CHANGING FOREST WATER YIELDS IN RESPONSE TO CLIMATE WARMING: RESULTS FROM LONG-TERM EXPERIMENTAL WATERSHED SITES ACROSS NORTH AMERICA

Julia A Jones[1], Irena F Creed[2], Adam Spargo[2], James M Buttle[3], Mary Beth Adams[4], Fred D Beall[5], Eric Booth[6], John L Campbell[4], David W Clow[7], Kelly Elder[4], Chelcy Rae Ford[4], Nancy B Grimm[8], Patricia Ramlal[9], Amartya Saha[10], Stephen D Sebestyen[4], David Spittlehouse[11], Shannon M Sterling[12], Mark W Williams[13], Rita D Winkler[11], Huaxia Yao[12]

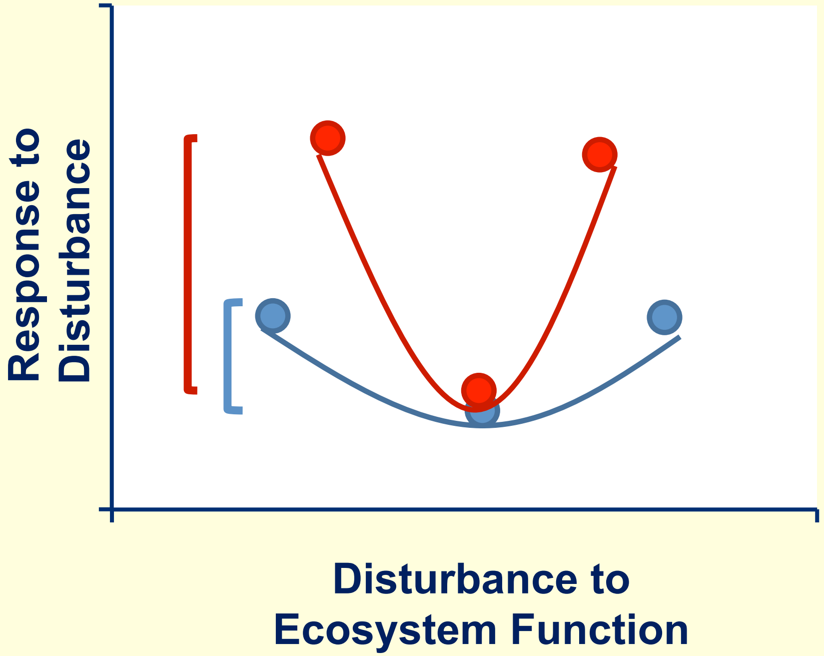
1. Oregon State University, 2. Western University, 3. Trent University, 4. USDA Forest Service, 5. Natural Resources Canada, 6. University of Wisconsin, Madison, 8. US Geological Survey, 11. Arizona State University, 12. Fisheries and Oceans Canada, 13. Florida International University, 15. BC Ministry of Forests, 16. Dalhousie University, 17. University of Colorado, 19. Ontario Ministry of the Environment

CLIMATE CHANGE AND WATER YIELD

- Models project differences in future warming among biomes, which complicates decisions managing forests.
- **How resilient are catchment water yields in different biomes to climate change?**
- **Can existing long-term data inform us about future conditions?**

