Measurement of Hydrogen Pools at Intermediate Spatial Scales Using Cosmic-Ray Neutron Probes at the T.W. Daniel Experimental Forest Instrumented Research Site

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1. Introduction

- The gap between expanding hydrologic model resolution and conventional point-scale observations continues to widen
- Up-scaling of point measurements to larger scales in order to validate and calibrate hydrological models continues to be a challenge
- Feedback between land surface and atmospheric energy and water fluxes is poorly understood primarily due to lack of quality observations

The COsmic-ray Soil Moisture Observing System (COSMOS)

- Phase I, 2009-2013: NSF funded national network of 50 cosmic-ray neutron sensors to provide real-time soil moisture data, proof of concept stage
- Phase II, 2013-?: Expansion to 500 sensors
- Cosmic-ray sensor measures relative number of fast and thermal neutrons in sensor support volume
- Fast neutrons most strongly related to changes in hydrogen in soil water
- Thermal neutrons thought to be affected by changes in hydrogen from other pools, like snow and canopy water

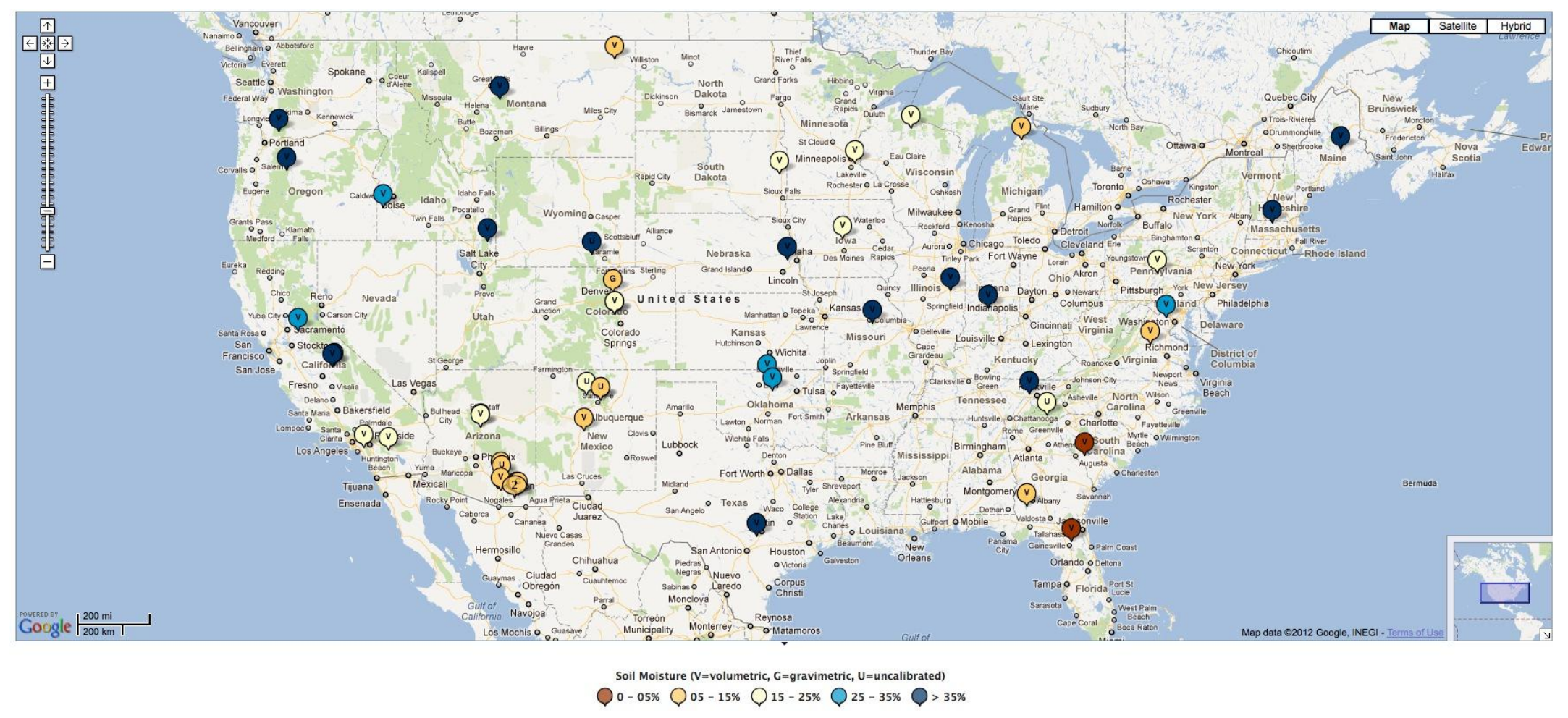
COSMOS Science priorities:

