MIT JOINT PROGRAM
SCIENCE POLICY
GLOBAL CHANGE

Report 306
November 2016

A Drought Indicator based on Ecosystem Responses to Water Availability: The Normalized Ecosystem Drought Index

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—Ronald G. Prinn and John M. Reilly,
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A Drought Indicator based on Ecosystem Responses to Water Availability: The Normalized Ecosystem Drought Index

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Abstract: Drought is one of the most destructive natural disasters causing serious damages to human society, and studies have projected more severe and widespread droughts in the coming decades associated with the warming climate. Although several drought indices have been developed for drought monitoring, most of them were based on large scale environmental conditions rather than ecosystem transitional patterns to drought. Here, we propose using the ecosystem function oriented Normalized Ecosystem Drought Index (NEDI) to quantify drought severity, loosely related to Sprengel's and Liebig's Law of the Minimum for plant nutrition. Extensive eddy covariance measurements from 60 AmeriFlux sites across 8 IGBP vegetation types were used to validate the use of NEDI. The results show that NEDI can reasonably capture ecosystem transitional responses to limited water availability, suggesting that drought conditions detected by NEDI are ecosystem function oriented. The widely used Palmer Drought Severity Index (PDSI), on the other hand, does not have a clear relationship with ecosystem responses to drought conditions because ecosystem adaptation ability is not considered in PDSI calculation.

1 This report is a chapter of Kuang-Yu Chang's doctoral dissertation.

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1. Introduction

Drought is one of the most devastating natural disasters that can cause serious agricultural, economic and social impacts in the world (Wilhite, 2000). Several studies project increased aridity over land and more widespread droughts associated with the future warming climate (Mpelasoka *et al.*, 2008; Feyen, 2009; Seager *et al.*, 2007; 2009; Dai, 2011). Therefore, it is imperative to define a proper drought measure that can objectively quantify drought characteristics, such as onset, severity and duration. Current drought measures often identify droughts as the departures of soil water balance from normal conditions—such as the Palmer Drought Severity Index (PDSI) (Palmer, 1965), the self-calibrating PDSI (Wells *et al.*, 2004) and the Soil Moisture Deficit Index (SMDI) (Narasimhan and Srinivasan, 2005)—or as the deviations from normal precipitation patterns, such as the Standardized Precipitation Index (SPI) (McKee *et al.*, 1993) and the Standardized Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano *et al.*, 2010; Beguería *et al.*, 2014).

Although the drought indices cited above can provide practical information for drought monitoring, those approaches are based on large-scale, controlled environmental conditions rather than specific ecosystem responses to limited water availability. Therefore, drought conditions identified by those drought indices may misrepresent actual ecosystem behavior, since ecosystems can have various adaptation and acclimation mechanisms against limited water availability (Lu and Zhuang, 2010; Liu *et al.*, 2011). These mechanisms are related to the issue that a particular ecosystem found at any location may represent an assemblage of species that are in their fundamental ecological niche (Peterson, 2003), which already includes historical climatological conditions such as periodic droughts. Here, we propose an ecosystem-function-oriented Normalized Ecosystem Drought Index (NEDI) to quantify drought severity. This method is based on detecting variational signals in normalized evapotranspiration strength[1] through a modified Variable Interval Time Averaging (VITA) technique traditionally used for turbulence studies (Blackwelder and Kaplan, 1976). The general concept is inspired by Sprengel's and Liebig's Law of the Minimum for plant nutrition (van der Ploeg *et al.*, 1999). We examined the applicability of NEDI with evapotranspiration field measurements from 60 eddy covariance towers across 8 different vegetation types defined by the International Geosphere–Biosphere Programme classification (IGBP). The drought conditions suggested by PDSI were also analyzed in the same fashion to compare the differences between NEDI and PDSI.

1 Normalized evapotranspiration strength is defined as the ratio between evapotranspiration and potential evapotranspiration.

2. Methodology

2.1 Normalized Ecosystem Drought Index (NEDI)

Similar to Vicente-Serrano *et al.* (2010), we use the difference between monthly precipitation (P) and monthly potential evapotranspiration (PET) to estimate water availability (W) in ecosystems. However, we represent water supply with total precipitation collected in the previous month instead of the value in the current month to account legacy effects for precipitation become an available water source. Therefore, the water availability for the month *i* can be represented as

$$W_i = P_{i-1} - PET_i,$$

which is positive with water surplus and vice versa, neglecting groundwater storage and runoff. The monthly NEDI is then defined by normalizing the W_i series with the maximum water surplus or deficit value shown in the W_i series for each ecosystem, which can be represented as

$$NEDI_i = \frac{W_i}{\max(abs(W_i))}.$$

The NEDI defined above can quantify the water availability at each site from −1 (driest condition) to 1 (wettest condition).

The Thornthwaite PET (Thornthwaite, 1948), which requires only the mean monthly surface air temperature and latitude, was used to estimate the monthly water demand required for NEDI calculation. Although limitations have been found in using the Thornthwaite PET (Jensen *et al.*, 1990; Donohue *et al.*, 2010; van der Schrier *et al.*, 2011), Dai (2011) showed that using the more sophisticated Penman-Monteith PET only exhibits limited effects in the PDSI calculation. Therefore, the Thornthwaite PET was used in our calculation to bypass the extensive amount of data required for using the Penman-Monteith PET.

2.2 Modified Variable Interval Time Averaging (VITA)

Based on a running variance concept, the VITA technique (Blackwelder and Kaplan, 1976) has been widely applied to detect turbulence characteristics in unsteady flows. The localized variance used in VITA for each time interval T is calculated as

$$var(t,T) = \frac{1}{T}\int_{t-T/2}^{t+T/2} p_{(t')}{}^2 dt' - [\frac{1}{T}\int_{t-\frac{T}{2}}^{t+\frac{T}{2}} p_{(t')} dt']^2,$$

where *p* and *t* stands for detection parameter and observation time, respectively. When the streamwise velocity is used for the detection parameter, turbulence patterns are then identified if rapid changes are detected in the localized variance, suggesting the existence of high velocity fluctuations.

We extend this running variance concept to ecosystem drought monitoring by labeling the detection parameter with the corresponding NEDI, then sorting by NEDI values in place of the time domain used in the original VITA. This modified VITA is defined as

$$var(NEDI,N) = \frac{1}{N}\int_{NEDI_i}^{NEDI_{i+N}} p_{(t')}{}^2 dt' - [\frac{1}{N}\int_{NEDI_i}^{NEDI_{i+N}} p_{(t')} dt']^2,$$

where i and N are the i^{th} NEDI and the analyzed window size, respectively. The crop coefficient K_c, defined as the ratio between actual evapotranspiration and potential evapotranspiration (Doorenbos and Pruitt, 1977; Allen *et al.*, 1998) and the water use efficiency (WUE) defined as the Net Ecosystem Exchange (NEE) divided by the actual evapotranspiration, were used as detection parameters for ecosystem drought because K_c represents a nondimensional measure for evapotranspiration, and WUE represents the ability of ecosystems to assimilate carbon given their water use. Therefore, if rapid changes in K_c are detected by the modified VITA technique, the corresponding NEDI are then recorded as thresholds for ecosystem transitional responses to drought conditions. In order to prevent K_c from being unrealistically high, especially when Thornthwaite PET is calculated as zero during wintertime, an upper bound for K_c is assigned to 3. The analysis window size was selected as 10 points to smooth out high frequency variations in the raw data. Different sets of K_c upper bounds and window sizes were tested, and the results were similar to the values presented here.