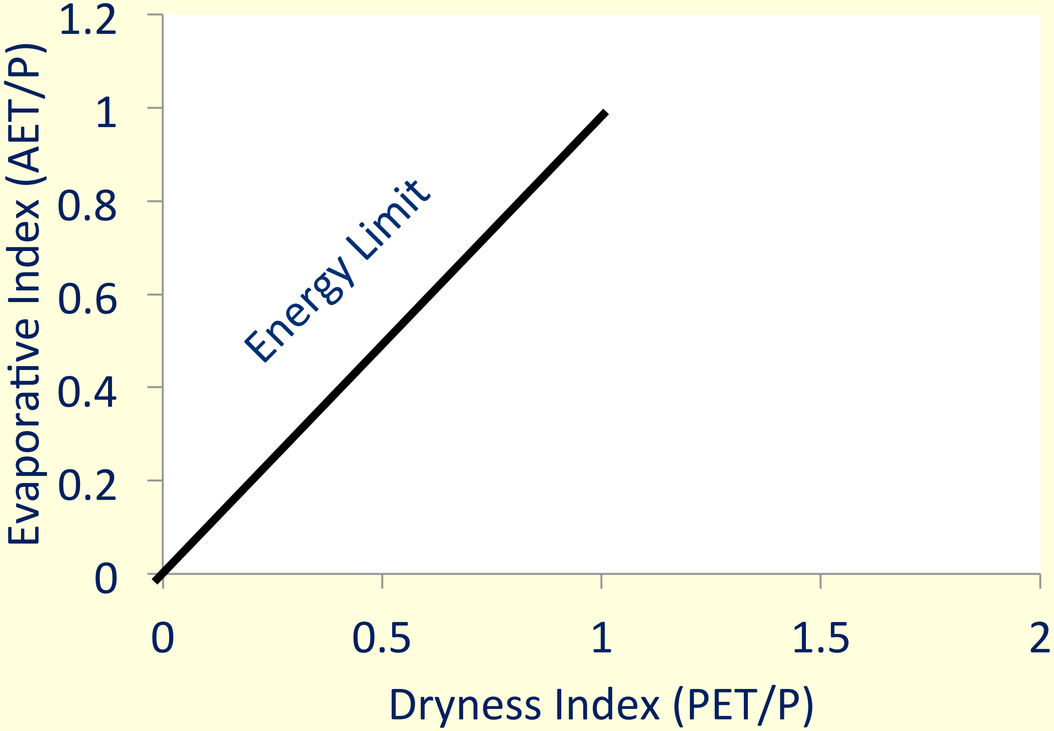
RESILIENCE

- Resilience: Ability to absorb changes while maintaining a particular ecosystem function (Holling 1973): **water yield**.
- In ecosystems with:
  - → High resilience: disturbances have small effect on response variables.
  - → Low resilience: disturbances have large effect on response variables.
- We apply a Budyko framework to assess the resilience of water yields from headwater catchments to climate change.

