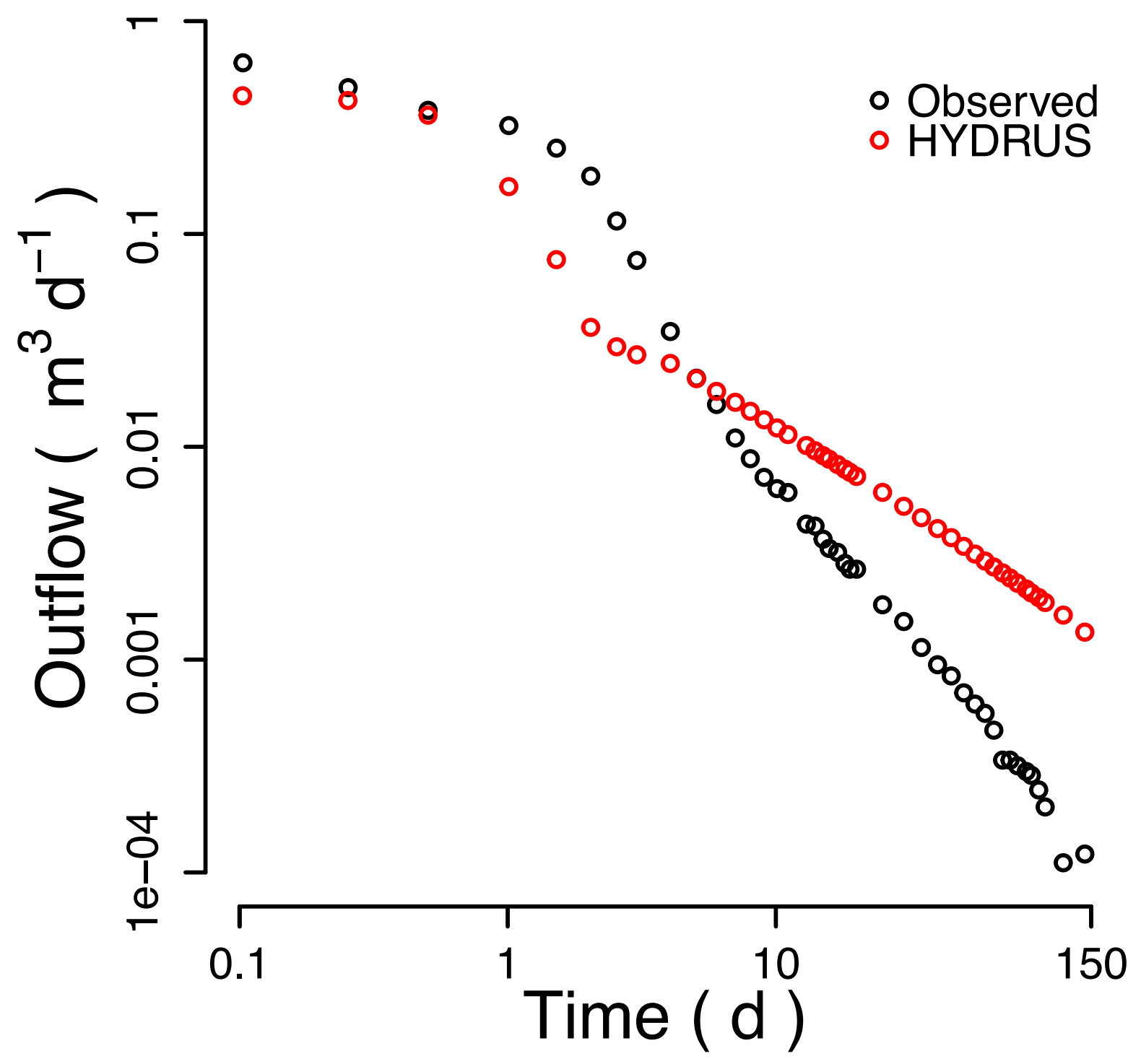


Soil model
- ● Tracer injections ($^{15}NO_3$ and D_2O)
- ☒ Lysimeter, 25 cm depth
- ☒ Lysimeter, 65 cm depth
- ☒ Soil probe, T_{soil} and θ
- \+ Tensiometer, Ψ
- ○ Tipping bucket (inflow), Q_{in}
- — Tipping bucket catchment
- × Tipping bucket (outflow), Q_{out}
- ✳ Sprinkler head (H_2O)
- ● Tree trunk