VITA is used to test for drought as a limiting factor following the general concept of Sprengel's and Liebig's Law of Minimums for plant nutrition (van der Ploeg *et al.*, 1999). Here ecological drought is defined as when drought is the dominant factor limiting ecosystem function, as indicated in this case by K_c and WUE although this method could be used with other quantifiable ecosystem values. When drought is not the limiting factor, other variables will then control K_c and WUE, so variability in the form of increased variance will appear, and be detected by VITA. The threshold for when the variance increases thus represents the NEDI threshold.

3. Data

3.1 AmeriFlux dataset

The half-hourly based eddy covariance datasets across 60 AmeriFlux sites from 1991 to 2015 are used in this study.[2] These sites encompass a variety of vegetation types and climatic conditions (**Table 1**).

2 http://ameriflux.lbl.gov

Table 1. The AmeriFlux sites used in this study.

Site name	Lat.	Long.	Vegetation type (IGBP)	Data period	Source
ARM SGP Main (US-ARM)	36.61	-97.49	Croplands	12/31/2000–01/27/2013	Fischer *et al.* (2007)
Audubon Research Ranch (US-Aud)	31.59	-110.51	Grasslands	06/07/2002–09/26/2011	Qi *et al.* (2000)
Bartlett Experimental Forest (US-Bar)	44.06	-71.29	Deciduous broadleaf forest	12/31/2003–01/14/2013	Richardson *et al.* (2007)
Blodgett Forest (US-Blo)	38.90	-120.63	Evergreen needleleaf forest	06/02/1997–10/10/2007	Goldstein *et al.* (2000)
Bondville (US-Bo1)	40.01	-88.29	Croplands	08/25/1996–12/30/2010	Meyers & Hollinger (2004)
Bondville Companion (US-Bo2)	40.01	-88.29	Croplands	05/13/2004–12/28/2008	Bernacchi *et al.* (2005)
Brooks Field Site 10 (US-Br1)	41.97	-93.69	Croplands	01/01/2005–11/09/2011	Cammalleri *et al.* (2014)
Brooks Field Site 11 (US-Br3)	41.97	-93.69	Croplands	01/01/2005–11/09/2011	Sakai *et al.* (2016)
Canaan Valley (US-CaV)	39.06	-79.42	Grasslands	01/06/2004–11/18/2010	Yang *et al.* (2007)
Chestnut Ridge (US-ChR)	35.93	-84.33	Deciduous broadleaf forest	05/11/2005–01/13/2011	Cammalleri *et al.* (2014)
Duke Forest Open Field (US-Dk1)	35.97	-79.09	Grasslands	01/01/2001–12/31/2008	Katul *et al.* (2003)
Duke Forest Hardwoods (US-Dk2)	35.97	-79.10	Mixed forest	01/01/2001–12/31/2008	Katul *et al.* (2003)
Duke Forest Loblolly Pine (US-Dk3)	35.98	-79.09	Evergreen needleleaf forest	01/01/1998–12/31/2008	Katul *et al.* (2003)
Florida Everglades Shark River Slough Long Hydroperiod Marsh (US-Elm)	25.55	-80.78	Permanent wetlands	07/22/2008–12/31/2013	Schedlbauer *et al.* (2012)
Florida Everglades Taylor Slough Short Hydroperiod Marsh (US-Esm)	25.44	-80.59	Permanent wetlands	01/01/2008–12/31/2013	Schedlbauer *et al.* (2012)
Flagstaff Managed Forest (US-Fmf)	35.14	-111.73	Evergreen needleleaf forest	07/29/2005–12/31/2010	Dore *et al.* (2010)
Fort Peck (US-FPe)	48.31	-105.10	Grasslands	01/01/2000–12/28/2008	Cammalleri *et al.* (2014)

(continued on next page)

