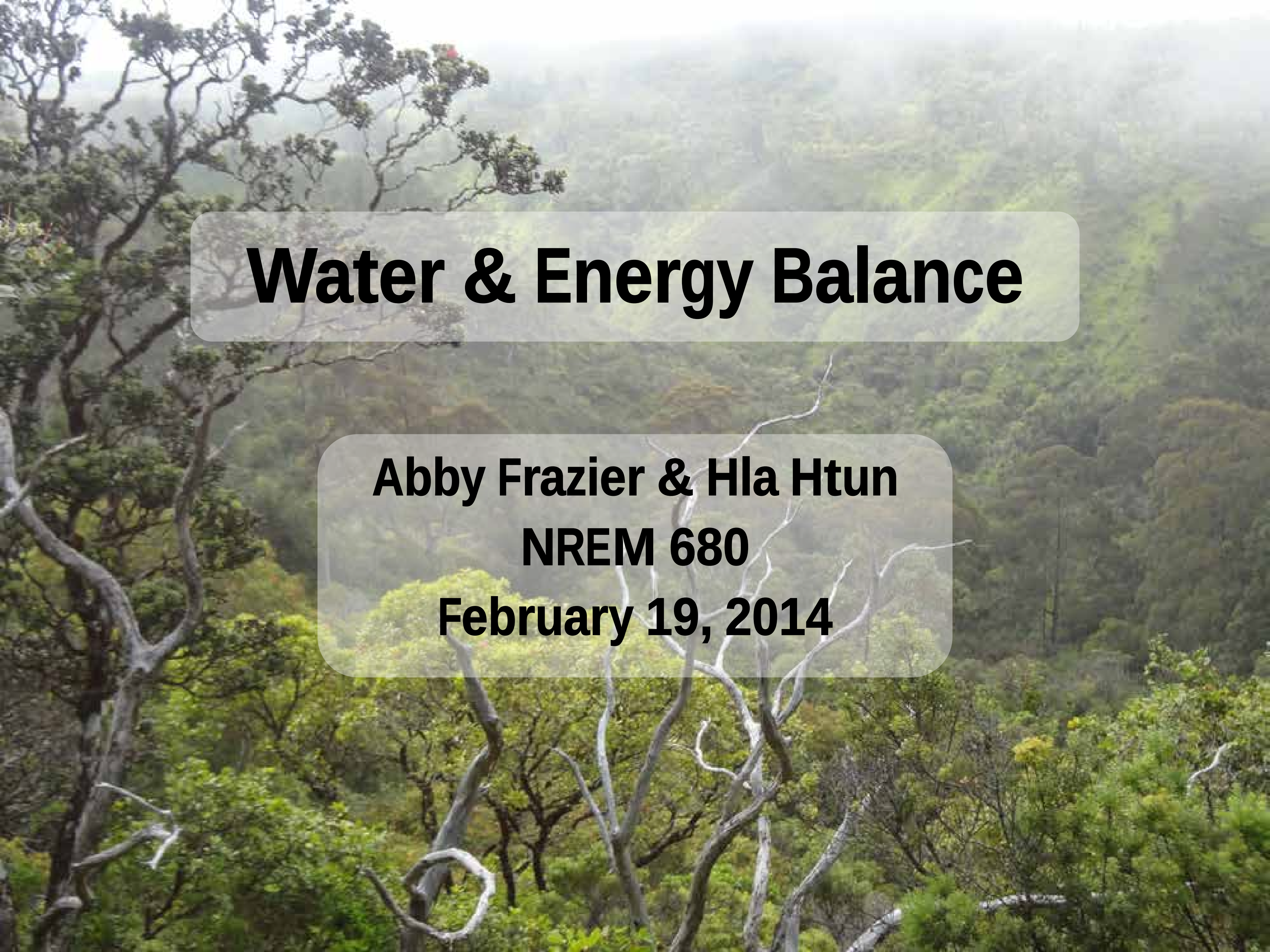


Water & Energy Balance

Abby Frazier & Hla Htun

NREM 680

February 19, 2014

Outline

- Energy Balance Basics & Methods
- Water Balance Basics & Methods
- Paper – Hydraulic Redistribution
- More HR Literature

Global Radiation Budget

- **Net Radiation:** The difference between incoming and outgoing flows of radiation (R_{net} = IN – OUT)

IN:

Shortwave (SW↓ or K↓)

Longwave (LW↓ or L↓)

OUT:

Reflected SW (SW↑ or K↑)

Emitted LW (LW↑ or L↑)

$$R_{net} = (K\downarrow + L\downarrow) - (K\uparrow + L\uparrow)$$

$$R_{net} = K\downarrow - K\uparrow + L\downarrow - L\uparrow$$

Final Net Radiation Equation:

$$R_{net} = (1-\alpha)K\downarrow + \sigma\,(\varepsilon_{sky}T^4_{sky} - \varepsilon_{surf}T^4_{surf})$$

Surface Energy Budget

$$R_{net} = H + LE + G + P + \Delta S$$

- G is 0 over 24 hours, so can be ignored
- Biomass storage and Photosynthesis are very small and usually can be ignored

$$R_{net} = H + LE$$

- Surface characteristics control the partitioning of net radiation into LE and H based on surface MOISTURE
  - **BOWEN RATIO (β)= H / LE**

Energy Balance Methods

- Net Radiation
- Ground (soil) heat flux
- Biomass heat storage
- Sensible Heat

Energy Balance in Hawai‘i Example:
Giambelluca et al. 2009

Eddy Covariance System

Net Radiometer

Sources:
http://thermophysical.tainstruments.com
http://www.automationdirect.com
http://www.kippzonen.com

Heat Flux Sensor

Soil Moisture Probe

Type K/ J thermocouple

Scintillometer

Water Balance

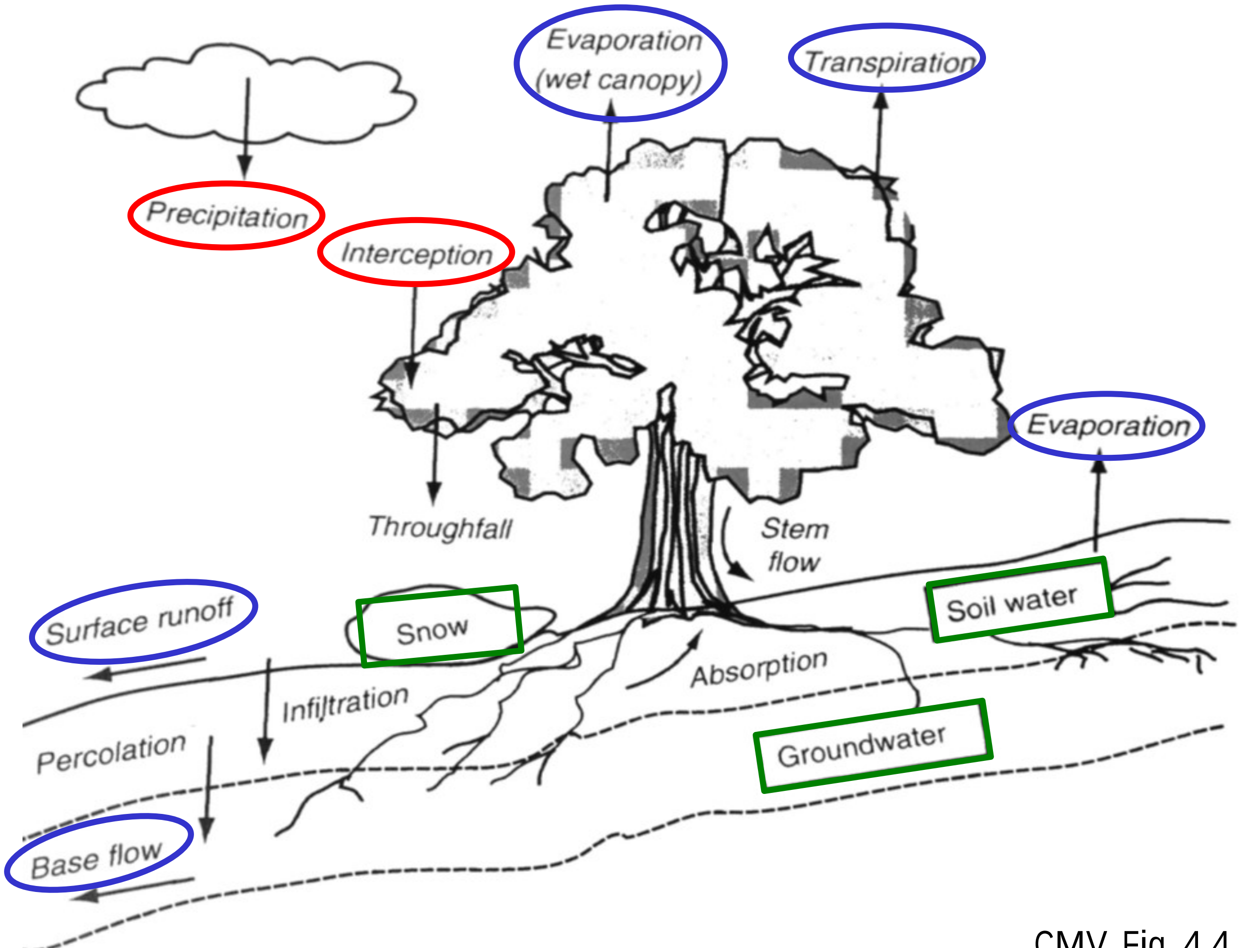
INPUT = OUTPUT + Δ Storage

Water balance equation

RF + CWI + IRR = RO + ET + GWR + Δ S

Where:

- RF = Rainfall
- CWI = Cloud Water Interception
- IRR = Irrigation
- RO = Runoff
- ET = Evapotranspiration
- GWR = Ground Water Recharge
- ΔS = Change in Storage