1. Soil moisture controls on weather and climate models, ecological processes, and hydrologic flow processes

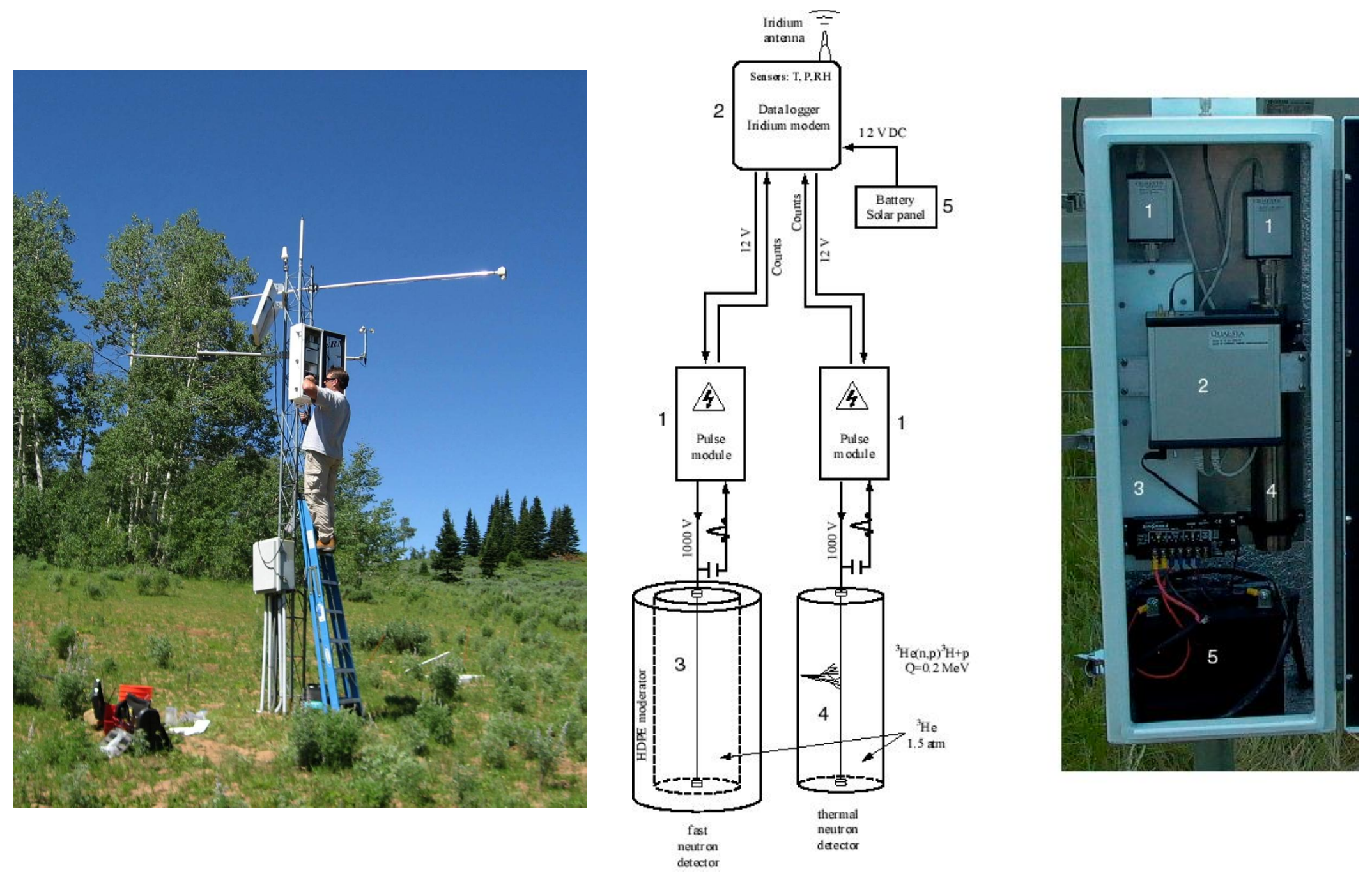
2. Water storage on/in vegetation canopies

