Budyko guide to exploring sustainability of water yields from catchments under changing environmental conditions

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Budyko Curve

Russian climatologist
1920 –2001

Budyko Curve describes the theoretical energy and water limits on the catchment water balance (P-ET=Q).

Budyko Curve provides a “business as usual” reference condition for the water balance.

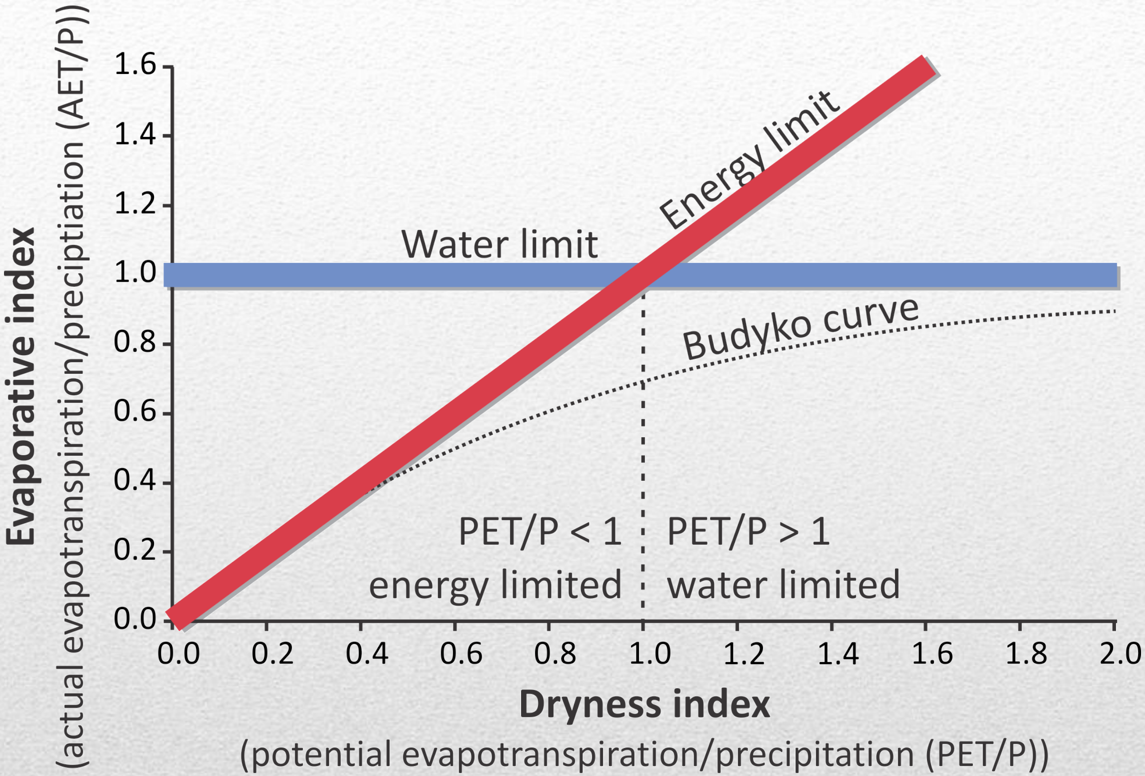
If we assume it depicts the expected partitioning of P into ET and Q,

then we can begin to account for the reasons why sites depart from the baseline.

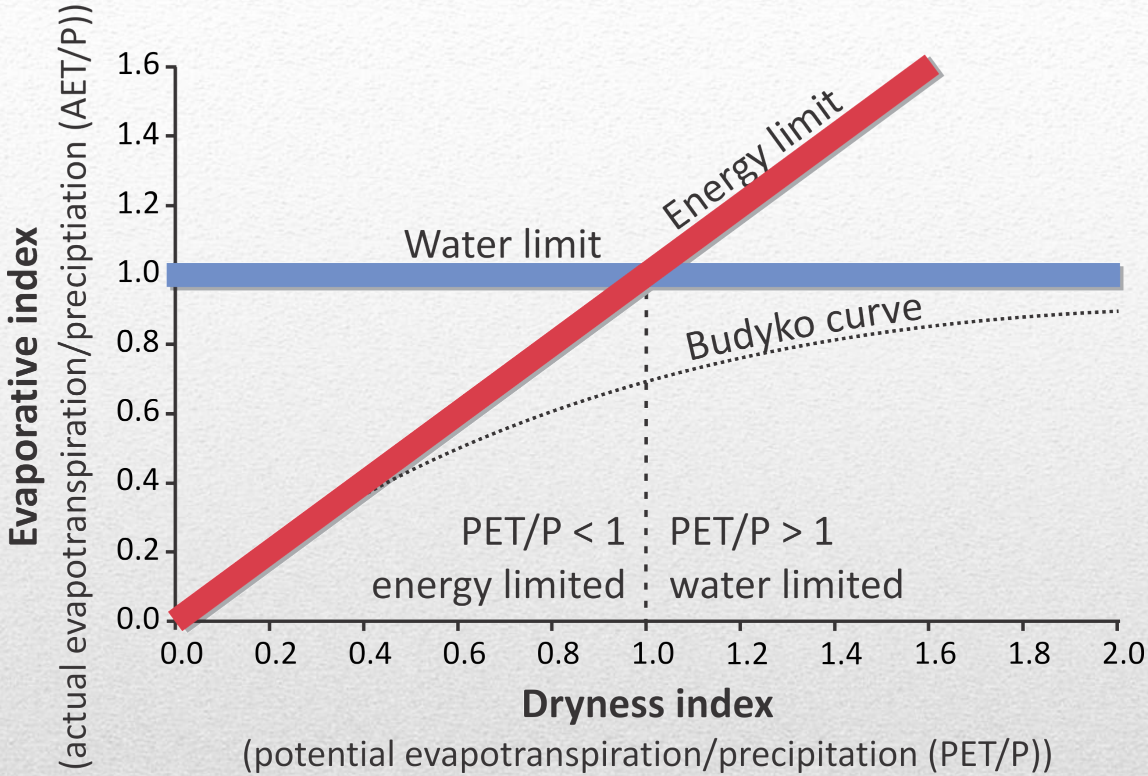
Can the Budyko Curve be used to identify catchments undergoing shifts in water yields or at risk of undergoing these shifts?

Water limit (AET=P);
a site cannot plot above the **blue line** unless there is input of water beyond precipitation.

Energy limit (AET=PET); a site cannot plot above the **red line** unless precipitation is being lost from the system by means other than discharge.



Budyko Curve



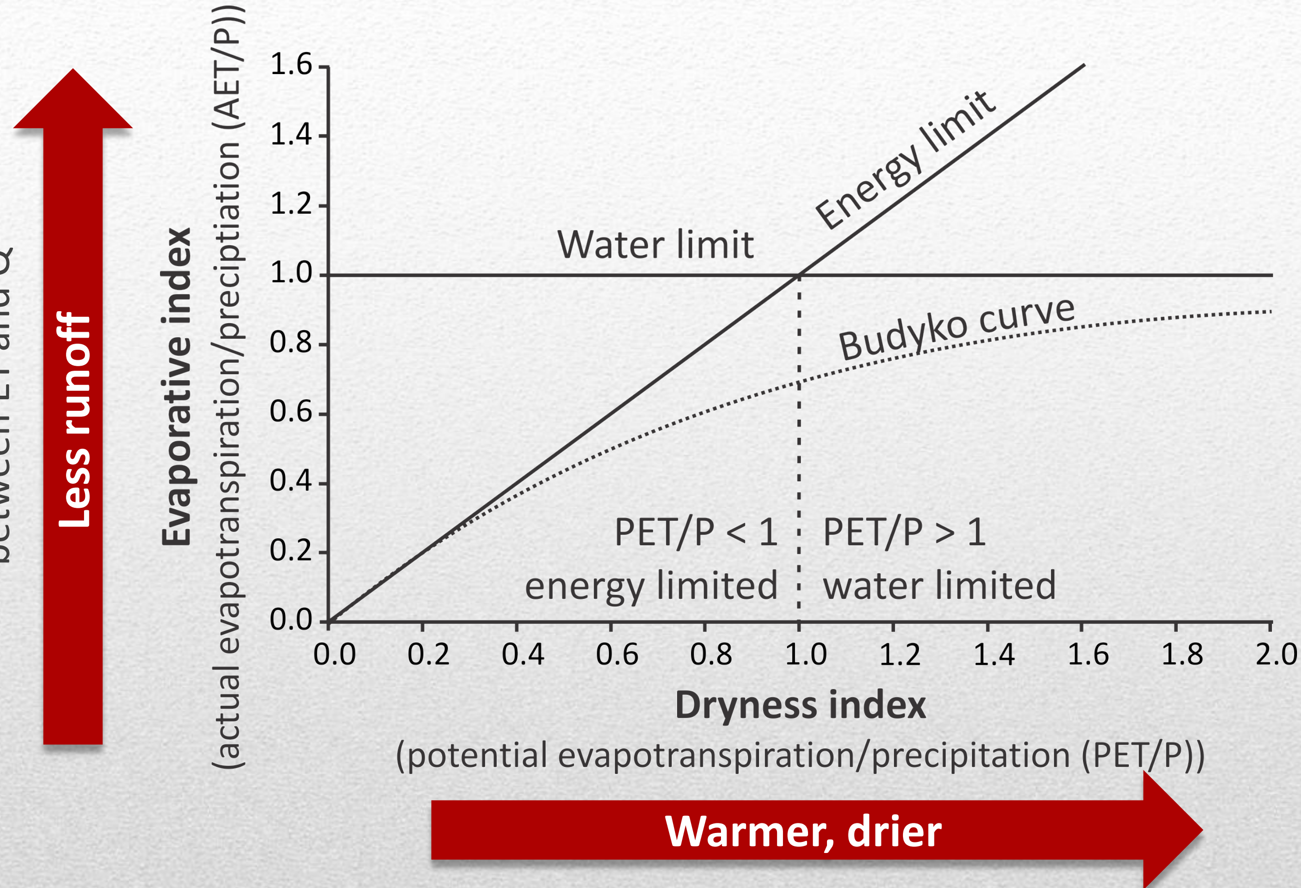
Energy limited (wet);
AET is limited by the amount of thermal energy that is available.

Water limited (dry);
AET is limited by the amount of water that is available.

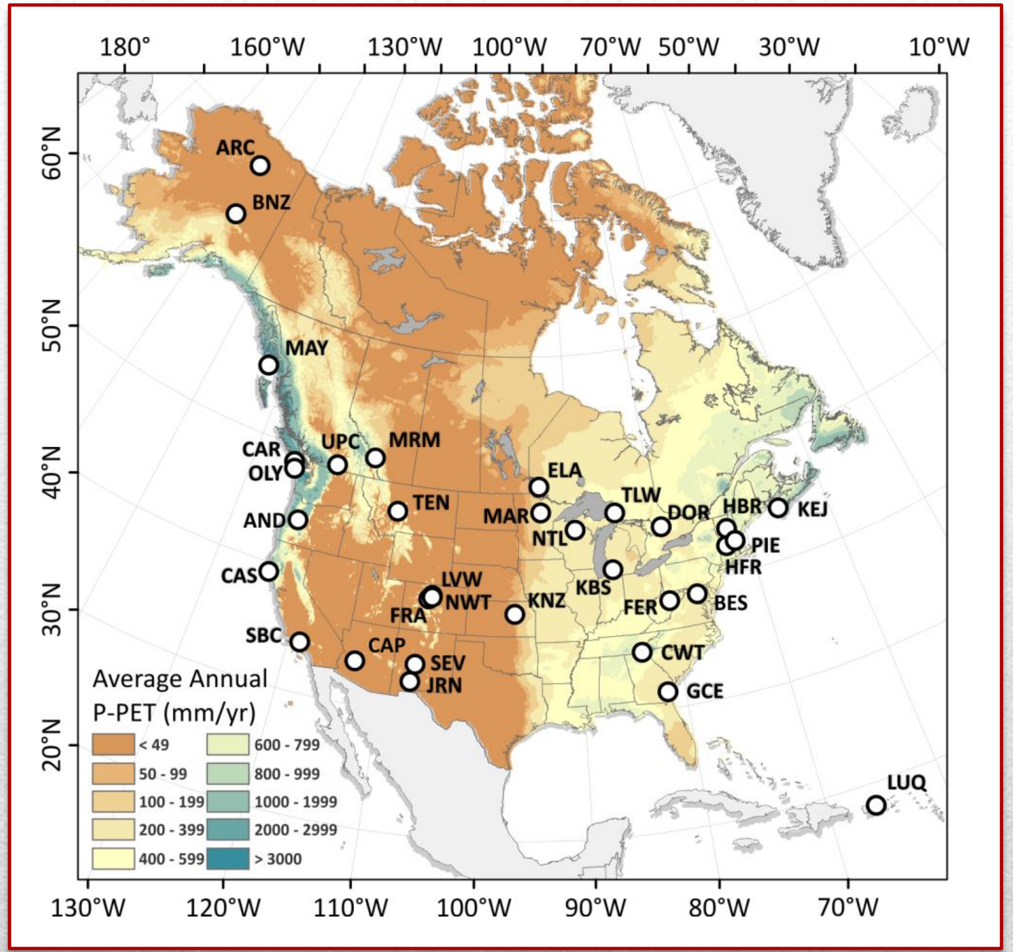
Budyko Curve

Budyko Curve

VERTICAL deviations
reflect a change in partitioning
between ET and Q



HORIZONTAL deviations
reflect a change in the climatic conditions
(temperature, precipitation)



- Network of catchments across North America
- Represent longest existing paired records of meteorology and hydrology.
- Provide opportunity to explore effects of climate on water yields in headwaters

- Backdrop: P-PET (30-yr climate normals, 1971 to 2000)

North American Network

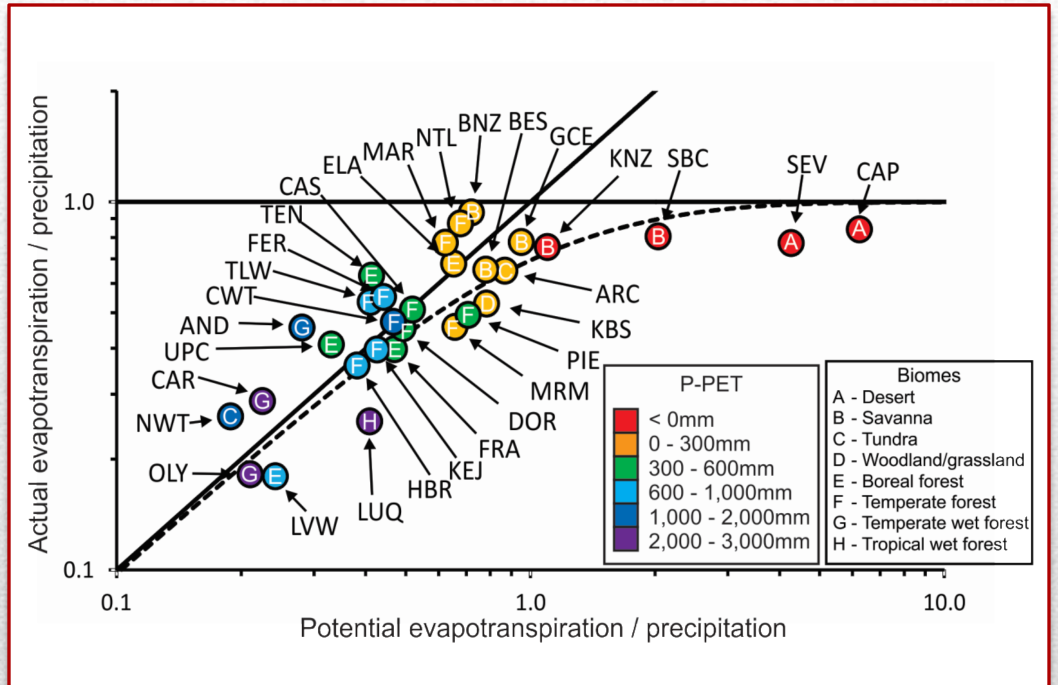
(1) Under **stationary conditions (naturally occurring oscillations)**, catchments will fall on the Budyko Curve.

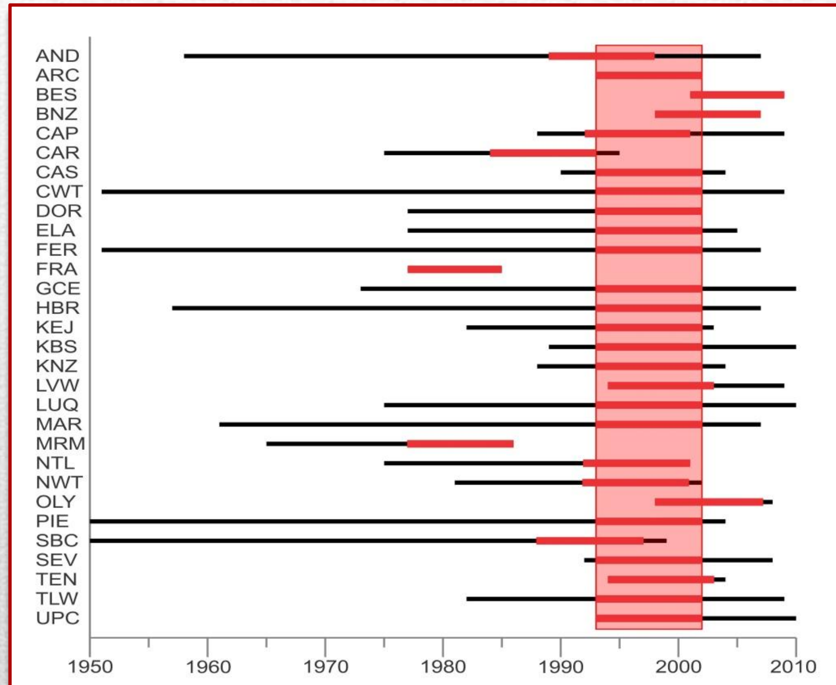
(2) Under **non-stationary conditions (anthropogenic climate change)**, catchments will deviate from the Budyko Curve in a predictable manner.