CMV, Fig. 4.4

Water Balance Methods - Inputs

Cloud Water Interception – fog screen

Rainfall – Rain Gauge

Cloud Water Interception Study

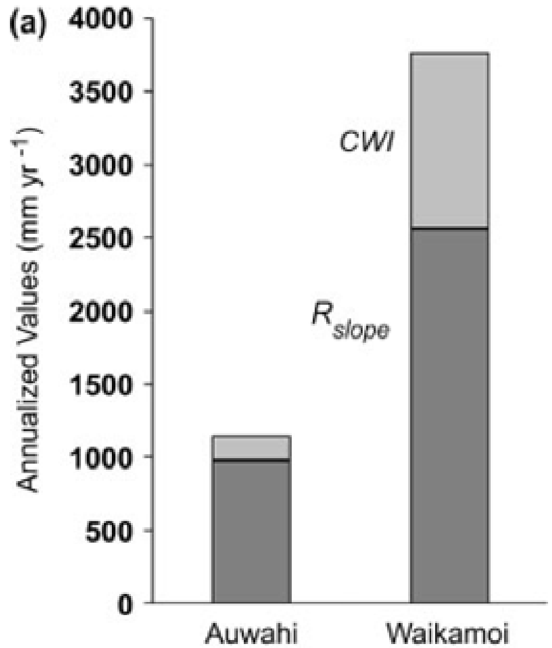
Giambelluca et al. 2011

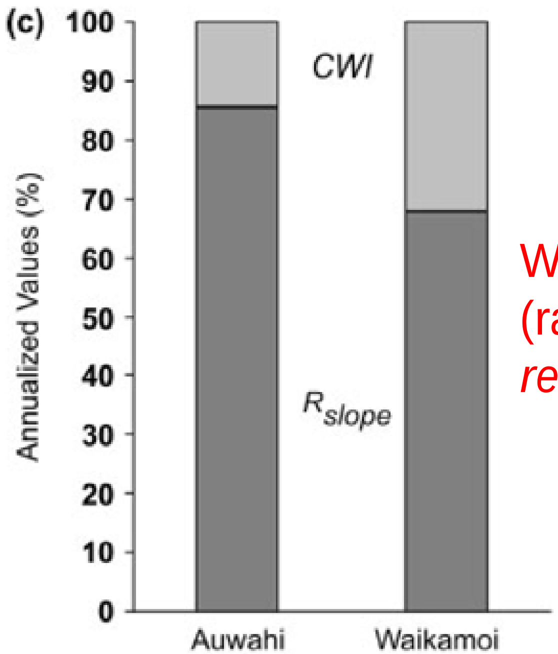
•Used two methods to calculate CWI (planar fog screens and canopy water balance) at 2 sites on Maui

•Found that planar fog screens are not very accurate (poorly account for wind-driven rainfall, varying wind direction, etc.)

•Results: at the wet windward site: CWI made up **32% of total precip**, and at the dry leeward site, CWI was **15% of total precip**

Water Input (rainfall + CWI)





Water Input (rainfall + CWI): *relative units*

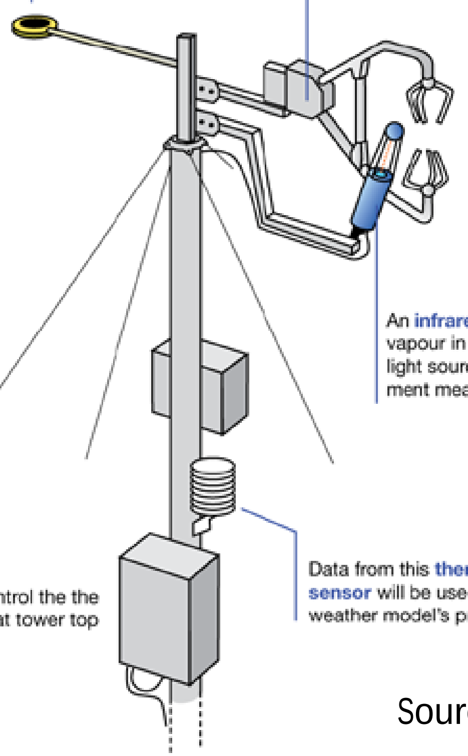
Water Balance Methods - Outputs

Evapotranspiration - Eddy Covariance System

Observations at **three research towers in Vancouver** provide information on the energy and water exchange between the urban surface and the atmosphere. The towers are equipped with sophisticated instruments that can track the energy received from the sun and atmosphere, the heat exchange, and the evaporation of water vapour of the city.

A radiometer measures sunlight and thermal radiation exchange between the urban surface and the atmosphere.

An ultrasonic anemometer measures smallest motions of wind by means of ultrasound waves. Sound waves travel slightly faster if they are carried with the wind as opposed to travel against wind.



A combination of an ultrasonic anemometer and an infrared gas analyzer can be used to directly calculate how much water vapour and energy is exchanged between the urban surface and the atmosphere. For example, after people have turned on their lawn sprinklers, we statistically measure that upward moving air is slightly more humid than parcels that come from higher levels of the atmosphere and that are direr.

An infrared gas analyzer measures concentrations of water vapour in the air. The instrument operates by shining an infrared light source across a short path. This high-performance instrument measures 150 times a second.

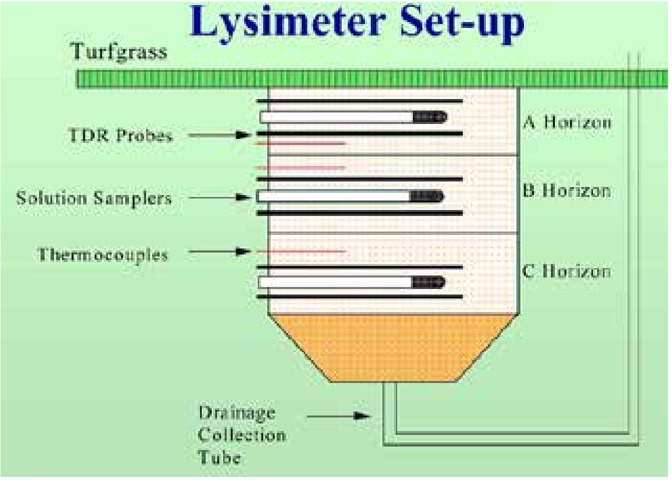
Analyzer electronics control the the measurements at tower top

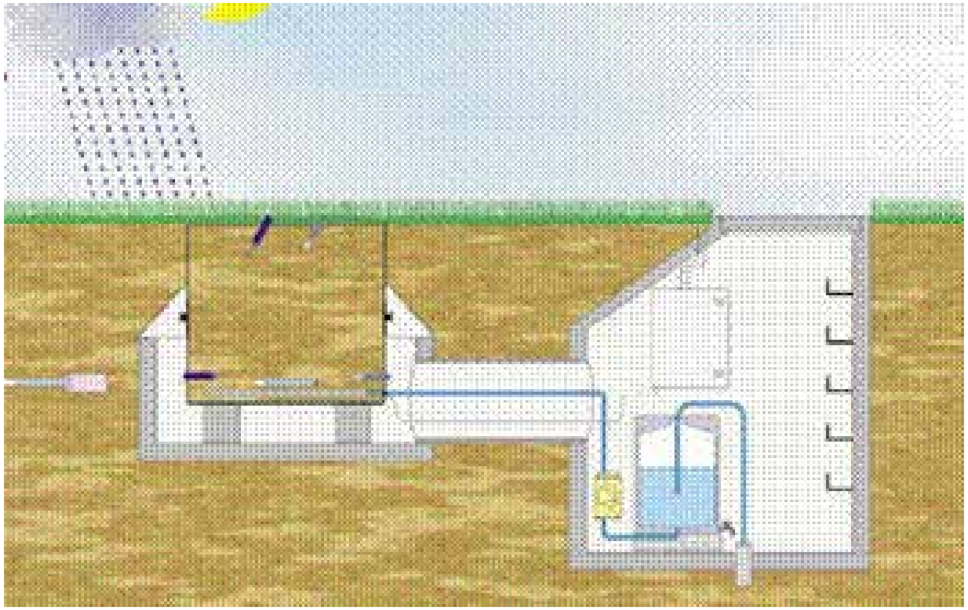
Data from this thermometer / humidity sensor will be used to validate the weather model's prediction.