Site name	Lat.	Long.	Vegetation type (IGBP)	Data period	Source
Freeman Ranch Mesquite Juniper (US-FR2)	29.95	-98.00	Woody savannas	01/01/2005–12/29/2008	Heinsch *et al.* (2004)
Freeman Ranch Woodland (US-FR3)	29.94	-97.99	Woody savannas	07/17/2004–12/31/2012	Heinsch *et al.* (2004)
Flagstaff Unmanaged Forest (US-Fuf)	35.09	-111.76	Evergreen needleleaf forest	09/06/2005–12/31/2010	Dore *et al.* (2008)
Flagstaff Wildfire (US-Fwf)	35.45	-111.77	Grasslands	06/15/2005–12/31/2010	Dore *et al.* (2008)
GLEES (US-GLE)	41.36	-106.24	Evergreen needleleaf forest	10/01/2004–12/31/2012	Zeller & Nikolov (2000)
Great Mountain Forest (US-GMF)	41.97	-73.23	Mixed forest	05/19/1999–12/31/2004	Lee *et al.* (2001)
Harvard Forest (US-Ha1)	42.54	-72.17	Deciduous broadleaf forest	10/28/1991–12/31/2014	Moore *et al.* (1996)
Howland Forest Main (US-Ho1)	45.20	-68.74	Evergreen needleleaf forest	01/01/1996–12/31/2009	Hollinger *et al.* (1999)
Fermi Agricultural (US-IB1)	41.86	-88.22	Croplands	03/28/2005–12/31/2011	Matamala *et al.* (2008)
Fermi Prairie (US-IB2)	41.84	-88.24	Grasslands	10/06/2004–12/31/2011	Matamala *et al.* (2008)
Kansas Field Station (US-KFS)	39.06	-95.19	Grasslands	06/16/2007–12/31/2012	Cochran *et al.* (2016)
Konza Prairie (US-Kon)	39.08	-96.56	Grasslands	08/22/2006–12/31/2012	Logan & Brunsell (2015)
Kennedy Space Center Scrub Oak (US-KS2)	28.61	-80.67	Closed shrublands	06/29/1999–12/31/2006	Powell *et al.* (2006)
Lost Creek (US-Los)	46.08	-89.98	Wetland	01/01/2000–12/31/2014	Sulman *et al.* (2009)
Metolius Intermediate Pine (US-Me2)	44.45	-121.56	Evergreen needleleaf forest	01/01/2002–12/31/2014	Law *et al.* (2004)
Metolius Second Young Pine (US-Me3)	44.32	-121.61	Evergreen needleleaf forest	01/01/2004–12/31/2009	Sun *et al.* (2004)
Metolius First Young Pine (US-Me5)	44.44	-121.57	Evergreen needleleaf forest	06/17/1999–12/31/2002	Law *et al.* (2003)
Morgan Monroe State Forest (US-MMS)	39.32	-86.41	Deciduous broadleaf forest	01/01/1999–12/31/2014	Pryor *et al.* (1999)
Missouri Ozark (US-MOz)	38.74	-92.20	Deciduous broadleaf forest	01/01/2004–12/31/2014	Gu *et al.* (2006)
Marys River Fir Site (US-MRf)	44.65	-123.55	Evergreen needleleaf forest	01/01/2005–02/17/2012	He *et al.* (2015)
North Carolina Loblolly Pine (US-NC2)	35.80	-76.67	Evergreen needleleaf forest	01/01/2005–12/31/2010	Noormets *et al.* (2010)
Mead Irrigated (US-Ne1)	41.17	-96.48	Croplands	05/25/2001–05/31/2013	Suyker *et al.* (2004)
Mead Irrigated Rotation (US-Ne2)	41.16	-96.47	Croplands	06/04/2001–05/31/2013	Suyker *et al.* (2004)
Mead Rainfed (US-Ne3)	41.18	-96.44	Croplands	06/04/2001–05/31/2013	Suyker *et al.* (2004)
Niwot Ridge (US-NR1)	40.03	-105.55	Evergreen needleleaf forest	11/01/1998–12/31/2014	Turnipseed *et al.* (2002)
Ohio Oak Openings (US-Oho)	41.55	-83.84	Deciduous broadleaf forest	01/01/2004–12/31/2013	DeForest *et al.* (2006)
Park Falls (US-PFa)	45.95	-90.27	Mixed forest	01/01/1995–12/31/2014	Desai *et al.* (2014)
Florida Everglades Shark River Slough Mangrove Forest (US-Skr)	25.36	-81.08	Evergreen broadleaf forest	01/01/2004–09/12/2011	Barr *et al.* (2009)
Sky Oaks Old (US-SO2)	33.37	-116.62	Closed shrublands	01/01/1997–12/31/2006	Stylinski *et al.* (2002)
Sky Oaks Young (US-SO3)	33.38	-116.62	Closed shrublands	01/01/1997–12/31/2006	Stylinski *et al.* (2002)
Austin Cary (US-SP1)	29.74	-82.22	Evergreen needleleaf forest	07/01/2000–12/31/2011	Fang *et al.* (1998)
Mize (US-SP2)	29.76	-82.24	Evergreen needleleaf forest	01/01/1999–12/31/2008	Fang *et al.* (1998)
Donaldson (US-SP3)	29.75	-82.16	Evergreen needleleaf forest	01/01/1999–12/31/2010	Fang *et al.* (1998)
Santa Rita Creosote (US-SRC)	31.91	-110.84	Open shrublands	01/01/2008–12/31/2014	Crow *et al.* (2015)
Santa Rita Mesquite Savanna (US-SRM)	31.82	-110.87	Woody savannas	12/31/2003–12/31/2015	Scott *et al.* (2008)
Sylvania Wilderness (US-Syv)	46.24	-89.35	Mixed forest	01/01/2001–12/31/2014	Desai *et al.* (2005)
Tonzi Ranch (US-Ton)	38.43	-120.97	Woody savannas	01/01/2001–12/31/2014	Baldocchi *et al.* (2004)
Vaira Ranch (US-Var)	38.41	-120.95	Grasslands	01/01/2000–12/31/2014	Baldocchi *et al.* (2004)
Walker Branch (US-WBW)	35.96	-84.29	Deciduous broadleaf forest	12/31/1994–06/06/2007	Hanson *et al.* (2005)
Willow Creek (US-WCr)	45.81	-90.08	Deciduous broadleaf forest	01/01/1998–12/31/2014	Desai *et al.* (2005)
Lucky Hills Shrubland (US-Whs)	31.74	-110.05	Open shrublands	06/29/2007–12/31/2015	Scott (2010)
Kendall Grassland (US-Wkg)	31.74	-109.94	Grasslands	05/06/2004–12/31/2015	Scott *et al.* (2010)
Wind River Field Station (US-Wrc)	45.82	-121.95	Evergreen needleleaf forest	01/01/1998–12/31/2015	Paw U *et al.*, (2004)

We calculated NEDI on a monthly scale based on the half-hourly measurements to obtain the Thornthwaite PET, K_c and NEDI at each site. These results were then classified into needleleaf forest, broadleaf forest, mixed forest, grasslands, savannas, shrublands, croplands and wetlands IGBP ecosystem types.

3.2 PDSI dataset

We used the global monthly 2.5°×2.5° PDSI dataset (Dai, 2011) from the National Center for Atmospheric Research Climate Analysis Section.[3] The AmeriFlux site locations were matched to the PDSI dataset, to compare the PDSI and NEDI results under potential drought patterns (Table 1).

4. Results and Discussions

4.1 Evapotranspiration Deficits and Crop Coefficients

It is clear that decreasing NEDI (suggesting a shift toward a drier regime) is associated with increasing evapotranspiration deficit (differences between the Thornthwaite PET and observed evapotranspiration) across different climatic conditions for all non-forest type ecosystems except wetlands. This suggests that NEDI can be an useful tool for drought monitoring in less complicated ecosystems (**Figure 1**). However, the correlation between NEDI and evapotranspiration deficit is not significant at forest ecosystems, which suggests that evapotranspiration in forest ecosystems is not only controlled by available water stored in the ecosystems but by other limiting factors.

To avoid biases from the varying magnitudes of site-dependent evapotranspiration deficit, the transitional patterns of ecosystem drought were analyzed by the modified VITA technique with the non-dimensional crop coefficient K_c serving as the detection parameter. Rapid changes in local variance of K_c were found for all investigated ecosystem types when NEDI changes signs (**Figure 2**), suggesting significant changes in normalized evapotranspiration strength. Moreover, the local means of K_c are generally low (limited evapotranspiration) with slight changes in local variance when NEDI is negative, and they tend to be high (approaching potential evapotranspiration) with evident changes in local variance when NEDI is positive. The highly varying normalized evapotranspiration K_c with positive NEDI suggests that the available stored water is not the controlling factor to evapotranspiration when sufficient water is provided, whereas, water availability is Sprengel's (Liebig's) limiting factor under ecosystem drought conditions. These results indicate that, in terms of evapotranspiration, ecosystems

3 http://www.cgd.ucar.edu/cas/catalog/climind/pdsi.html

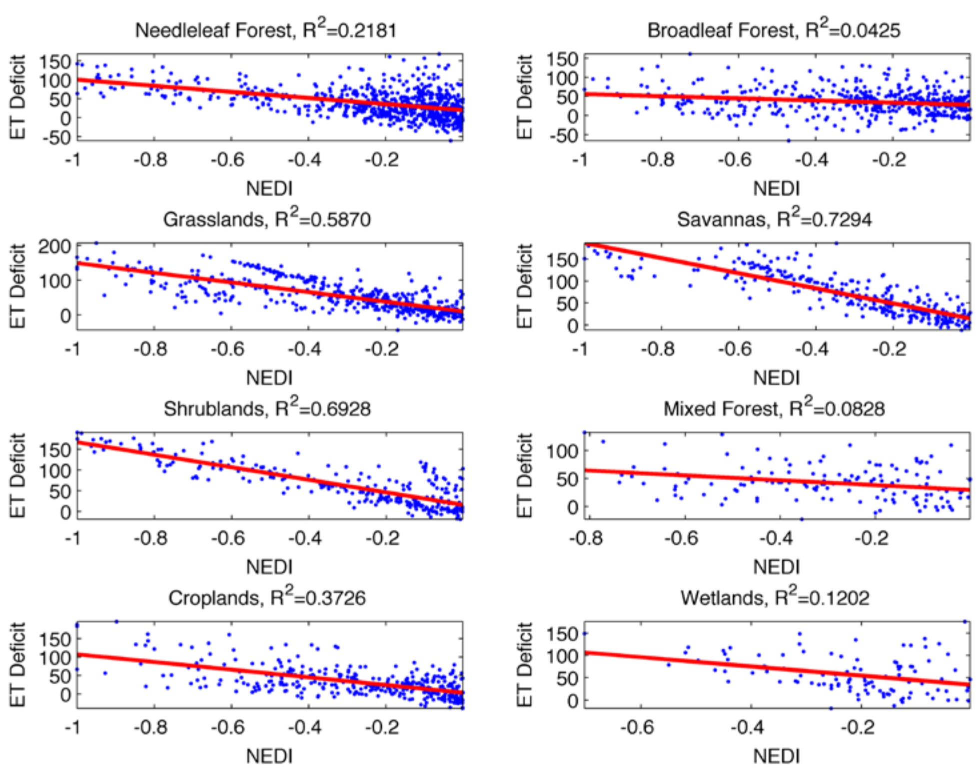

Figure 1. Scatterplots between NEDI and ET deficit (blue dots). Red lines are linear regression lines with corresponding R^2 values.