Hypotheses

Do the catchments fall on the Budyko Curve?

Distribution of sites on Budyko Curve based on "common" 10 year period of data

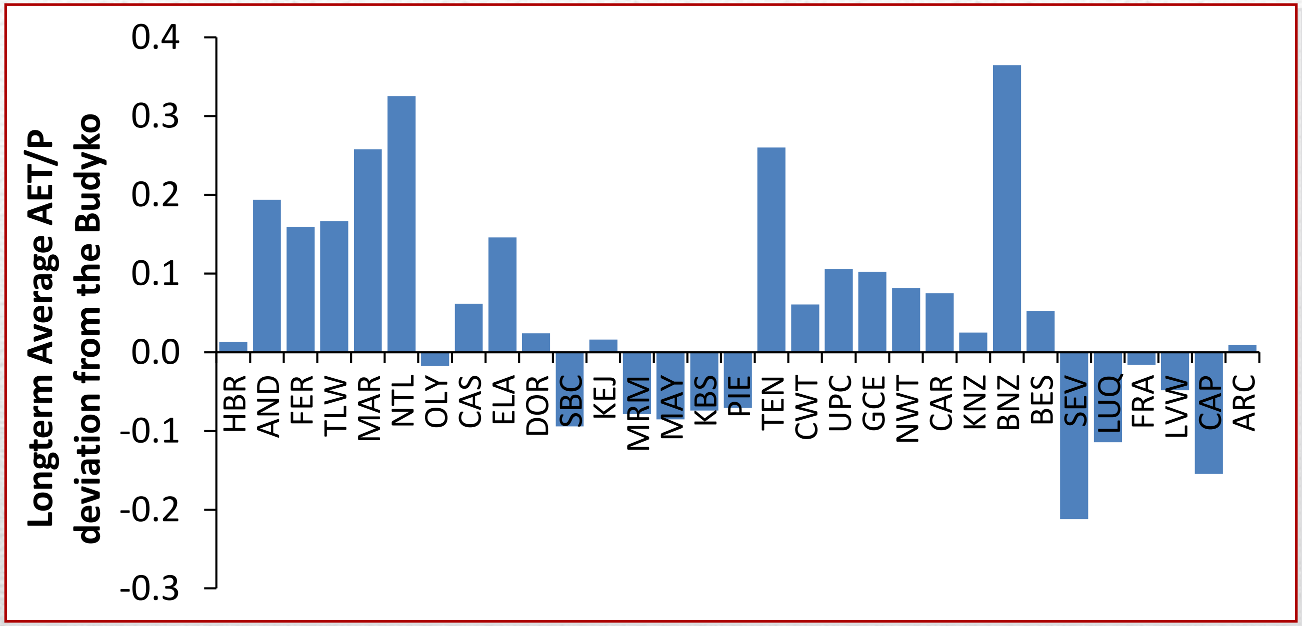




Budyko Curve

Jones JA et al. (2012). *Ecosystem processes and human influences regulate streamflow response to climate change at long-term ecological research sites.* BioScience 62: 390–404.

Long term average deviation in AET/P (i.e., partitioning between ET and Q)



Deviations from Budyko Curve

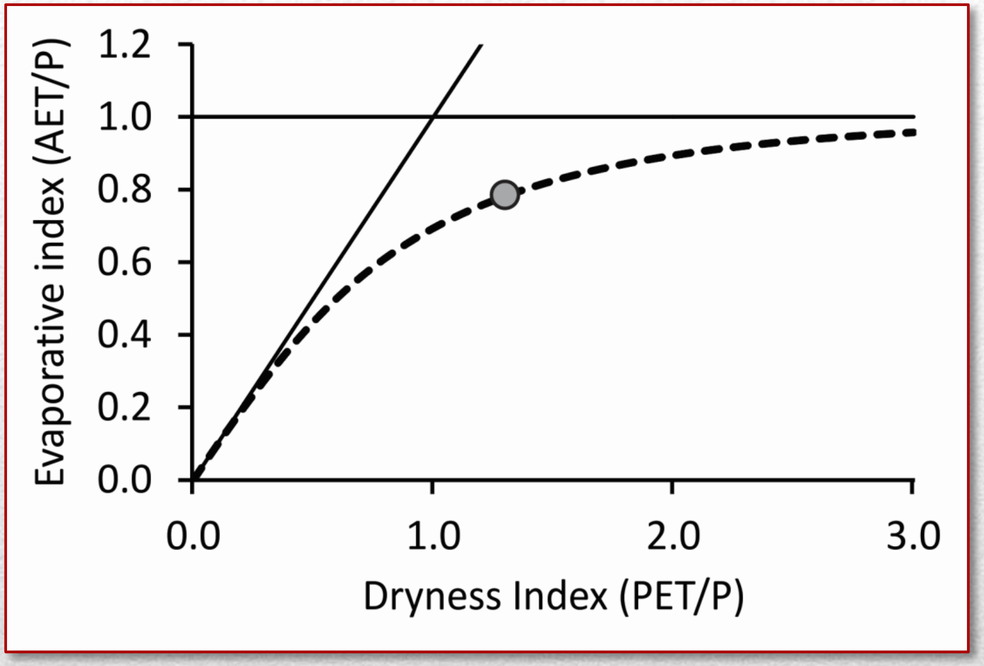
Reasons for falling off the Budyko Curve

1. Inadequate representation of P and T (Loch Vale)
2. Inadequate representation of ET (Andrews)
3. Inadequate representation of Q (Marcell)
4. Forest conversion (Coweeta)
5. Forest disturbance (Luquillo)

1. Today's Focus: Response to changing climatic conditions

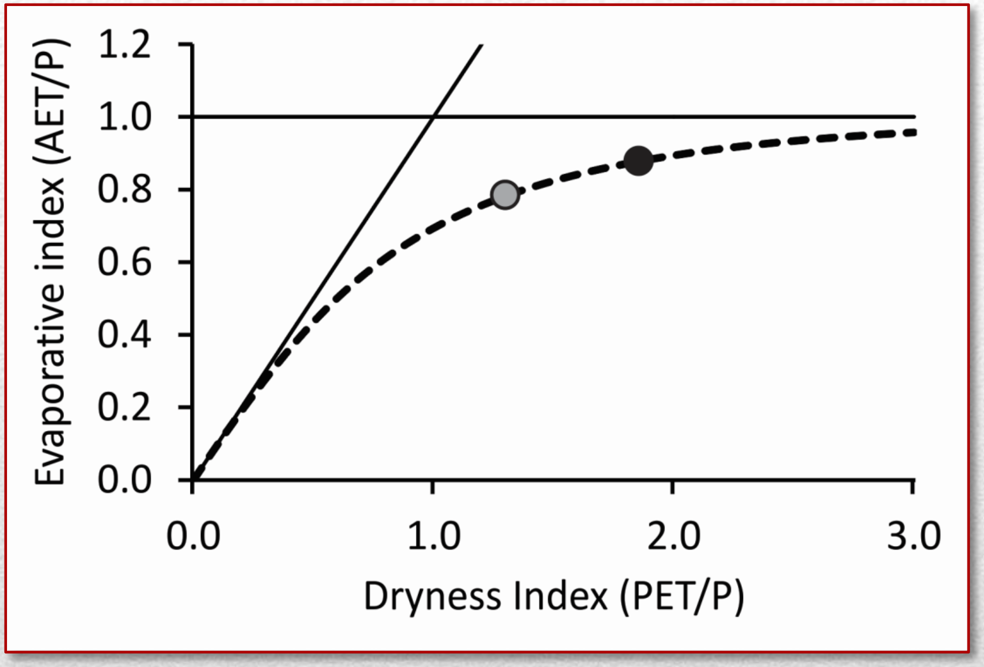
Deviations from Budyko Curve

We assume that the Budyko Curve represents the **reference condition** for the time period prior to anthropogenic climate change being detected in water yields.



Climate related deviations: the "d" statistic

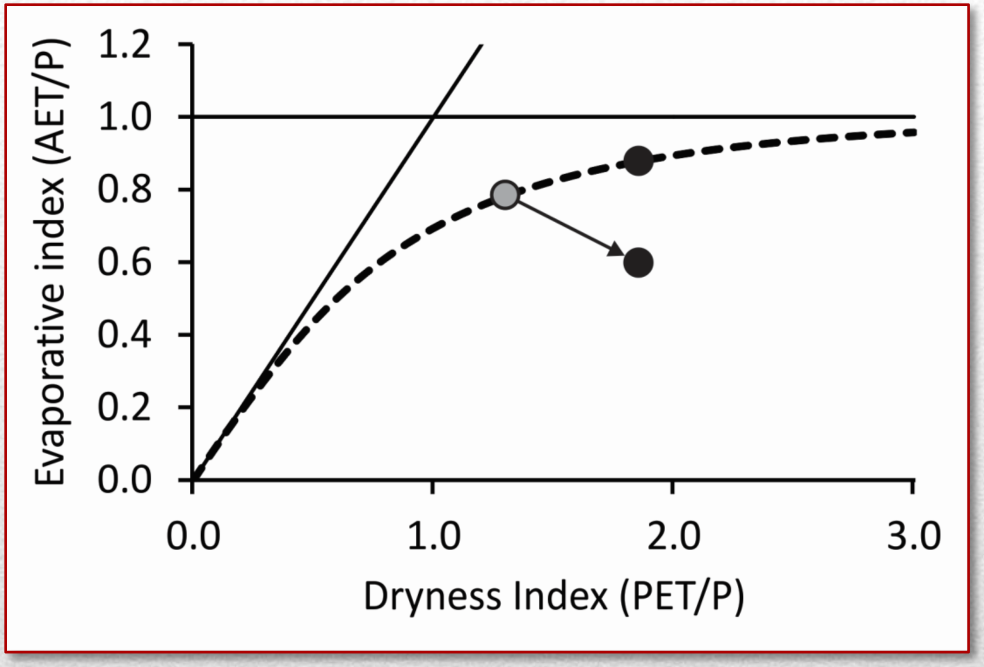
For naturally occurring climate oscillations, the partitioning between ET and Q should move up and down with the Budyko Curve.



Climate related deviations: the “d” statistic

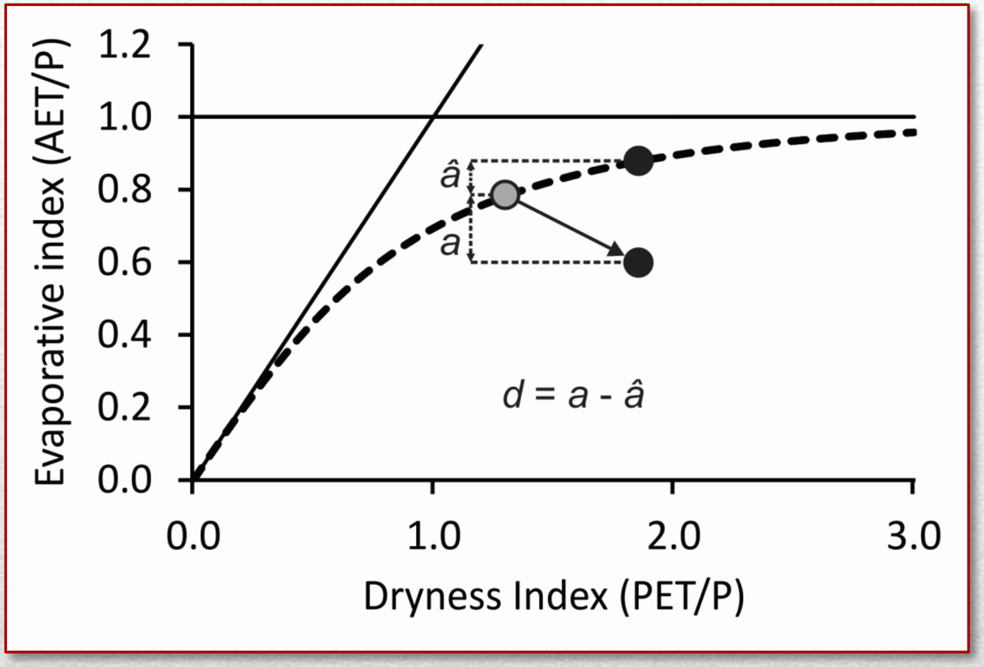
If the partitioning between ET and Q moves away from the Budyko Curve,

then this can be attributed to anthropogenic climate change.



Climate related deviations: the "d" statistic

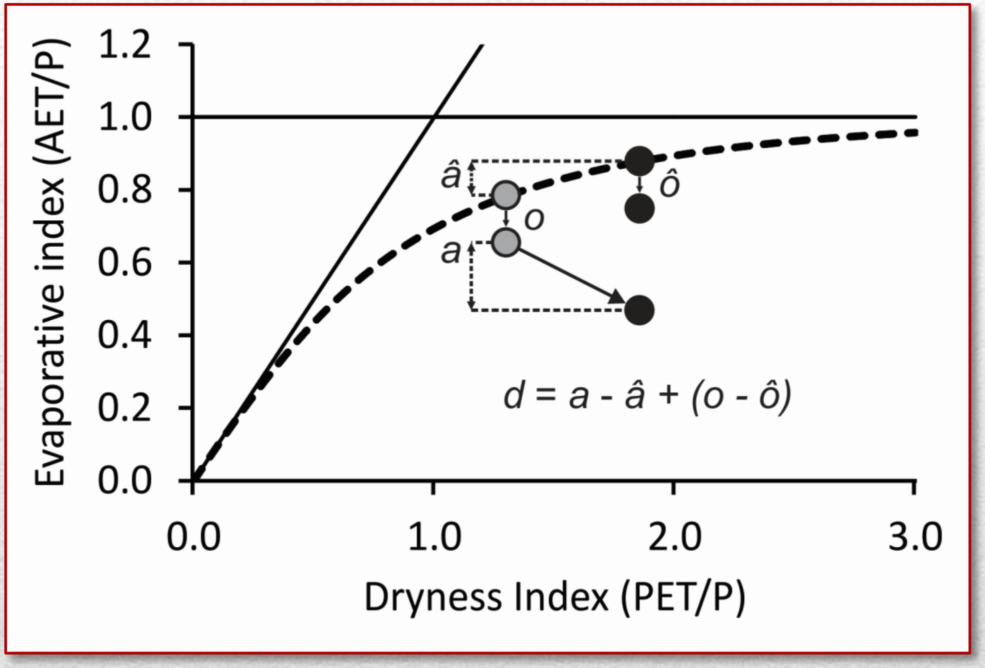
The “d” statistic, the deviation in AET/P due to climate change, is calculated.



Climate related deviations: the “d” statistic

We know that not all catchments fall on the Budyko Curve for reasons unrelated to climate (i.e., *o* and *ô* on plot).

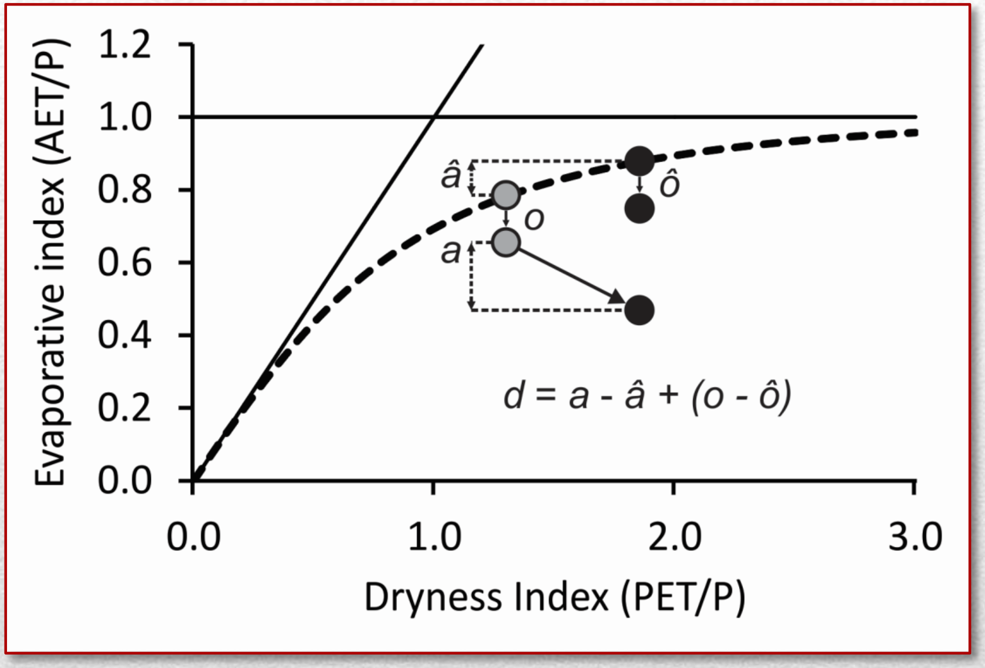
We assume these offsets are constant before and after climate change, and so this term becomes zero.



Climate related deviations: the "d" statistic

Negative *d* represents a downward shift and an increase in Q (more water yield).