Source: http://www.geog.ubc.ca/~achristn/infrastructure/oakridge-full.gif

Water Balance Methods - Outputs

Evapotranspiration – Weighing Lysimeter

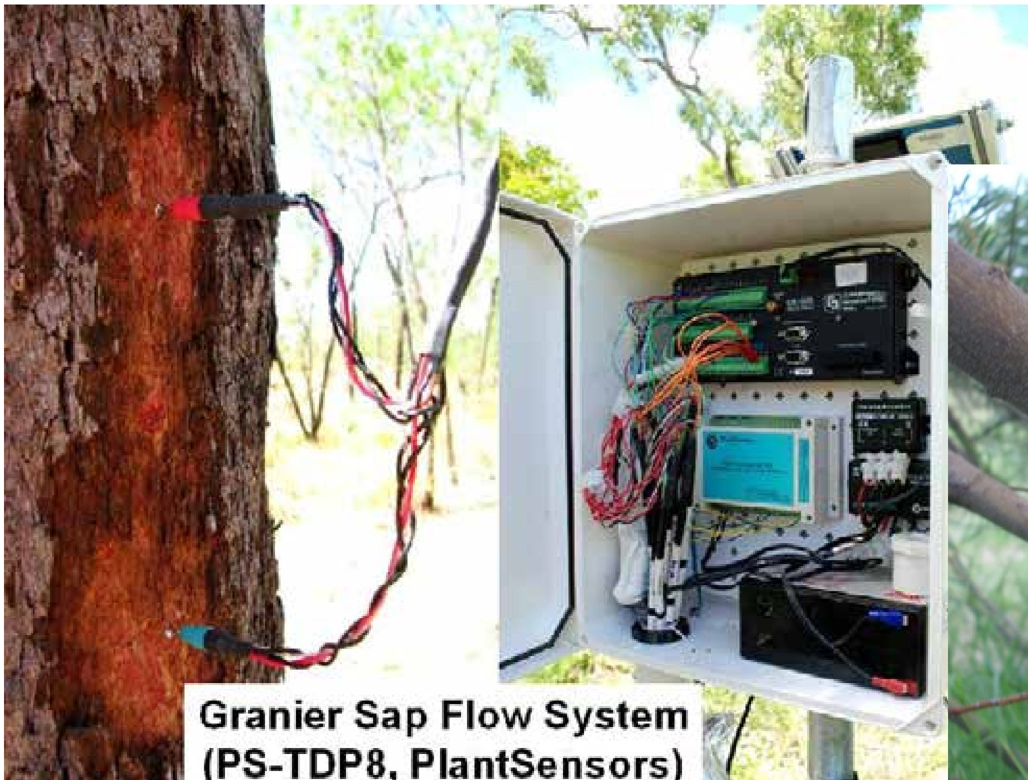




Evaporation – Evaporation Pan

Water Balance Methods - Outputs

Transpiration – Sap Flow



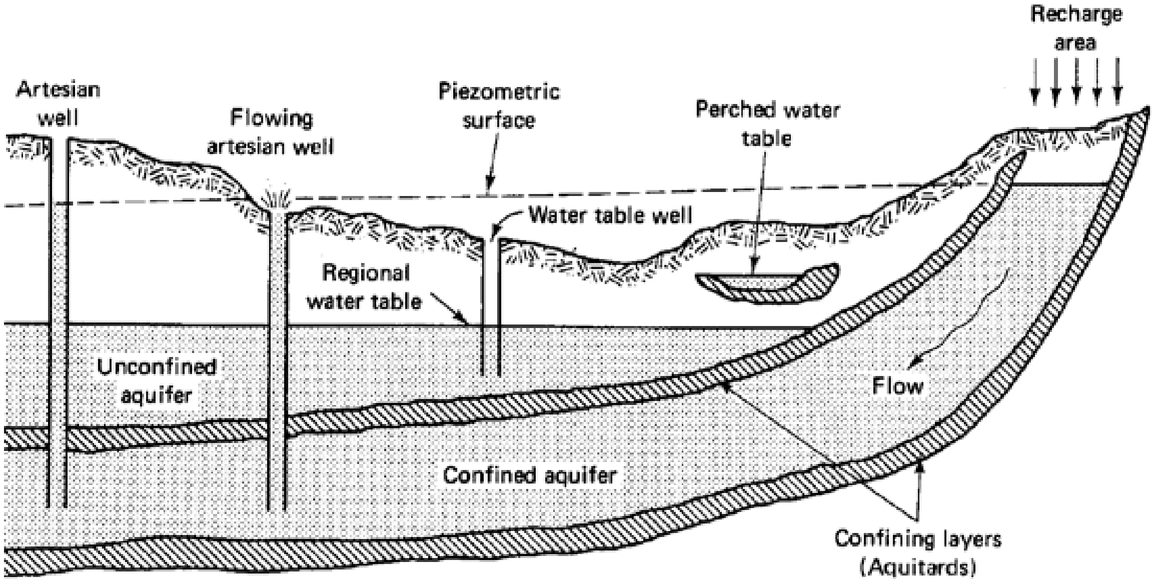
Thermal Dissipation Method
http://www.plantsensors.com/
Granier 1985, 1987
Hawai‘i Example: Kagawa et al. 2009

Heat Ratio Method
http://www.ictinternational.com/sfm1.html
Burgess et al. 2001

Water Balance Methods - Outputs

Groundwater Flow Measurement

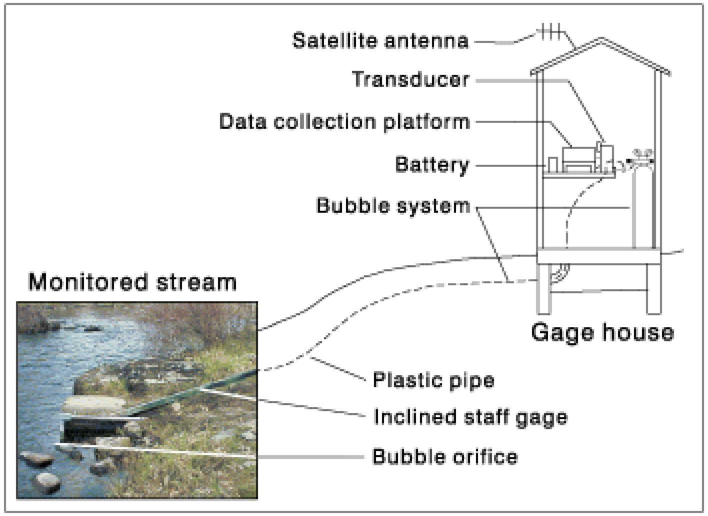
- Monitoring wells
- Piezometers (a tube or pipe)



Shallow water table (unconfined aquifer) monitoring well

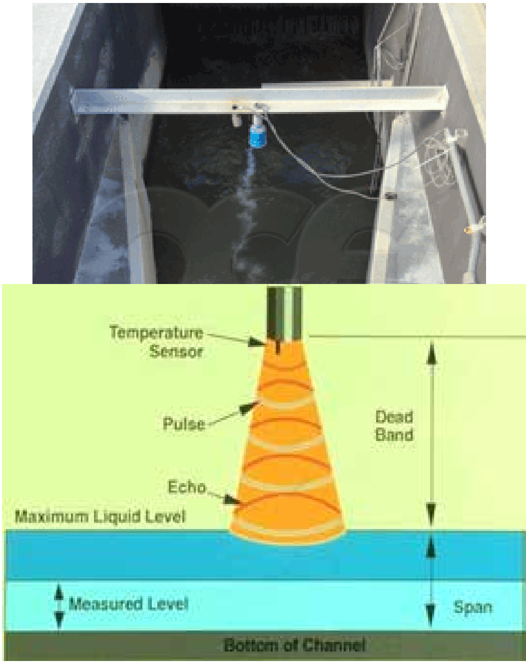
Water Balance Methods - Outputs

Surface **Runoff** Measurement Instruments



Gas Bubbler

Pressure transducers



Ultrasonic sensors

They all give Volumetric Flow rate

Flume

Sources: http://usgs.gov
http://www.fao.org
http://www.bae.ncsu.edu

Water Balance Methods - Storage

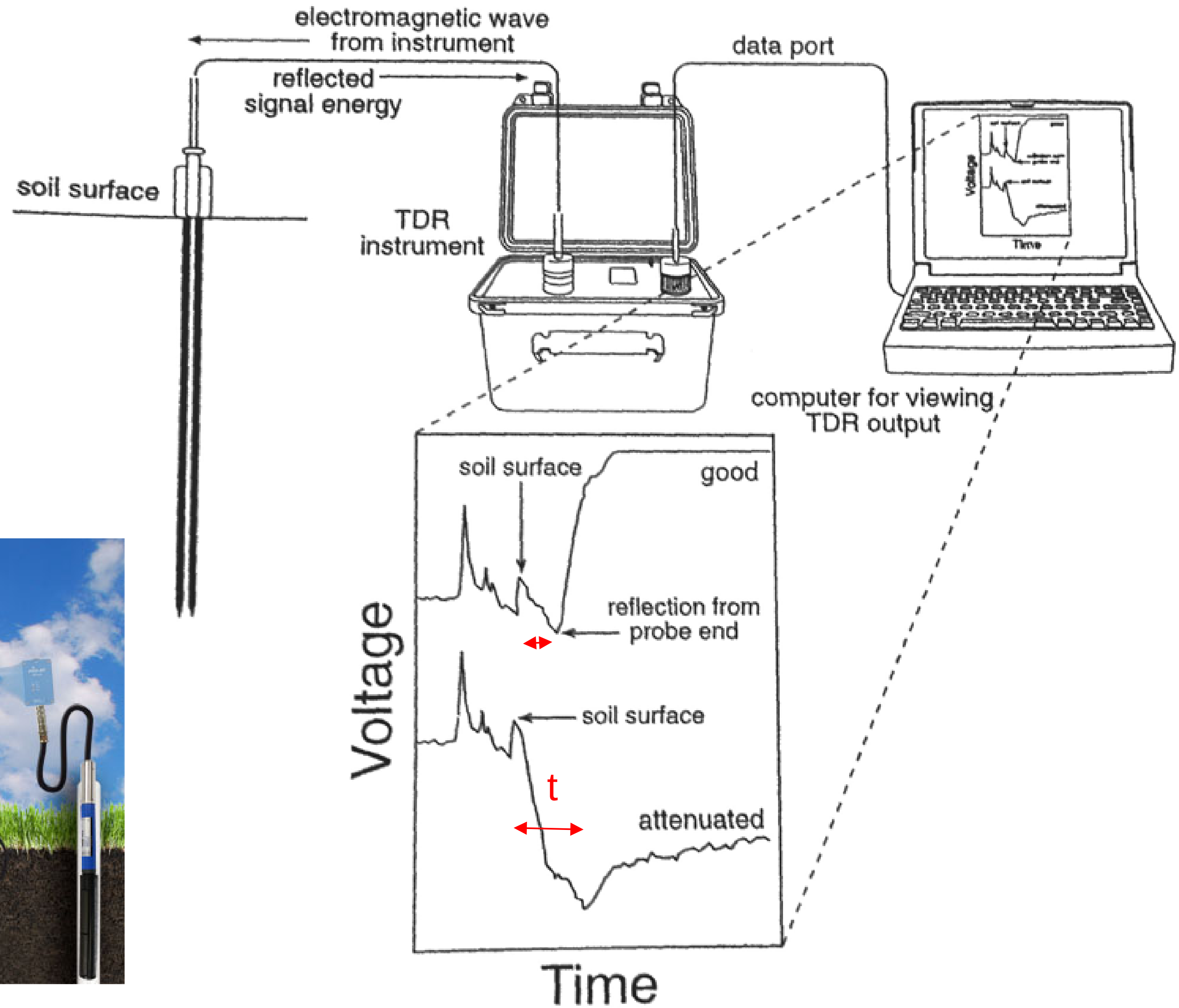
Soil Moisture

- **Gravimetric Technique**
  - Soil core collection
  - Drying oven and a balance
- Simple, low cost, used to calibrate other most other methods, usable under a range of soil depths and moisture conditions
- Gives mass and volumetric soil moisture content

- **Thermocouple Psychrometry**
  - Water potential based on the relative vapor pressure of water in the environmental system with that of free, pure water at an equivalent temperature and pressure

Source: Jackson et al. 2000 (Book -Methods in Ecosystem Science)