3. Frozen precipitation

4. Remote sensing of soil moisture



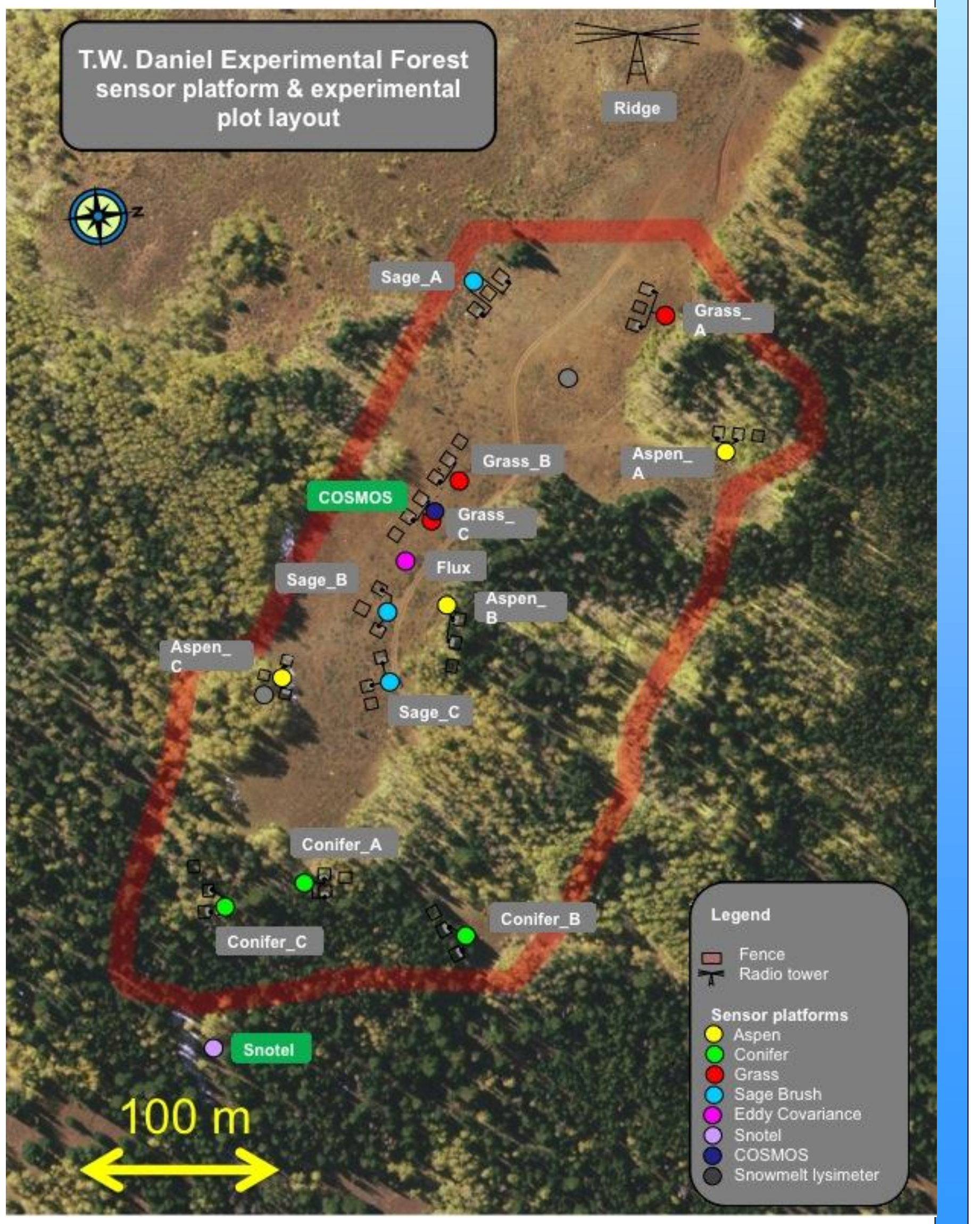
Distribution of deployed cosmic-ray neutron probes in COSMOS network around USA as of 3/19/12. Hourly data available realtime at http://cosmos.hwr.arizona.edu/.



From left to right, photograph of cosmic-ray probe at TW Daniel Experimental Forest (TWDEF) near Logan UT. Schematic diagram and photograph of sensor illustrating how fast and thermal neutrons are detected, stored and transmitted (From Zreda 2012).

2. Research Question

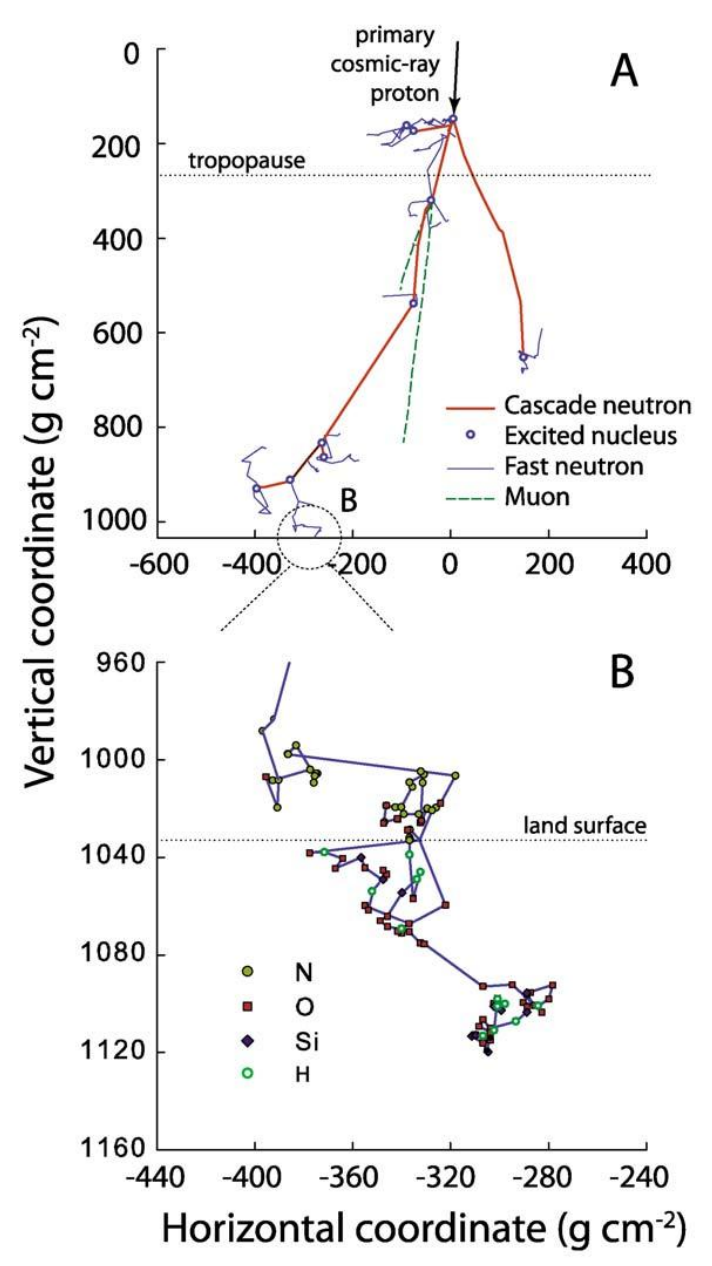
The cosmic-ray neutron probe is sensitive to all pools of hydrogen within the support volume. Multiple H-pools contribute simultaneously from soil, vegetation and snow. Therefore, how can the various H-pools be isolated and distinguished in order to 'sense' soil water relevant to hydrologic applications?