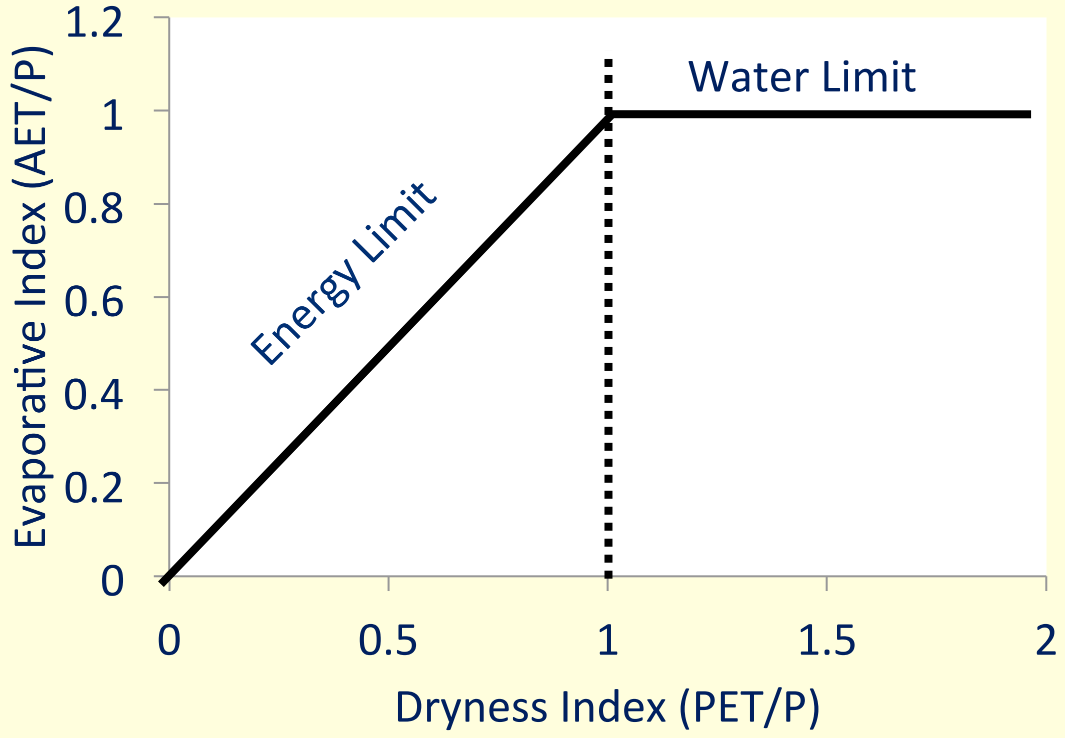


BUDYKO CURVE

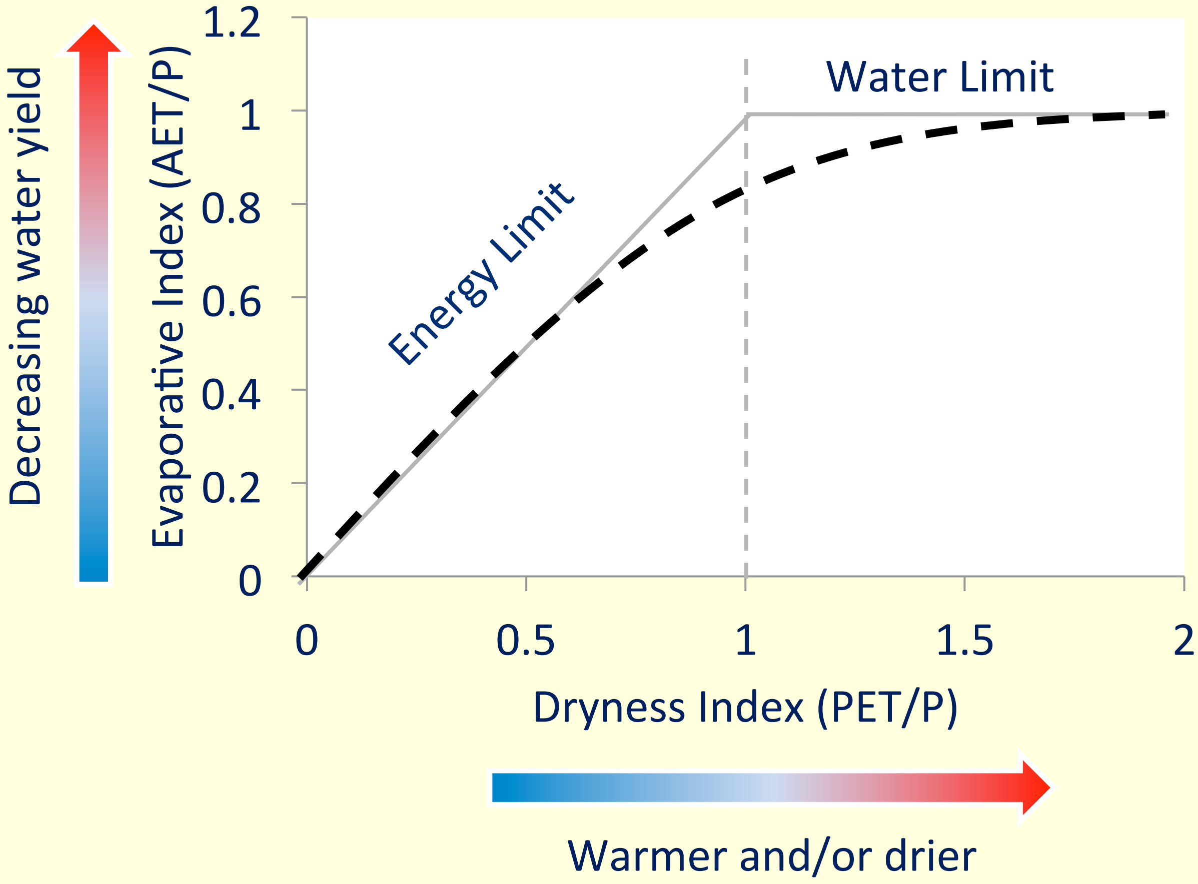
The Budyko curve describes the relationship between potential evapotranspiration (PET) and actual evapotranspiration (AET), each normalized by precipitation (P).



BUDYKO CURVE



BUDYKO CURVE

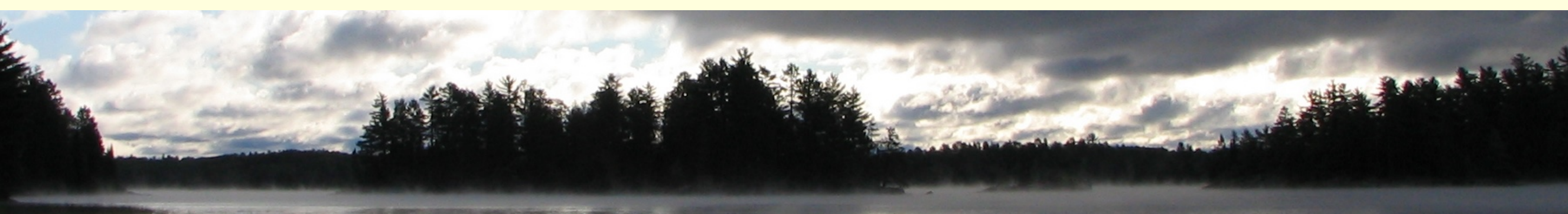


RESEARCH QUESTIONS

- How has water partitioning between evapotranspiration and runoff, as reflected by position on the Budyko curve, responded over time to climate warming in forested headwaters?
- Have forest type and management affected water yield resilience to climate change?

HYPOTHESES

- In response to climate warming:
  - → **Resilient** catchments will shift along the Budyko curve indicating little change in water yield.
  - → **Less resilient** catchments will deviate upward from the curve, indicating a decrease in water yield.
- More resilient sites will be relatively undisturbed catchments with older forests being more resilient than younger forests and mixed forests being more elastic than either purely coniferous or deciduous forests.



SITE SELECTION

- Started from over 100 potential LTER, USFS, USGS, Canadian HELP sites
- Selected sites with:
  - →No anthropogenic disturbance since 1950.
  - →At least 15 year record since 1980.
  - →Detectable shifts from cooler to warmer temperatures.
  - →Multiple catchments used if they had contrasting catchment properties.
- 21 catchments at 12 sites.

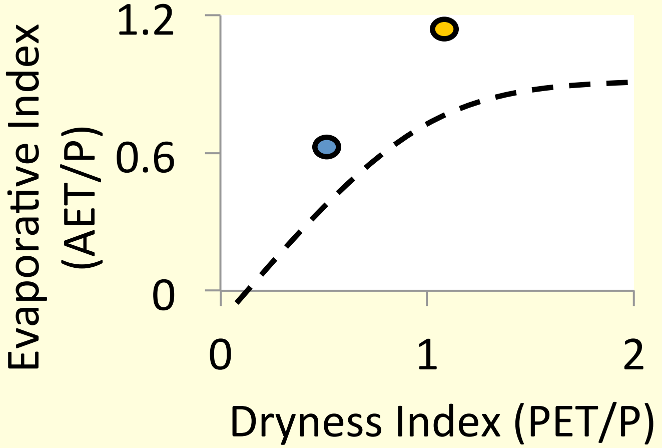
METHODS

- Water-year PET calculated as a function of average monthly temperature according to Hamon (1963) formula.
- Water-year AET estimated using water balance approach: $AET = P - Q - \Delta S$
  - → ΔS = change in water storage volume, assumed to be zero.

