Application of cosmic-ray probes to long-term monitoring of soil moisture: A new tool for assessing sustainable agropastoralism in drylands

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With acknowledgements to:
K. Caylor, K. Soderberg, M. O'Connor, R. Rosolem, W.J. Shuttleworth, X. Zeng, S. Stillman, T. Ferre, C. Zweck, B. Chrisman, D. Desilets, G. Womack

NSF, Hydroinnova, Questa Instruments

Dryland facts

Cover ~41% of Earth's land surface containing 38% of global population (Reynolds 2007)

By 2020 IPCC predicts increase in water stress from 75m to 250m people in Africa due to climate change (2007 IPCC)

In sub-Saharan Africa 80m reliant on agriculture (either crop or domestic animals) (Reynolds 2007)

60% of Sub-Saharan Africa is pastoral or agropastoral land (Robinson 2011)

80m rural smallholders practicing livestock-based or mixed livestock-crop-based agriculture (Robinson 2011)

Regions have some of the highest levels of poverty and food insecurity in the world and vulnerable to climate change (Thornton 2002, and Thomas 2005)

70% of African pastoral/agropastoral areas are drylands where PET 200% more than rainfall, here small holders rely almost **entirely** on livestock husbandry (Notenbaert 2009)

Two great challenges: dryland productivity
food security

Compounding factors:

1. Population growth: there are more lives depending on each hectare (Notenbaert 2009).

2. *Land conversion*: usually to cropping, this leaves fewer hectares available (Herrero 2009) and potentially greater dependence on groundwater supplies.

3. *Legacy of land degradation*: today the same hectare produces less forage (Dregne 2002).

4. *Increasingly unpredictable climate*: results in fewer productive hectares per year, and is expected to reduce viable pastoral areas by 20% in 40 years (Falkenmark 2008, Thornton 2006).

Productivity issues

The **diminishing supply of resources** for livestock-based agriculture is what is crippling the system's productivity and increasing people's vulnerability (Thornton et al. 2006, Andersson et al. 2011)

Need for basic understanding of system and to address **supply** side of problem

In agriculture, this is being addressed in "Blue Revolution", where research in drought tolerance genetics and water conservation practices aim to deliver "more crop per drop" and improve water use efficiency

However, this is at the scale of a single plant, pastoralism occurs at the landscape scale and additional complexities must be taken into account that dominant system behavior and response!

Complexities of dryland ecosystems

The overwhelming importance of spatiotemporal heterogeneity: Patchy vegetation structure and variable, pulse-like arrival of the key limiting resource, water (Ryan 2007)

Feedbacks: Plant communities have strong feedbacks on environmental conditions and their own subsequent performance (Rietkerk 2004).

Impacts at larger spatial scales: Areas of enhanced forage productivity do not translate directly or linearly into food and economic benefits for humans. Livestock are intermediate consumers, the "middlemen," and their success depends on spatial extent and patterns of resource availability (Ayantunde 2008).

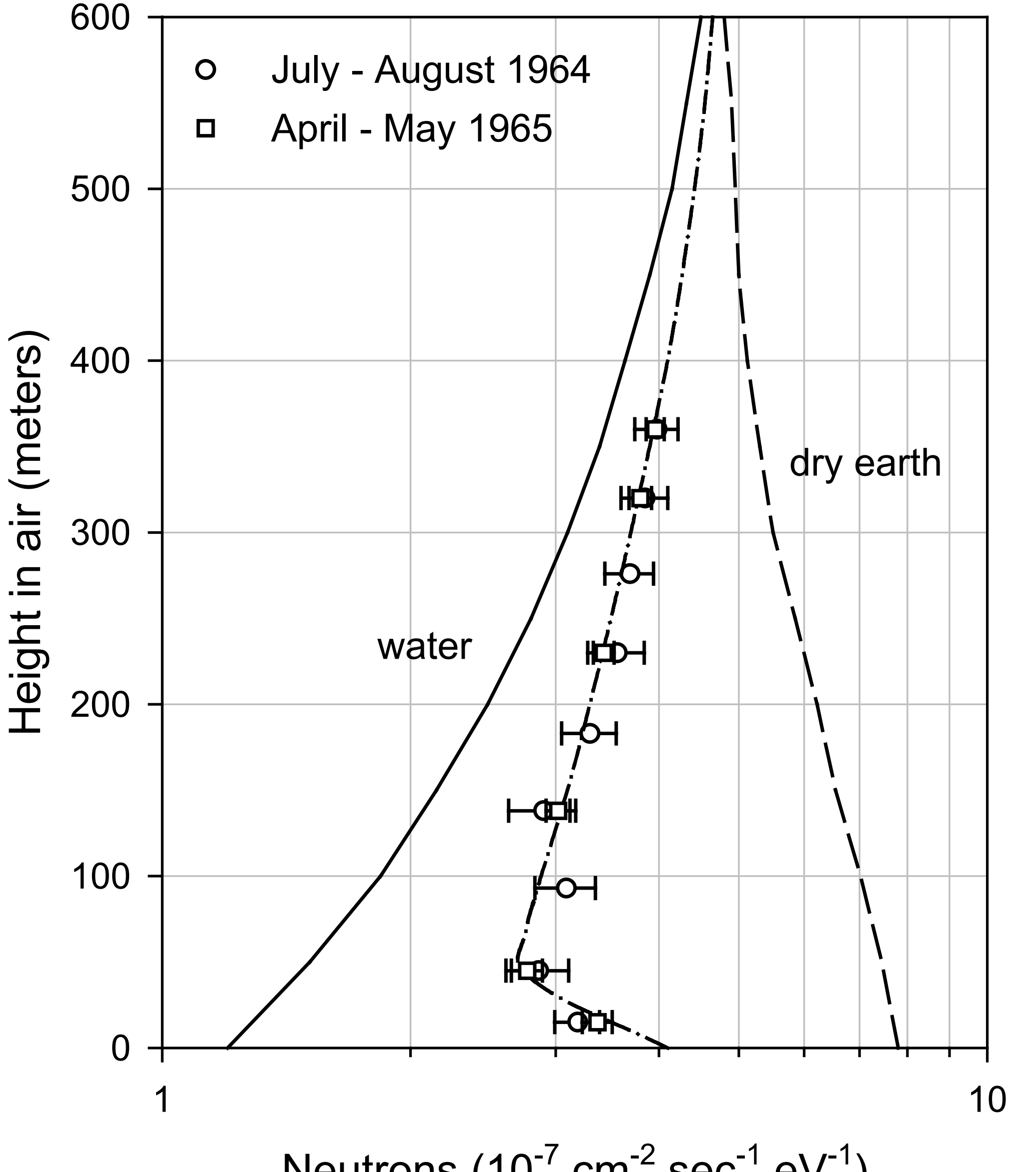
Scale of physics: Water distribution, infiltration, evaporation, and transpiration range from the 10^0 to 10^1 m scales, heterogeneous vegetation organization occurs from 10^1 to 10^2 m scales, and humans and livestock utilize and impact the landscape at 10^2 to 10^4 m scales (Ludwig 2000).