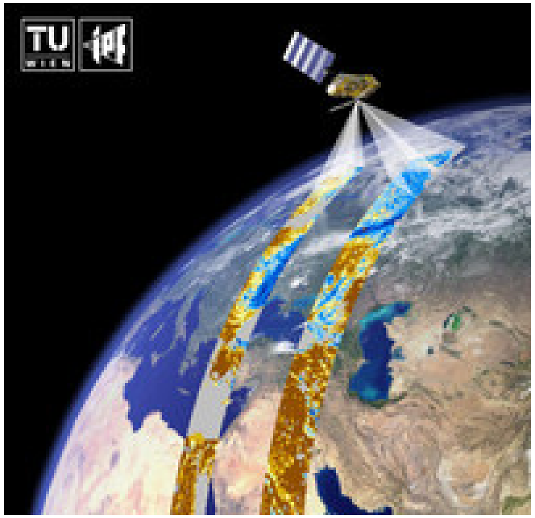
Time Domain Reflectometry



http://www.mesasystemsco.com/category.php?cat=3
CMV Fig 13.3

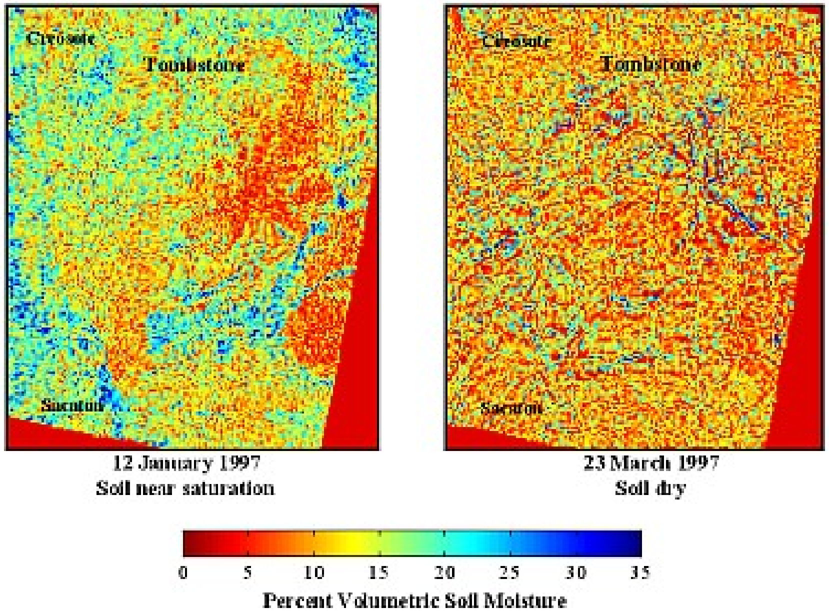
Water Balance Methods - Storage

Soil Moisture



Remote Sensing

- Thermal infrared techniques
- Microwave (Top 2-5 cm, shallower than 10 cm)
- Optical (visible/near infrared) – (solar radiation as a direct energy source)
- Indirectly to root-zone soil moisture



Sources: Adapted from www.usta.edu
https://www.ipf.tuwien.ac.at

Water Balance Methods - Processes

Throughfall & Stemflow

Throughfall

Stemflow

Sources: www.usgs.com
http://www.inbo.be

Example in Hawai‘i: Takahashi et al. 2011

Water Balance Methods - Processes

Stable Isotopes

- Stable isotope ratio analyses at natural abundance tell us spatial and temporal variations in water-use activities in:
  - Hydrology (evaporation and condensation)
  - Ecology (transpiration, leaf-water enrichment, CO_2-to-H_2O ratio)
- ^{2}H and ^{18}O isotopes

Mass Spectrometer

Source: West et al. 2006

Some Isotopes Studies in Hawai‘i:
Scholl et al. 2002, 2007

Stable Isotope Study in Hawai‘i

Scholl et al. 2007

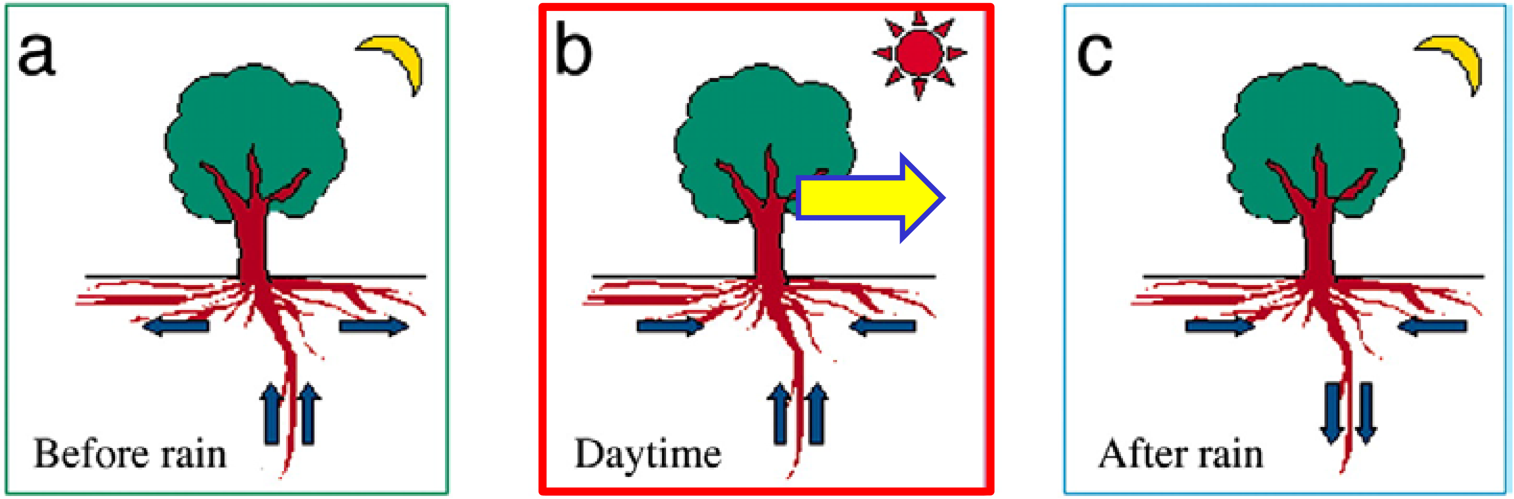
- Used stable isotope signatures to identify orographic cloud water at 2 sites on Maui
- Cloud Water is enriched in ^{18}O and ^{2}H compared to rain water
- Collected rainwater and cloud water data - stable isotope samples were analyzed for $\delta^{18}O$ and $\delta^{2}H$
- Used a two end-member mixing model to estimate the proportion of orographic cloud water (as opposed to other types of precipitation)

$$f_{CWnet} = \frac{\delta_{CW} - \delta_{RWend}}{\delta_{CWend} - \delta_{RWend}}$$

- Orographically driven cloud water estimated to be 37% of total precip at windward site (46% of total at leeward site)

Hydraulic Redistribution

- Water moves through roots along water potential gradients (wet to dry)
- Roots have higher hydraulic conductivity than soil (preferred pathway)

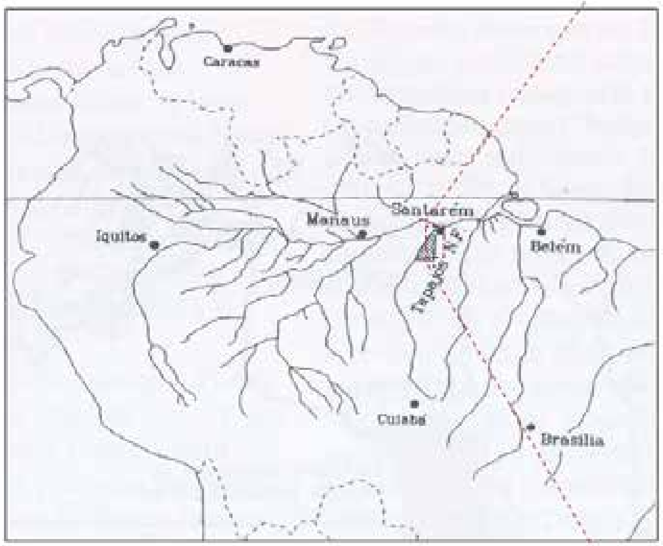


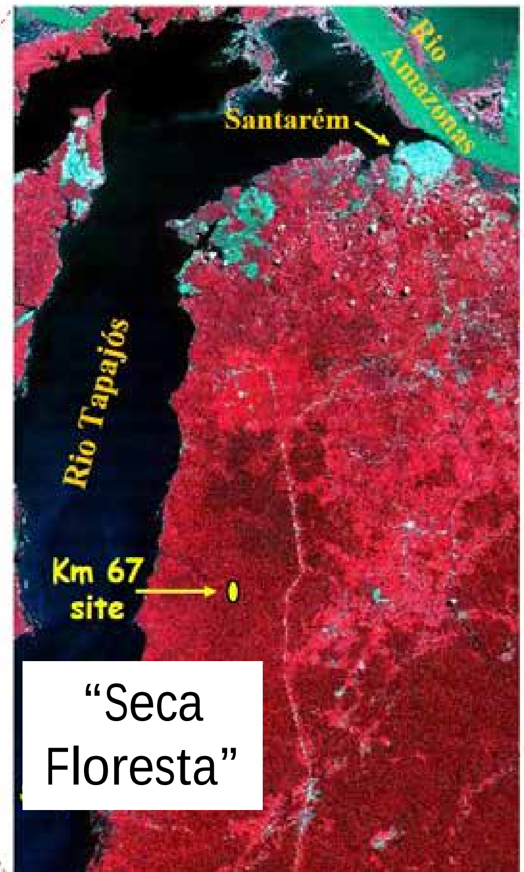
Transpiration

Lee J et al. PNAS 2005;102:17576-17581

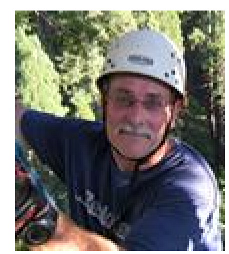
Hydraulic redistribution in three Amazonian trees

Tapajos National Forest, Para, Brazil





Rafael Silva Oliveira, Professor, Department of Botany, State University of Campinas



Todd Dawson, Professor, Department of Integrative Biology and Environmental Science, Policy & Management, University of California at Berkeley

Saleska, S. R., Miller, S. D., Matross, D. M., Goulden, M. L., Wofsy, S. C., da Rocha, H. R., ... & Silva, H. (2003). Carbon in Amazon forests: unexpected seasonal fluxes and disturbance-induced losses. *Science*, *302*(5650), 1554-1557.