CLIMATE CHANGE

Calculated 5-water-year moving temperature averages.

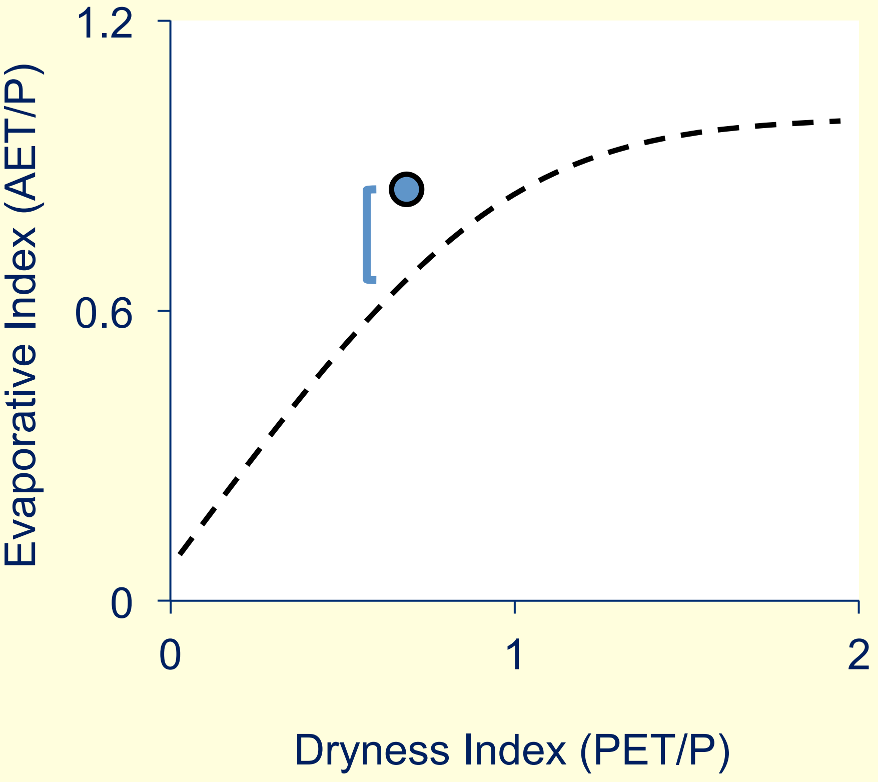
- "Cool" period: 5-wyr period with minimum temperature.
- "Warm" period: 5-wyr period after cool period that was warmer than subsequent 5-wyr periods by more than 1 standard deviation.



NEW METRICS

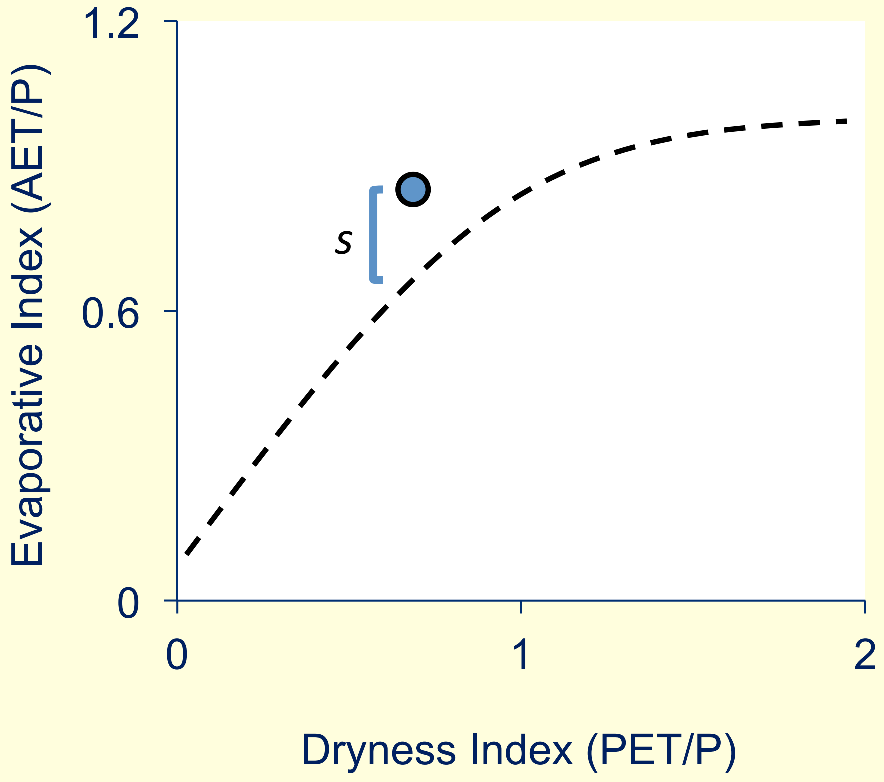
Deviation: A measure of change in a catchment's evaporative index (change in water yield) relative to the Budyko curve.