Cosmic-ray soil moisture probe in dryland agropastoralism

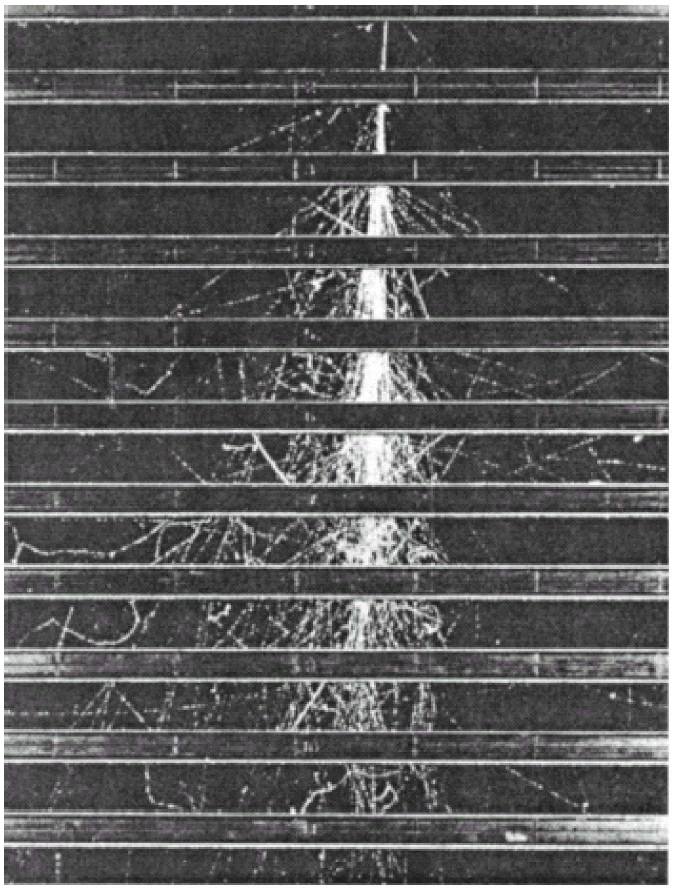
Introduce new landscape scale measurement tool, the **cosmic-ray neutron probe**, to help understand key water fluxes in patchy landscapes

Present case study of **land use change** in central Kenyan dryland

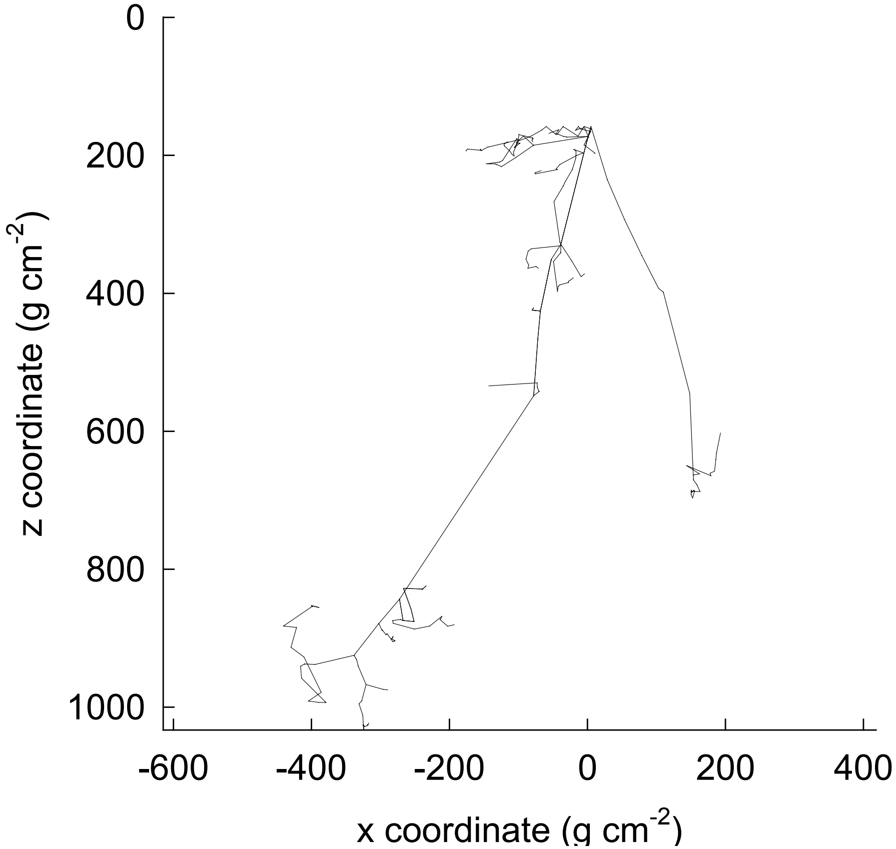
Propose future **observational studies** to help assess sustainable agropastoralism land use practices