Motivation of the Study

- Hydraulic Redistribution (HR) usually associated with arid or seasonal environments
- HR had not been documented for wet tropical ecosystems
- Evidence for HR in this forest during dry season

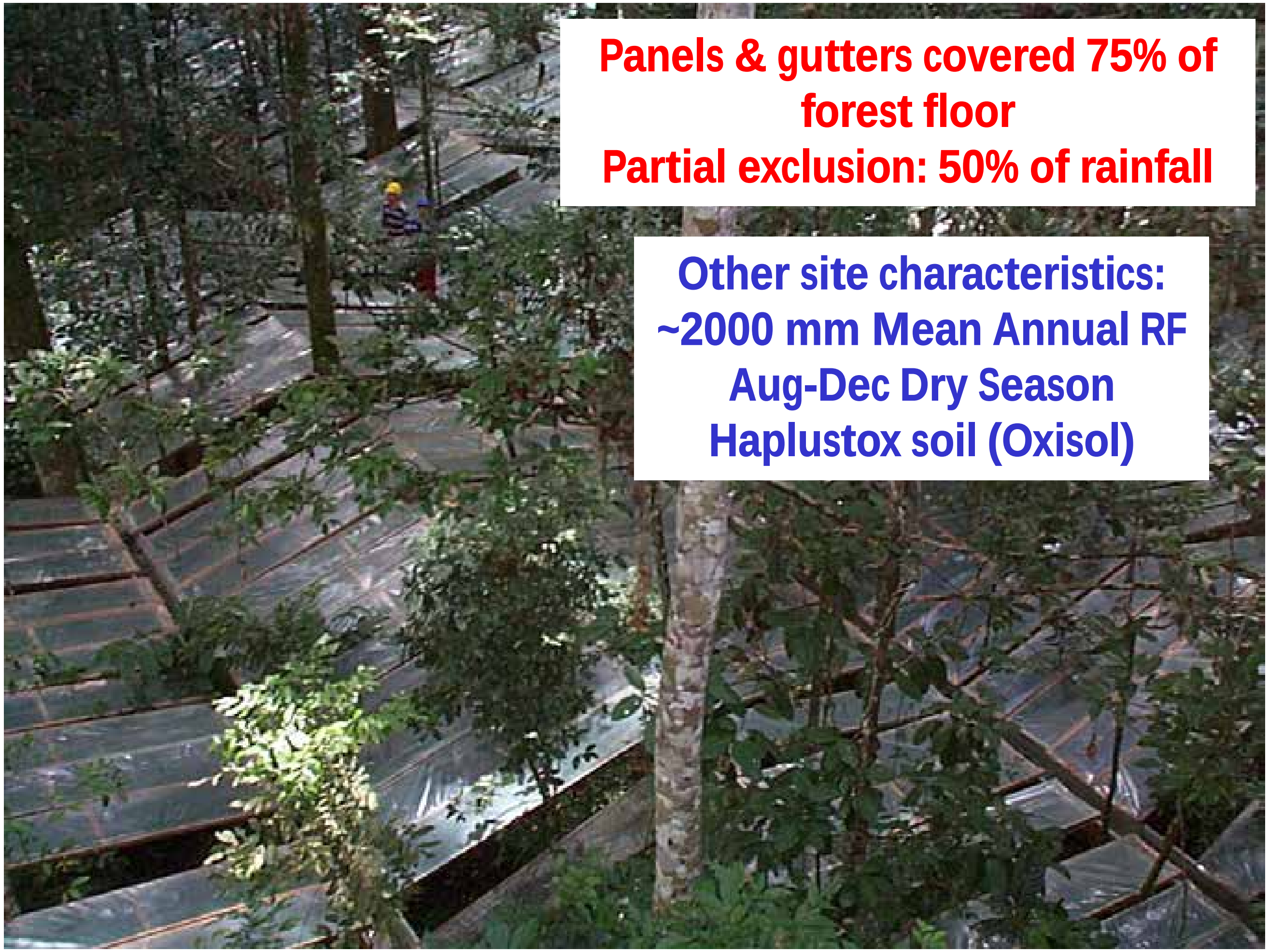
Objective: determine direction & magnitude of soil water redistribution by roots of 3 common Amazonian tree species

Study Site

- Tapajos National Forest – **Rainfall Exclusion Plot**

Two 1-ha plots (treatment & control)

Throughfall was partially excluded during rainy seasons using plastic panels and wooden gutters installed in the understory



Study Site

- Tapajos National Forest – **Rainfall Exclusion Plot**

Deep soil processes were studied using shafts excavated to 12 m depth

Plots were trenched on perimeters to isolate plots from surrounding forests (confirmed with isotopes)

Study Design

- 3 Tree Species (Di-morphic rooted)
  - All had dimorphic root system: 2-12 lateral roots extending horizontally, and a single descending tap root
- Chosen to represent 3 functional types
  - ***C. racemosa (understory)*** – not very deep rooted. Most common tree species in forest, 15 m height
  - ***P. robustum (mid-canopy)*** – 20-25 m height
  - ***M. huberi (canopy)*** – roots can extend deep. Dominant, timber tree, can reach 45 m (individuals chosen were 20 m to control for size difference)

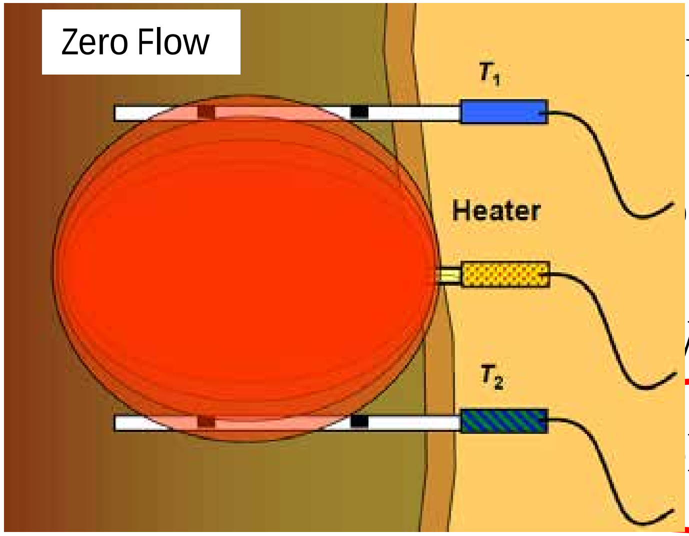
Methods

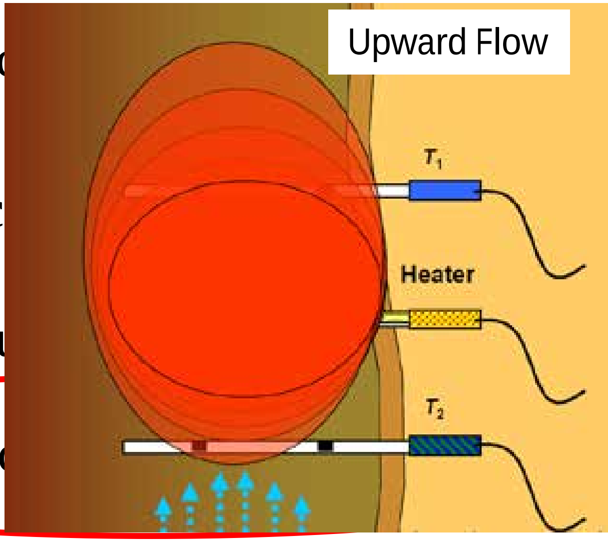
- Measured **Rainfall**, **Soil Water Data**, & **Sap Flow in Roots**

- **Rainfall** was measured above the canopy using an automated tipping-bucket rain gauge
- **Soil Water Data** (Volumetric Water Content) was measured using **Time Domain Reflectometry (TDR)** probes to a depth of 11 m

Methods

- **Sap Flow in Roots** measured using the **Heat Ratio Method (HRM)**, which measures the increase in temperature following a heat pulse at 2 symmetrical points (0.6 cm) above & below a heater
  - Allows bi-directional measurements of sap flow