- Two components:
  - →Static Deviation (s).
  - →Dynamic Deviation (d).



NEW METRICS

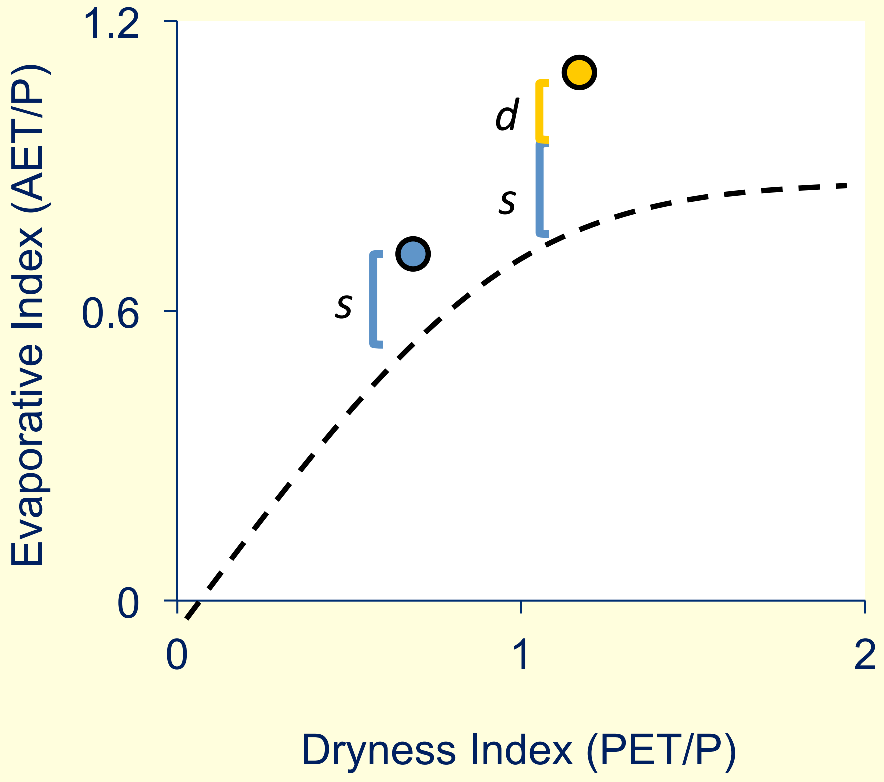
Static deviation (s):
Deviation from Budyko curve during cool period.



NEW METRICS

Dynamic deviation (d): Additional deviation from Budyko curve during warm period relative to the cool period.

- Assumed s to be constant over time.
- We consider d to be a response to warming.

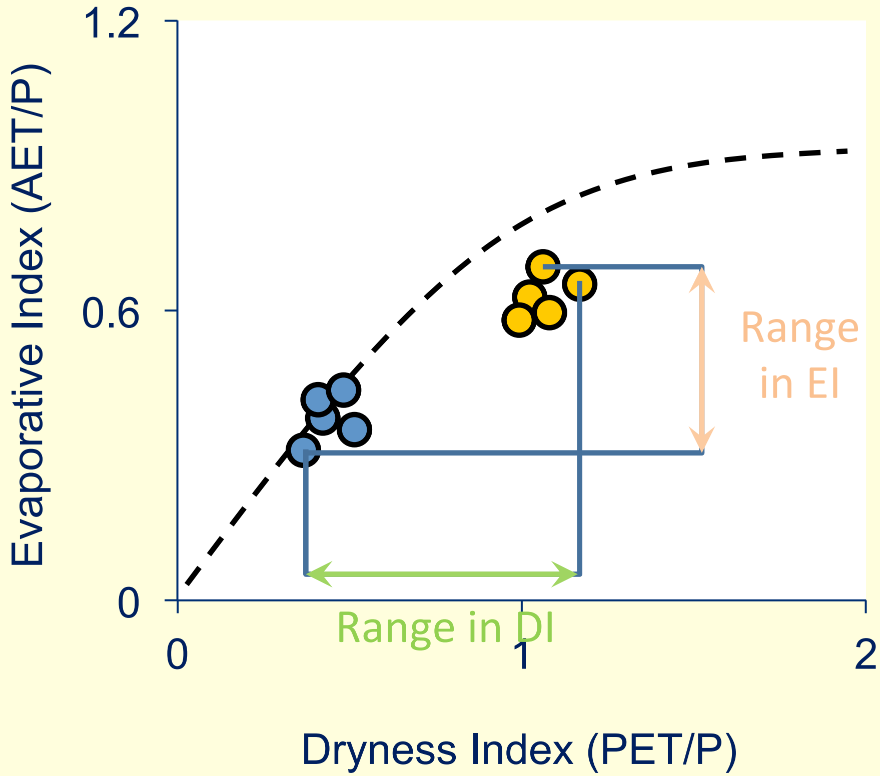


NEW METRICS

Elasticity (e): A measure of a catchment's ability to maintain water partitioning consistent with the Budyko curve during cool and warm periods.