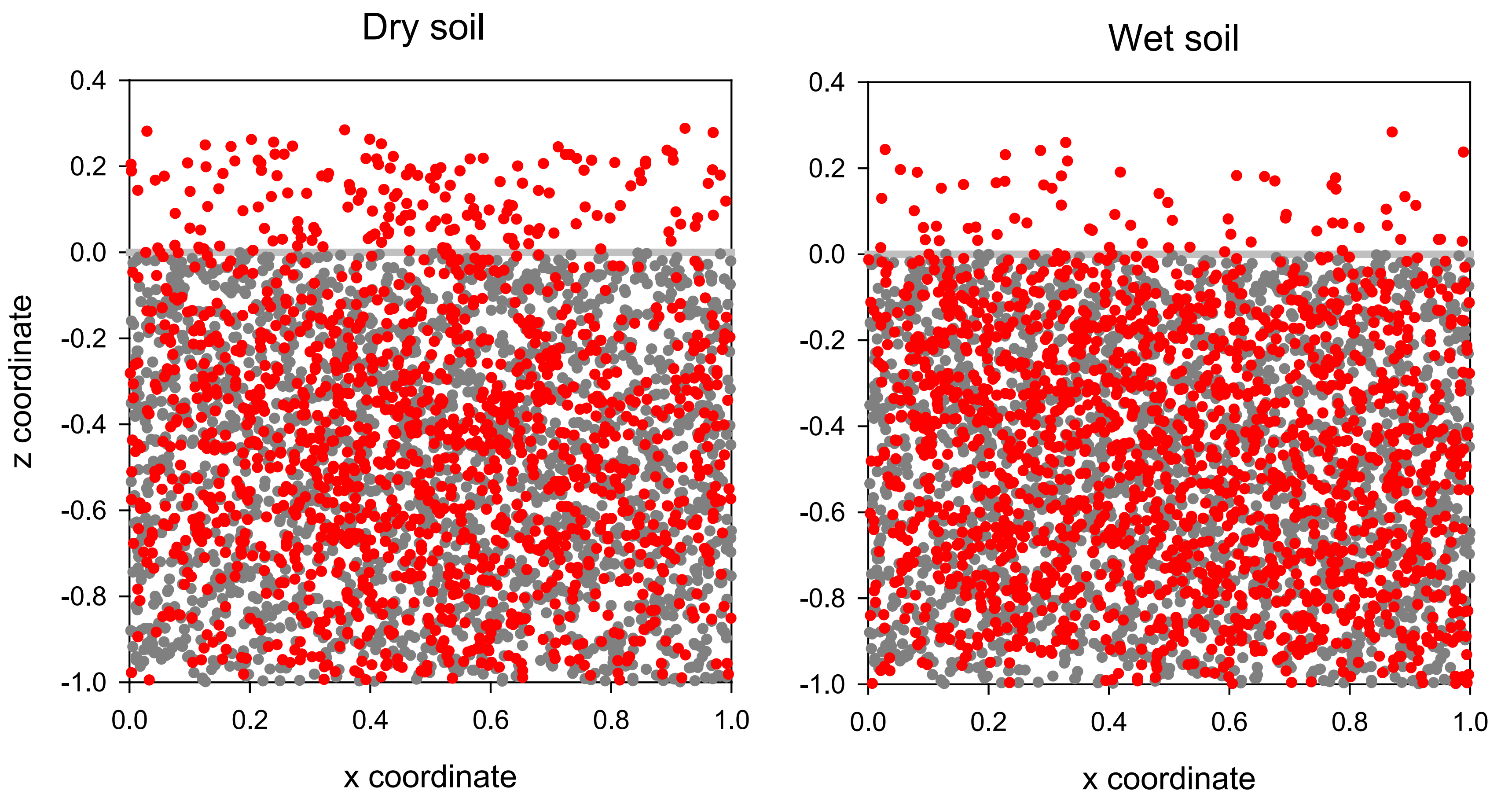
Hendrick, 1966



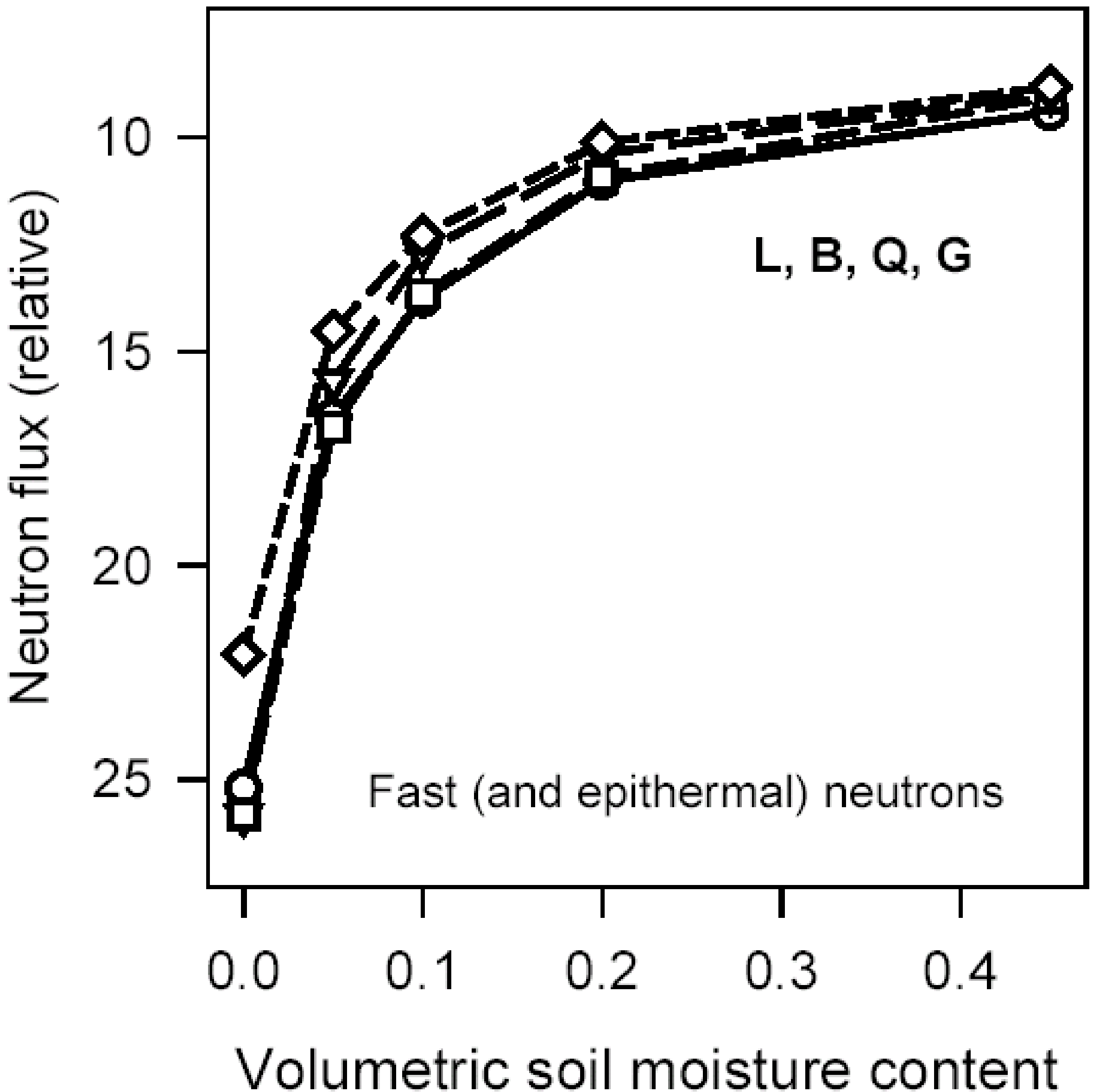
Secondary cosmic-ray particles produced in copper plates in a large cloud chamber. Skobeltzyn, 1927



Cascade initiated by a 10 GeV primary. All trajectories above 1 MeV are shown. (Simulations courtesy of D. Desilets, Sandia National Laboratories)

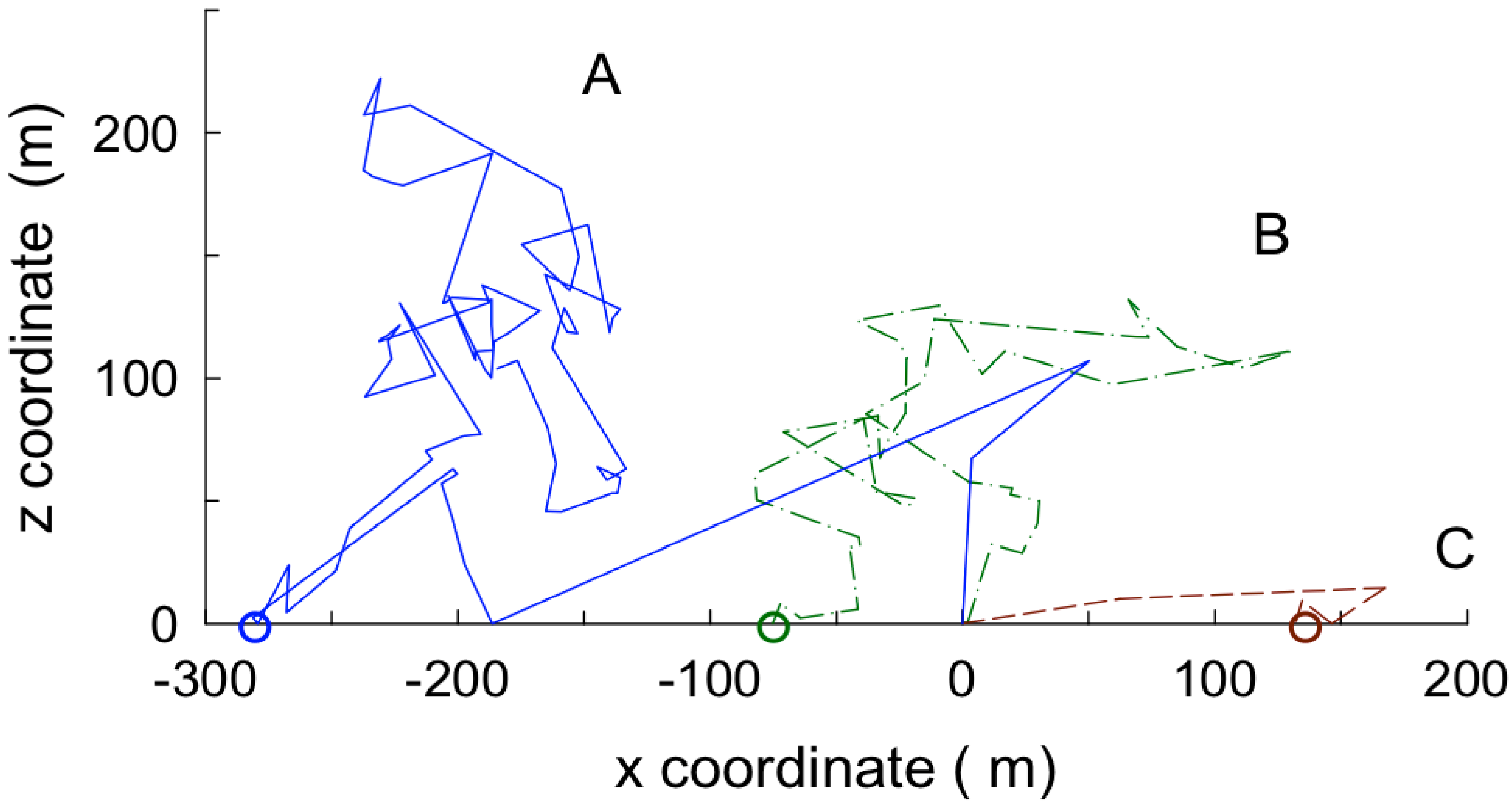


Dry soil
Wet soil
z coordinate
x coordinate
x coordinate
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
0.0
0.2
0.4
0.6
0.8
1.0