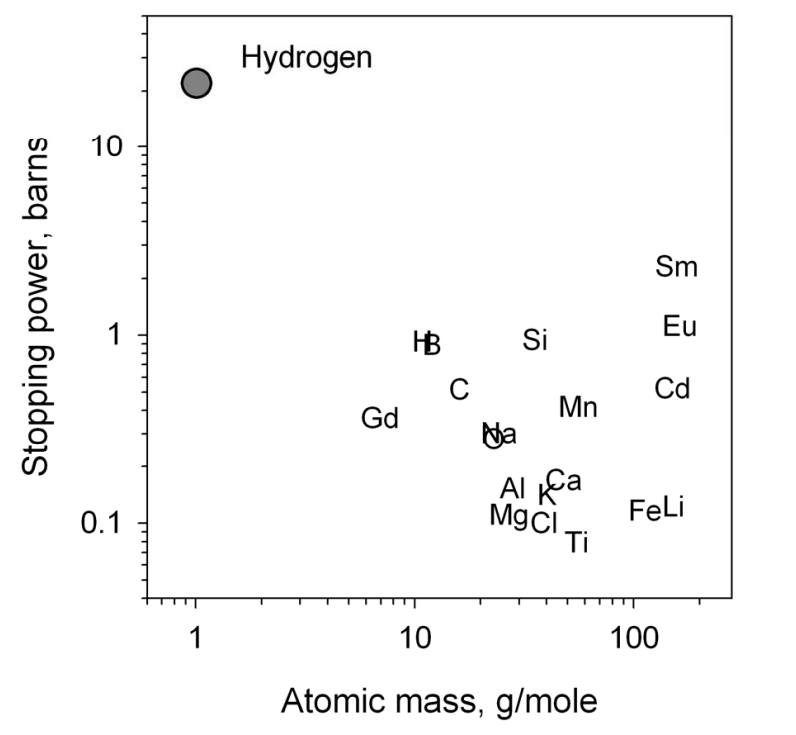
12-triplicate vegetation plots are shown in this TWDEF photo, where soil- and snow- water data are compared to neutron count data. Particle transport modeling is used to determine hypothetical relationships between neutron counts under different snow pack and soil moisture conditions.