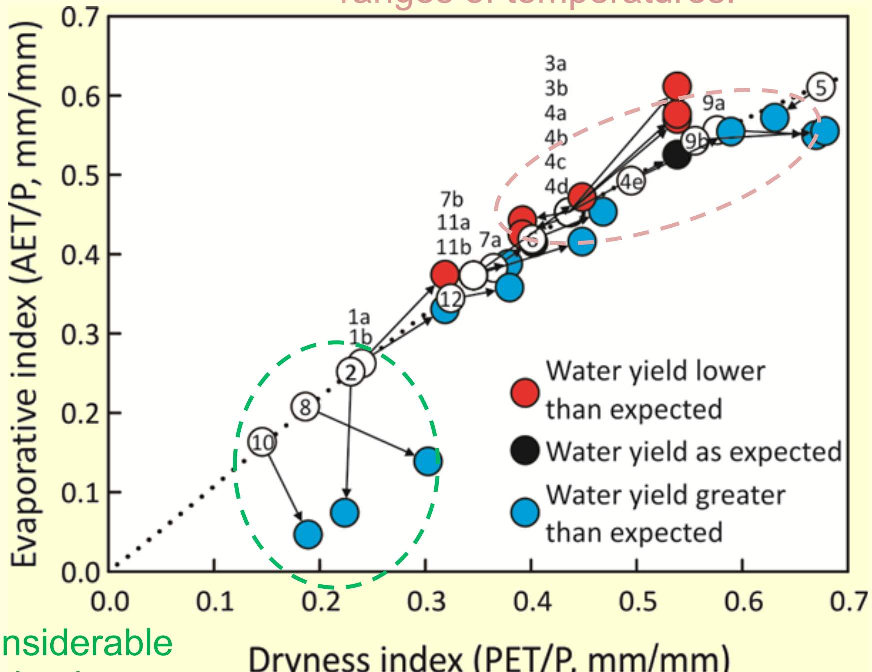
e = Range in DI / Range in EI

- Catchments with **high elasticity** partition P into Q and ET in a manner that varies predictably with the Budyko curve.
- Catchments with **low elasticity** partition water less predictably.



DYNAMIC DEVIATION (d)

Little variation in water yields with relatively wide ranges of temperatures.

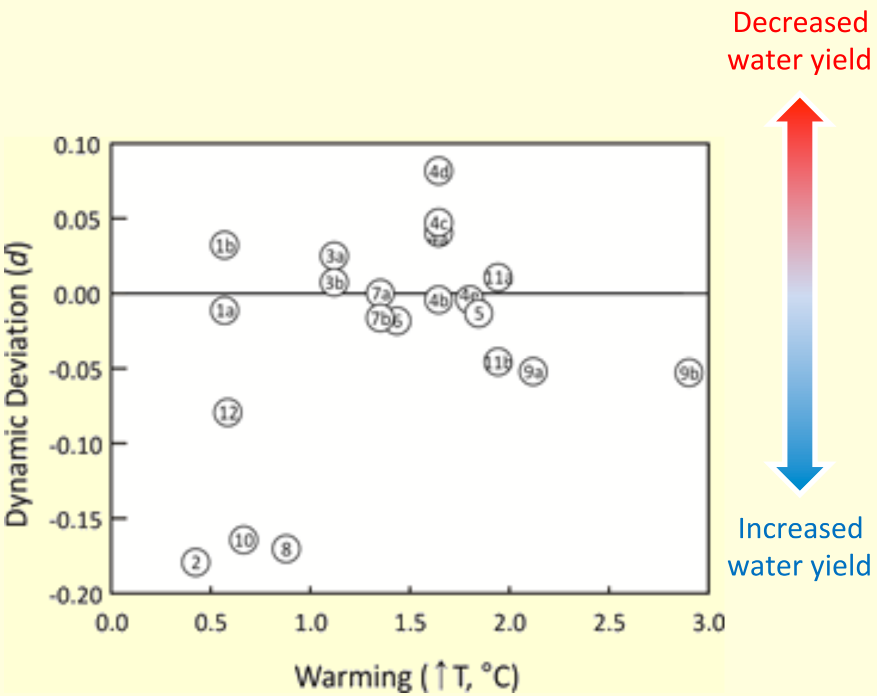


Considerable variation in water yields with small changes in temperature.