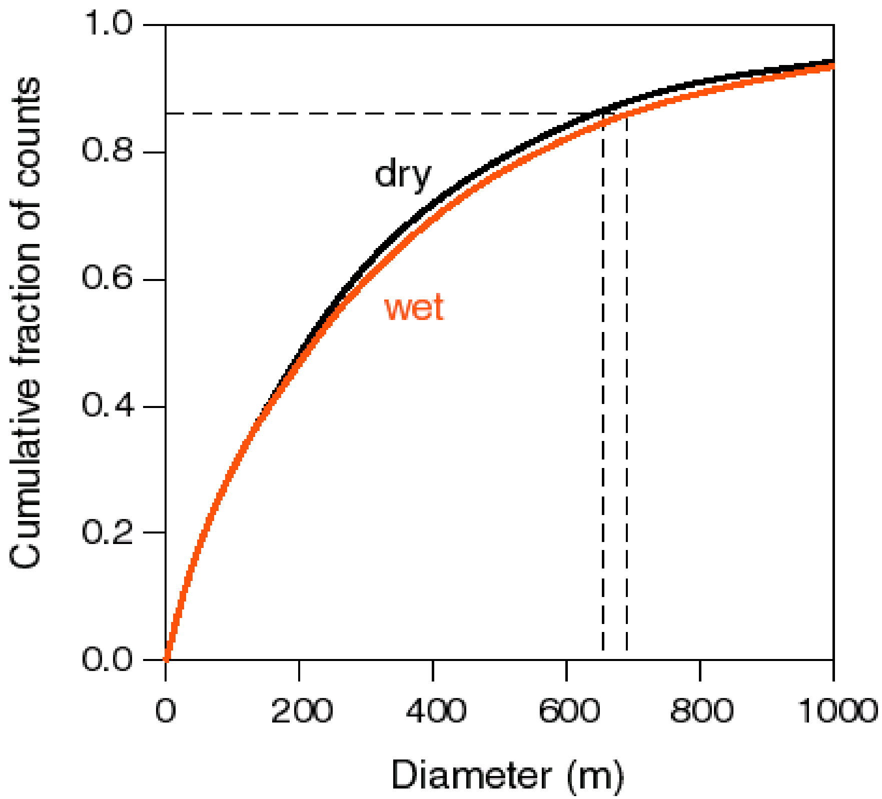


L, B, Q, G
Fast (and epithermal) neutrons
Neutron flux (relative)
10
15
20
25
0.0
0.1
0.2
0.3
0.4
Volumetric soil moisture content

Zreda 2008

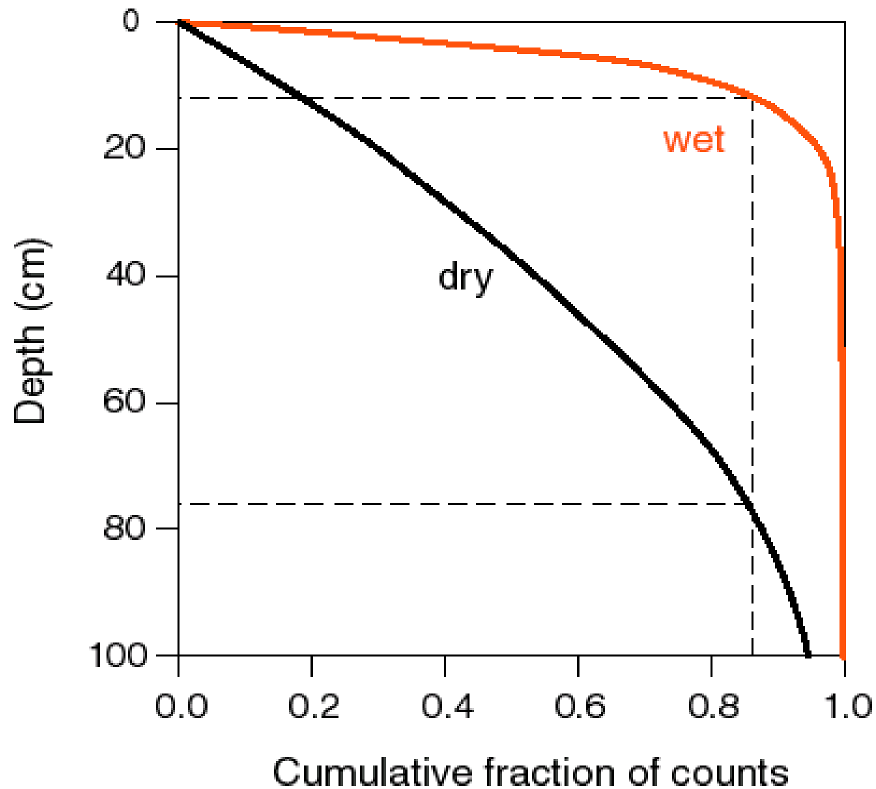


Desilets, 2011



86% of neutrons from within 335 m radius in dry air at sea level

Increases with increasing altitude (decreasing pressure)



86% of neutrons from within a depth of 70 cm (dry)

Depth decreases to 12 cm in wet soils

Independent of altitude (and pressure)

Zreda, 2008

Low cost, low power, robust, realtime data transmission, relatively inexpensive ($15k), well developed scientific principles, large support volume (although moving vertical boundary) (Zreda 2008, Desilets 2010)