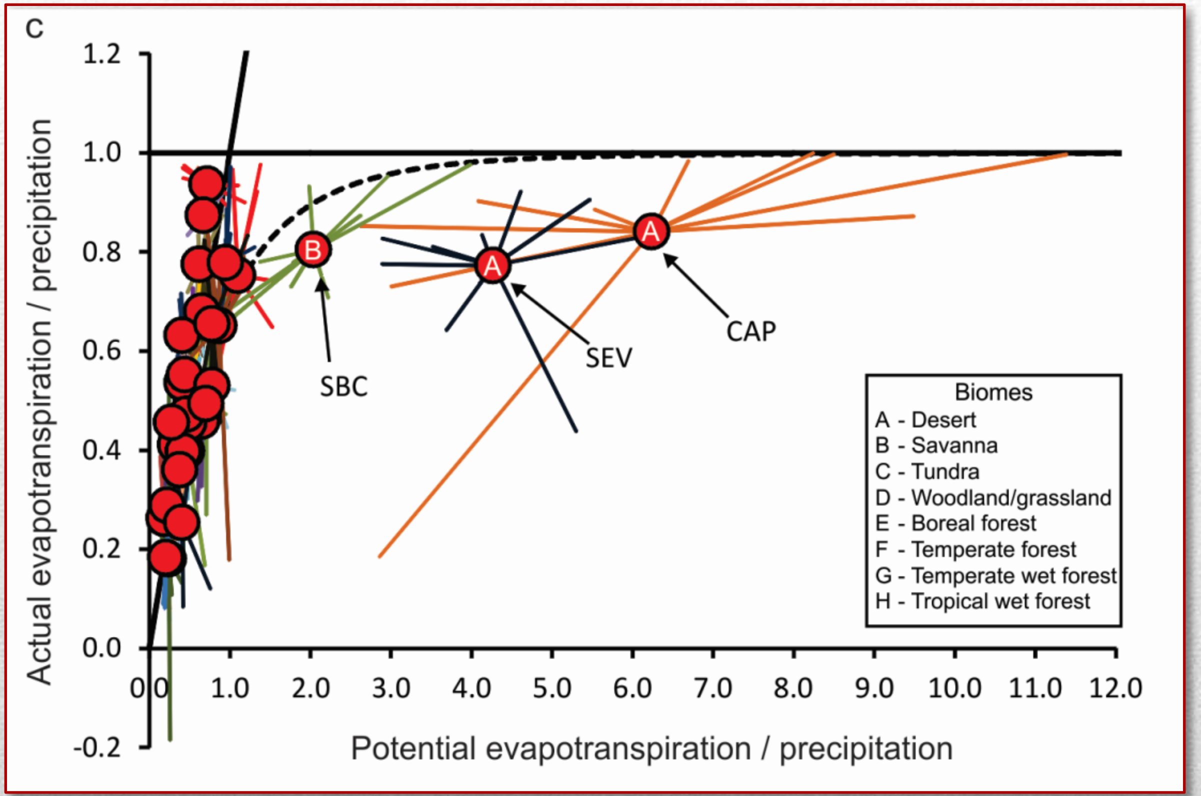
Positive *d* represents an upward shift an a decrease in Q (less water yield).



Climate related deviations: the "d" statistic

Can we identify catchment properties that influence water yields?

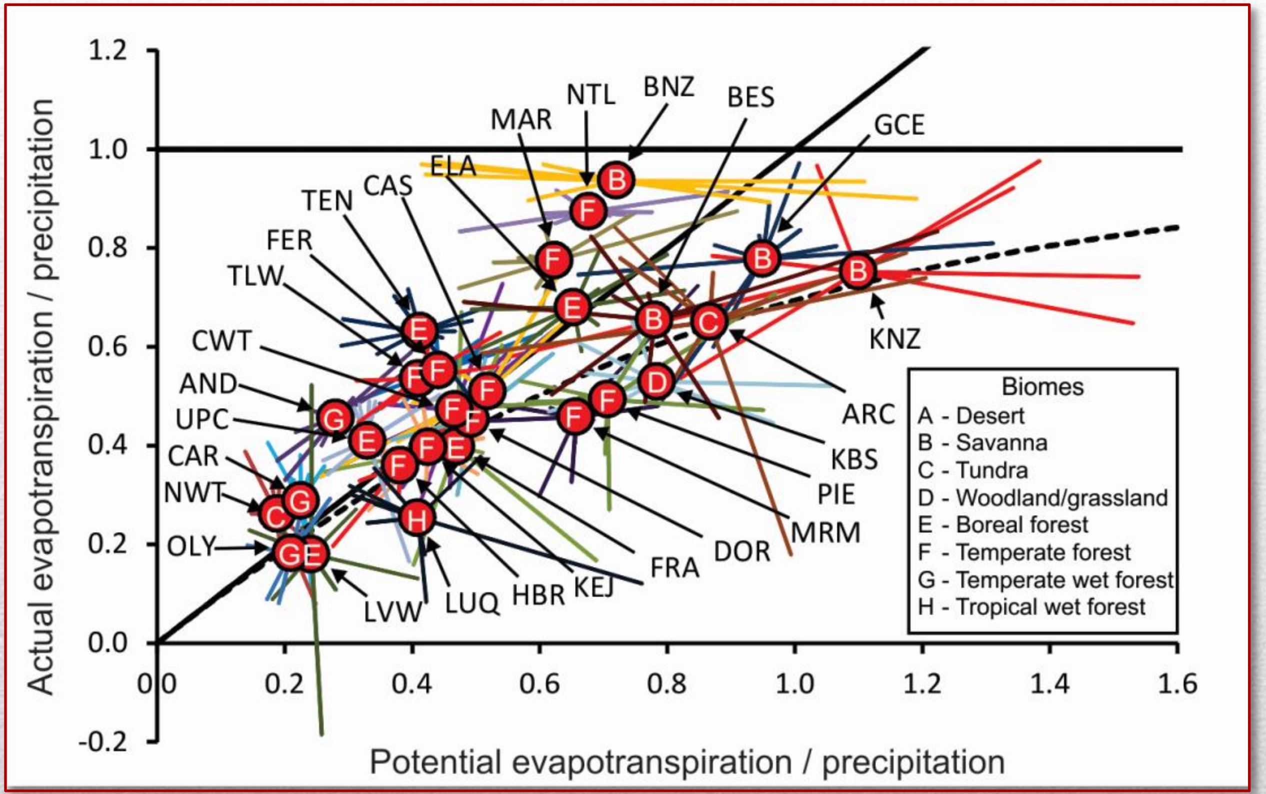
Spider plots showing year-to-year deviations from long term average



Inter-annual variation along Budyko Curve

Jones JA et al. (2012). *Ecosystem processes and human influences regulate streamflow response to climate change at long-term ecological research sites.* BioScience 62: 390–404.

Spider plots showing year-to-year deviations from long term average

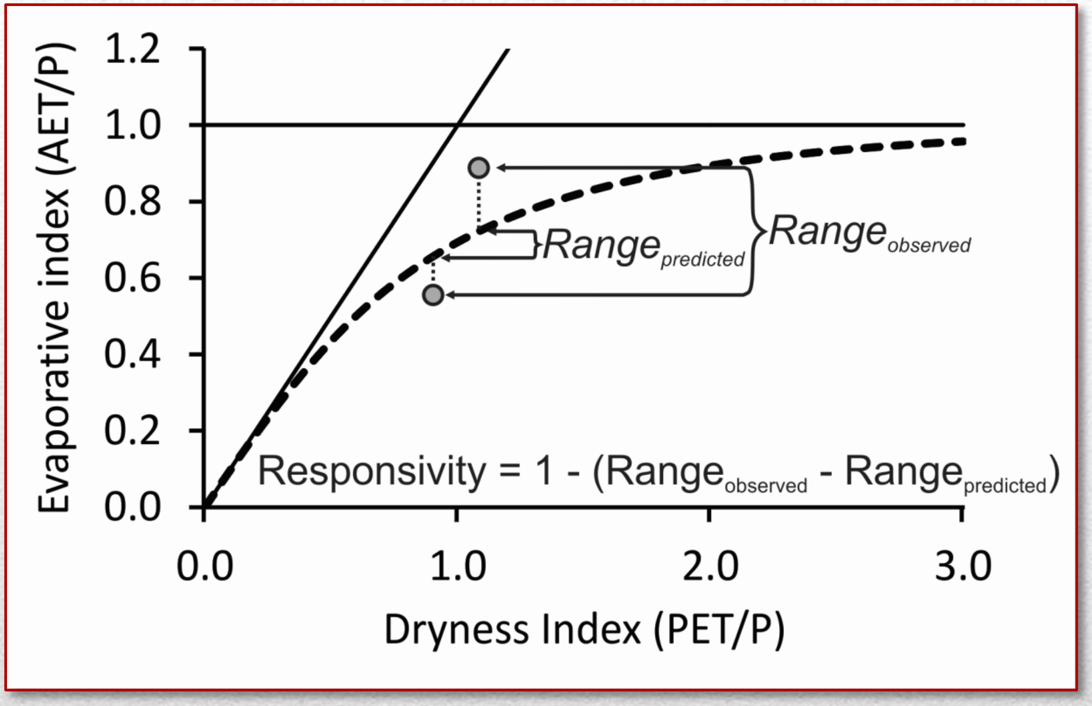


Inter-annual variation along Budyko Curve

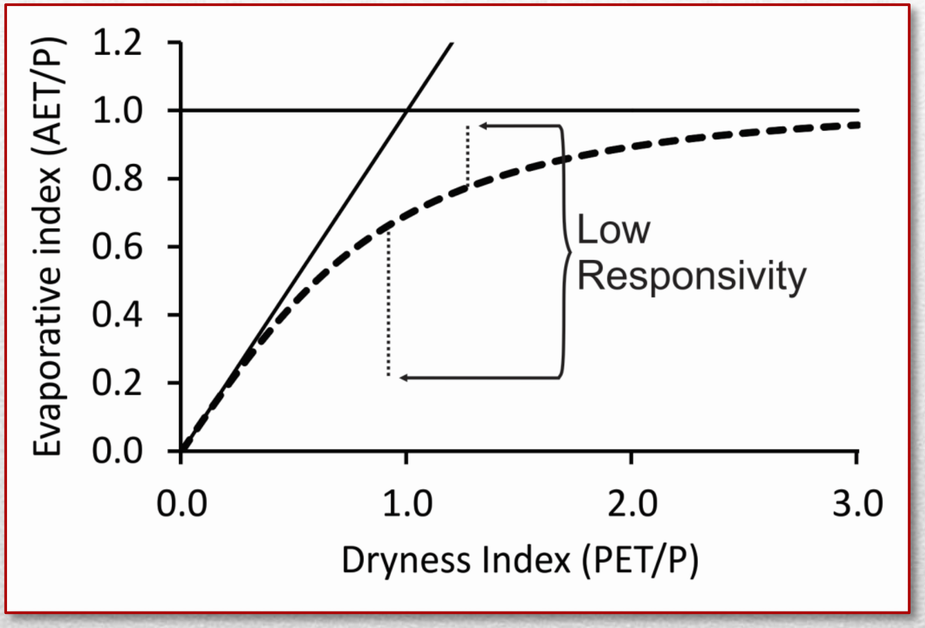
Jones JA et al. (2012). *Ecosystem processes and human influences regulate streamflow response to climate change at long-term ecological research sites.* BioScience 62: 390–404.

Pre climate change responsivity

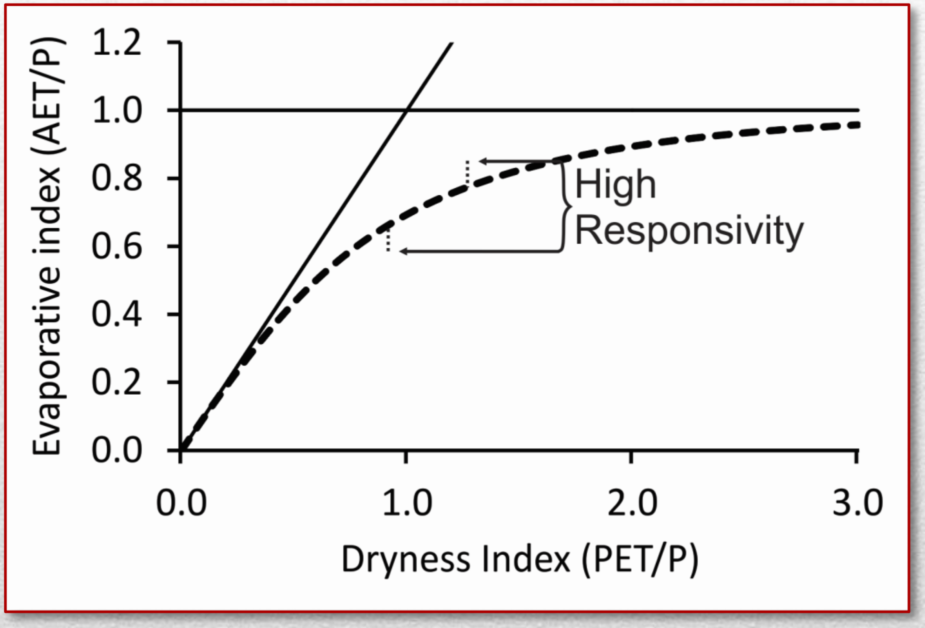
Responsivity is measured as the maximum range in AET/P after accounting for natural deviation in the Budyko Curve.



LOW RESPONSIVITY
Water yields are
not synchronized to P



HIGH RESPONSIVITY
Water yields are
synchronized to P

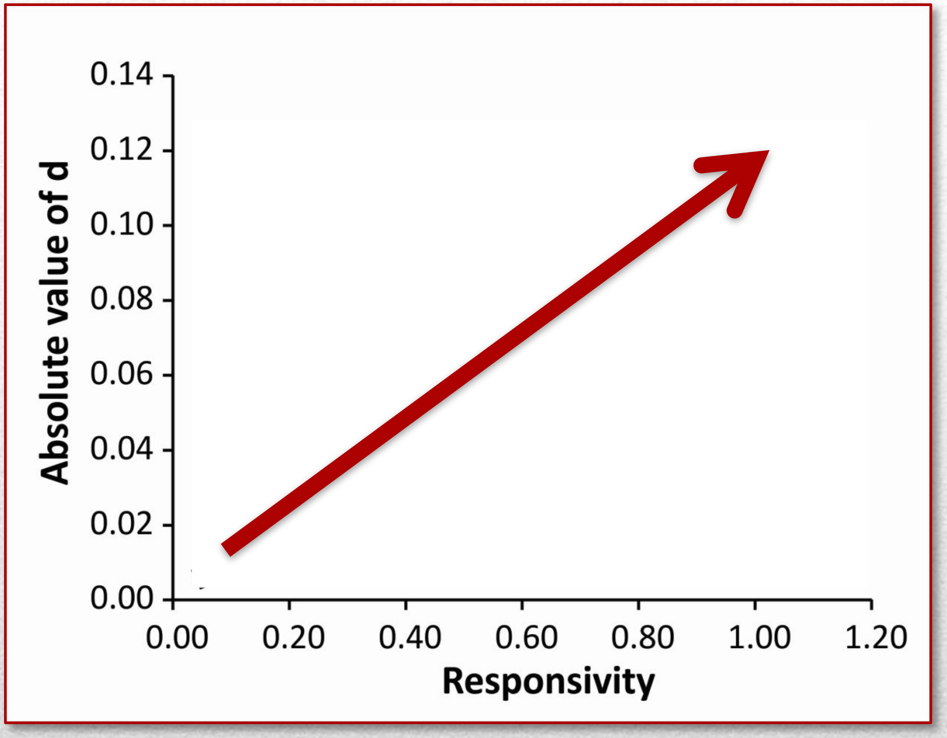


High *vs.* low responsivity

PREDICTION #1:

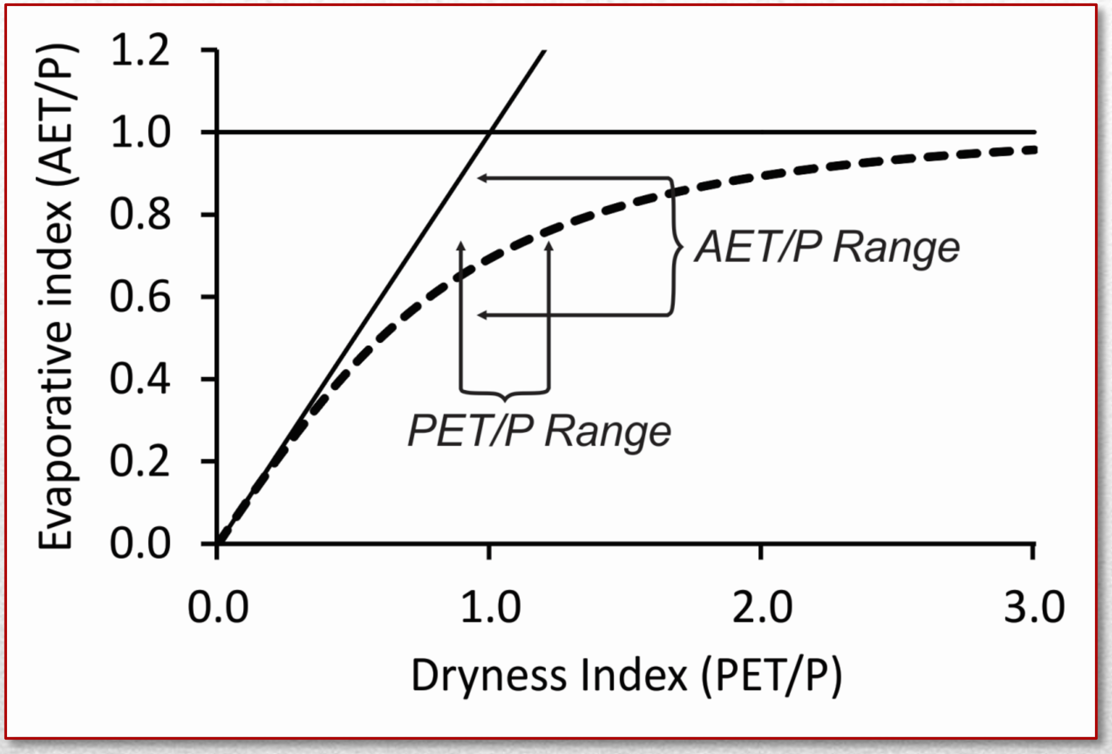
Larger deviations in catchments with ***higher responsivity***

(catchments cannot buffer against climate change and water yields strongly linked to the atmosphere).