respond differently in wet and dry regimes, and the use of the NEDI can successfully identify drought conditions based on transitional patterns found in normalized evapotranspiration strength.

Although the threshold separating wet and dry regimes is universally defined by NEDI across all the investigated ecosystem types, the results shown in Figure 2 suggest that the sensitivity between NEDI and K_c varies with ecosystem type. In general, the sensitivity for grasslands, savannas and shrublands is higher than for the other ecosystems. This implies that water availability is the limiting factor at these ecosystems while other ecological limiting factors are equally important for the other ecosystems. If we prescribe ecosystem drought severity based on the magnitude of K_c, we can conceptually define mild drought ($K_c = 0.75$), severe drought ($K_c = 0.5$) and extreme drought ($K_c = 0.25$) with NEDI below −0.1, −0.3 and −0.8 (**Figure 2**), respectively. We note this ecosystem drought severity scale may not be applicable to broadleaf forest and mixed forest because for them, K_c stops decreasing at around 0.5, regardless of further decrease in NEDI. There are two possible explanations for this behavior: (1) Ecosystem adaptation strategy is different in these two ecosystems, preventing further decreases in K_c even under extreme ecosystem drought; or (2) there are not enough samples for extreme ecosystem drought in our dataset for these two ecosystems, making the interpretation of NEDI calculations in respect to drought difficult.

On the other hand, PDSI is only weakly correlated with evapotranspiration deficit, and the decrease in PDSI (increase in drought severity) is not associated with an increase in evapotranspiration deficit (**Figure 3**). This result suggests that large-scale drought conditions detected by PDSI do not necessarily correspond to ecosystem drought. Similar to the analyses with NEDI, the dependence of normalized evapotranspiration K_c on PDSI was investigated by applying the modified VITA technique for individual ecosystem types (**Figure 4**). Contrary to the NEDI results, local mean and local variance of K_c do not have any distinguishable pattern with PDSI across different ecosystems, and there is no clear distinction between the dry and wet regimes defined by PDSI and normalized K_c. This supports our hypothesis that ecosystem drought conditions are detected by NEDI, but are poorly detected by PDSI.

4.2 Water Use Efficiency (WUE)

Huxman *et al.* (2004) found a strong relationship between Water Use Efficiency (WUE) and precipitation, which highlights the importance of rain-use efficiency on ecological processes and suggests that water limitation can

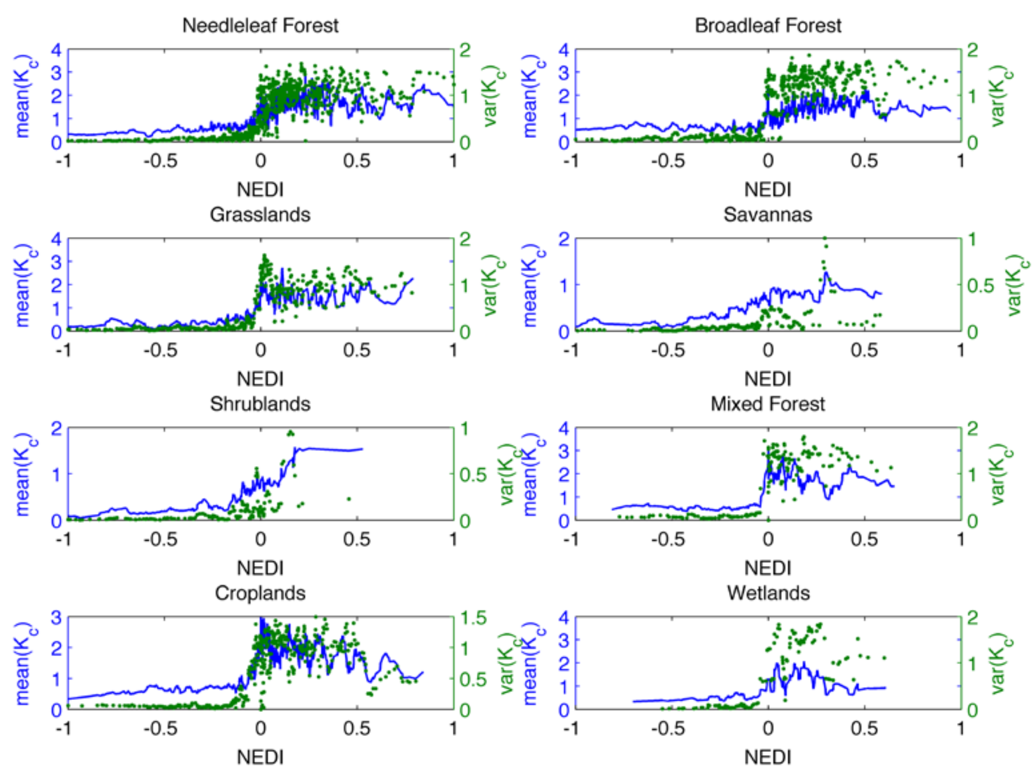

Figure 2. The local mean (blue lines) and the local variance (green dots) of normalized evapotranspiration strength calculated by the modified VITA technique with non-dimensional crop coefficient K_c vs NEDI.