~80% of Kenya is arid or semi-arid

Low, variable rainfall

Traditional pastoralist social-ecological systems

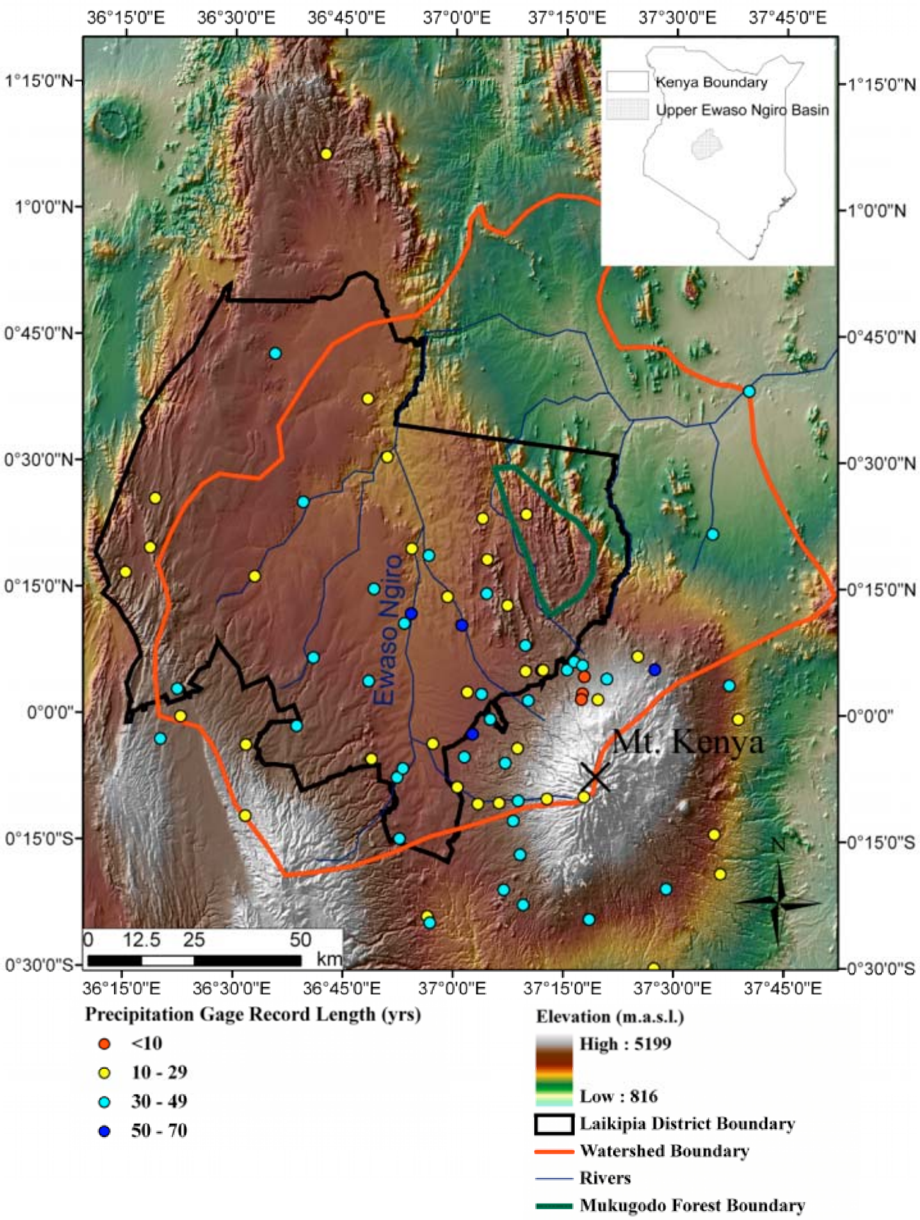
↑ Human & livestock populations

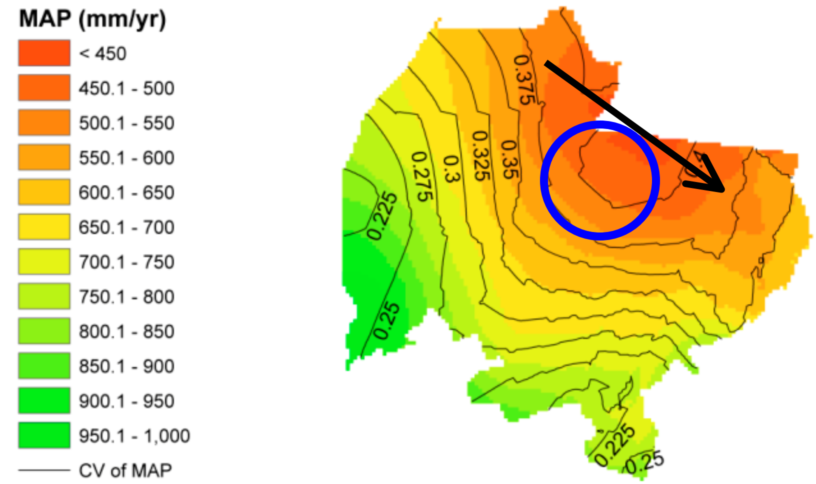
↓ Mobility

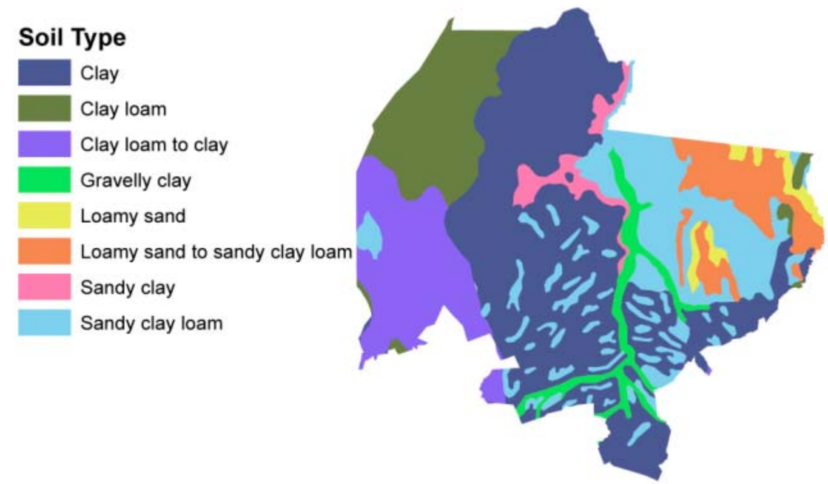
Ecosystem Change

Photo: July 2006 during 18 month drought

Field site: Kenya







(Franz 2010)

Political boundaries and land use

Kenya Independence 1963

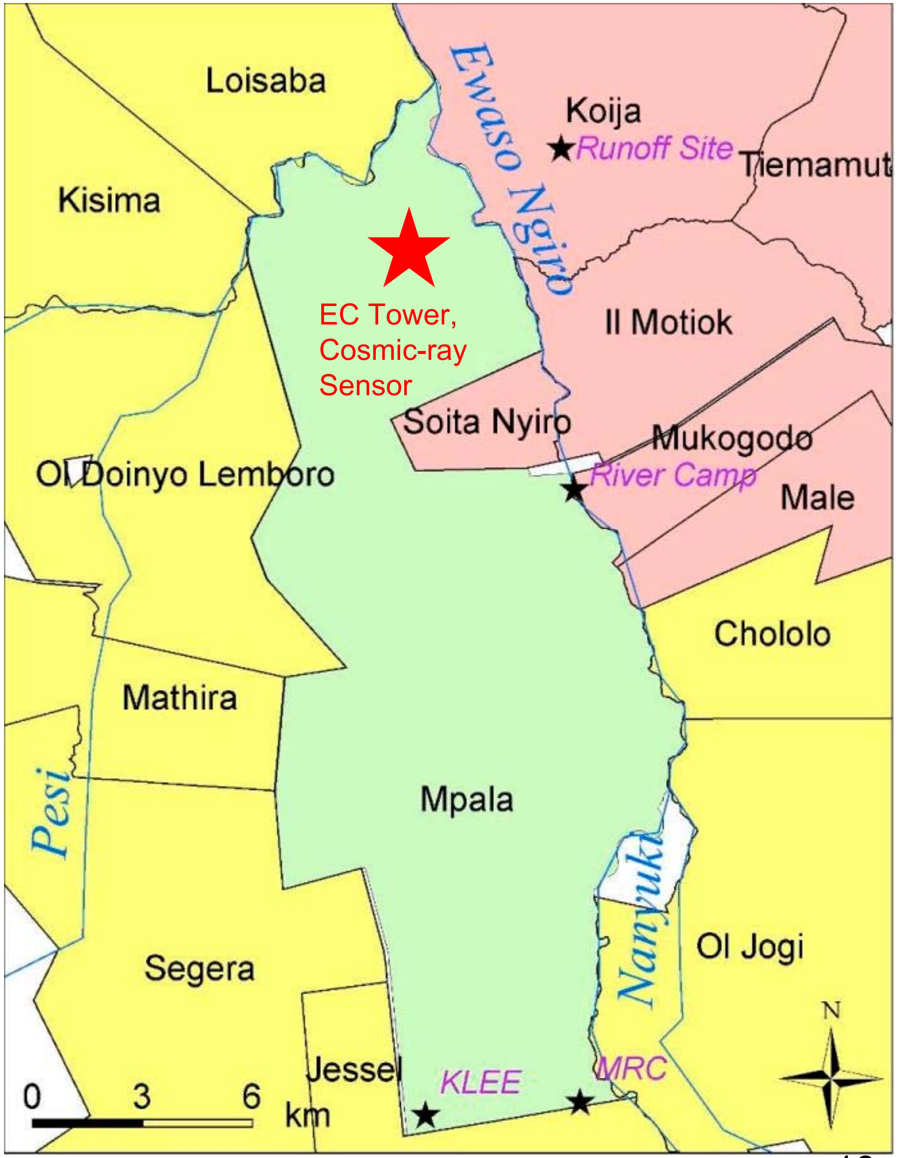
Land Groups Act of 1968: Group Ranches

- Registration of permanent members
- Allocation of grazing quotas
- Group ranch committee