3. The Cosmic-ray Neutron Probe

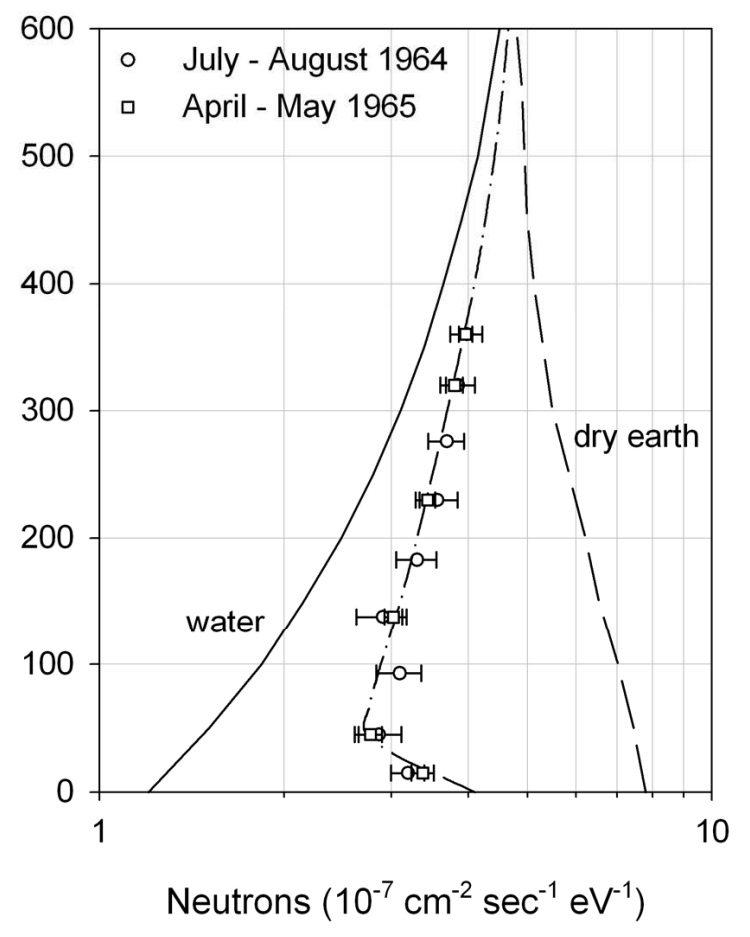
High energy protons from galactic sources cause cascades of secondary neutrons throughout the atmosphere. The secondary neutrons constantly change energy levels through collisions with various atoms, where hydrogen plays a dominant role in the process because of its relatively large stopping power. The sensor works by counting the number of fast and thermal neutrons above the ground surface, with more neutron counts being correlated to drier soil and lower counts to wetter soil. Experiments of neutron detection above the earth's surface indicate the range of influence that dry earth and water have on the relative neutron counts (7:1 ratio). Particle transport modeling indicates that 86% of counted neutrons at a detector originate within a 350 m radius circle and are independent of soil moisture. However, counted neutrons above the surface are highly dependent on the vertical soil moisture profile, with dry conditions having an effective depth 70 cm and fully saturated conditions 12 cm.



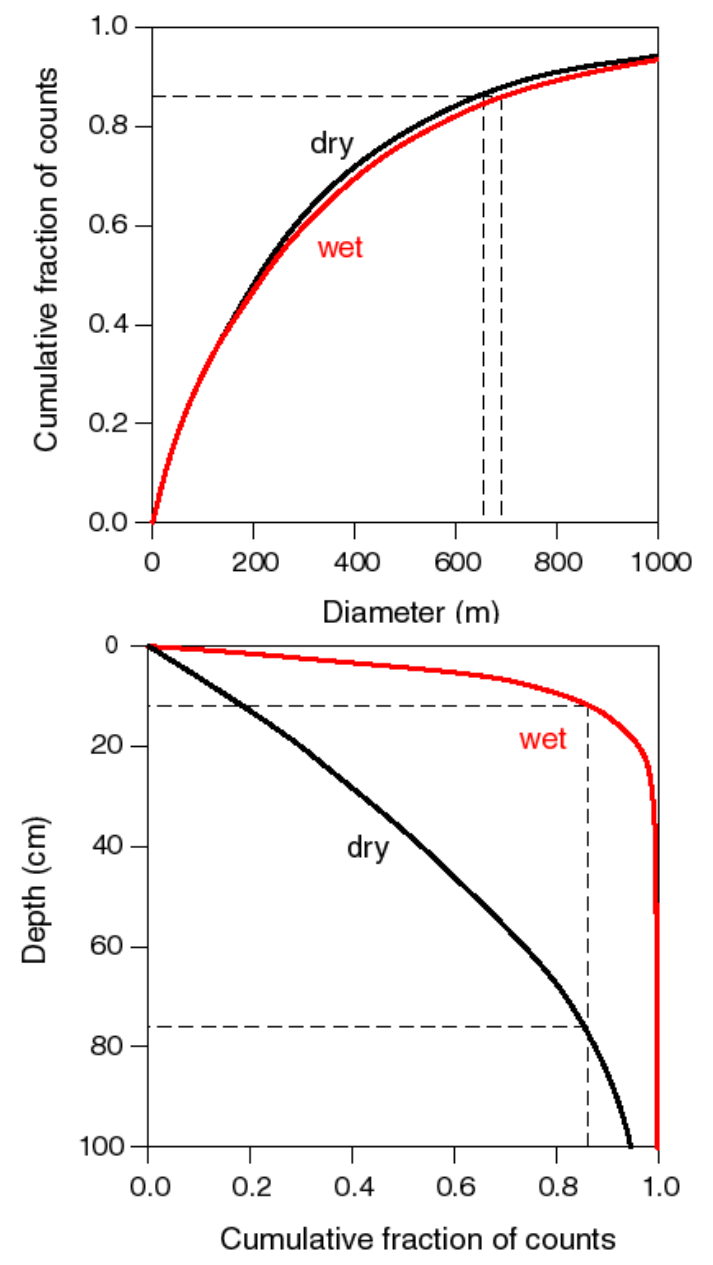
Life history of high energy proton, to secondary neutron cascade, and eventual absorption via inelastic collisions with elements (From Desilets, 2010)



Comparison of stopping power between various elements (From Zreda, 2012)