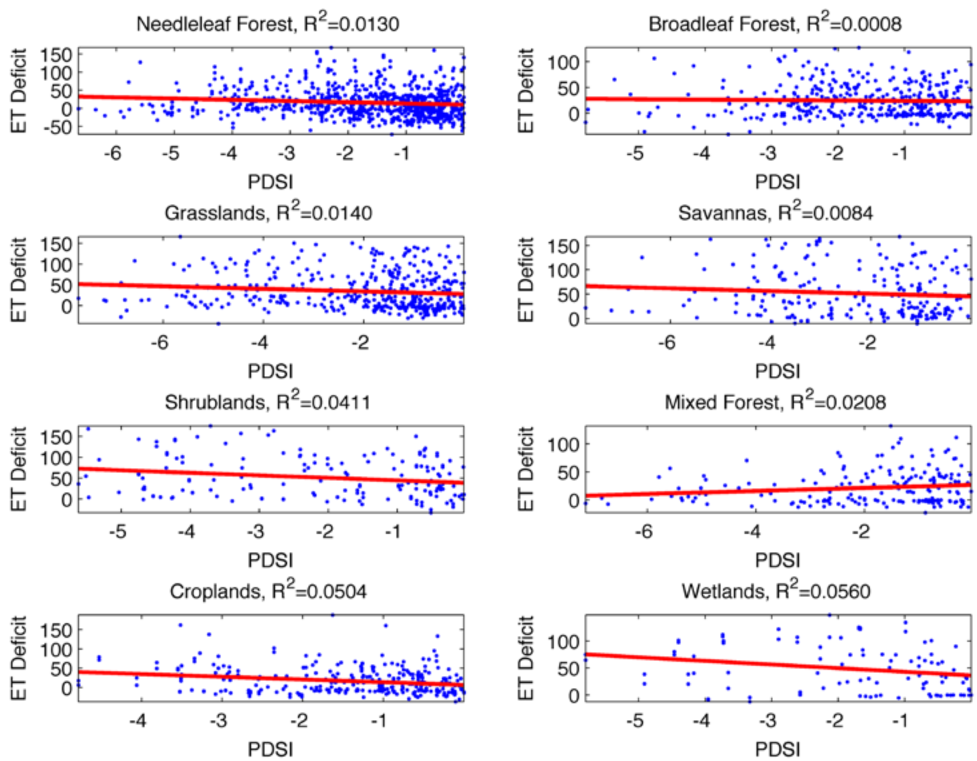

Figure 3. Scatter plots between PDSI and ET deficit (blue dots). Red lines are linear regression lines with corresponding R^2 values.

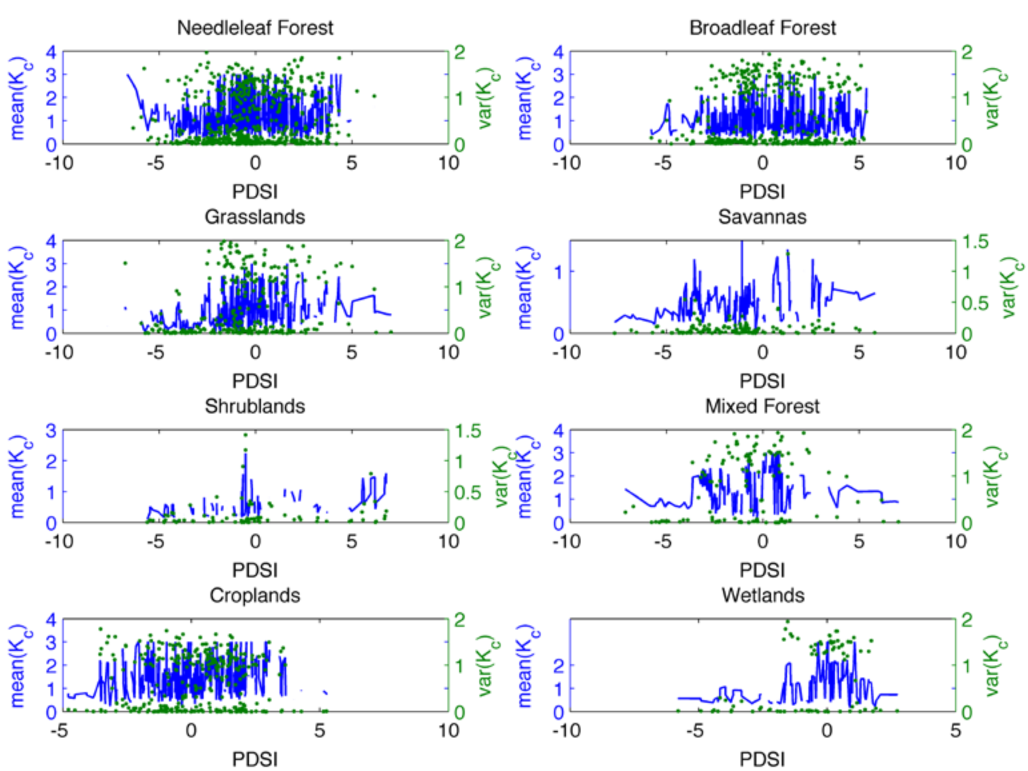

Figure 4. The local mean (blue lines) and the local variance (green dots) of normalized evapotranspiration strength calculated by the modified VITA technique with non-dimensional crop coefficient K_c vs PDSI.

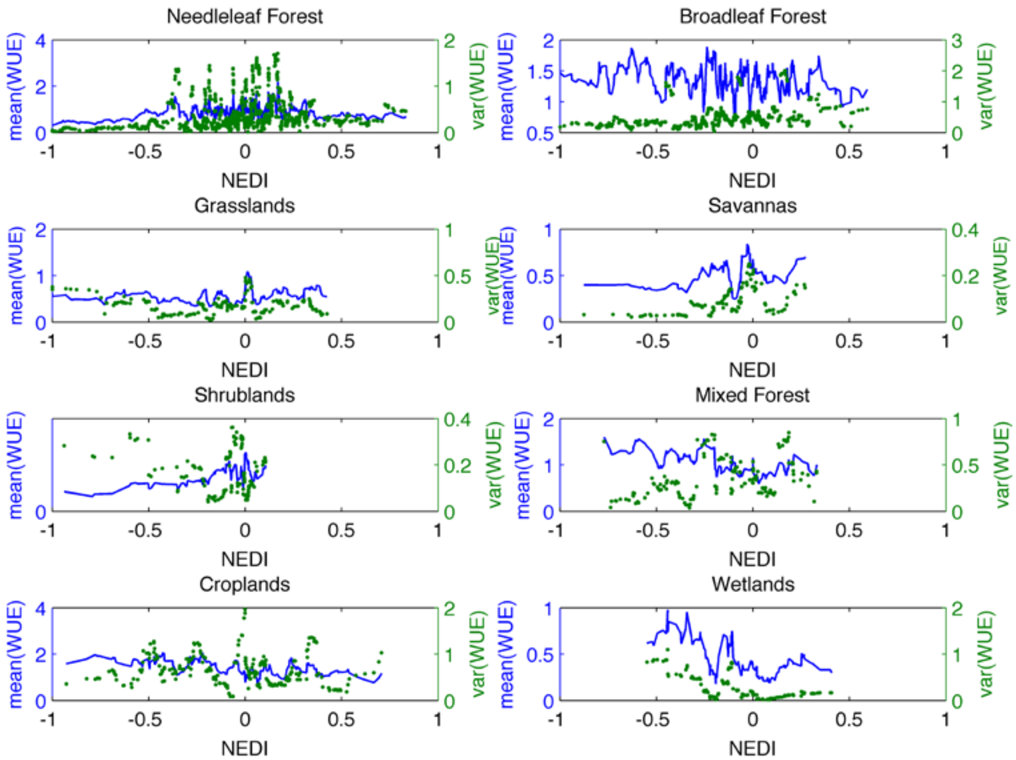

Figure 5. The local mean (blue lines) and the local variance (green dots) of plant water use efficiency (WUE) calculated by the modified VITA technique plotted against NEDI.

impose a common constraint on net primary production. Using a remotely sensed dataset with artificial neural networks, Lu and Zhuang (2010) identified a two-stage pattern in WUE changes with drought severity. Specifically, their results showed that WUE increases when the intensity of drought is moderate and WUE tends to decrease under severe drought. Here, we further investigate the relationship between WUE and ecosystem drought severity by using the modified VITA technique with WUE as the detection parameter. The WUE used in this study was defined as the ratio between monthly NEE from eddy-covariance and monthly evapotranspiration.