Pre climate change responsivity *vs.* "d"

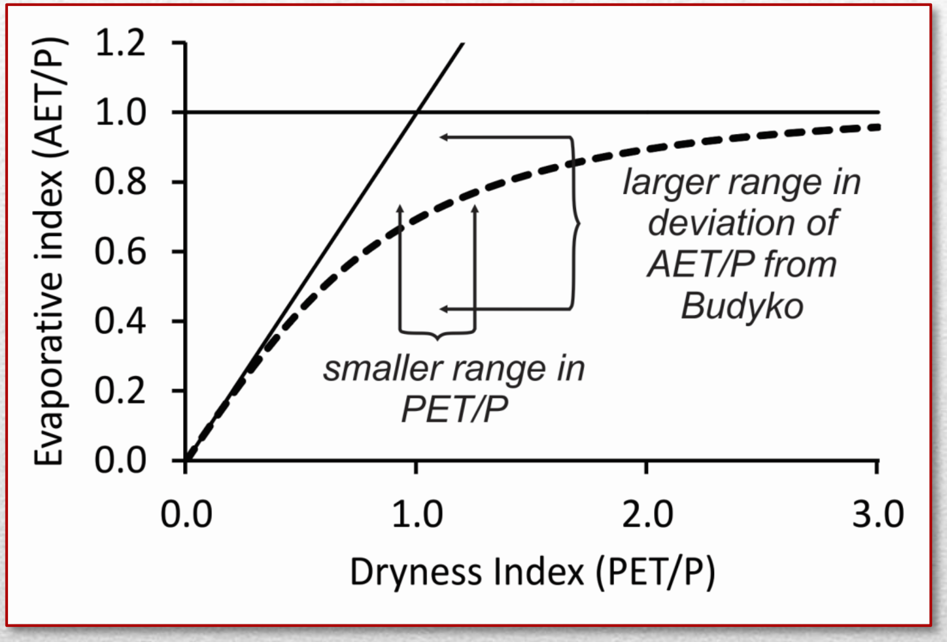
Elasticity is measured as the ratio of range of PET/P to AETP/P.

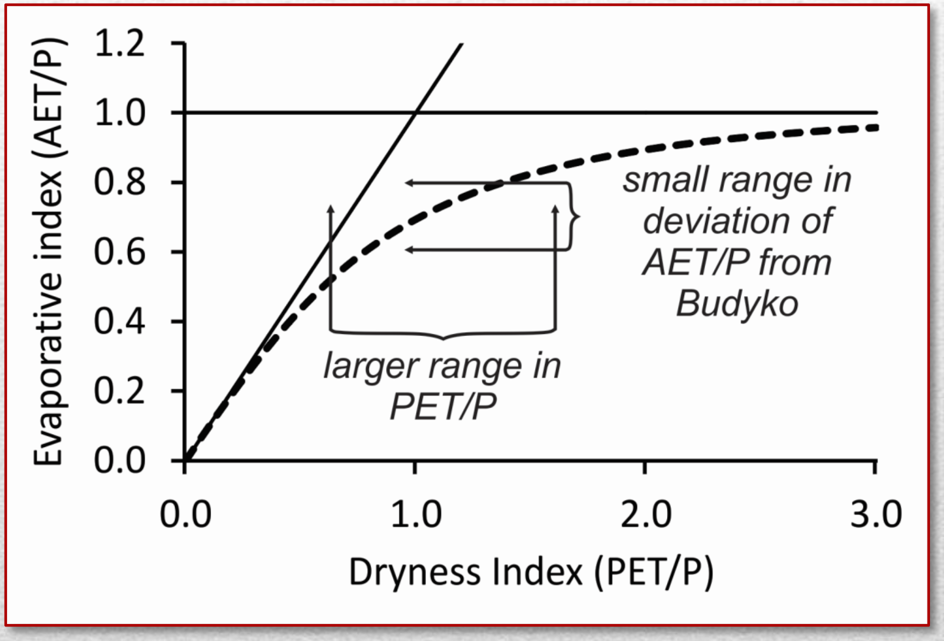


Pre climate change elasticity

LOW ELASTICITY (<1)
small PET/P range
relative to AET/P range

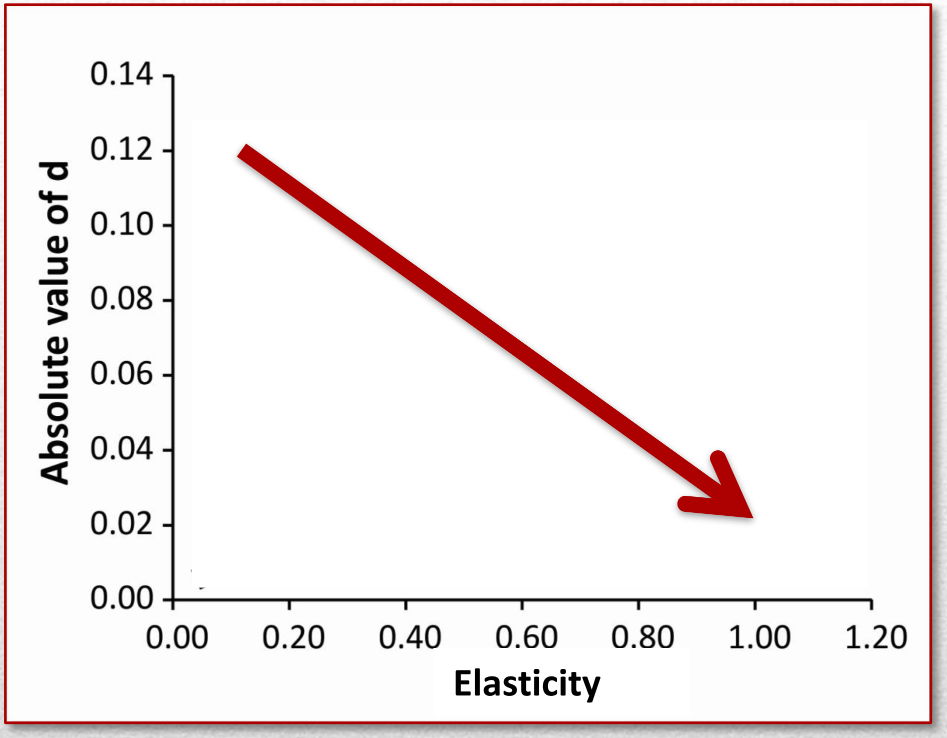
HIGH ELASTICITY (>1)
large PET/P range
relative to AET/P range



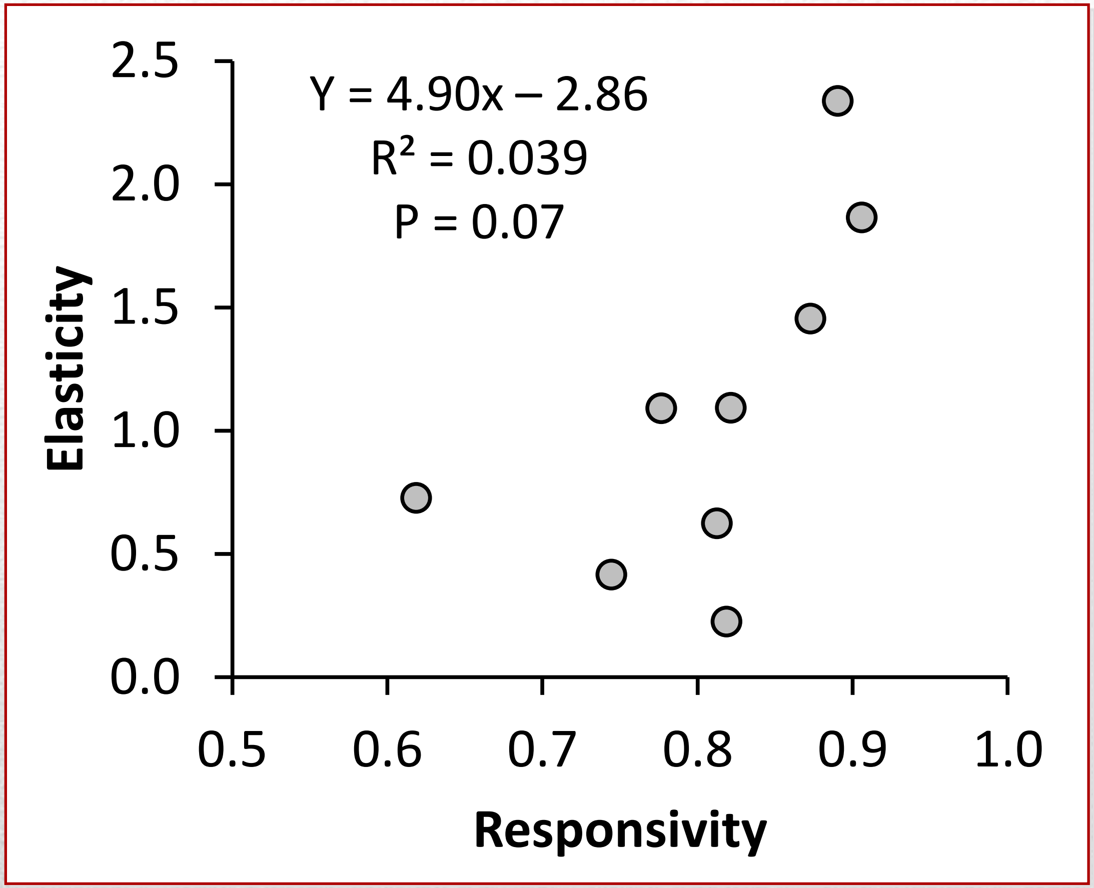


High *vs.* low elasticity

PREDICTION #2:
Larger deviations in catchments with ***lower elasticity*** (*(*catchments cannot acclimate/adapt to changing climatic conditions)



Pre climate change elasticity *vs.* "d"



Responsivity *does not* imply elasticity

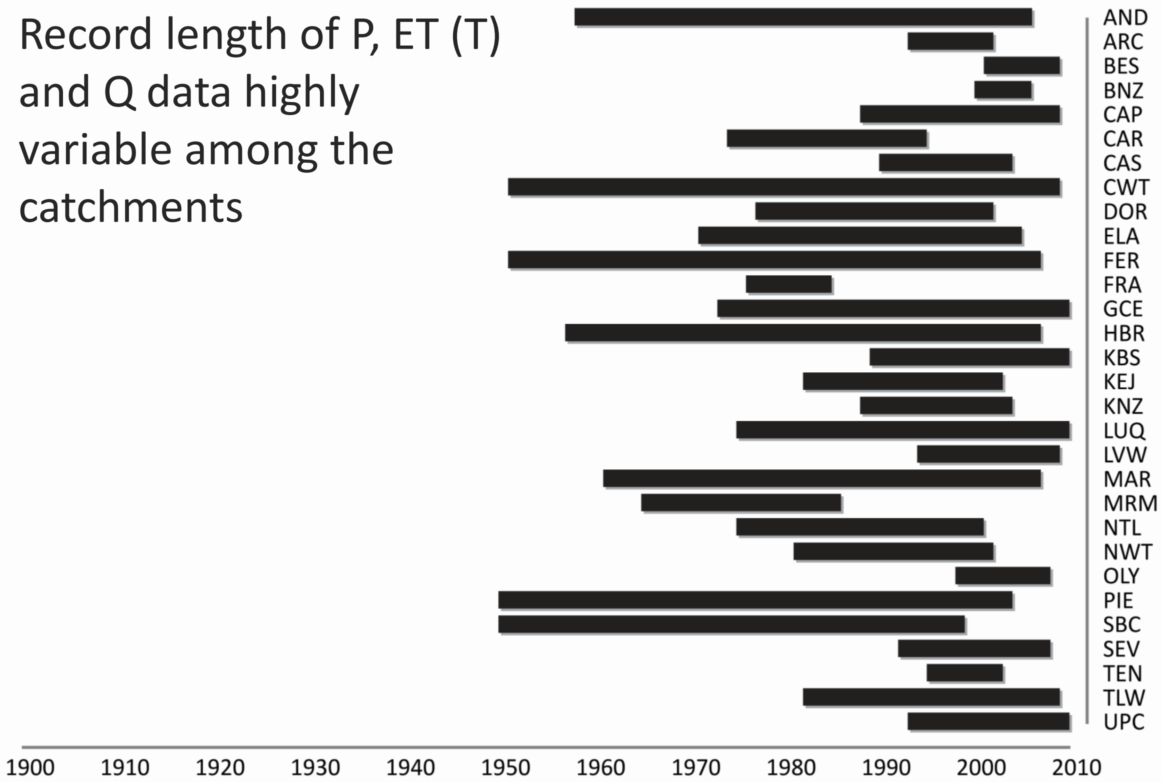
Applying these metrics to test hypotheses

Defining the onset of anthropogenic climate change to identify pre *vs.* post behavior

Wang and Henjazi adopted a constant breakpoint (1970) to detect the effects of global environmental change on water yields across USA

Wang D and M Hejazi. (2011). *Quantifying the relative contribution of the climate and direct human impacts on mean annual streamflow in the contiguous United States*. Water Resour. Res. 47: W00J12, doi:10.1029/2010WR010283.

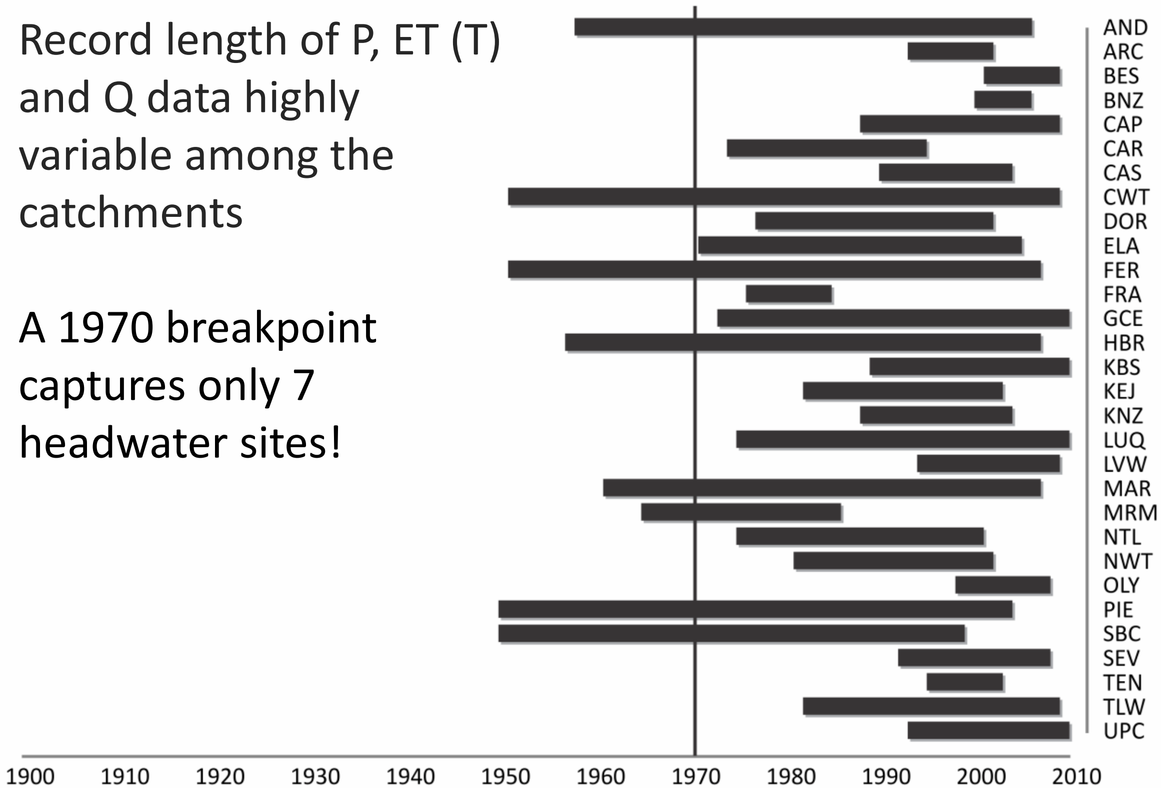
Record length of P, ET (T) and Q data highly variable among the catchments



Constant breakpoint

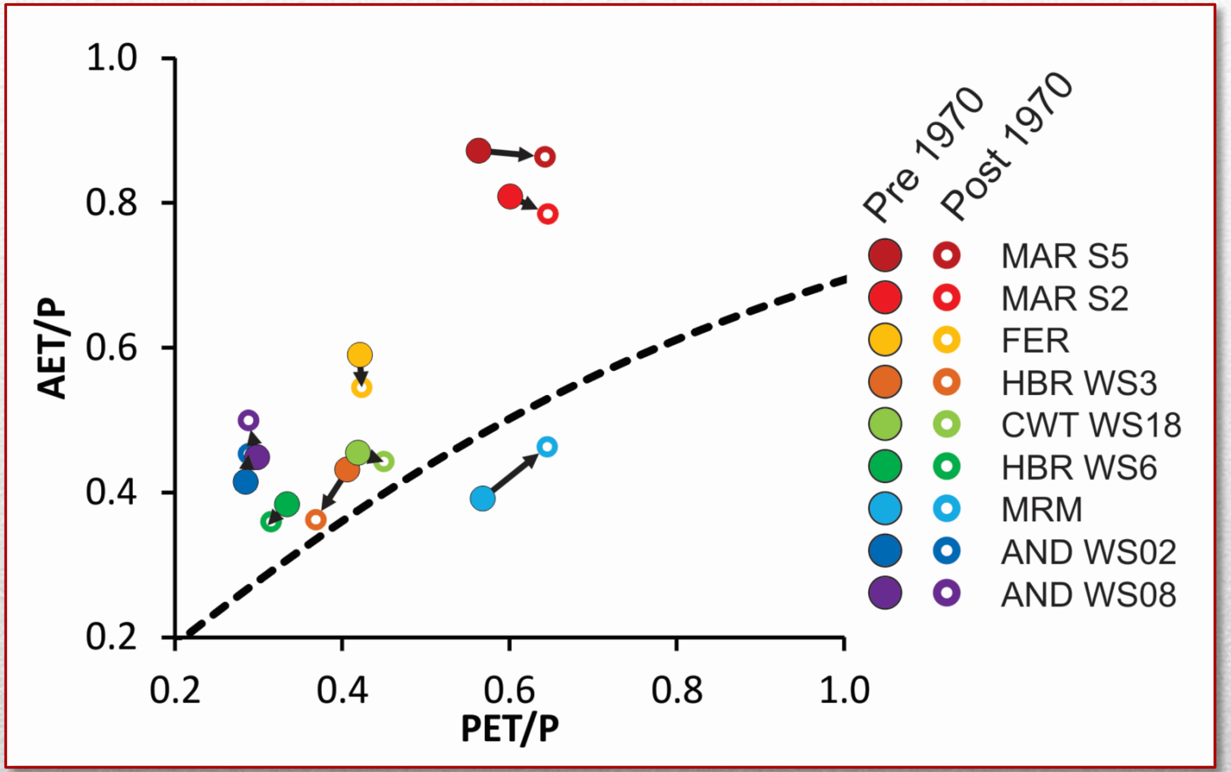
Record length of P, ET (T) and Q data highly variable among the catchments

A 1970 breakpoint captures only 7 headwater sites!