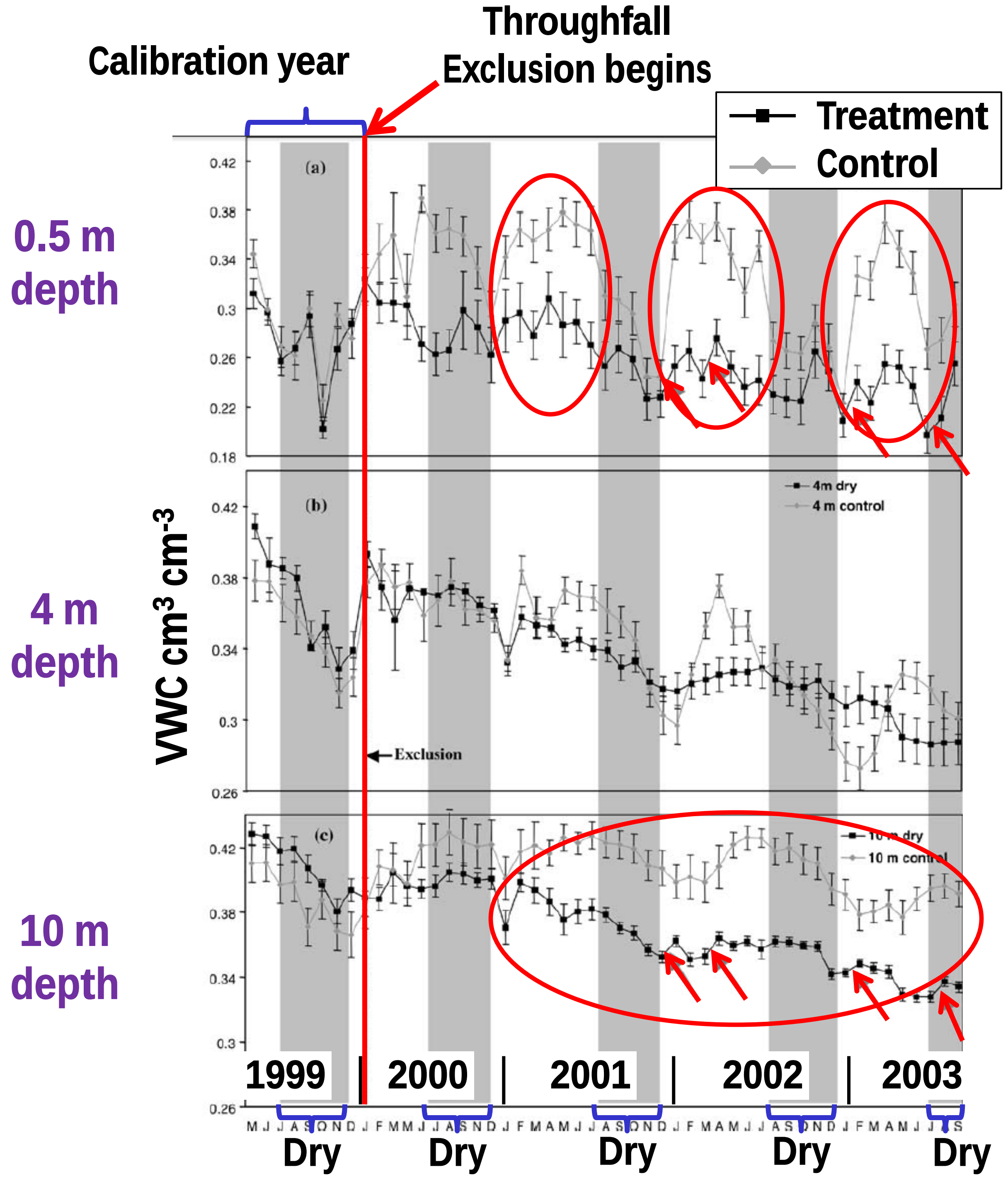


$$\textbf{Volumetric flow} = (V_s) * \textbf{Cross-sectional Area of sapwood}$$

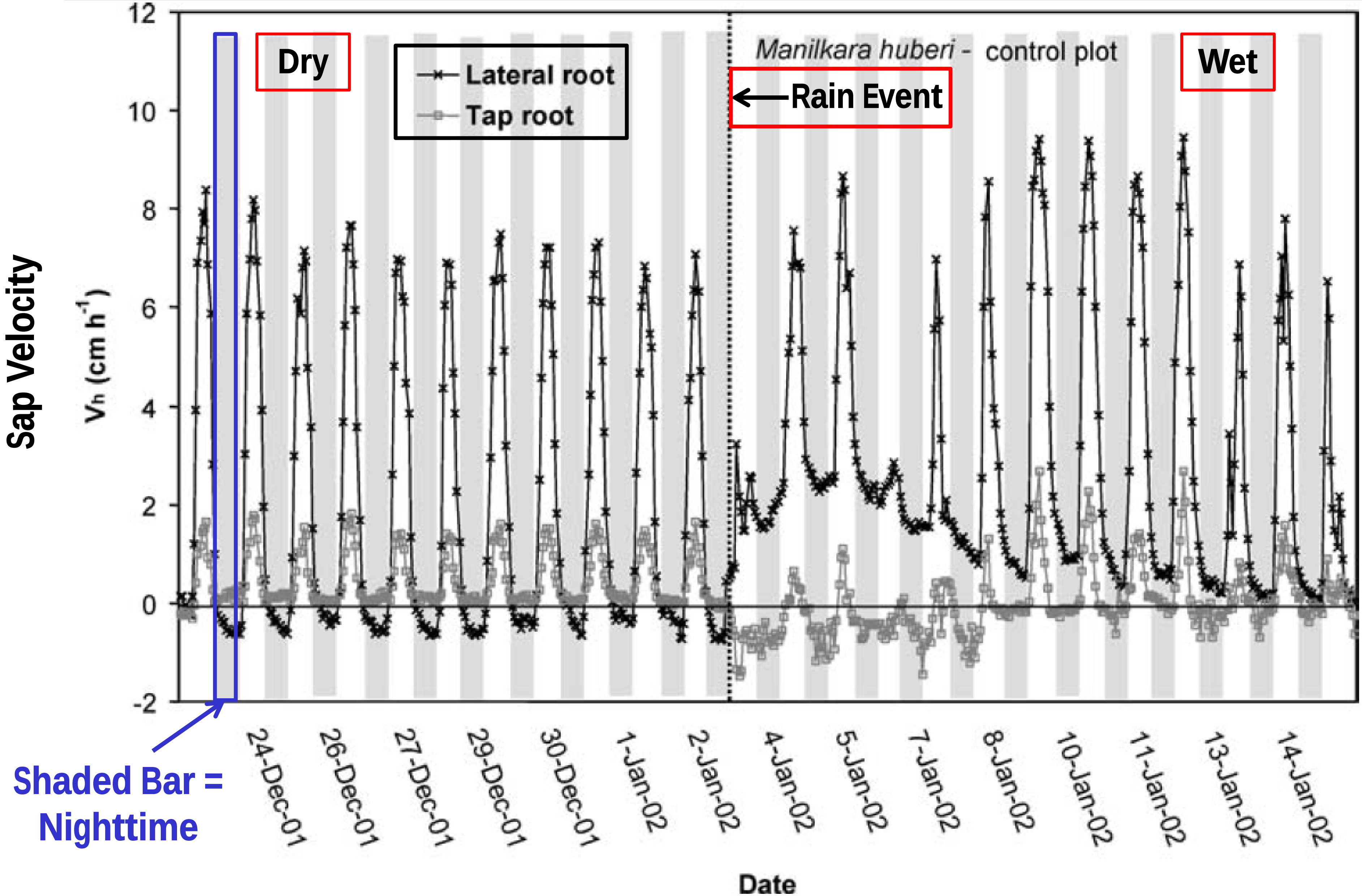
Burgess et al. 2001

Results – Soil Moisture

- **Arrows show simultaneous periods of recharge in shallow and deep layers**
- **Suggests HR!**

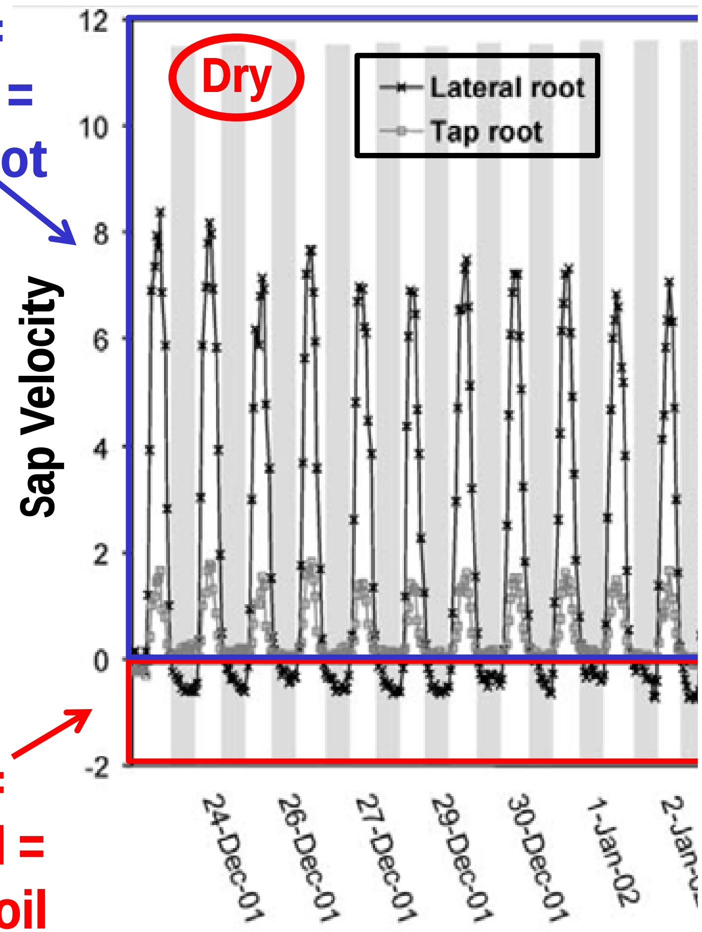


Results – Root Sap Flow (Control Plot)



Results – Root Sap Flow (Control Plot)

Positive =
Basipetal =
Soil to Root



Reverse =
Acropetal =
Root to Soil

Dry Season Nighttime:

*Reverse (Root To Soil) sap flow in LATERAL roots

*Positive (Soil To Root) in TAP roots

à Plants conducting hydraulic lift (HL)

DRY

Root to soil

WET

Soil to root

Results – Root Sap Flow (Control Plot)

