The climatic water balance in an ecological context

Nathan L. Stephenson
Thesis: Consideration of the climatic water balance improves our ability to understand and forecast the effects of climatic changes on the biological world.

(1) The superiority of the climatic water balance in ecological studies.

(2) In a changing climate, increasing water availability will NOT counteract the effects of increasing evaporative demand. … And why soil moisture may be less important than you think!

(3) Don’t forget AET!
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Traditional view: At broad scales, vegetation type is a function of some measure of annual energy supply, annual water supply, or their ratios or differences.
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The Big Problem: The traditional view does not consider the seasonal interactions of energy and water. E.g., with nearly identical mean annual temperature and precipitation:

- **Deciduous broad-leaved forest**
  - Erie, Pennsylvania

- **Evergreen needle-leaved forest**
  - Portland, Oregon
(1) By explicitly incorporating the seasonal interactions of energy and water, the climatic water balance is biologically more meaningful than traditional climatic metrics.
Actual evapotranspiration (AET) reflects the simultaneous availability of biologically usable energy and water, and is therefore an index of site potential for productivity.

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<thead>
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<th>Month</th>
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<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
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**Water supply** (rain plus snow melt water)

**Potential evapotranspiration**

**AET**

![Graph showing monthly water supply and potential evapotranspiration](image)
Climatic water deficit (D) is evaporative demand that is not met by available water, and is thus an index of potential effects of drought stress on plants. *(Don’t confuse with soil water deficit!)*
Surplus is an index of biologically unusable water – excess water that leaves a site, through runoff or subsurface flow, without being evaporated or transpired.
(2) The climatic water balance (AET and D) is better correlated with the distribution of vegetation types. Example: North American coniferous and deciduous forest distributions.
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(3) The climatic water balance exhibits these properties across more than ten orders of magnitude of spatial scale.
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Summary -- the superiority of the climatic water balance in ecological studies:

- More biologically meaningful.
- Better correlated with biological processes and vegetation and species distributions.
- Exhibits these properties across >10 orders of magnitude of spatial scale.
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At continental and global scales, most authors have treated metrics of energy and water supplies as orthogonal axes. That is, they recognize that water does NOT counteract the effects of energy.
Yet at local to regional scales, some of those same authors additively combine metrics of energy and water supplies into a single "moisture scalar," thus assuming that the effects of water and energy counteract one another.

E.g., Whittaker’s moisture scalar combines metrics related to evaporative demand (slope aspect and exposure) with metrics related to water availability (slope position and proximity to water).

**"Topographic moisture gradient"**

Whittaker & Niering 1965, *Ecology*
For understanding and forecasting plant distributions, we care less about soil moisture than the dynamics that gave us that soil moisture.
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\textit{Normal precip}, but high evaporative demand.
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Consider these scenarios in terms of annual AET and D. The colored dots represent species’ climatic niches; dotted diagonal are isolines of constant PET.
Because $\text{PET} = \text{AET} + \text{D}$, drought (low precipitation) can only result in increases in D that are precisely offset by identical declines in AET.
Adding the right amount of water can put the site back to exactly where it started in climate space.
In contrast, because \( \text{PET} = \text{AET} + D \), increasing PET must increase AET, D, or both. That is, the effects of changing PET are nearly orthogonal those of changing water availability ...
... so that adding water CANNOT put the site back to exactly where it started in climate space ...
... and big enough increases in PET and water availability will move the site to another species’ climatic niche, even though soil moisture hasn’t changed.
What are some implications for the effects of climatic changes on mountain ecosystems?

Example: Unlike temperature changes, precipitation changes should not be expected to cause coordinated directional shifts in species’ elevations.
PET declines sharply with increasing elevation.

Data from Shreve 1915

Santa Catalina Mtns, AZ, summer of 1911

Evaporative rate (cc/day)

- South-facing slopes
- North-facing slopes

Elevation (m)

A spherical porous cup atmometer

Livingston 1935, *Ecology*
PET declines sharply with increasing elevation.
Thus, temperature-induced increases in PET will alter a site’s water balance to support species currently found at lower elevations. This is why we expect temperature-induced upslope migrations.
At a given elevation, local water availability depends on things like soil depth, proximity to water, etc.
Declining precipitation will alter a site’s water balance to support species currently found at sites with lower water availability but at the same elevation …
... and increasing precipitation will alter a site’s water balance to support species currently found at sites with higher water availability but at the same elevation. This is why we DON’T expect precip-induced elevational changes.
These expectations are empirically supported by observations of species’ distributions along natural climatic gradients.
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Parting thoughts:

“Moisture availability” is a slippery term of limited value, and can only be understood in **two** dimensions. E.g., does an increase in both AET and D yield a wetter or a drier environment? Arguably, both!

In many (most?) cases it’s better to drop the concept of “moisture availability” in favor of explicit consideration of AET and D.
Thank you for your attention!