The two-stage changes in WUE proposed by Lu and Zhuang (2010) were detected at needleleaf forest, savannas and shrublands, where local means of WUE were higher when NEDI is greater than –0.5 and then slightly decreased when ecosystem drought severity became more intense (**Figure 5**). Similar patterns were shown in grasslands and croplands, although the changes in the WUE magnitude during extreme ecosystem drought were mild. Such two-stage patterns cannot be found in broadleaf forest, mixed forest and wetlands, possibly because there was no extreme ecosystem drought in the available dataset as discussed in Section 4.1.

The WUE patterns shown in Figure 5 are strongly dependent on the variations of evapotranspiration and carbon assimilation strength in each VITA window. The local means of WUE systematically varies with NEDI in certain ecosystem types, although there is no rapid transition detected in local variance. In general, both evapotranspiration and NEE decrease when NEDI is lower than –0.5, except for broadleaf forest, mixed forest and wetlands (results not shown). In this regime, the decreasing trend for carbon assimilation is stronger than those for evapotranspiration, resulting in lower WUE during severe ecosystem drought, though the change in WUE is less significant at grasslands and croplands. On the other hand, evapotranspiration and carbon assimilation both increase at similar rates as NEDI decreases for broadleaf and mixed forests, resulting in a slightly increasing trend in WUE during severe ecosystem drought. The difference in WUE responses to ecosystem drought suggests that broadleaf forest and mixed forest might have different adaptation strategy than the other vegetated ecosystem types under limited water availability. However, more data recording ecosystem responses to drought is needed to validate this hypothesis.

5. Conclusions

In this study, we developed the Normalized Ecosystem Drought Index (NEDI) to objectively quantify drought severity in terms of ecosystem transitional responses to limited water availability. Eddy covariance measurements from 60 AmeriFlux sites across 8 IGBP vegetation types were used to examine the validity of NEDI. The results show that, based on a modified VITA analysis, normalized evapotranspiration strength K_c decreases correspondingly with NEDI, suggesting that NEDI can reasonably characterize ecosystem responses to drought severity. The same analysis was performed to PDSI; however, no clear relationship can be found between normalized evapotranspiration strength and drought severity indicated by PDSI.

Moreover, the low data requirement and simplicity natures in NEDI make it straightforward to apply NEDI to different scientific disciplines for drought detection and analysis at various spatial and temporal scales. We applied NEDI to investigate plant WUE dependency on water availability, using a modified VITA analysis, and the results show that most vegetated ecosystems exhibit two-stage changes in WUE (Lu and Zhuang, 2010), except broadleaf forest and mixed forest. It is possible that the differences found in WUE dependence on water availability are driven by the differences in plant adaptation strategy to drought, but more extensive studies are required to evaluate this hypothesis.

Acknowledgments

We thank Dr. Ankur Desai Dr. Ge Sun for their valuable comments. We thank the principal investigators of the AmeriFlux network, and the U.S. Department of Energy's Office of Science for funding the AmeriFlux data resources. We thank the U.S. Department of Energy Lawrence Berkeley Lab Ameriflux Network Management Project for core site support. This research was supported through the National Science Foundation award EF1137306/MIT subaward 5710003122 to the University of California Davis; and other government, industry and foundation sponsors of the MIT Joint Program on the Science and Policy of Global Change. For a complete list of sponsors and U.S. government funding sources, please visit http://globalchange.mit.edu/sponsors/all.

6. References

Allen, R.G., L.S. Pereira, D. Raes, and M. Smith, 1998: Crop evapotranspiration: Guidelines for computing crop requirements. *Irrig. Drain. Pap. No. 56, FAO*, 300, doi:10.1016/j.eja.2010.12.001.

Baldocchi, D.D., L. Xu, and N. Kiang, 2004: How plant functional-type, weather, seasonal drought, and soil physical properties alter water and energy fluxes of an oak-grass savanna and an annual grassland. *Agric. For. Meteorol.*, **123**, 13–39, doi:10.1016/j.agrformet.2003.11.006.

Barr, J.G., J.D. Fuentes, V. Engel, and J.C. Zieman, 2009: Physiological responses of red mangroves to the climate in the Florida Everglades. *J. Geophys. Res.*, **114**, 1–13, doi:10.1029/2008JG000843.

Beguería, S., S.M. Vicente-Serrano, F. Reig, and B. Latorre, 2014: Standardized precipitation evapotranspiration index (SPEI) revisited: parameter fitting, evapotranspiration models, tools, datasets and drought monitoring. *Int. J. Climatol.*, **34**, 3001–3023, doi:10.1002/joc.3887.

Bernacchi, C.J., S.E. Hollinger, and T. Meyers, 2005: The conversion of the corn / soybean ecosystem to no-till agriculture may result in a carbon sink. *Glob. Chang. Biol.*, **11**, 1867–1872, doi:10.1111/j.1365-2486.2005.01050.x.

Blackwelder, R.F., and R.E. Kaplan, 1976: On the wall structure of the turbulent boundary layer. *J. Fluid Mech.*, **76**, 89, doi:10.1017/S0022112076003145.

Cammalleri, C., M.C. Anderson, and W.P. Kustas, 2014: Upscaling of evapotranspiration fluxes from instantaneous to daytime scales for thermal remote sensing applications. *Hydrol. Earth Syst. Sci.*, **18**, 1885–1894, doi:10.5194/hess-18-1885-2014.

Cochran, F. V, N.A. Brunsell, and A.E. Suyker, 2016: A thermodynamic approach for assessing agroecosystem sustainability. *Ecol. Indic.*, **67**, 204–214, doi:10.1016/j.ecolind.2016.01.045.

Crow, W.T., F. Lei, C. Hain, M.C. Anderson, R.L. Scott, D. Billesbach, and T. Arkebauer, 2015: Robust estimates of soil moisture and latent heat flux coupling strength obtained from triple collocation. *Geophys. Res. Lett.*, **42**, 8415–8423, doi:10.1002/2015GL065929.

Dai, A., 2011: Drought under global warming: A review. *Wiley Interdiscip. Rev. Clim. Chang.*, **2**, 45–65, doi:10.1002/wcc.81.

DeForest, J.L., A. Noormets, S.G. McNulty, G. Sun, G. Tenney, and J. Chen, 2006: Phenophases alter the soil respiration-temperature relationship in an oak-dominated forest. *Int. J. Biometeorol.*, **51**, 135–144, doi:10.1007/s00484-006-0046-7.

Desai, A.R., P.V. Bolstad, B.D. Cook, K.J. Davis, and E.V. Carey, 2005: Comparing net ecosystem exchange of carbon dioxide between an old-growth and mature forest in the upper Midwest, USA. *Agric. For. Meteorol.*, **128**, 33–55, doi:10.1016/j.agrformet.2004.09.005.

Desai, A.R., 2014: Influence and predictive capacity of climate anomalies on daily to decadal extremes in canopy photosynthesis. *Photosynthesis Research*, **119**, 31-47, doi:10.1007/s11120-013-9925-z.

Donohue, R.J., T.R. Mcvicar, and M.L. Roderick, 2010: Assessing the ability of potential evaporation formulations to capture the dynamics in evaporative demand within a changing climate. *J. Hydrol.*, **386**, 186–197, doi:10.1016/j.jhydrol.2010.03.020.