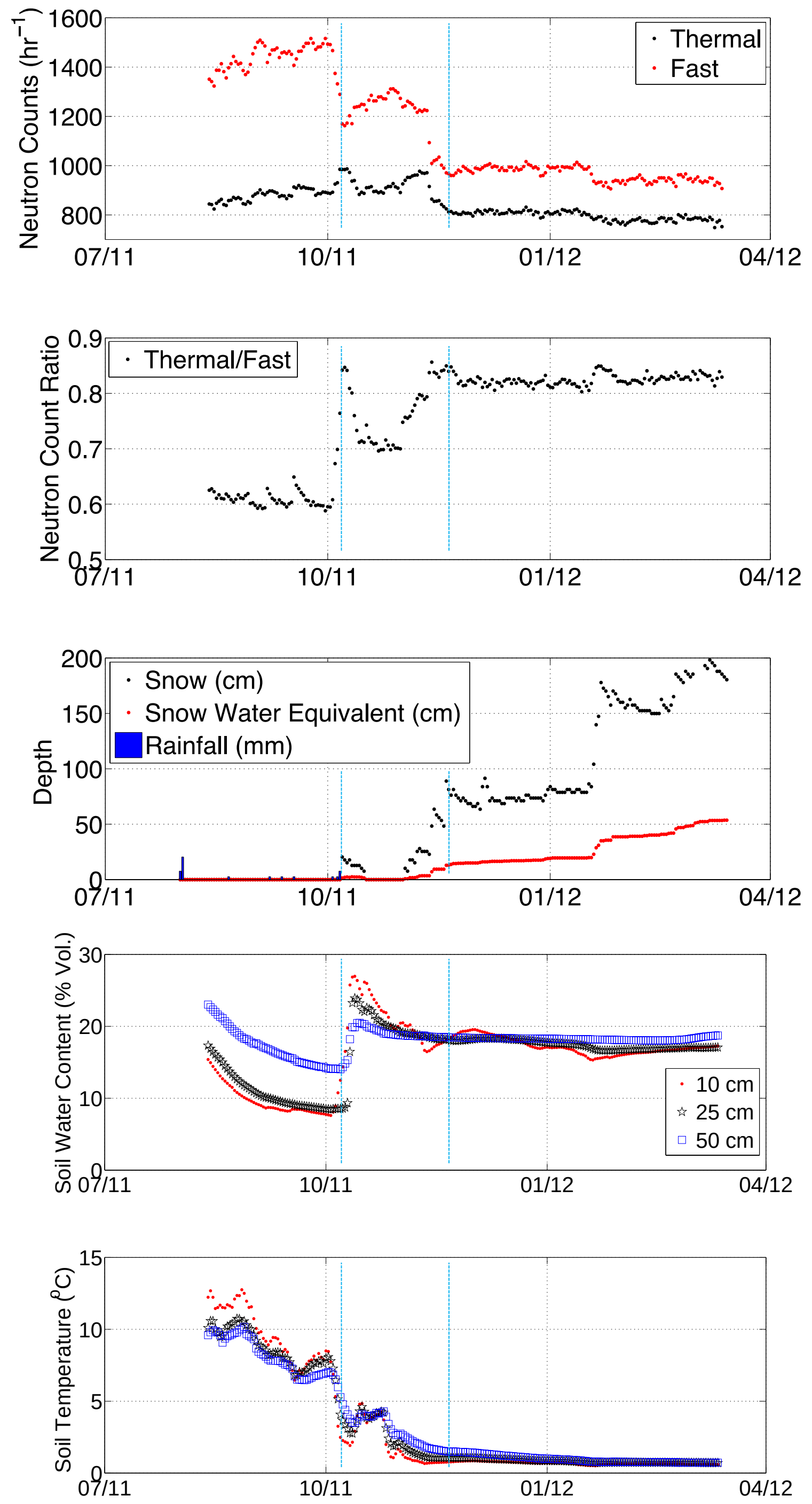


Measurements of neutron intensity above earth's surface and theoretical bounds of dry earth and water (From Hendrick 1966)



Horizontal and vertical footprints determined from particle transport modeling (From Zreda, 2008)

4. Observations



Time series of daily neutron counts, rainfall, snowfall, soil moisture and soil temperature from August 2011 to March 2012.