During the warm period:

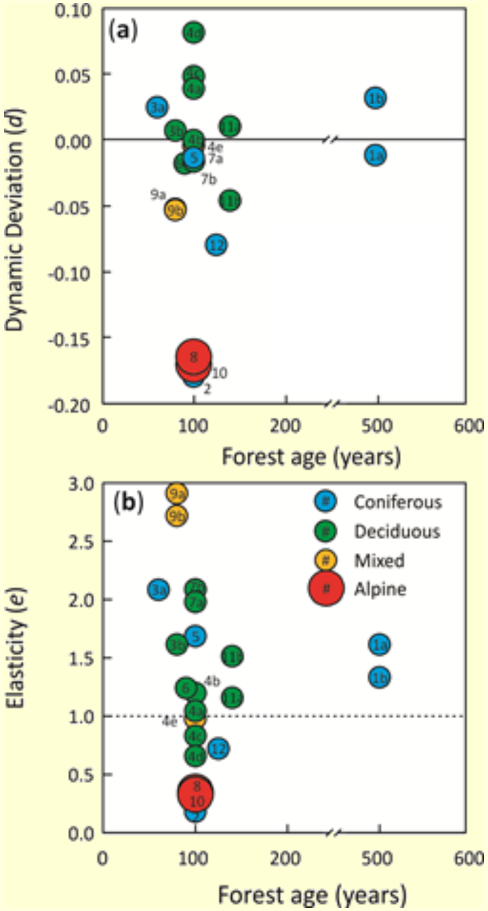
- **No obvious patterns**: most sites moved along the Budyko curve.
- 7 catchments had water yields lower than expected.
- 3 catchments as expected.
- 11 catchments had water yields greater than expected.
- Only 3 catchments were considerably different.

DYNAMIC DEVIATION (d) vs. EXTENT OF WARMING



- Water yields increased most at sites with small changes in temperature.
- Water yields increased less at sites with intermediate to large changes in temperature.
- What explains d?

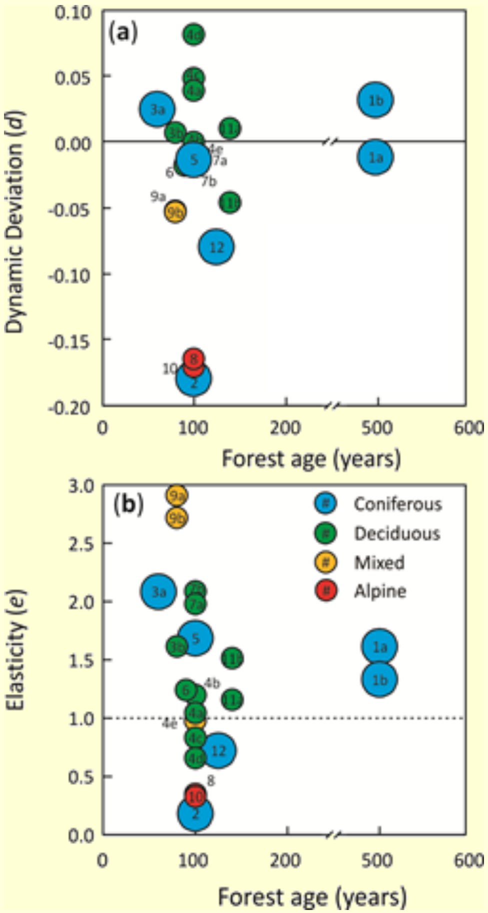
BUDYKO METRICS AND FOREST TYPE



Alpine:

- Among lowest d and e values:
  - →Large water yield increases associated with increased rates of glacier/ permafrost melting.

BUDYKO METRICS AND FOREST TYPE

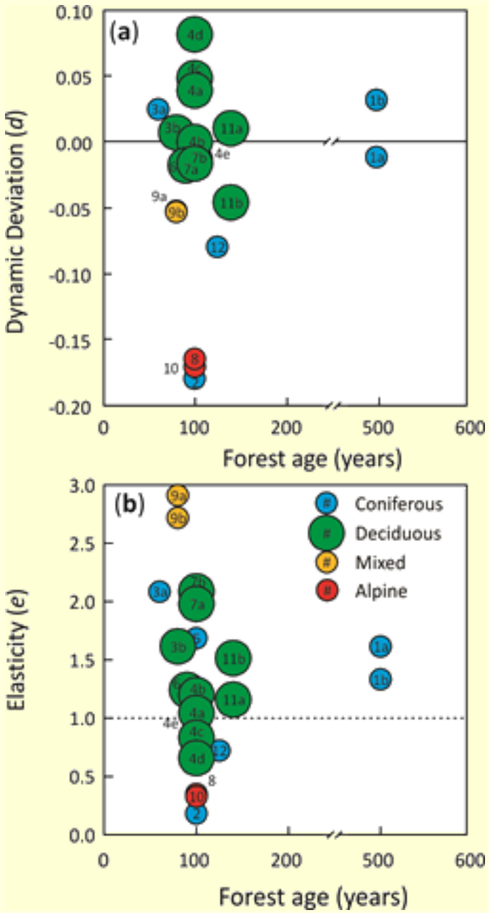


Coniferous:

- Catchments with lowest e had most negative d (i.e., larger-than-expected water yields).
- Catchments with highest e had near-zero d (i.e., partitioned water consistent with the Budyko curve).

→ Coniferous forests have better control on stomatal response during hot and dry conditions.