Microclimate station
- Air temperature, T_{air}
- Solar radiation, R
- Relative humidity, Φ
- Wind, U

Figure 3 (above). Instrumentation and location of the proposed $^{15}NO_3$ tracer injection on the soil model.



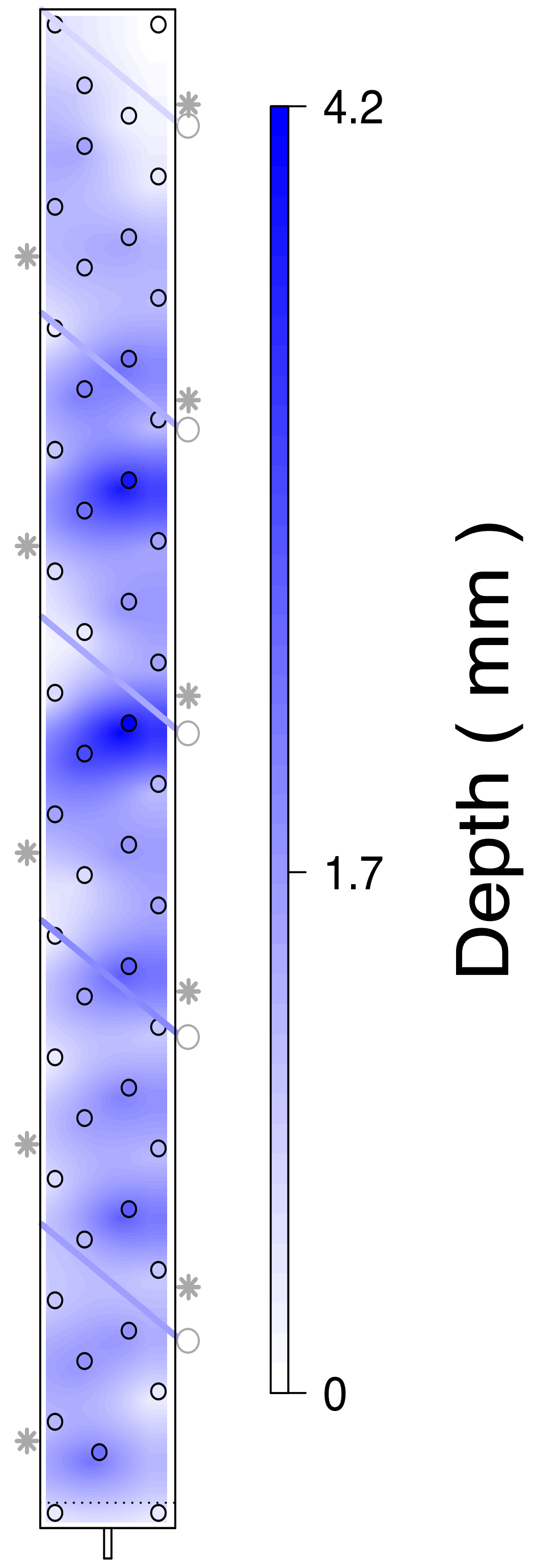


Figure 4 (above). Typical spatial pattern of irrigation. The numbers on the scale bar represent the minimum, maximum, and mean depths of irrigation.

Figure 5 (left). Preliminary results during model calibration from modeling the drainage experiment in Hewlett and Hibbert (1963).