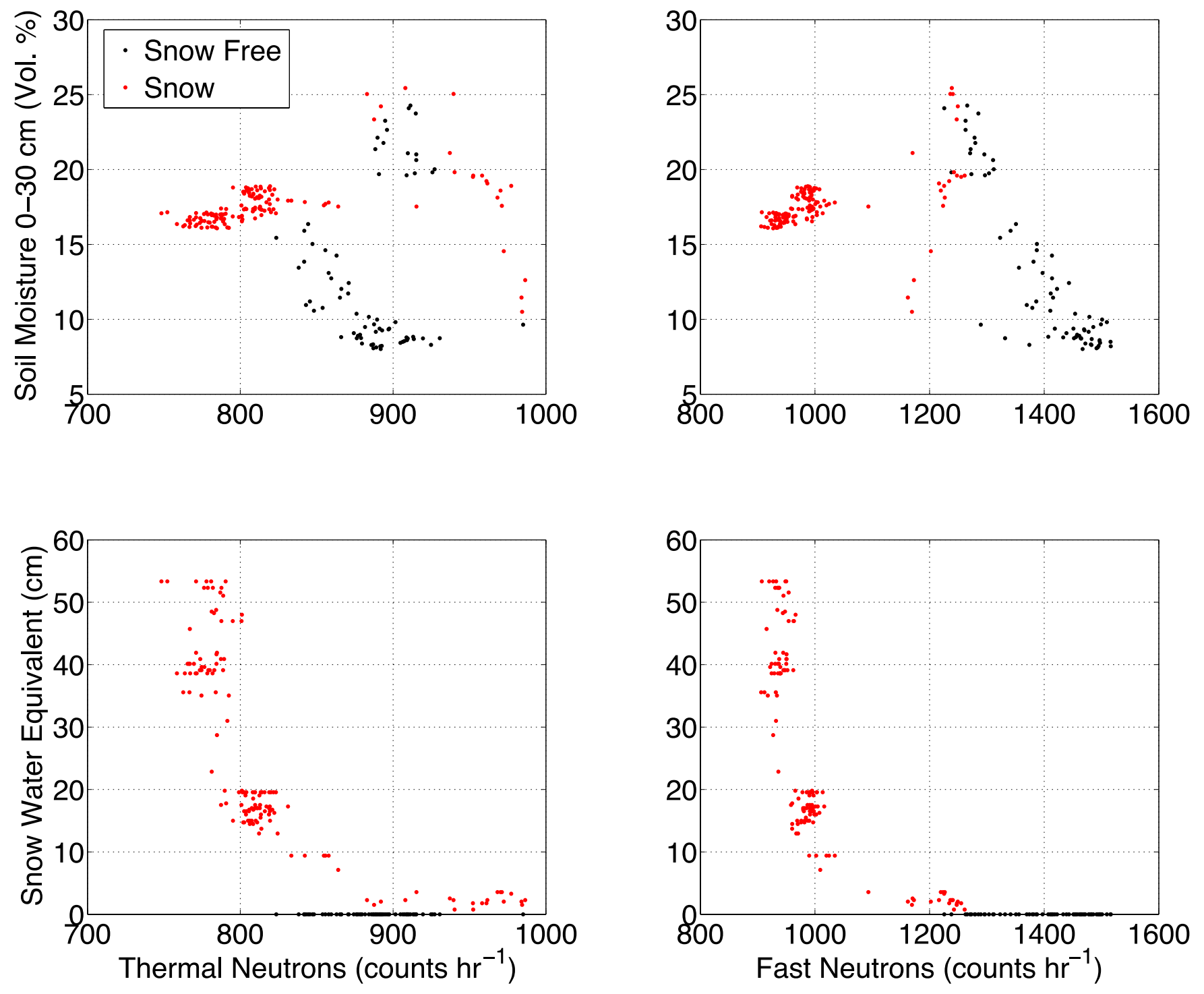
The cosmic-ray neutron probe was installed at TWDEF on August 13, 2011. Here we present the average hourly neutron counts over the day for fast and thermal, daily rainfall, daily snow depth, and daily snow water equivalent from a Snotel site located 300 m from the cosmic-ray sensor. Finally we report the average soil moisture and temperature from 108 TDT sensors distributed around the cosmic-ray footprint in various land types.

Scatter plots of fast and thermal neutrons vs. average soil moisture and SWE illustrate several things:

1)two distinct clusters of points for snow free and snow conditions,

2)thermal neutrons illustrate more hysteric behavior during wetting and drying periods as previously observed (Desilets 2010),

3)thermal neutrons are sensitive to ~25 cm SWE, and fast neutrons are sensitive to ~10 cm SWE.