Doorenbos, J., and W.O. Pruitt, 1977: Guidelines for predicting crop water requirements. FAO Irrigation and Draingage Paper 24. Food and Agriculture Organization of the United Nations. Rome. 145p.

Dore, S., and Coauthors, 2008: Long-term impact of a stand-replacing fire on ecosystem CO_2 exchange of a ponderosa pine forest. *Glob. Chang. Biol.*, **14**, 1801–1820, doi:10.1111/j.1365-2486.2008.01613.x.

Dore, S., and Coauthors, 2010: Carbon and water fluxes from ponderosa pine forests disturbed by wildfire and thinning. *Ecol. Appl.*, **20**, 663–683, doi:10.1890/09-0934.1.

Fang, C., J.B. Moncrieff, H.L. Gholz, and K.L. Clark, 1998: Soil CO_2 efflux and its spatial variation in a Florida slash pine plantation. *Plant Soil*, **205**, 135–146, doi:10.1023/a:1004304309827.

Feyen, L., and R. Dankers, 2009: Impact of global warming on streamflow drought in Europe. *J. Geophys. Res. Atmos.*, **114**, 1–17, doi:10.1029/2008JD011438.

Fischer, M.L., D.P. Billesbach, J.A. Berry, W.J. Riley, and M.S. Torn, 2007: Spatiotemporal variations in growing season exchanges of CO_2, H2O, and sensible heat in agricultural fields of the Southern Great Plains. *Earth Interact.*, **11**, doi:10.1175/EI231.1.

Goldstein, A.H., and Coauthors, 2000: Effects of climate variability on the carbon dioxide, water, and sensible heat fluxes above a ponderosa pine plantation in the Sierra Nevada (CA). *Agric. For. Meteorol.*, **101**, 113–129, doi:10.1016/S0168-1923(99)00168-9.

Gu, L., and Coauthors, 2006: Direct and indirect effects of atmospheric conditions and soil moisture on surface energy partitioning revealed by a prolonged drought at a temperate forest site. *J. Geophys. Res.*, **111**, 1–13, doi:10.1029/2006JD007161.

Guttman, N.B., 1998: COMPARING THE PALMER DROUGHT INDEX AND THE STANDARDIZED PRECIPITATION INDEX ’ ties of the PDSI and its variations have been the referenced studies show that the intended. *J. Am. Water Resour. Assoc.*, **34**, 113–121, doi:10.1111/j.1752-1688.1998.tb05964.x.

Hanson, P.J., S.D. Wullschleger, R.J. Norby, T.J. Tschaplinski, and C.A. Gunderson, 2005: Importance of changing CO 2 , temperature , precipitation , and ozone on carbon and water cycles of an upland-oak forest : incorporating experimental results into model simulations. *Glob. Chang. Biol.*, **11**, 1402–1423, doi:10.1111/j.1365-2486.2005.00991.x.

He, Y., J. Yang, Q. Zhuang, J.W. Harden, A.D. Mcguire, Y. Liu, G. Wang, and L. Gu, 2015: Incorporating microbial dormancy dynamics into soil decomposition models to improve quantification of soil carbon dynamics of northern temperate forests. *J. Geophys. Res. Biogeosciences*, **120**, 2596–2611, doi:10.1002/2015JG003130.

Heinsch, F.A., J.L. Heilman, K.J. McInnes, D.R. Cobos, D.A. Zuberer, and D.L. Roelke, 2004: Carbon dioxide exchange in a high marsh on the Texas Gulf Coast: Effects of freshwater availability. *Agric. For. Meteorol.*, **125**, 159–172, doi:10.1016/j.agrformet.2004.02.007.

Hollinger, D.Y., S.M. Goltz, E. a Davidson, J.T. Lee, K. Tu, and H.T. Valentine, 1999: Seasonal patterns and environmental control of carbon dioxide and water vapour exchange in an ecotonal boreal forest. *Glob. Chang. Biol.*, **5**, 891–902, doi:10.1046/j.1365-2486.1999.00281.x.

Huxman, T.E., and Coauthors, 2004: Convergence across biomes to a common rain-use efficiency. *Nature*, **429**, 651–654, doi:10.1038/nature02561.

Jensen M.E., R.D. Burman, R.G. Allen (Editors), 1990: Evapotranspiration and Irrigation Water Requirements. ASCE Manuals and Reports on Engineering Practices No. 70. ASCE, New York, NY, USA, 360 pp.

Katul, G., R. Leuning, and R. Oren, 2003: Relationship between plant hydraulic and biochemical properties derived from a steady-state coupled water and carbon transport model. *Plant, Cell Environ.*, **26**, 339–350, doi:10.1046/j.1365-3040.2003.00965.x.

Law, B.E., O.J. Sun, J. Campbell, V.T. S, and P. Thornton, 2003: Changes in carbon storage and fluxes in a chronoseuence of ponderosa pine. *Glob. Chang. Biol.*, **4**, 510–524, doi:10.1046/j.1365-2486.2003.00624.x.

Law, B.E., D. Turner, O.J. Sun, S. Van Tuyl, W.D. Ritts, and W.B. Cohen, 2004: Disturbance and climate effects on carbon stocks and fluxes across Western Oregon USA. *Glob. Chang. Biol.*, **10**, 1429–1444, doi:10.1111/j.1365-2486.2004.00822.x.

Lee, X., O.R. Bullock Jr, and R.J. Andres, 2001: Anthropogenic emission of mercury to the atmosphere in the northeast United States. *Geophys. Res. Lett.*, **28**, 1231–1234.

Liu, Y., J. Xiao, W. Ju, Y. Zhou, and S. Wang, 2011: Water use efficiency of China ’ s terrestrial ecosystems and responses to drought. *Nat. Publ. Gr.*, 1–12, doi:10.1038/srep13799.

Logan, K.E., and N.A. Brunsell, 2015: Influence of drought on growing season carbon and water cycling with changing land cover. Agric. For. Meteorol., 213, 217–225, doi:10.1016/j.agrformet.2015.07.002.

Lu, X., and Q. Zhuang, 2010: Evaluating evapotranspiration and water-use efficiency of terrestrial ecosystems in the conterminous United States using MODIS and AmeriFlux data. *Remote Sens. Environ.*, **114**, 1924–1939, doi:10.1016/j.rse.2010.04.001.

Matamala, A.R., J.D. Jastrow, R.M. Miller, and C.T. Garten, 2016: Temporal Changes in C and N Stocks of Restored Prairie : Implications for C Sequestration Strategies. *Ecol. Appl.*, **18**, 1470–1488 (http://www.jstor.org/stable/40062268).

McKee, T.B., N.J. Doesken, and J. Kleist, 1993: The relationship of drought frequency and duration to time scales. *Preprints, Eighth Conf. on Applied Climatology.* Anaheim, CA, Amer. Meteor. Soc., 179–184.

Meyers, T.P., and S.E. Hollinger, 2004: An assessment of storage terms in the surface energy balance of maize and soybean. *Agric. For. Meteorol.*, **125**, 105–115, doi:10.1016/j.agrformet.2004.03.001.

Moore, K.E., D.R. Fitzjarrald, R.K. Sakai, M.L. Goulden, J.W. Munger, and S.C. Wofsy, 1996: Seasonal Variation in Radiative and Turbulent Exchange at a Deciduous Forest in Central Massachusetts. *J. Appl. Meterology*, **35**, 122–134, doi:10.1175/1520-0450(1996)035<0122:SVIRAT>2.0.CO;2.