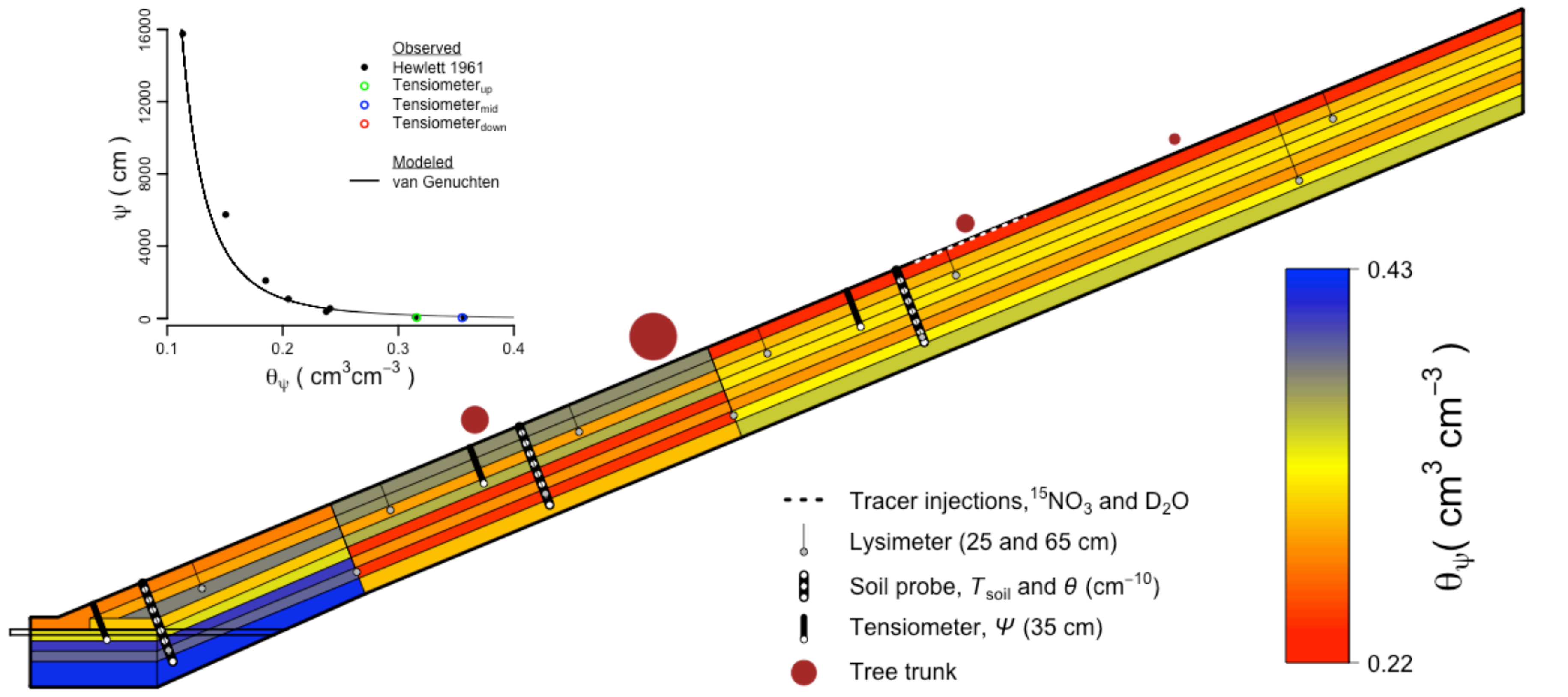


Figure 6 (above). Soil moisture data indicate there may be discontinuities in soil moisture along the hillslope. Tree trunks from trees that were growing in the hillslope over the last five decades are shown for comparison. They may have led to development of macropores and preferential flow networks. Irrigation experiments show there is no leakage due to cracks in the concrete walls or floor.

Figure 7 (below). Inflow, outflow, and soil moisture in three time periods over 3 months as the soil model was irrigated and wetting up to equilibrium. In Periods 1 and 2, the soil model was irrigated twice daily at the same rate. In Period 3, the soil model was irrigated at a much higher rate once daily.