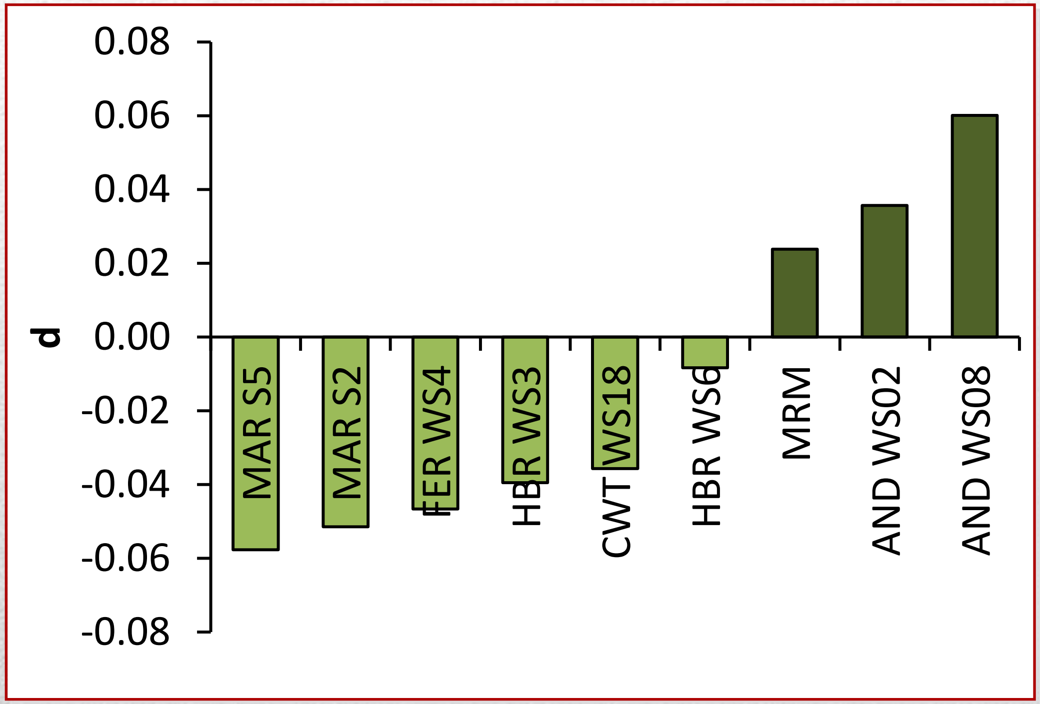
Constant breakpoint

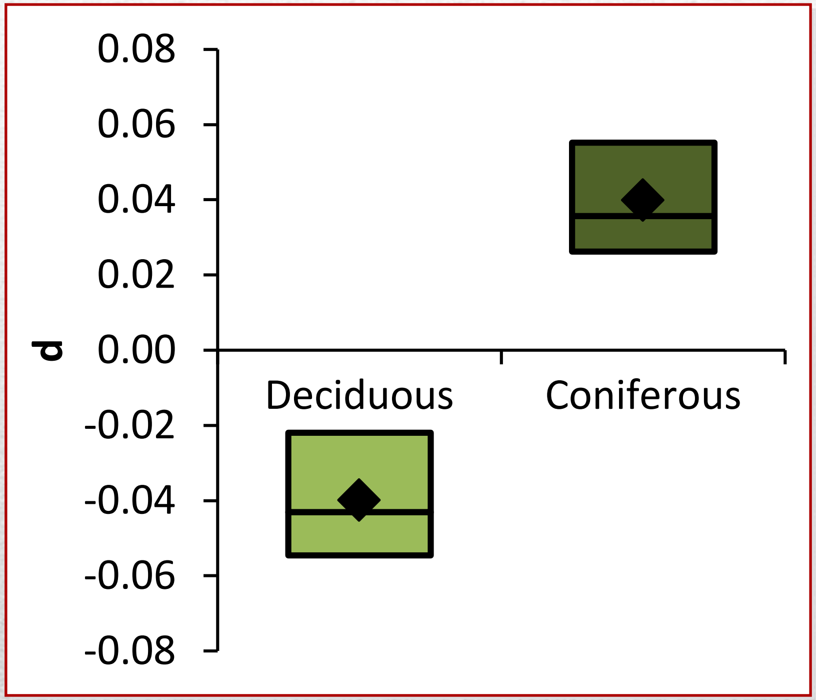
Some sites observing net positive changes while others observing net negative changes.



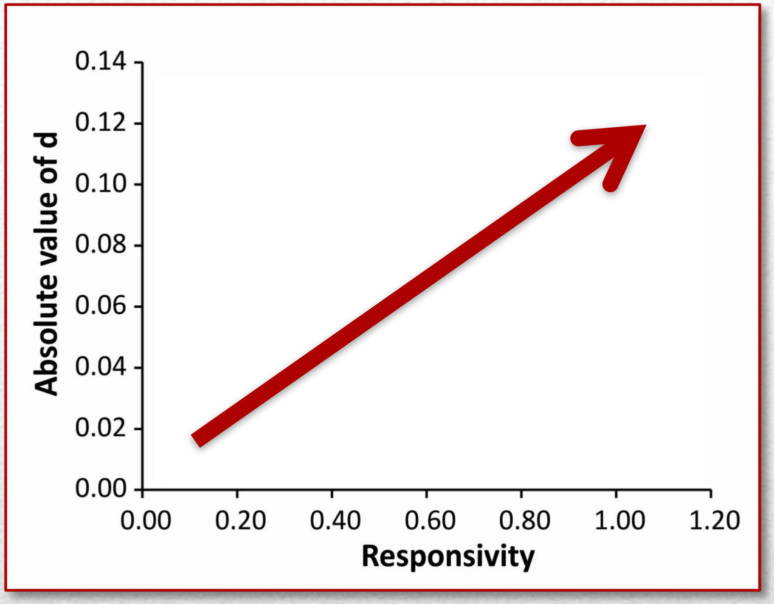
Constant breakpoint: pre *vs.* post changes

POSITIVE deviations (lower water yields) in coniferous forests and NEGATIVE deviations (higher water yields) in deciduous forests

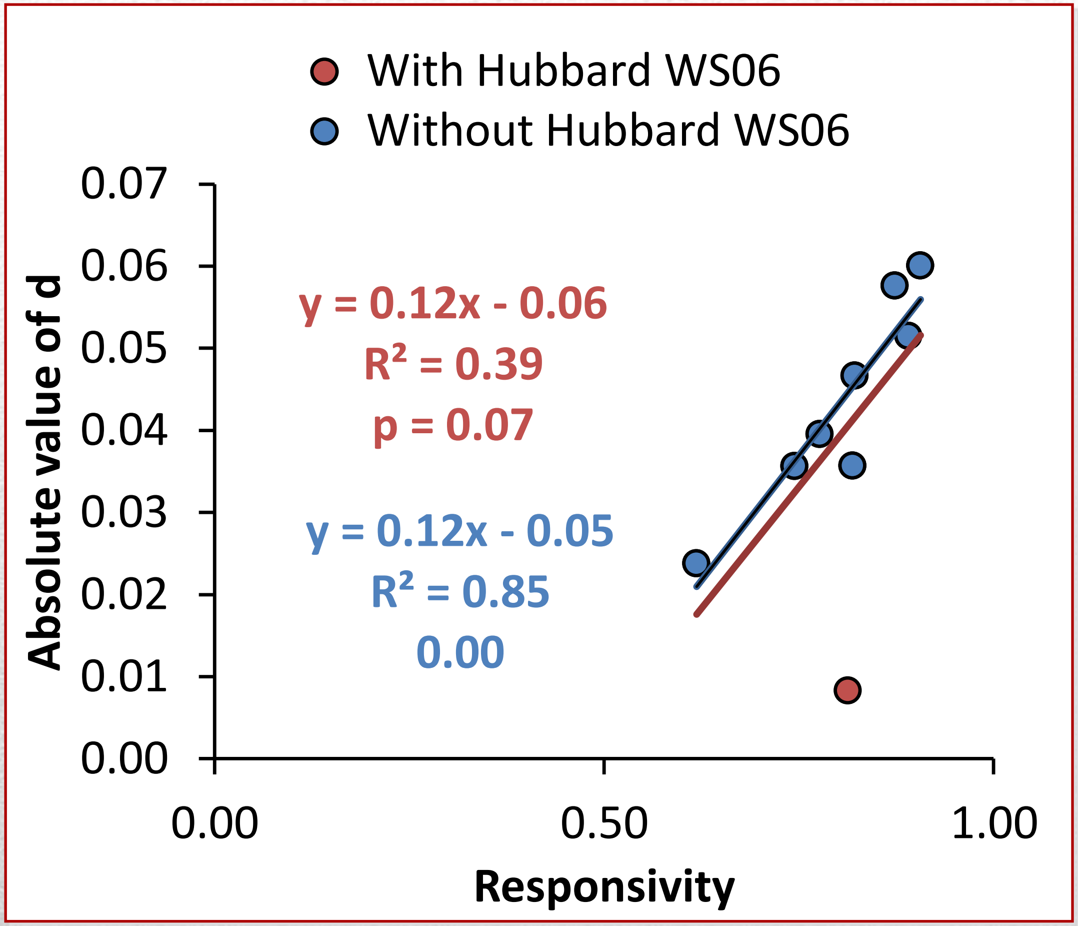




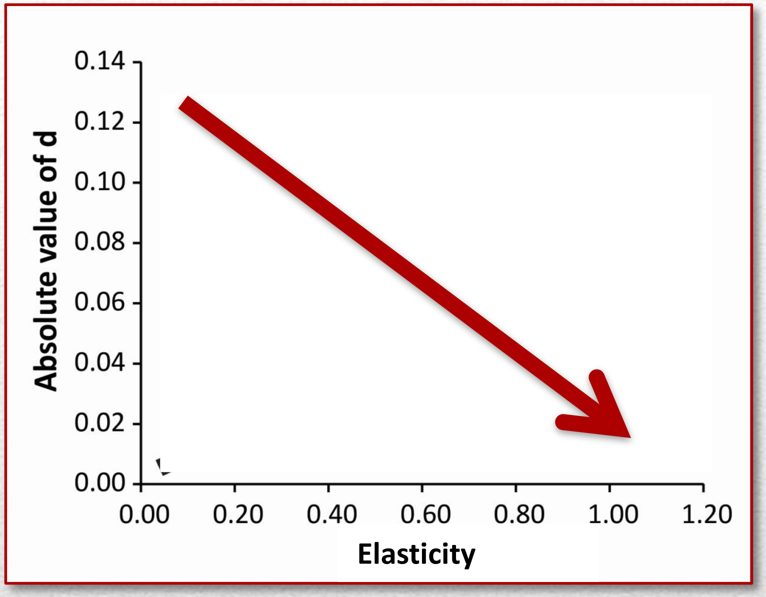
Constant breakpoint: deviation (“d”)



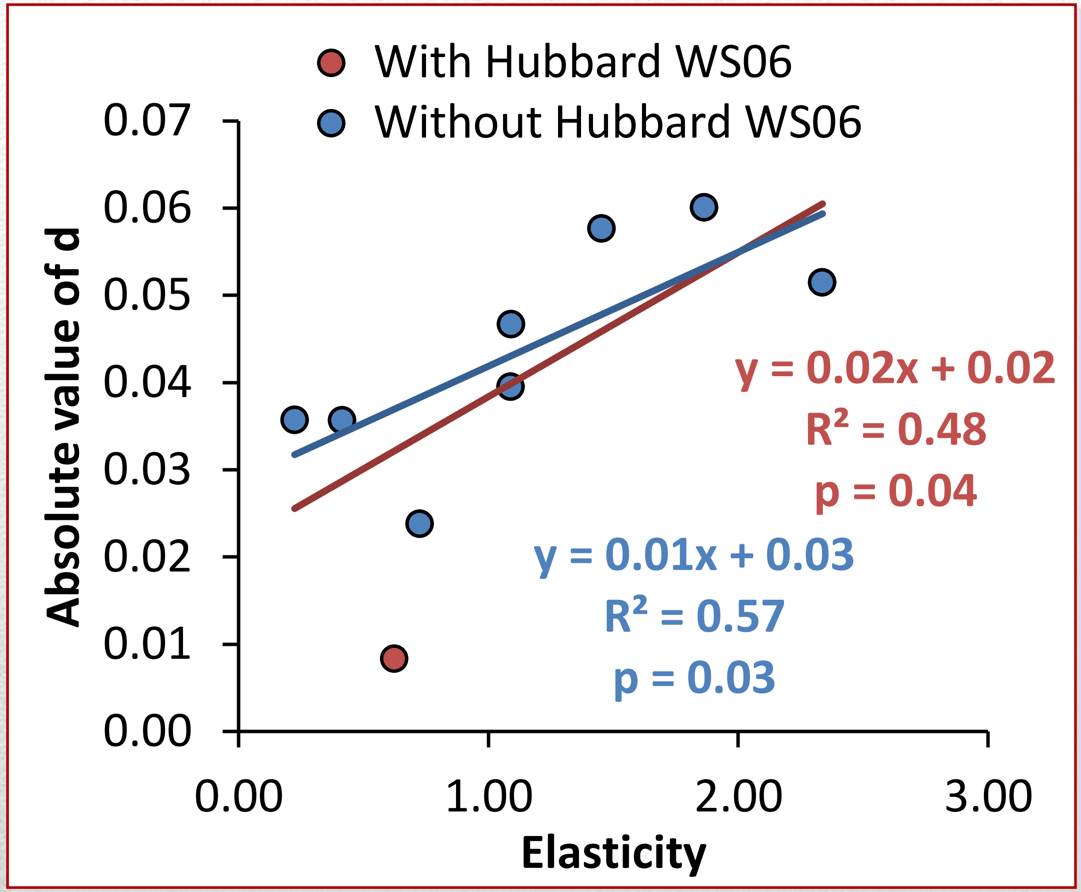
PREDICTION #1



Constant breakpoint: responsivity *vs.* “d”

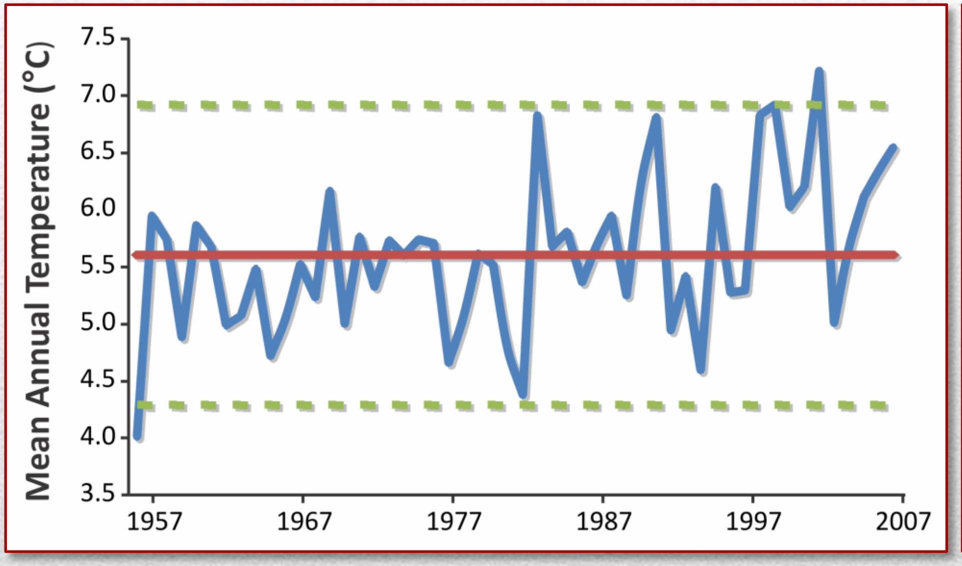


PREDICTION #2

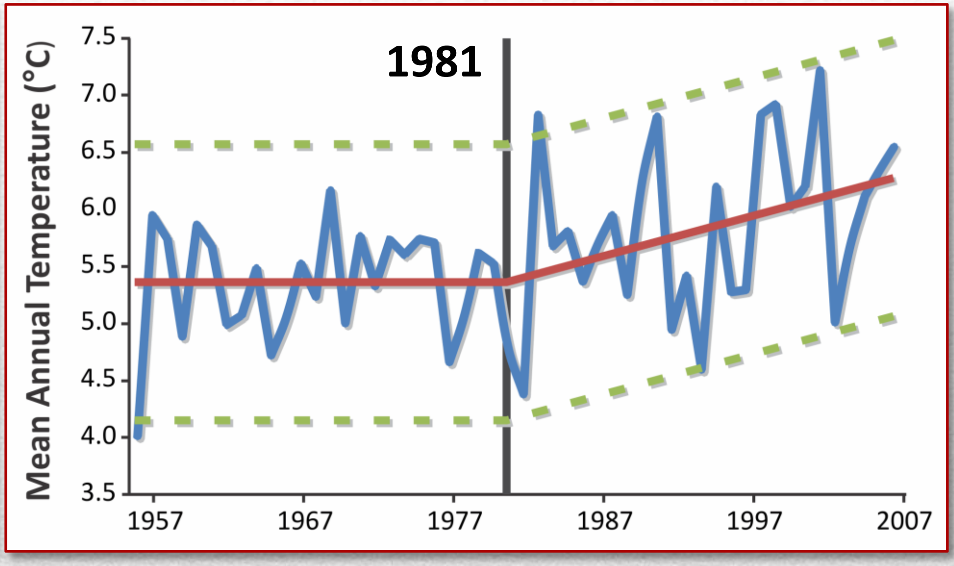


Constant breakpoint: elasticity *vs.* "d"

Use **AutoRegressive Integrated Moving Average** technique to check for breakpoints at each year from 1960 to 2000 (Ford et al. 2006).