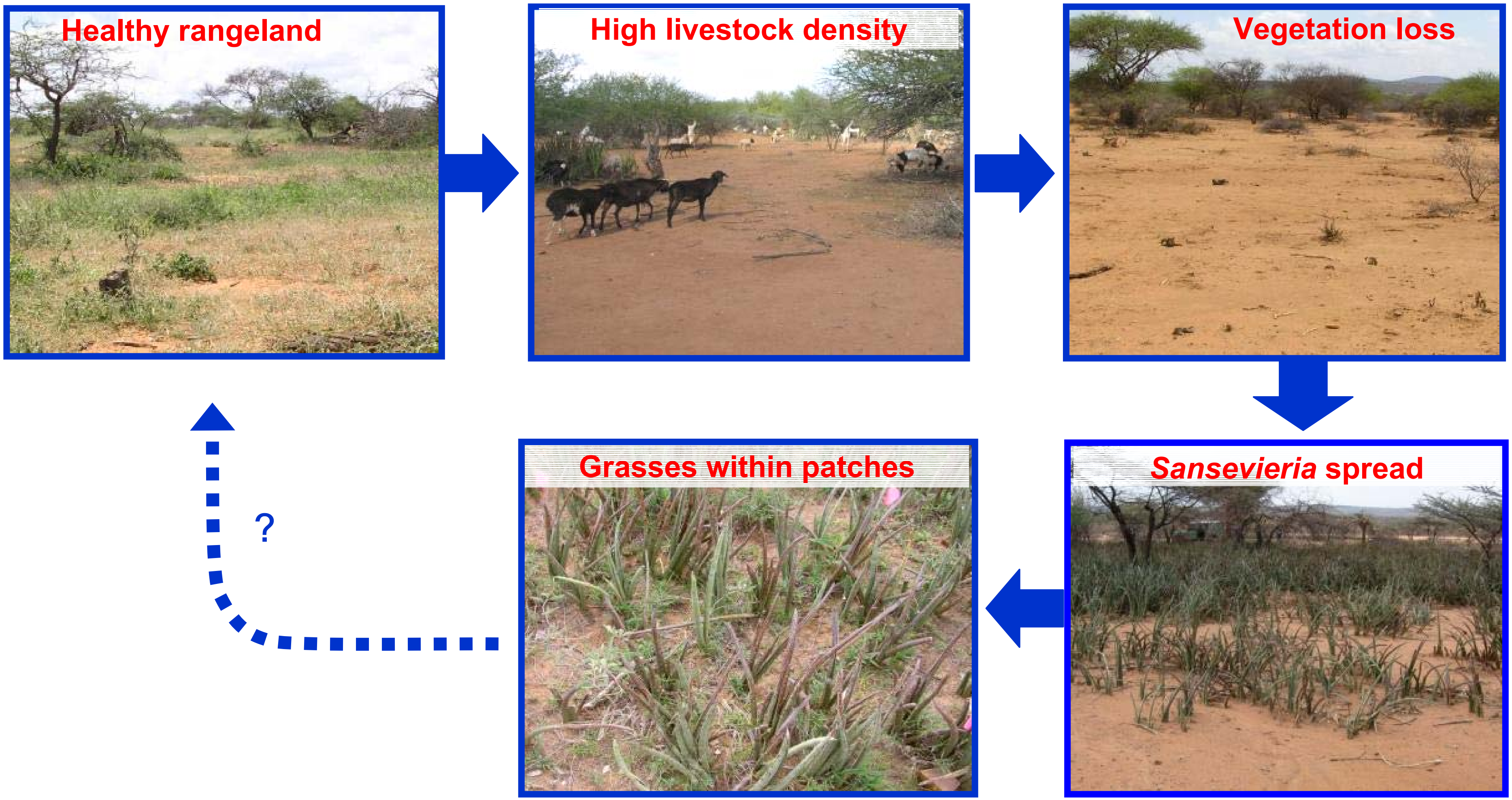
Fundamental Change in Semi-Nomadic Lifestyle

- Dramatic population and livestock growth
- Serious land degradation from overgrazing
- Replacement of tree-grass savanna with bare soil and undesirable succulent in last 2-3 decades

(Mwangi 2003, 2007 and King 2010)



The cycle of land degradation



(King *et al.* 2012)


Beginning in 2011, local communities started using river water and ground water to grow maize

Sustainability issues:
- conflicts with downstream neighbors
- may increase drought vulnerability

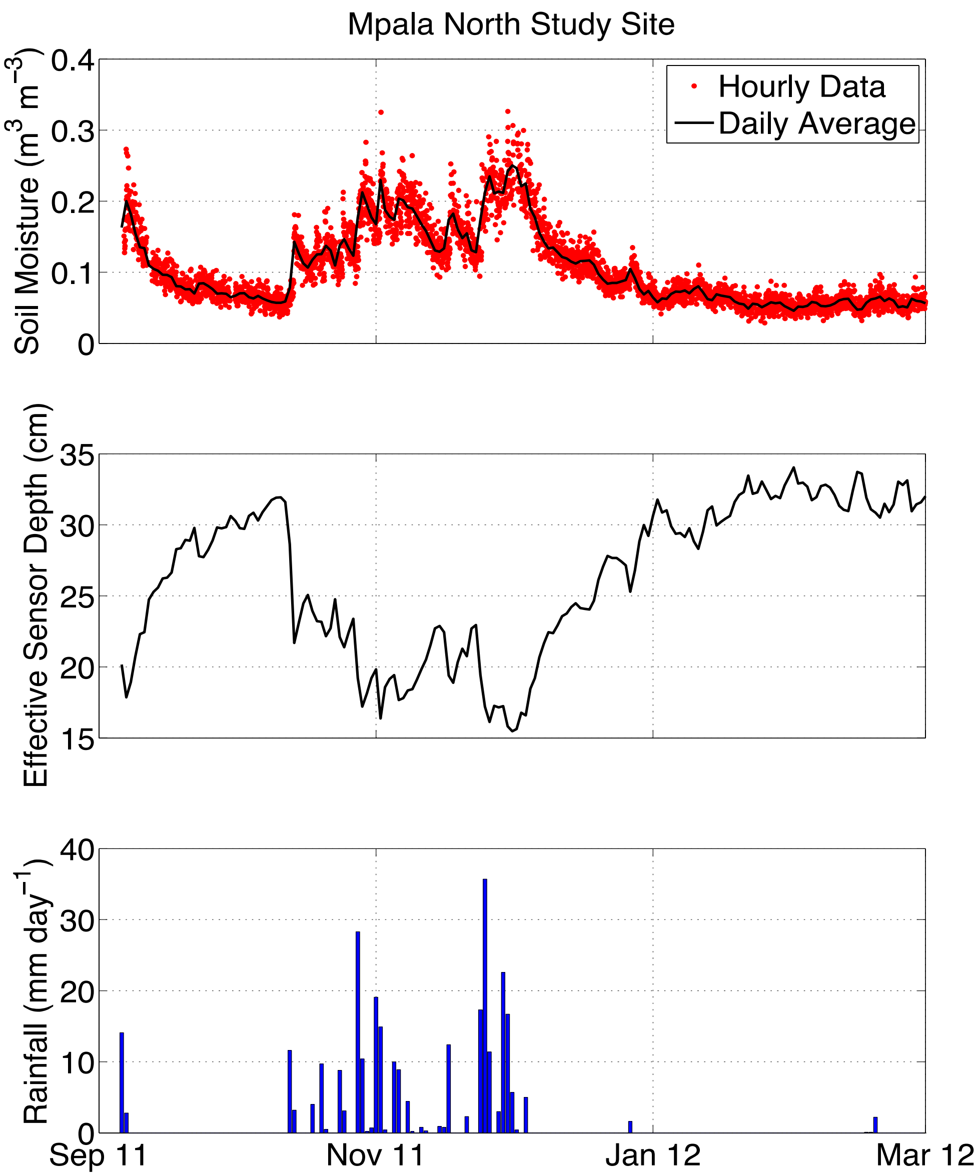
Observational study

Objective:

To quantify water, energy, and carbon fluxes and understand important ecosystem properties, like effective landscape infiltration and water use

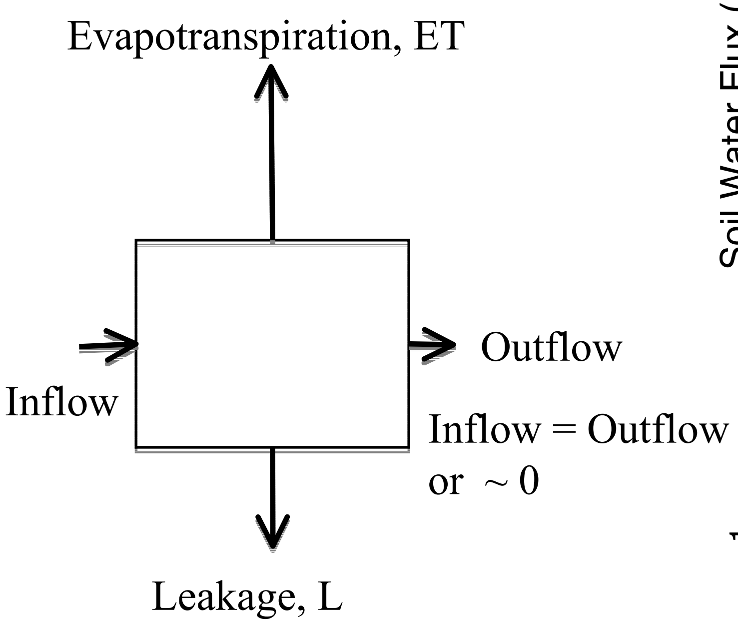
Methods:

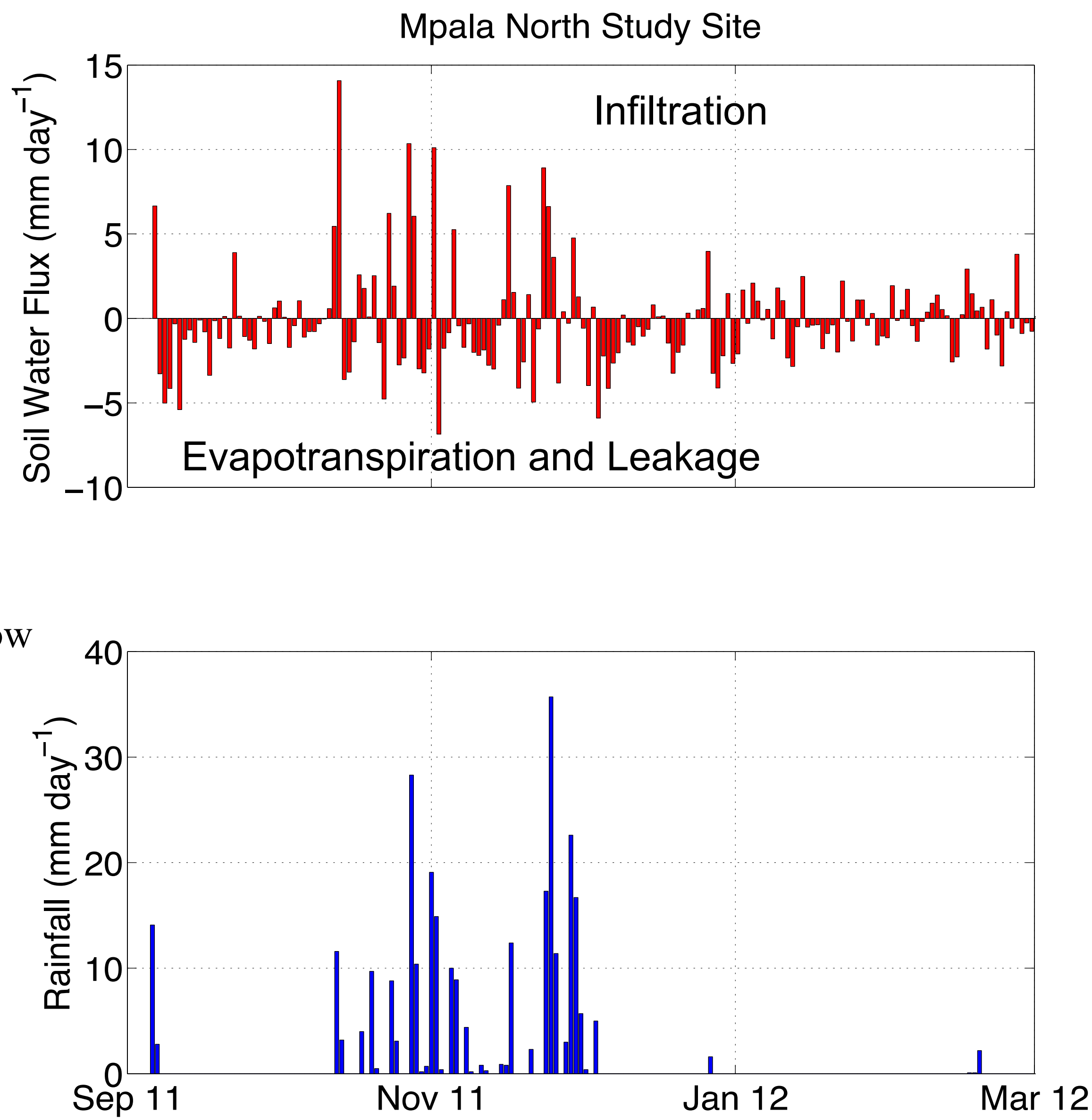
20 m tall **EC tower**, installed in 2009, Princeton University
Cosmic-ray neutron probe, installed in 2011, University of Arizona