BUDYKO METRICS AND FOREST TYPE

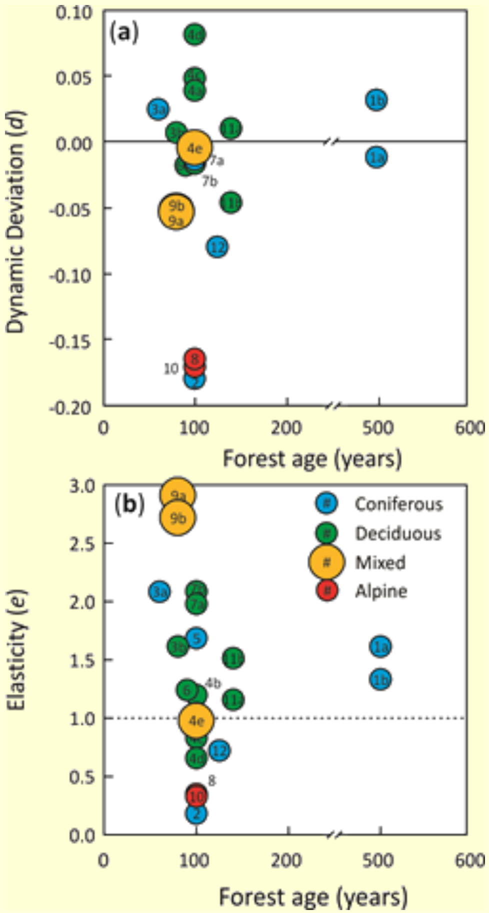


Deciduous:

- Catchments with lowest e had highest positive d (smaller than expected water yields).

→ Deciduous trees have less control on water use, which may be confounded by phenology (bud burst and leaf fall) desynchronizing as growing seasons change.

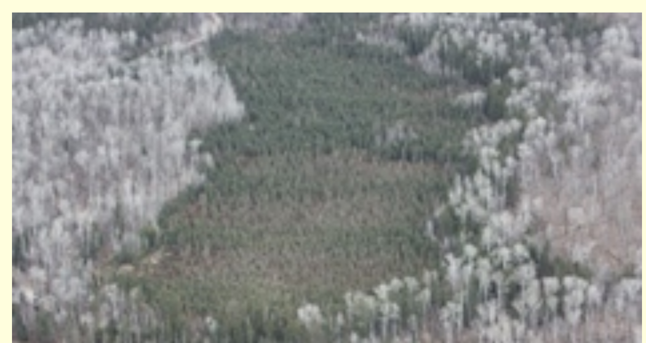
BUDYKO METRICS AND FOREST TYPE



Mixed: Near zero and mostly positive d, wide range of e

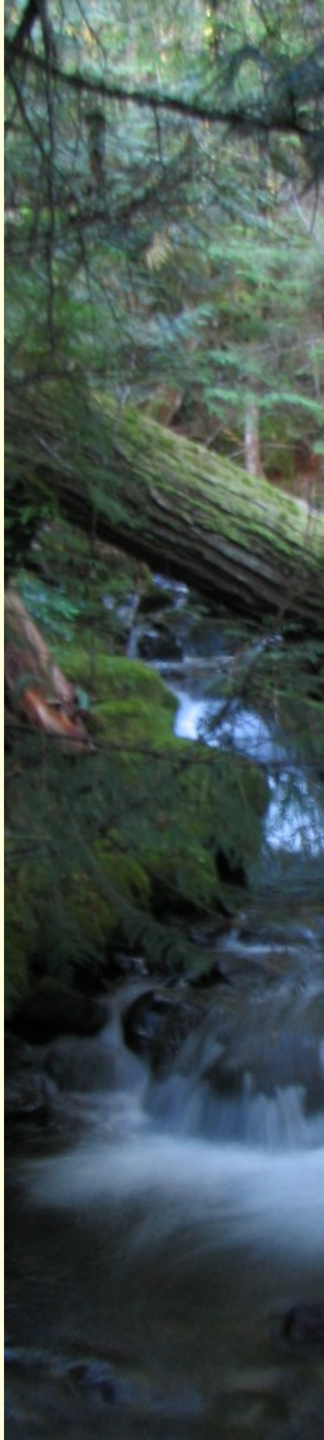
- Catchments stayed closest to Budyko curve, despite experiencing the greatest climate warming.

→ Does self-organization (i.e., stand composition and structure) in response to cool and warm periods as stands age “optimize” water partitioning and increase elasticity in these mixed forests?



DISCUSSION

- Retrospective analysis of catchment studies may identify ecosystem-scale responses that are important for validation of Earth Systems Models.
  - → The Budyko framework shows responses of water yields during warm periods that vary with forest type and management. Older forests may have been "tuned" by past climate variation.
- A Budyko framework and the new elasticity metric may be new tools for forest managers to use in the assessment of the resiliency of catchment water yields to climate warming.
  - → Forest managers should consider how forest composition and age affect hydrologic resilience.



ACKNOWLEDGEMENTS

- The University of Western Ontario International Research Award.
- NSERC Discovery Grant.
- Canadian Network of Aquatic Ecosystem Services NSERC Strategic Network Grant for grants to IFC.
- The Network of Centres of Excellence Sustainable Forest Management for support of the HELP database for Canadian catchments.
- The Long Term Ecological Research Network, US Forest Service, and US Geological Survey for access to the databases for US catchments.
- The US National Science Foundation and Long Term Ecological Research Network for support of the workshops that led to this collaboration.
- Robin Pike for insights about Carnation and Jennifer Knoepp for insights about Coweeta.