No breakpoint

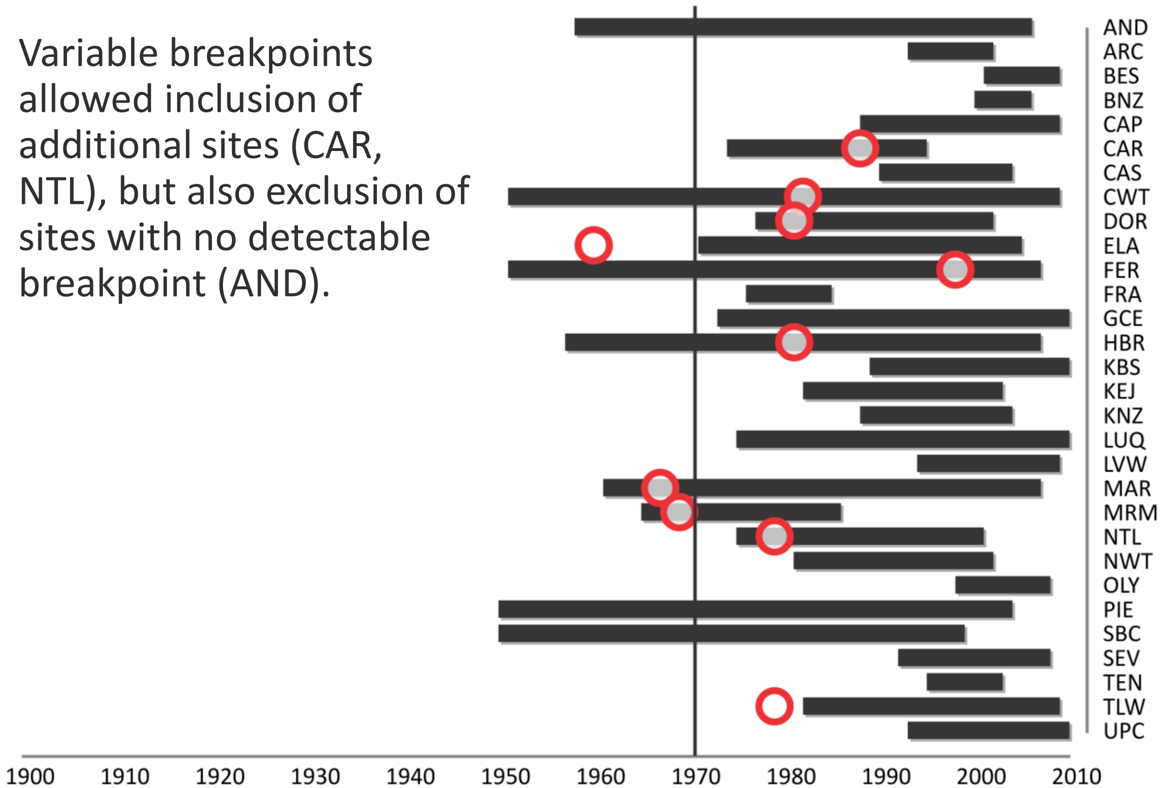


Breakpoint at 1981

Variable breakpoint

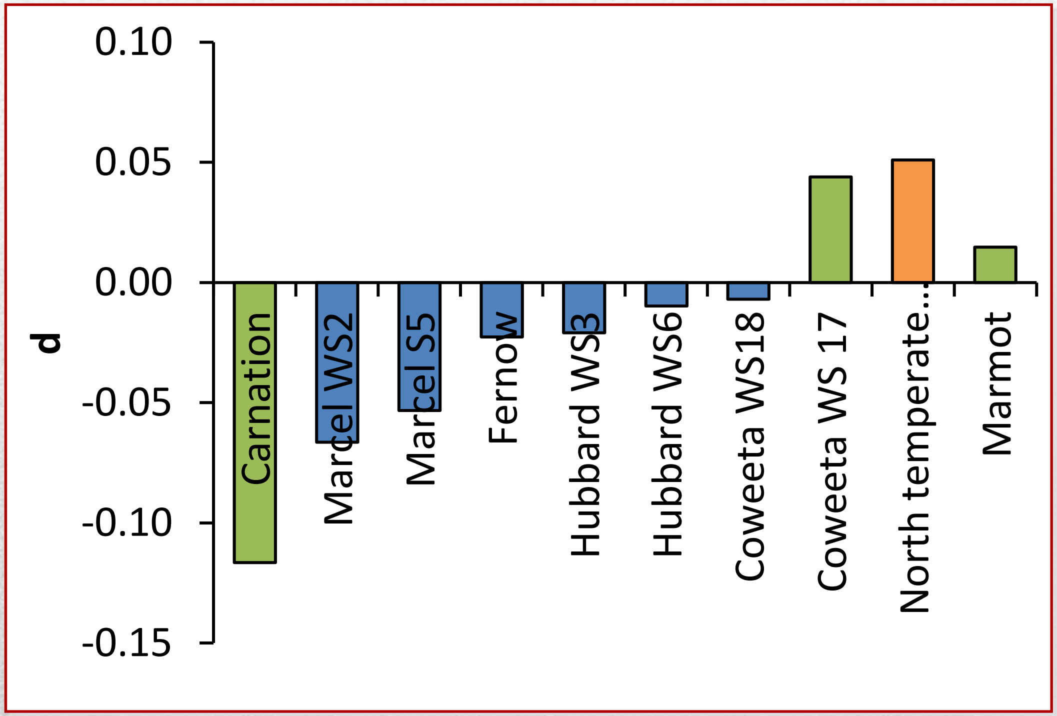
Ford CR, SH Laseter, WT Swank, JM Vose. (2011). *Can forest management be used to sustain water-based ecosystem services in the face of climate change?* Ecological Applications 21: 2049–2067.

Variable breakpoints allowed inclusion of additional sites (CAR, NTL), but also exclusion of sites with no detectable breakpoint (AND).

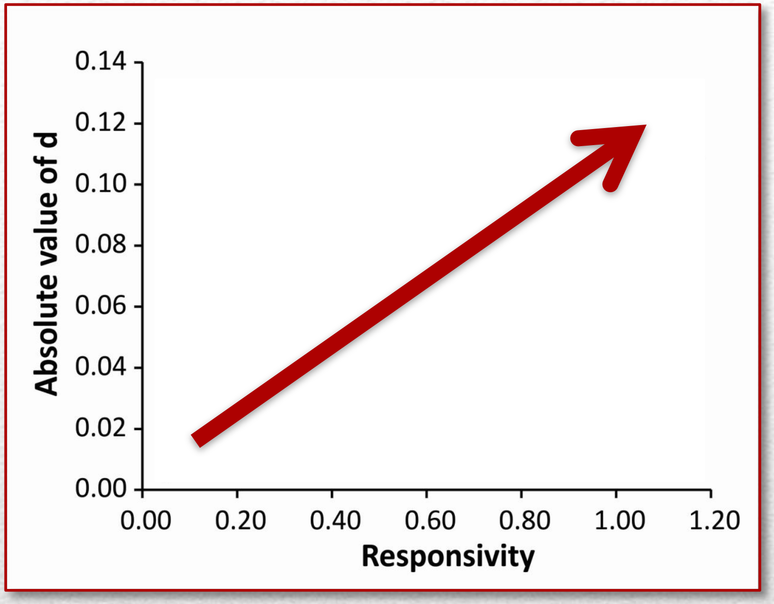


Variable breakpoint

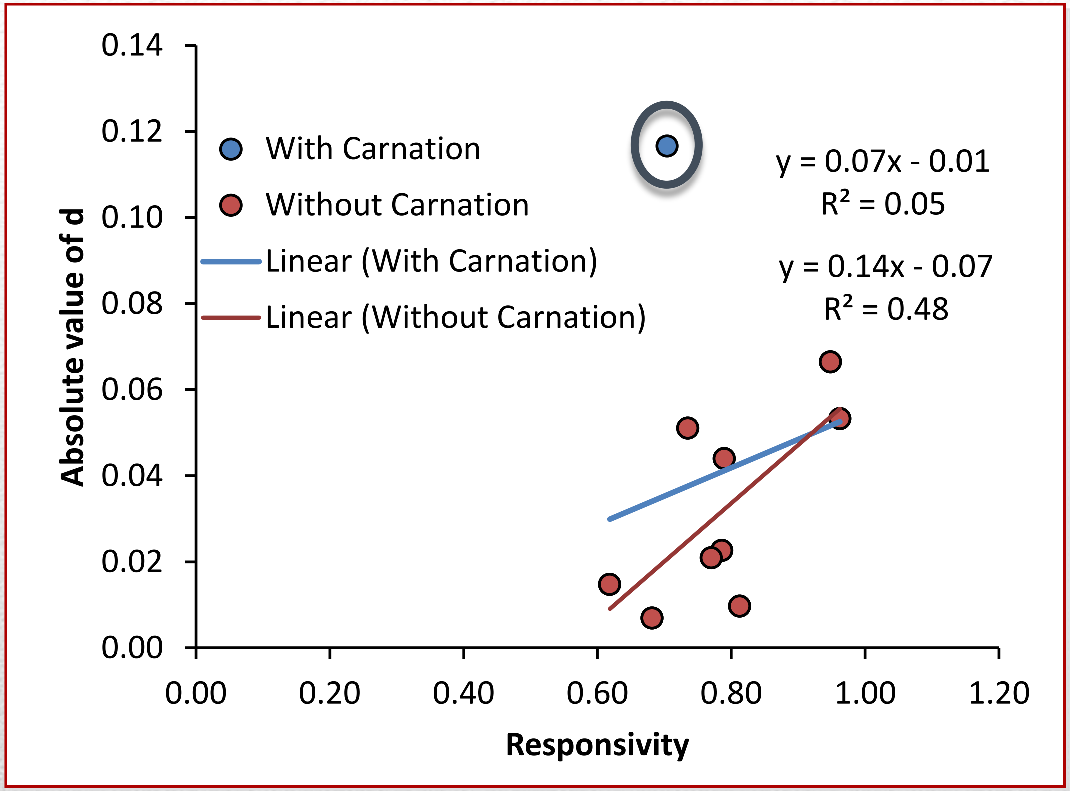
Similar separation of
deciduous (positive water yields) *vs.*
coniferous (negative water yields)
in the variable breakpoint analysis, except Carnation Creek.



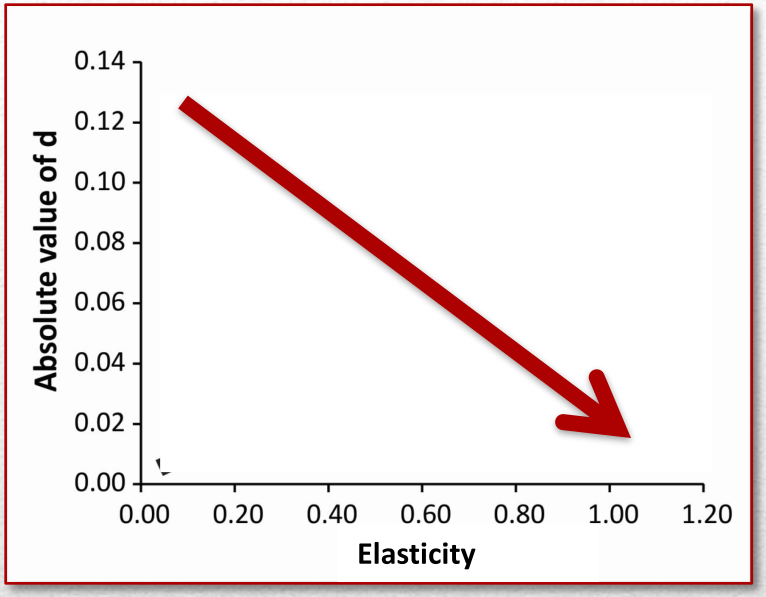
Variable breakpoint: deviation (“d”)



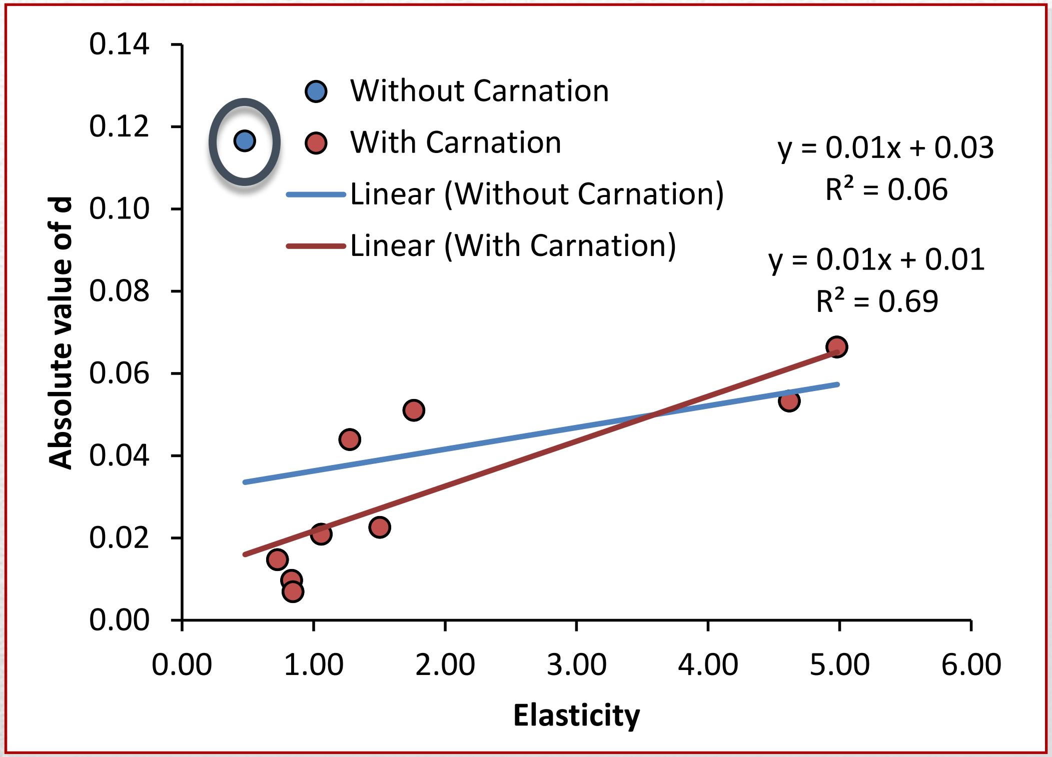
PREDICTION #1



Variable breakpoint: responsivity *vs.* “d”



PREDICTION #2



Variable breakpoint: elasticity *vs.* "d"

Constant *vs.* variable breakpoints

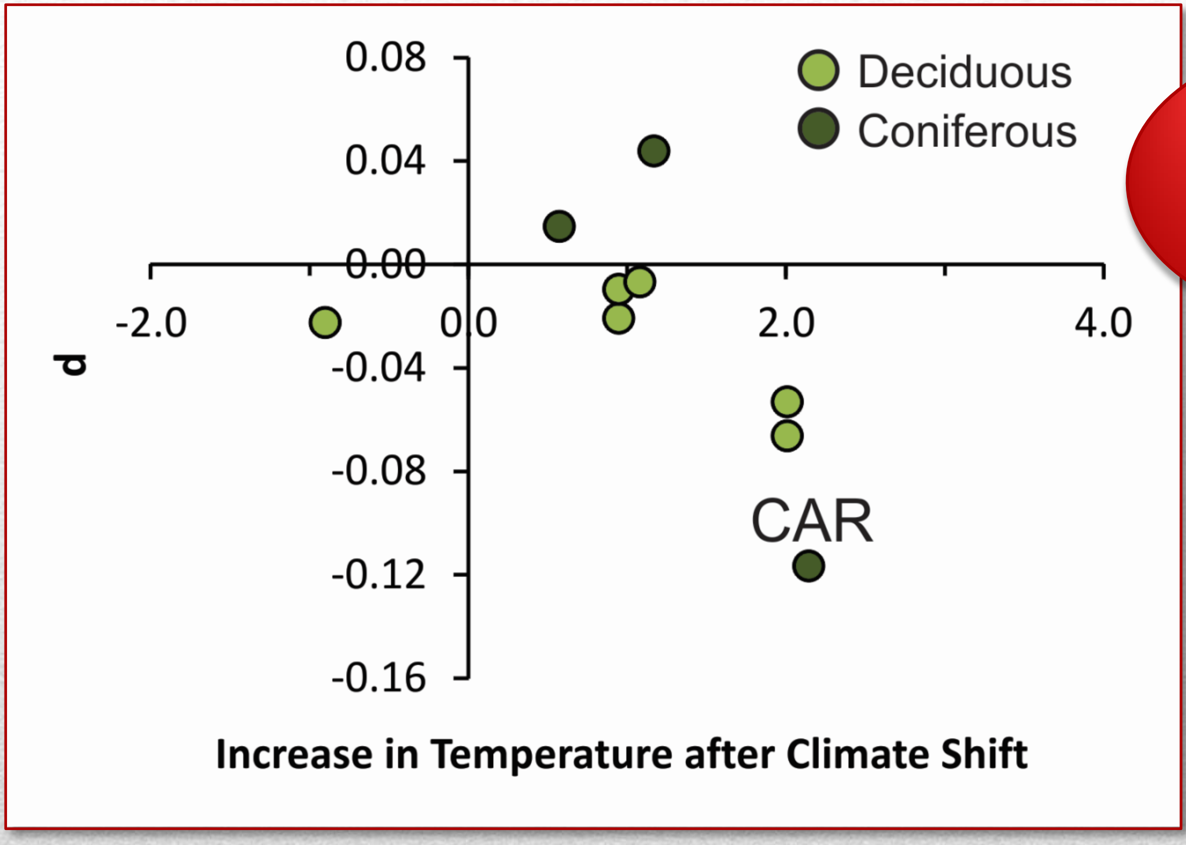
Similar relationships observed between responsivity and elasticity *vs.* absolute value of "d".