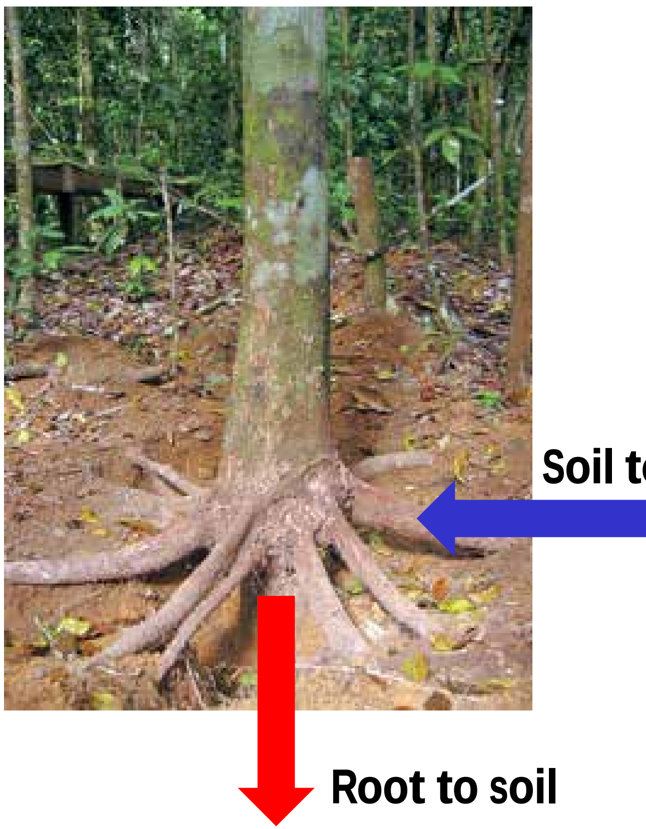
<u>Wet Season Nighttime:</u>

*Reverse (Root To Soil) sap flow in TAP roots

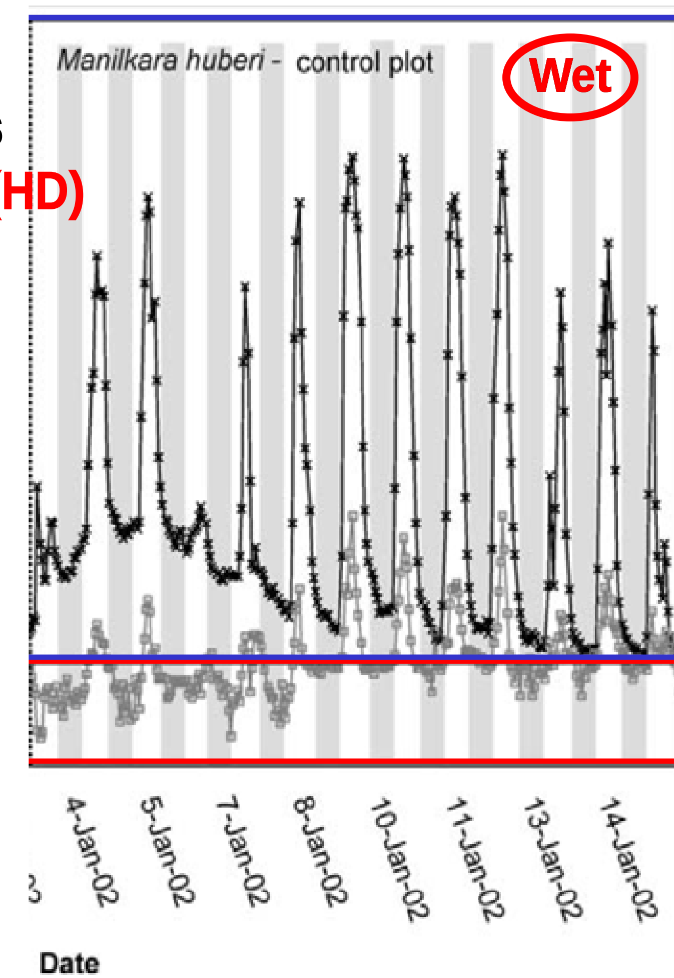
*Positive (Soil To Root) in LATERAL roots

à Plants conducting hydraulic descent (HD)

WET



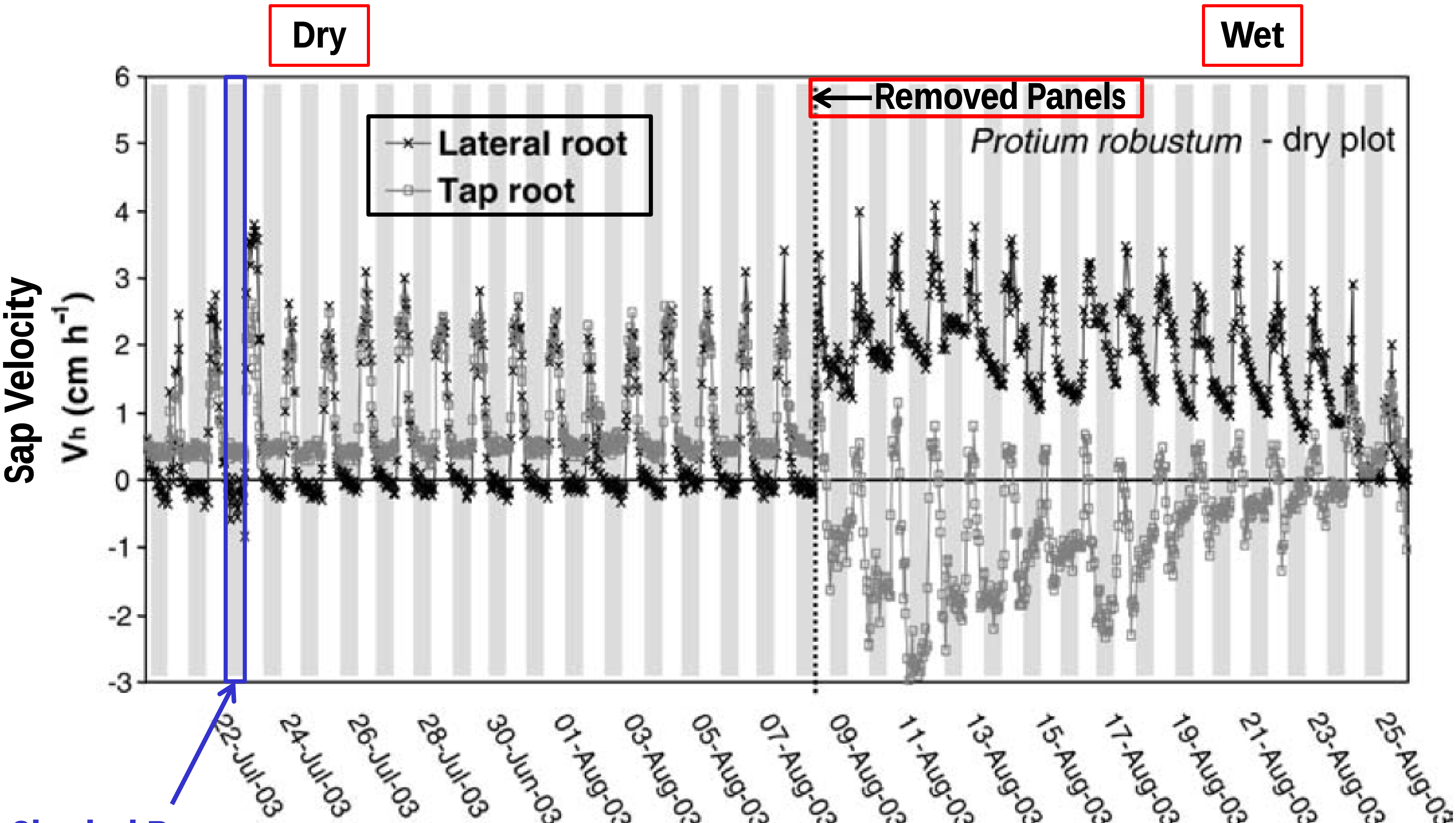
DRY



Positive = Basipetal = Soil to Root

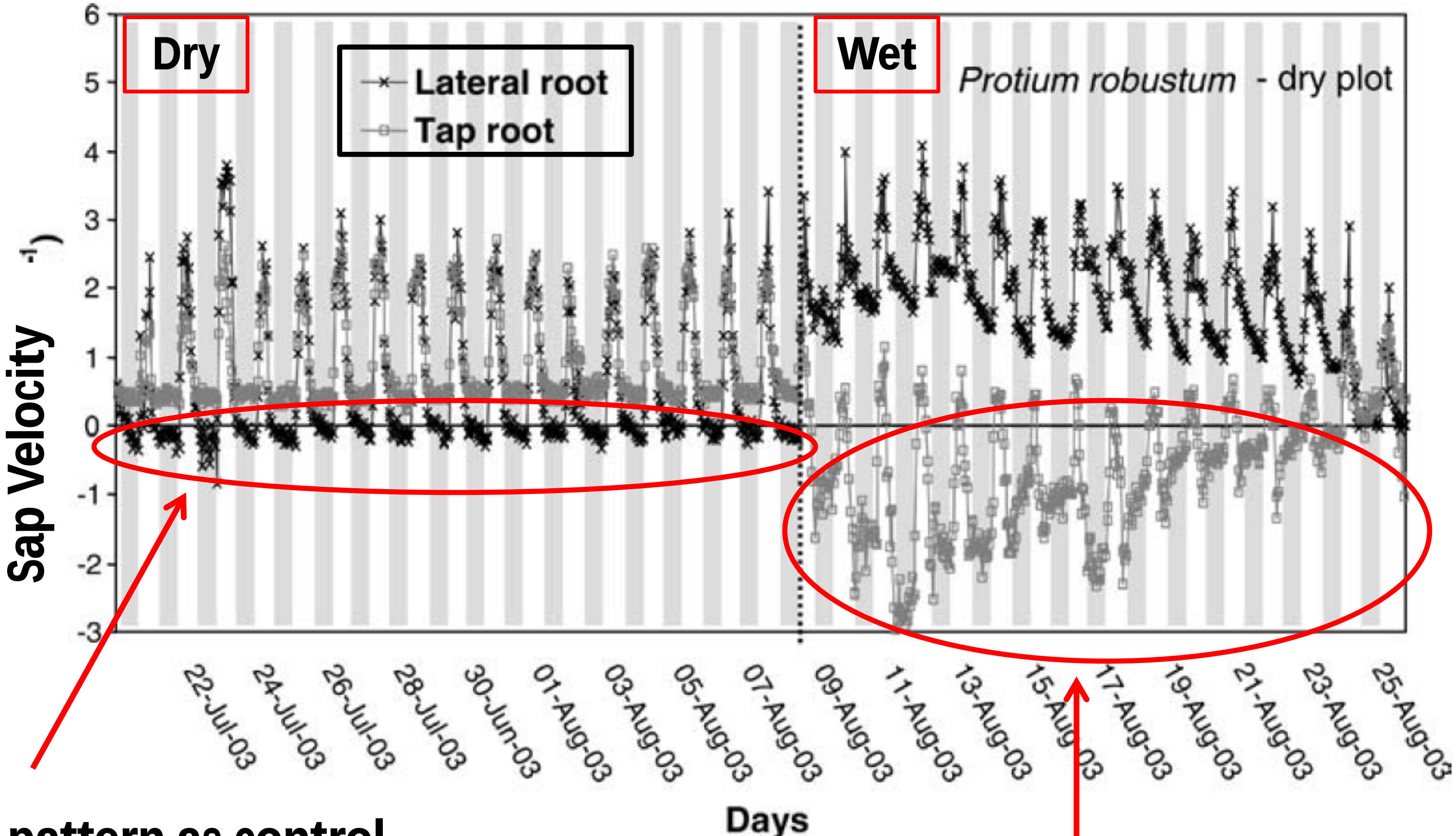
Reverse = Acropetal = Root to Soil

Results – Root Sap Flow (Treatment Plot)