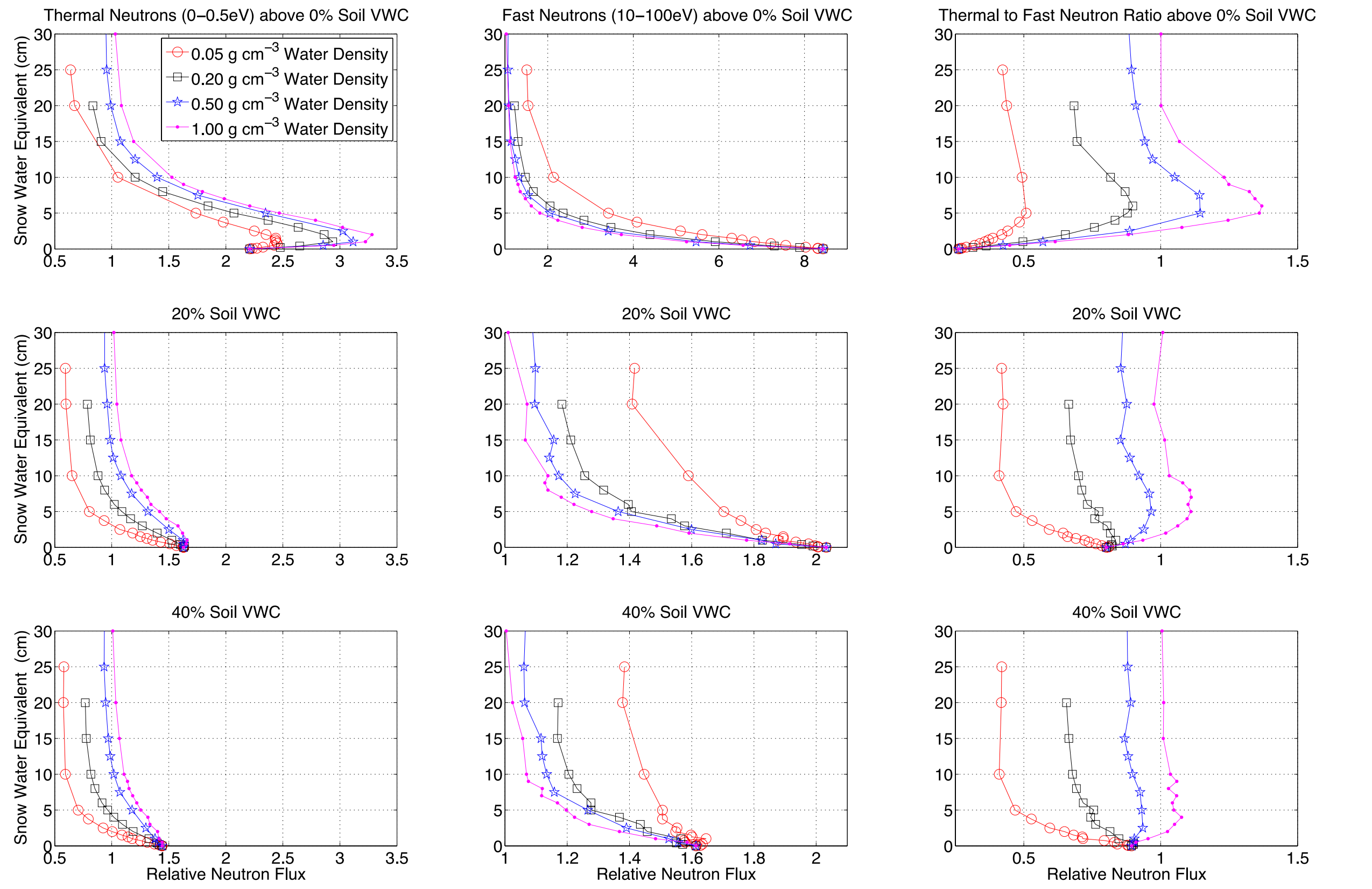
Scatter plots of fast and thermal neutrons vs. soil moisture and snow water equivalent illustrating neutron probe response to changes in hydrogen atoms in both pools.

5. Particle Transport Modeling

Using a general purpose Monte Carlo particle transport code (MCNPx, Pelowitz, 2005) we simulated different snow pack conditions overtopping different soil moisture conditions. For the simulations we setup a sensor 5-6 m above the surface and changed the height and density of the snow. All simulations were performed using vertical homogeneous layers of snow and soil moisture and each simulation was normalized to an infinite layer of liquid water with density 1.

▪Simulations confirm observations of relative neutron sensitivity of ~25 cm SWE for thermal neutrons and ~10 cm SWE for fast neutrons

▪Simulations indicate a dependence of water density on shape of sensitivity function, however, this is **not consistent** with current understanding, as neutrons are thought to respond to only **total mass**. We are currently investigating this inconsistency, but these types of sensitivity functions could ultimately be used to partition soil water, SWE, and snow depth.



Simulation results of fast and thermal neutrons to different snowpacks and underlying soil moisture conditions.

6. Summary and Conclusions

- A cosmic-ray neutron probe was installed in August 2011 at TWDEF, which is part of the COSMOS national network that provides intermediate scale measurements of hydrogen
- Fast and thermal neutron observations from TWDEF illustrate sensitivity to changes in both soil moisture and snow that form distinct clusters of points
- Numerical modeling of particles illustrates theoretical relationships that may be used to partition two pools of hydrogen with simultaneous measurements of thermal and fast neutrons, but more work is needed to validate numerical sensitivity functions

7. Future Work

- Currently only 1 site is used to represent snow depth and snow water equivalent. Additional snow data should be used to identify average conditions over the footprint, in particular during highly heterogeneous melting periods
- The discrepancy in neutron modeling and observations may be due to changes in canopy storage, which is less understood in both neutron modeling and observations at the site

8. References

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9. Acknowledgments

The COSMOS project is funded by the Atmospheric Science, Hydrology, and Ecology Programs of the US National Science Foundation (grant ATM-0838491). T Franz and M Zreda would like to thank D. Desilets of Sandia National Laboratories for his contributions to this work.