Variable breakpoint relationships reveal a "significant" outlier (Carnation Creek, BC).

Need to delve further into the data to identify causes for this outlier – examine magnitude of temperature increase after the breakpoint.

Is the outlier key to our understanding?

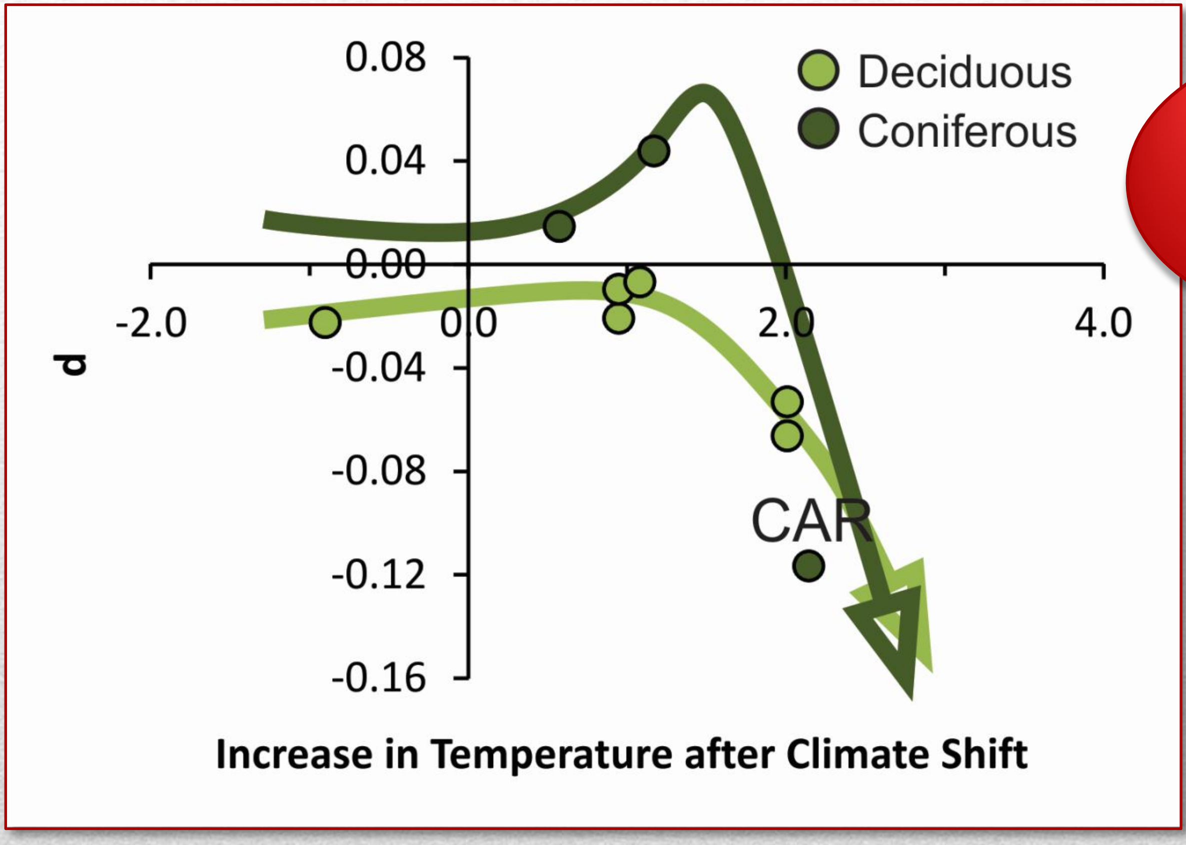
As temperature increases above 0, d increases



Average increase in temperature estimated by slope of line after breakpoint

Rate of temperature increase *vs.* “d”

As temperature increases above 0, d increases



Average increase in temperature estimated by slope of line after breakpoint

Rate of temperature increase *vs.* “d”

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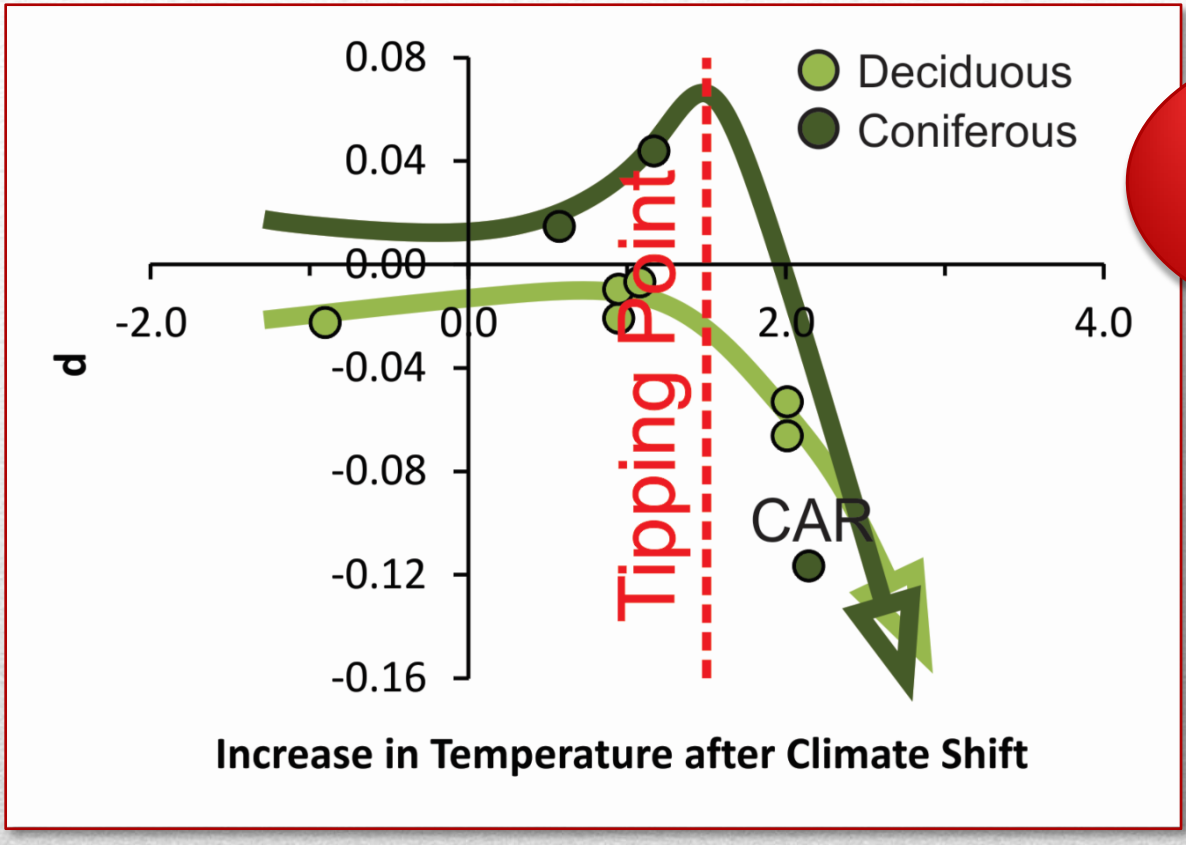


Average increase in temperature estimated by slope of line after breakpoint

Rate of temperature increase *vs.* "d"

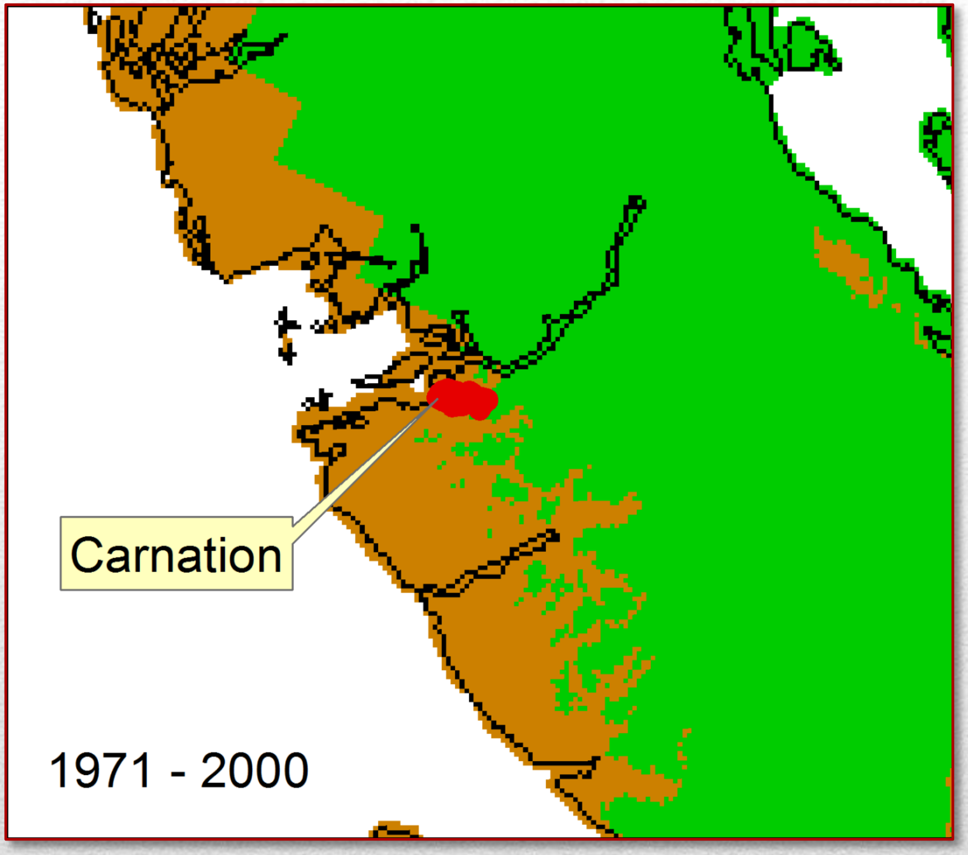
Outlier: Carnation Creek, BC

- Western hemlock
- Largest "d" and highest rate of anthropogenic climate change (2°C/decade)

Is water yield of the outlier catchment at greater risk because its tree species is "at the edge" of its climate tolerance?

Climatic Parameter	Parameter Mean	Parameter Range (min and max)
Annual mean temperature	5.13 °C	-4.66 to 12.93 °C
Annual total precipitation	1600 mm/year	237 to 4196 mm/year

Prior to anthropogenic climate change, Carnation Creek fell at the edge of the range of Western Hemlock.



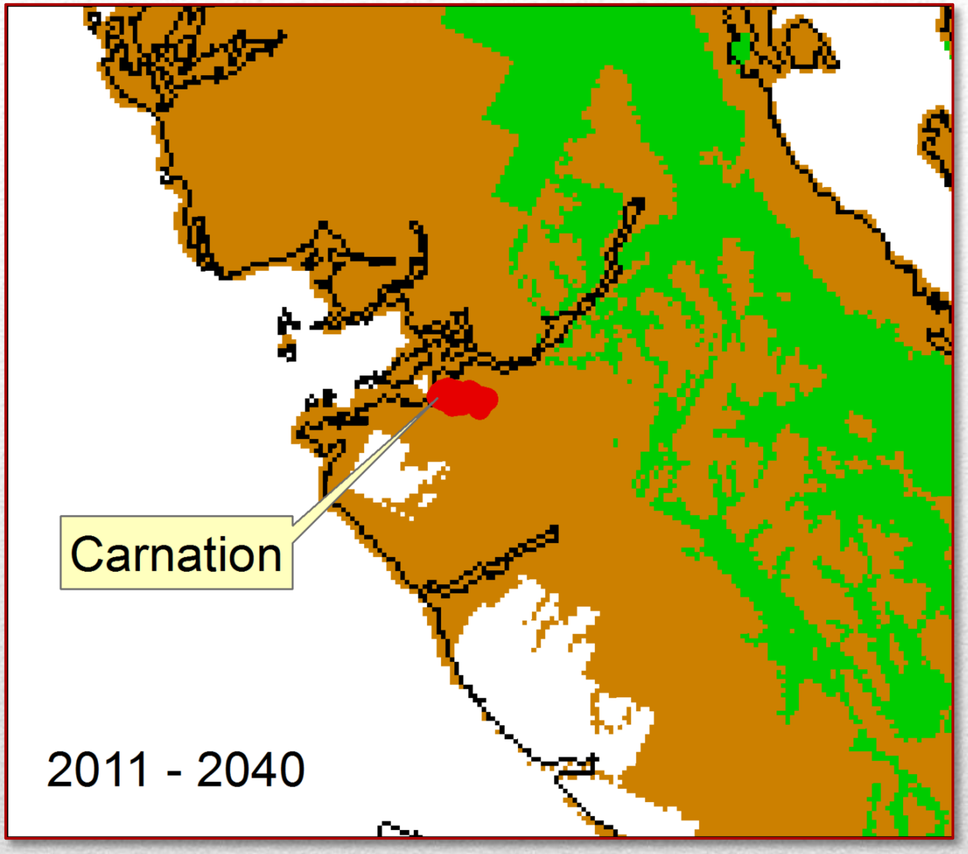
Maximum Range

5th – 95th Percentile

Baseline 1971 - 2000

McKenney DW, et al. (2007). *Potential impacts of climate change on the distribution of North American trees.* Bioscience 57: 939-948.

Based on CGCM model simulations, the range of Western Hemlock will recede on Vancouver Island.



Maximum Range

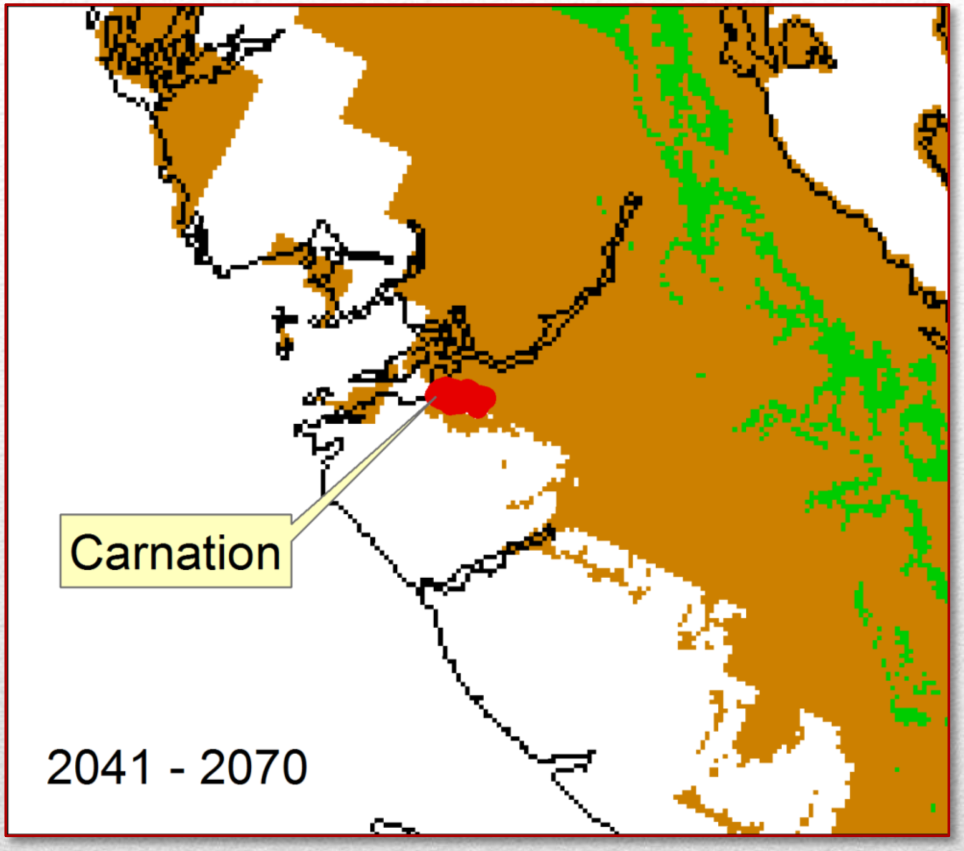
5th – 95th Percentile

First 30 years, 2011 - 2040

McKenney DW, et al. (2007). *Potential impacts of climate change on the distribution of North American trees.* Bioscience 57: 939-948.

Based on CGCM model simulations, the range of Western Hemlock will recede on Vancouver Island.

By mid 21st century, Carnation Creek will lie at the edge of the maximum range of Western Hemlock.