Shaded Bar = Nighttime

Results – Root Sap Flow (Treatment Plot)



Similar pattern as control plot (evidence of HL)

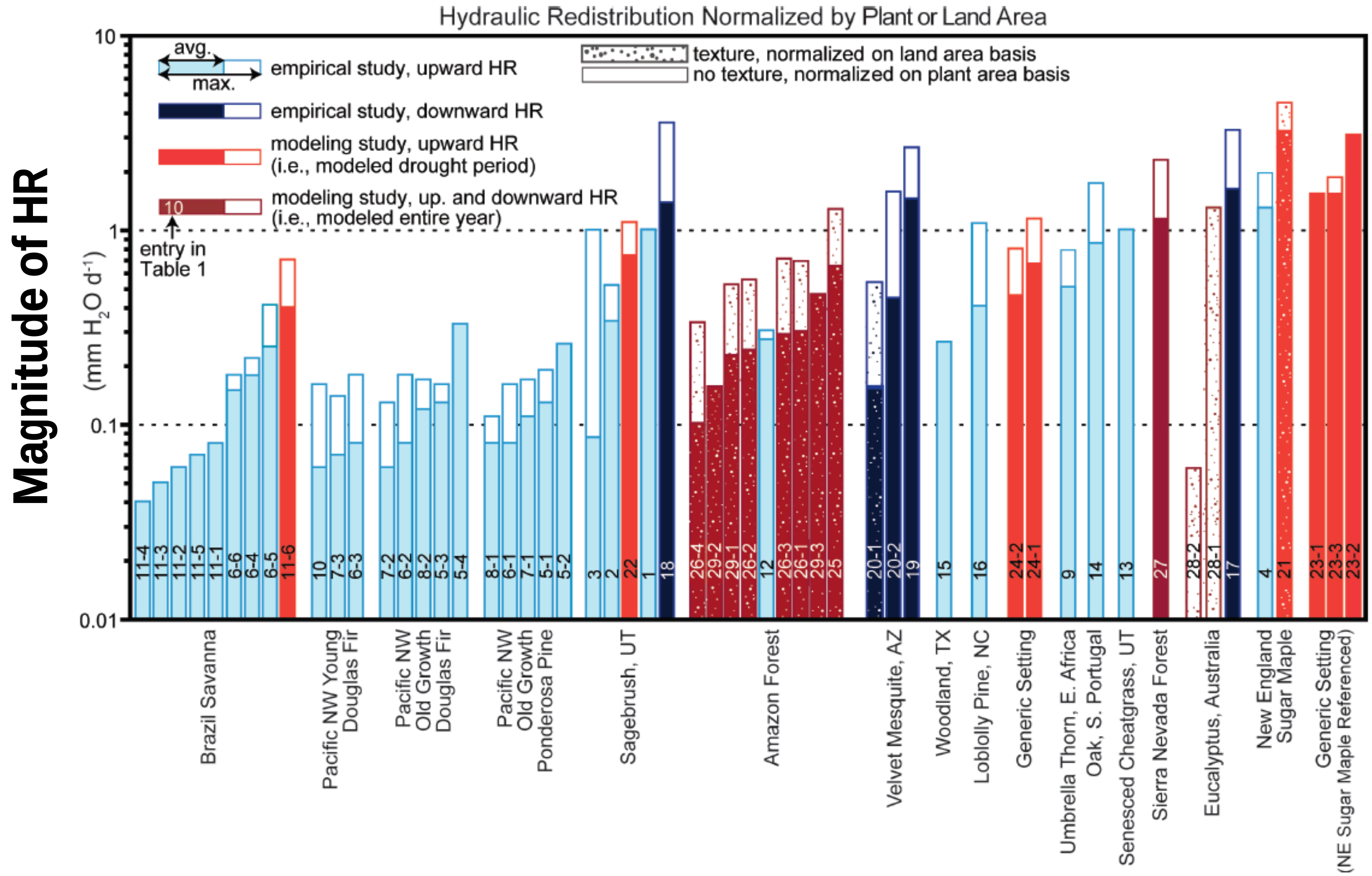
Similar pattern as control plot (evidence of HD). However, <u>magnitude</u> was greater, and lasted longer as a result of the very STEEP water potential gradient

Discussion & Conclusions

- HR exists in tropical rainforest trees
  - Evidenced by:
    1) Simultaneous peaks in recharge in deep and shallow layers (not possible by infiltration)
    2) Sap flow measurements in tree roots
- HR can influence the amount of dry season evapotranspiration
- Important to understand for modeling

Other HR Studies

- Many modeling & empirical studies across various ecosystems



Neumann R. B. & Cardon Z. G. New Phytologist (2012); 194: 337-352

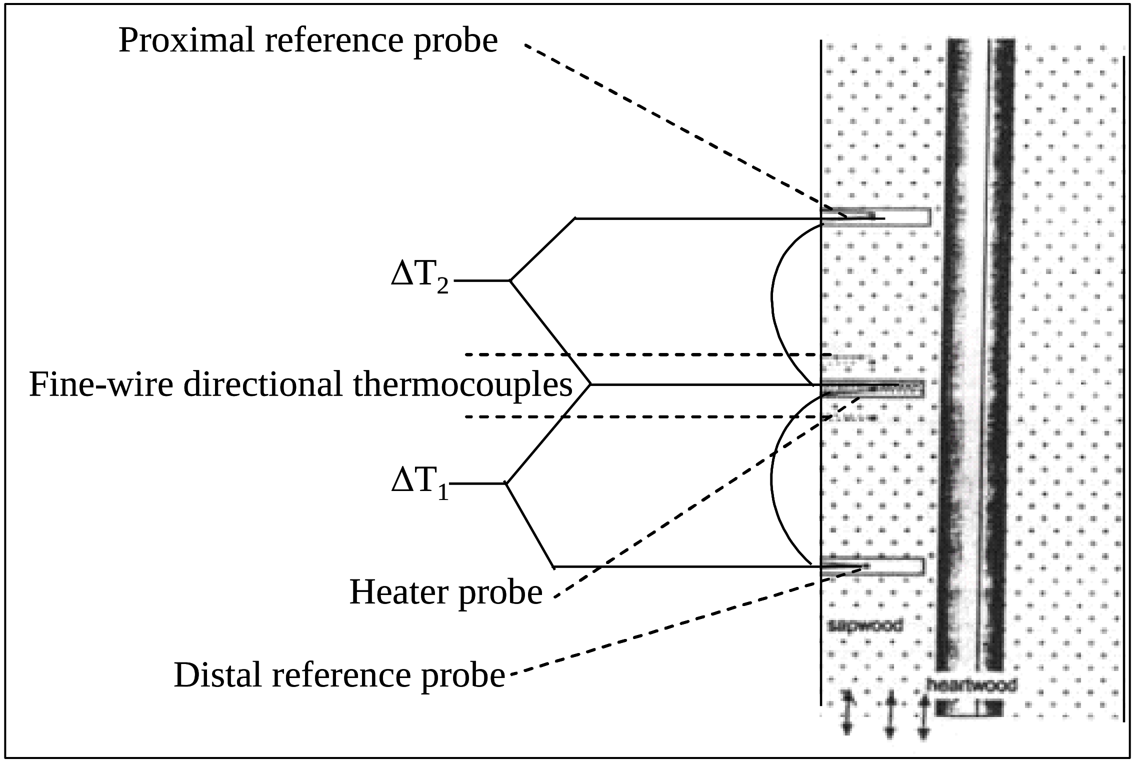
Recent HR Studies

Kizito et al. 2012

- HR in semi-arid Sahelian shrub species
- Measured sap flow using a modified thermal dissipation (Granier) technique (Brooks et al. 2002, 2006)

Bi-directional Thermal Dissipation Probe

DT_1: from raw data, difference between heater probe and distal reference probe
DT_2: from raw data, difference between heater probe and proximal reference probe
DT_3: from raw data, difference between directional indicating thermocouple



Recent HR Studies

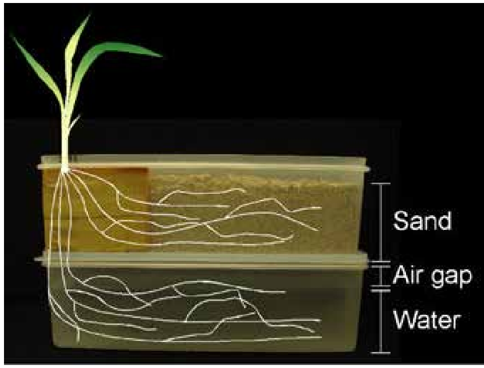
Querejeta et al. 2012

- ***Study***: Impact extent of mycorrhizosphere disturbance on Hydraulic Lift (HL)
- ***Hypothesis***: Higher HL from donor well-hydrated oaks to drought-stressed seedlings in control non-fungicide-treated mesocosms
- ***Methods***: Gravimetric and stable isotope (^2H) soil moisture contents accompanied by statistical analyses
- ***Results***: Contrary outcomes were observed as HL is higher in treated (fungicide-applied) mesocosms
- ***Possible Reasons***: Reduced soil hyphal network and viability hampered soil moisture retention and thus faster water depletion in the upper soil (steeper water potential gradient) à HL

Recent HR Studies

Sekiya et al. 2011

Study: Hydraulic Lift (HL) in agroecosystem: donor shoot-removed forage plants to neighboring vegetable crops for their productivity



Methods:
Split-root experiment with soil moisture sensor, diffusion porometer and thermographs both in lab and field conditions. They had a control and a treatment plot, where they cut all deep roots.

Results & Conclusion:
HL is present in deep rooted plants. Productivity is increased in crops when these deep rooted "donor plants" are present. This is very important in water scarce environments.

HR Today

- Main Research Questions:
  - Identifying the importance of HR contribution to total transpiration
  - Hydrological significance of HR
  - How do species interact with each other?
  - How do other factors affect HR? (Stand density, stand age, edge & patch dynamics, etc.)
- Root characteristics exert a strong influence over the magnitude of HR
- Models still difficult to validate…

Neumann R. B. & Cardon Z. G. New Phytologist (2012); 194: 337-352

Thank You!