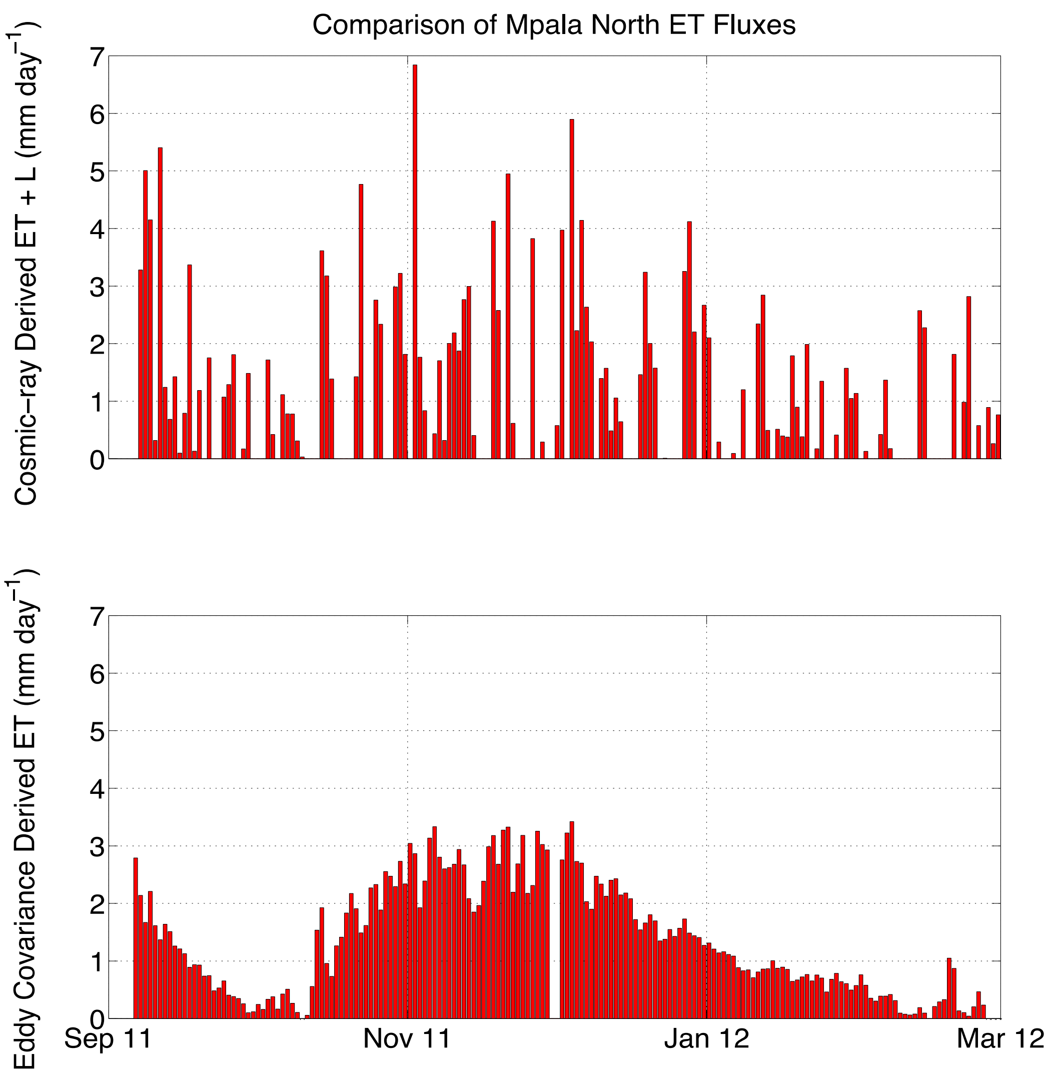


Need 1 calibration dataset of volumetric soil moisture to convert neutron counts to soil moisture content (Desilets 2010)

Cosmic-ray neutron Probe Control Volume, ~350 m radius cylinder and 25 cm depth

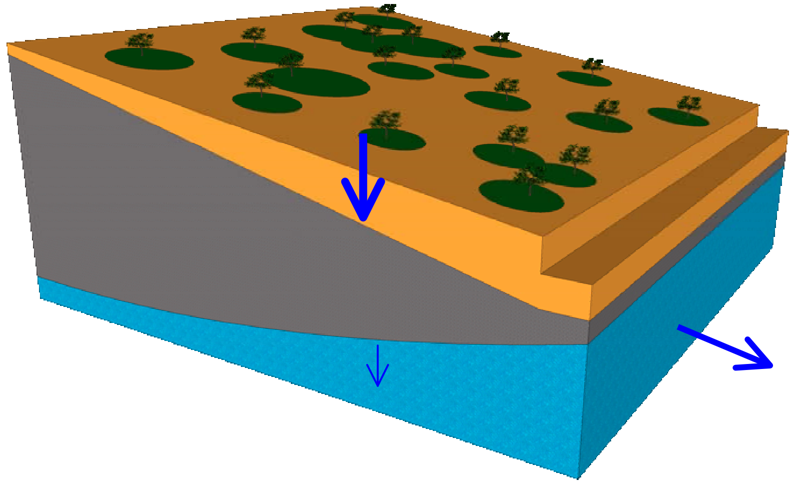




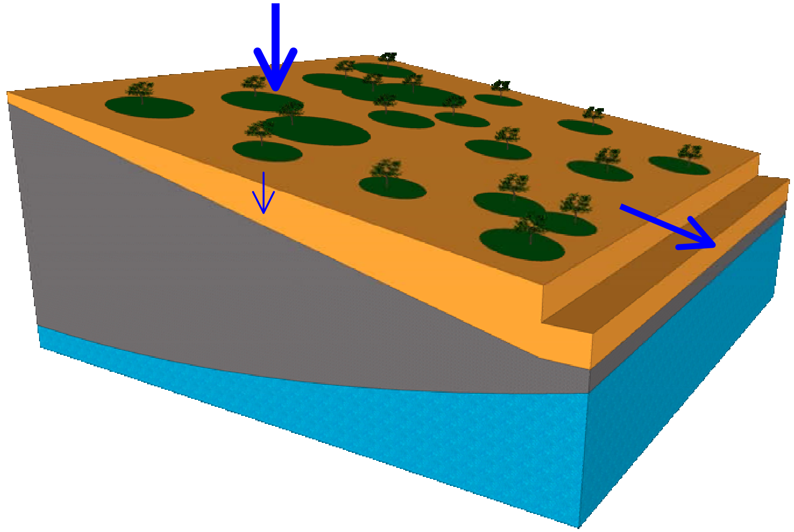


- Same dynamics despite differences in measurement physics
- Need additional filtering techniques to smooth neutron data and subsequent fluxes
- Need water balance model to partition ET and L
- Promising results to quantify ET and L in landscape
- Potential for mobile and remote sensing applications

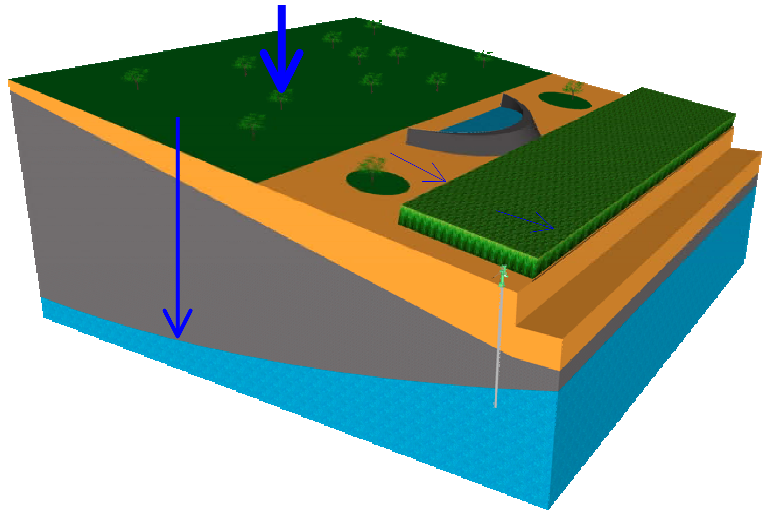
Historical landscape, high runoff and minimal deep infiltration for recharge



Historical landscape, high runoff and minimal deep infiltration for recharge



Modified landscape, capture runoff to irrigate crops, and plant grass to maximize deep infiltration and minimize vulnerability by setting up dual agropastoral land use



Need a suite of tools to show **experimentally** to scientists, government, and local community leaders, that land use intensification is sustainable in terms of overall water use and that it will reduce total vulnerability by diversifying food sources

Cosmic-ray neutron sensor has the potential to provide valuable dataset at the landscape scale to evaluate different land use practices and identify most suitable method for maximizing infiltration and deep drainage

Datasets would also be extremely valuable in irrigation systems where water schedules could be quantitatively determined and regulated to minimize overall water use

Questions?

For more information about the cosmic-ray neutron probe see the COSMOS web site:
http://cosmos.hwr.arizona.edu/