Maximum Range

5th – 95th Percentile

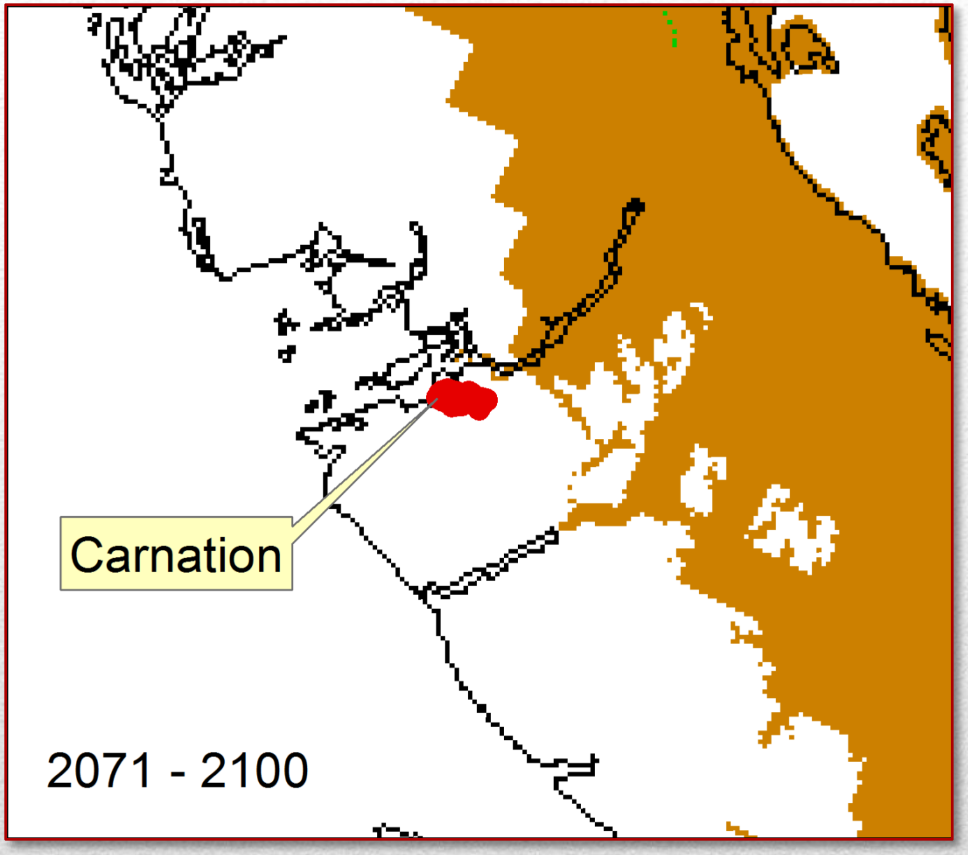
Second 30 years, 2041 - 2070

McKenney DW, et al. (2007). *Potential impacts of climate change on the distribution of North American trees.* Bioscience 57: 939-948.

Based on CGCM model simulations, the range of Western Hemlock will recede on Vancouver Island.

By mid 21st century, Carnation Creek will lie at the edge of the maximum range of Western Hemlock.

By end 21st century, Carnation Creek will lie outside the maximum range for Western Hemlock.

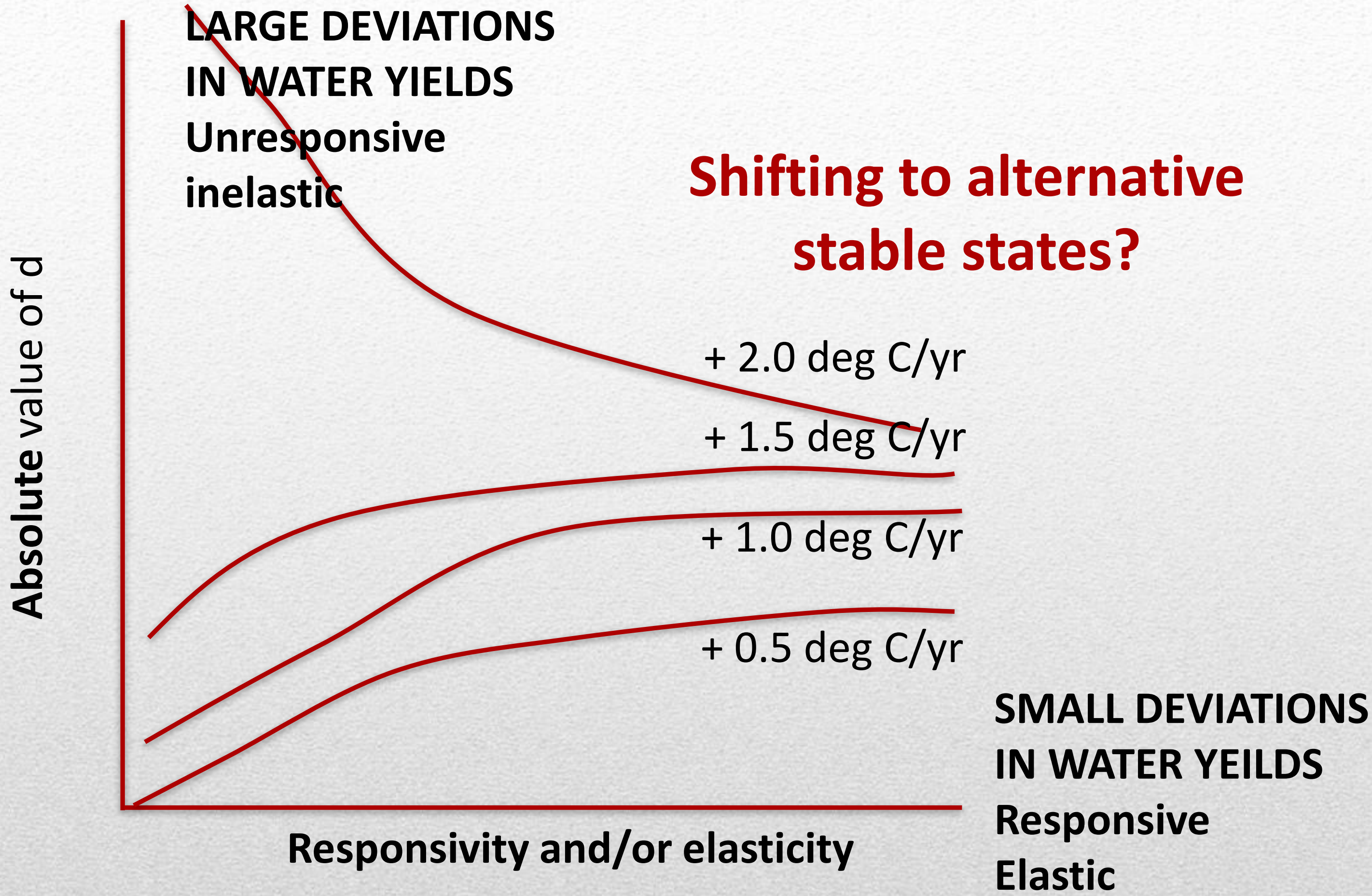


Maximum Range

5th – 95th Percentile

Third 30 years, 2071 - 2100

McKenney DW, et al. (2007). *Potential impacts of climate change on the distribution of North American trees.* Bioscience 57: 939-948.

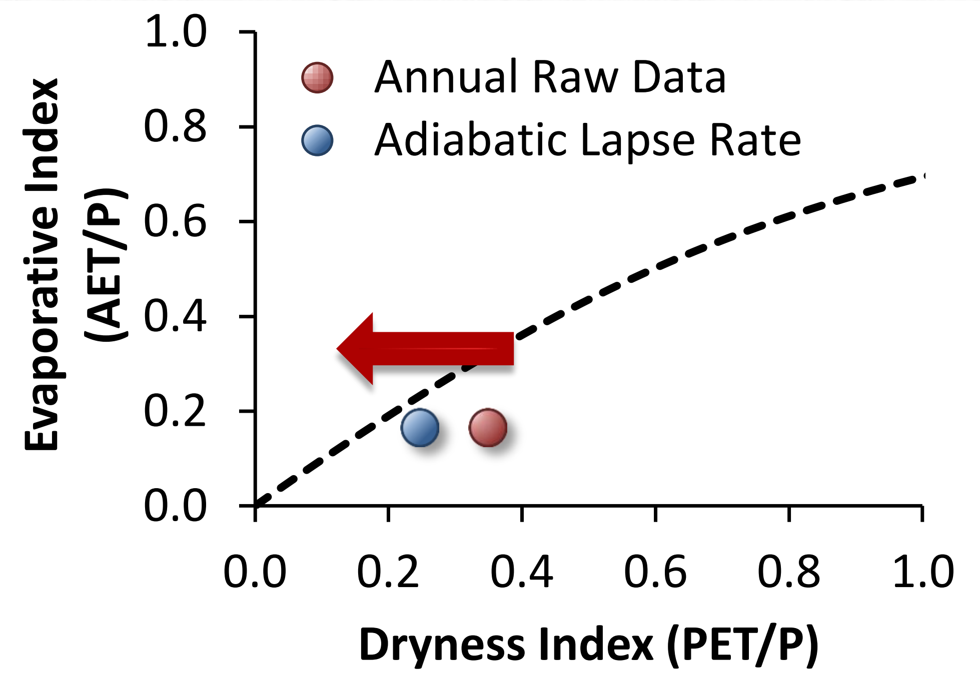


A better conceptual model of climate change effects on water yields

Acknowledgements

- NSERC Discovery Grant and Canada Research Chair Program
- "LTER Synthesis Workshops" funded by the LTER Network Office
- NSF LTER grants to participating USA sites
- USFS and USGS for initial establishment and continued support of watershed studies at many of the study sites
- NCE-SFM funded project on HydroEcological Landscapes and Processes (HELP) and the participating Canadian sites

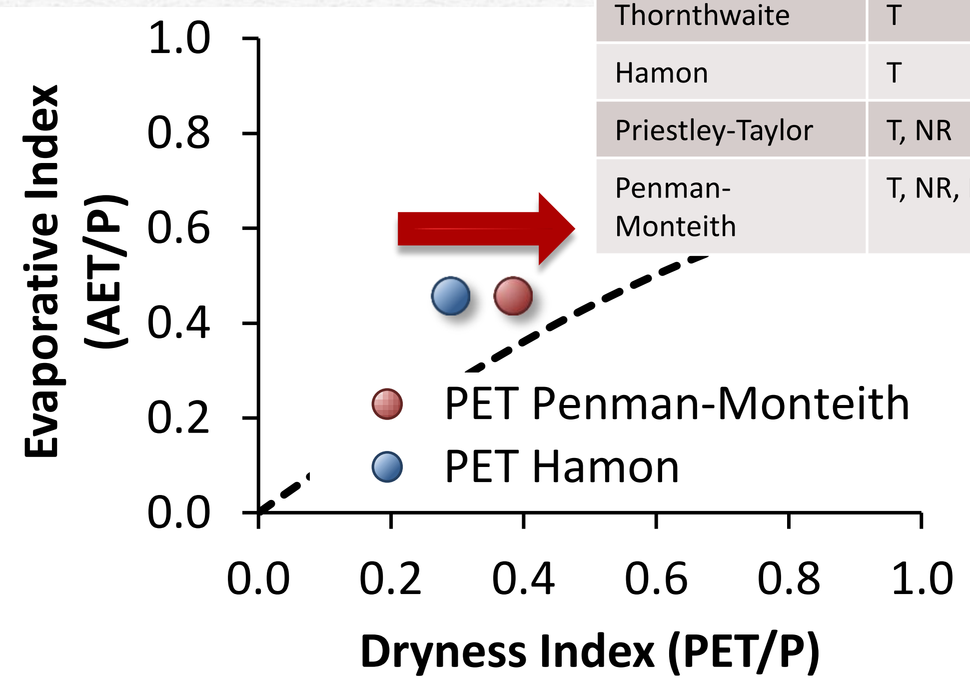
Loch Vale (LVW):
Failure to apply adiabatic lapse rate to meteorological data to account for orographic effects results in shift away from the curve.



(1) Inadequate representation of P, T

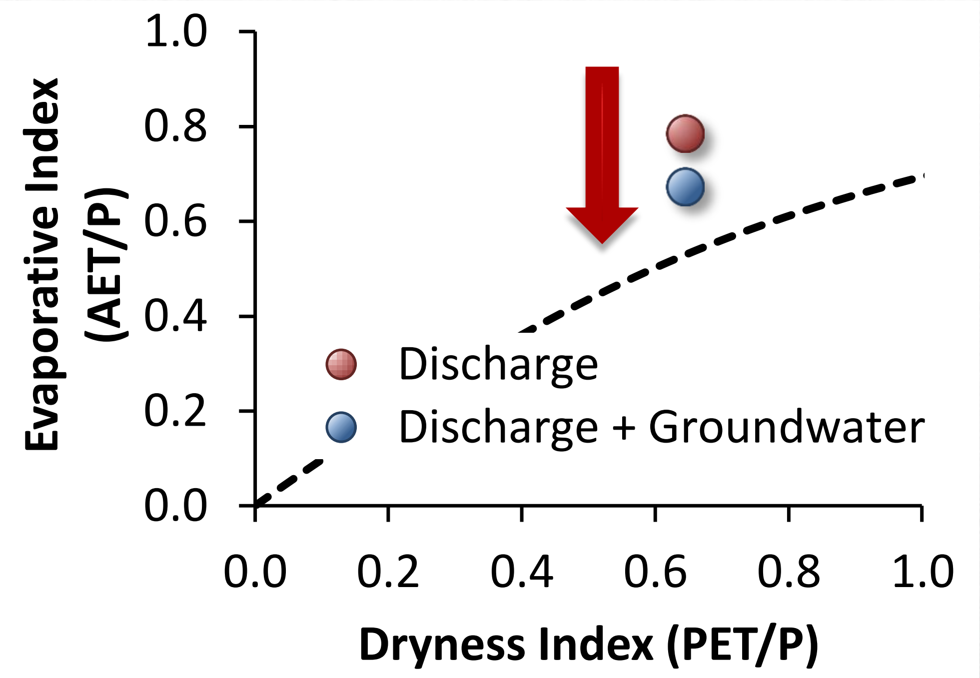
HJ Andrews (HJA):
Failure to consider net radiation, relative humidity and/or wind speed results in shift away from the curve.

Formula	Variables
Thornthwaite	T
Hamon	T
Priestley-Taylor	T, NR
Penman-Monteith	T, NR, RH, WS



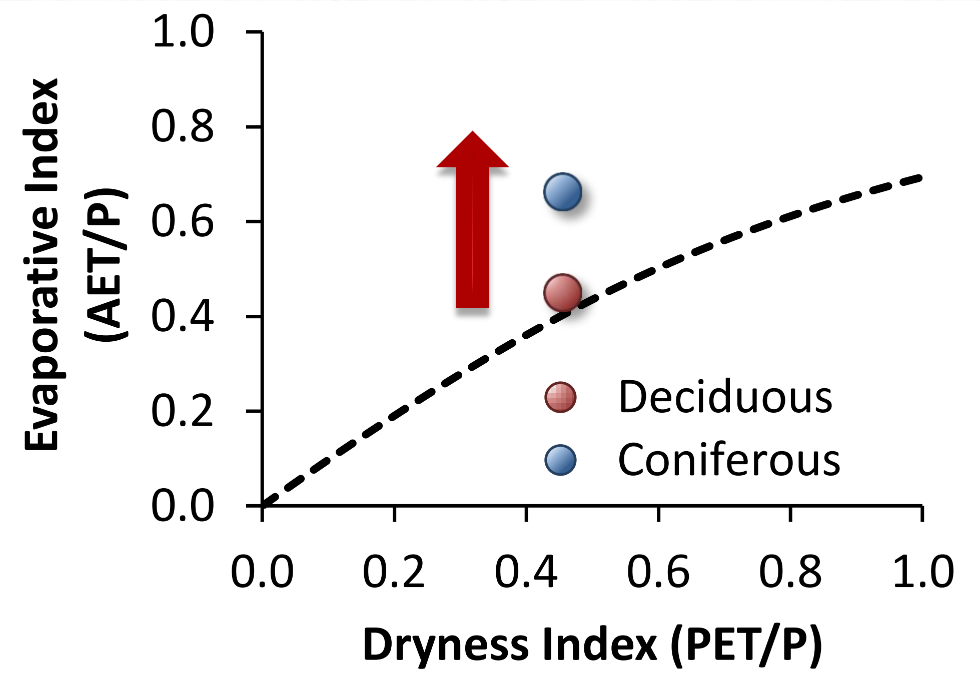
(2) Inadequate representation of ET

Marcel (MAR):
Failure to consider surface vs. groundwater losses of precipitaton.



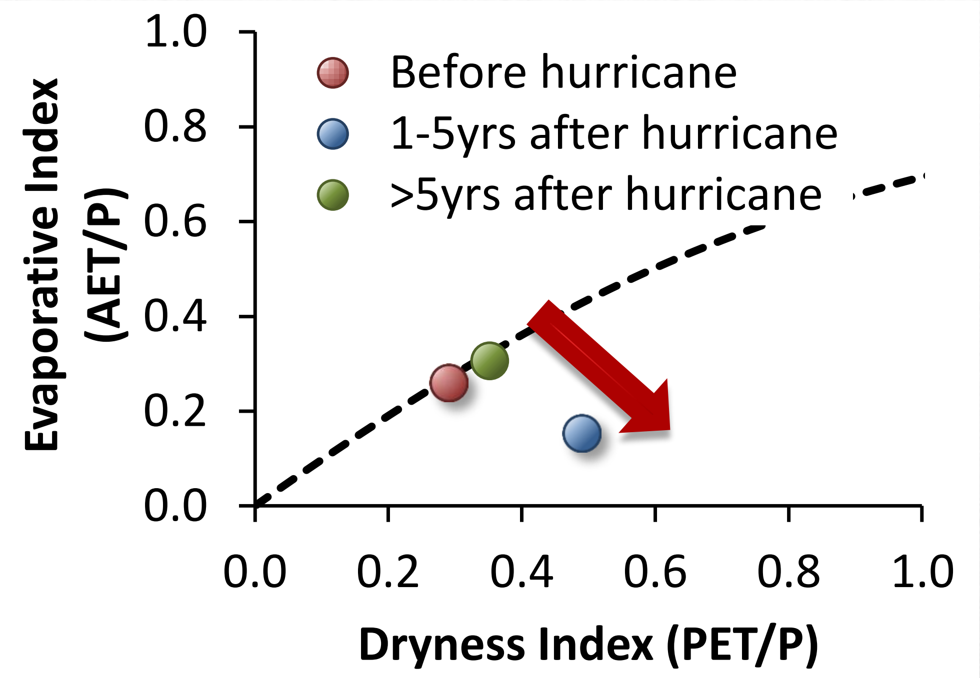
(3) Inadequate representation of Q

Coweeta (CWT):
Conversion of forest from deciduous to coniferous forest results in shift away from the curve.



(4) Forest management effects

Luqillo (LUQ):
Disturbance Effects



(5) Natural disturbance effects

- Responsivity and elasticity were directly correlated to climate related deviations from the Budyko Curve (among the catchments studied)
- Catchments where P and Q are synchronised catchments are more sensitive to climate change, that is they are tightly coupled with the atmosphere.

Constant breakpoint findings