Mpelasoka, F., K. Hennessy, R. Jones, and B. Bates, 2008: Comparison of suitable drought indices for climate change impacts assessment over Australia towards resource. *Int. J. Climatol.*, **1292**, 1283–1292, doi:10.1002/joc.

Narasimhan, B., and R. Srinivasan, 2005: Development and evaluation of Soil Moisture Deficit Index (SMDI) and Evapotranspiration Deficit Index (ETDI) for agricultural drought monitoring. *Agric. For. Meteorol.*, **133**, 69–88, doi:10.1016/j.agrformet.2005.07.012.

Noormets, A., M.J. Gavazzi, S.G. McNulty, J.-C. Domec, G.E. Sun, J.S. King, and J. Chen, 2010: Response of carbon fluxes to drought in a coastal plain loblolly pine forest. *Glob Chang Biol*, **16**, 272–287, doi:10.1111/j.1365-2486.2009.01928.x.

Palmer, W., 1965: Meteorological Drought. *Res. Pap.*, 1–65.

Paw U, K.T., and Coauthors, 2004: Carbon Dioxide Exchange Between an Old-growth Forest and the Atmosphere. *Ecosystems*, **7**, 513–524, doi:10.1007/s10021-004-0141-8.

Peterson, A.T., 2003: Predicting the geography of species’ invasions via ecological niche modeling. *Quart. Rev. Biol.* **78**, 419-433.

Powell, T.L., R. Bracho, J. Li, S. Dore, C.R. Hinkle, and B.G. Drake, 2006: Environmental controls over net ecosystem carbon exchange of scrub oak in central Florida. *Agric. For. Meteorol.*, **141**, 19–34, doi:10.1016/j.agrformet.2006.09.002.

Pryor, S.C., R.J. Barthelmie, and B. Jensen, 1999: Nitrogen dry deposition at an AmeriFlux site in a hardwood forest in the midwest. *Geophys. Res. Lett.*, **26**, 691, doi:10.1029/1999GL900066.

Qi, J., and Coauthors, 2000: Spatial and temporal dynamics of vegetation in the San Pedro River basin area. *Agric. For. Meteorol.*, **105**, 55–68, doi:10.1016/S0168-1923(00)00195-7.

Reichstein, M., and Coauthors, 2002: Severe drought effects on ecosystem CO_2 and H_2O fluxes at three Mediterranean evergreen sites: revision of current hypotheses? *Glob. Chang. Biol.*, **8**, 999–1017, doi:10.1046/j.1365-2486.2002.00530.x.

Richardson, A.D., J.P. Jenkins, B.H. Braswell, D.Y. Hollinger, S.V. Ollinger, and M.L. Smith, 2007: Use of digital webcam images to track spring green-up in a deciduous broadleaf forest. *Oecologia*, **152**, 323–334, doi:10.1007/s00442-006-0657-z.

Sakai, T., and Coauthors, 2015: Varying applicability of four different satellite-derived soil moisture products to global gridded crop model evaluation. *Int. J. Appl. Earth Obs. Geoinf.*, **48**, 51–60, doi:10.1016/j.jag.2015.09.011.

Schedlbauer, J.L., J.W. Munyon, S.F. Oberbauer, E.E. Gaiser, and G. Starr, 2012: Controls on ecosystem carbon dioxide exchange in short- and long-hydroperiod Florida everglades freshwater marshes. *Wetlands*, **32**, 801–812, doi:10.1007/s13157-012-0311-y.

Scott, R.L., W.L. Cable, and K.R. Hultine, 2008: The ecohydrologic significance of hydraulic redistribution in a semiarid savanna. *Water Resour. Res.*, **44**, 1–12, doi:10.1029/2007WR006149.

Scott, R.L., 2010: Using watershed water balance to evaluate the accuracy of eddy covariance evaporation measurements for three semiarid ecosystems. *Agric. For. Meteorol.*, **150**, 219–225, doi:10.1016/j.agrformet.2009.11.002.

Scott, R.L., E.P. Hamerlynck, G.D. Jenerette, M.S. Moran, and G.A. Barron-Gafford, 2010: Carbon dioxide exchange in a semidesert grassland through drought-induced vegetation change. *J. Geophys. Res. Biogeosciences*, **115**, 1–12, doi:10.1029/2010JG001348.

Seager, R., and Coauthors, 2007: Model projections of an imminent transition to amore arid climate in southwestern North America. *Science*, **1475**, 1181–1184, doi:10.1126/science.1139601.

Seager, R., and Coauthors, 2009: Mexican drought: An observational modeling and tree ring study of variability and climate change. *Atmosfera*, **22**, 1–31.

Stylinski, C.D., J.A. Gamon, and W.C. Oechel, 2002: Seasonal patterns of reflectance indices, carotenoid pigments and photosynthesis of evergreen chaparral species. *Oecologia*, **131**, 366–374, doi:10.1007/s00442-002-0905-9.

Sulman, B.N., Desai, A.R., Cook, B.D., Saliendra, N., and Mackay, D.S., 2009. Contrasting carbon dioxide fluxes between a drying shrub wetland in Northern Wisconsin, USA, and nearby forests. *Biogeosciences*, **6**, 1115-1126, doi:10.5194/bg-6-1115-2009.

Sun, O.J., J. Campbell, B.E. Law, and V. Wolf, 2004: Dynamics of carbon stocks in soils and detritus across chronosequences of different forest types in the Pacific Northwest , USA. *Glob. Chang. Biol.*, **10**, 1470–1481, doi:10.1111/j.1365-2486.2004.00829.x.

Suyker, A.E., S.B. Verma, G.G. Burba, T.J. Arkebauer, D.T. Walters, and K.G. Hubbard, 2004: Growing season carbon dioxide exchange in irrigated and rainfed maize. *Agric. For. Meteorol.*, **124**, 1–13, doi:10.1016/j.agrformet.2004.01.011.

Turnipseed, A.A., P.D. Blanken, D.E. Anderson, and R.K. Monson, 2002: Energy budget above a high-elevation subalpine forest in complex topography. *Agric. For. Meteorol.*, **110**, 177–201, doi:10.1016/S0168-1923(01)00290-8.

van der Ploeg, R.R., W. Bohm, and M.B. Kirkham, 1999: On the origin of the theory of mineral nutrition of plants and the law of the minimum. *Soil Sci. Soc. Am. J.*, **63**, 1055–1062.

van der Schrier, G., P.D. Jones, and K.R. Briffa, 2011: The sensitivity of the PDSI to the Thornthwaite and Penman-Monteith parameterizations for potential evapotranspiration. *J. Geophys. Res. Atmos.*, **116**, 1–16, doi:10.1029/2010JD015001.

Vicente-Serrano, S.M., S. Beguería, and J.I. López-Moreno, 2010: A multiscalar drought index sensitive to global warming: The standardized precipitation evapotranspiration index. *J. Clim.*, **23**, 1696–1718, doi:10.1175/2009JCLI2909.1.

Wells, N., S. Goddard, and M.J. Hayes, 2004: A self-calibrating Palmer drought severity index. *J. Climate*, **17**, 2335–2351.

Wilhite, D.A., 2000. *Drought as a natural hazard: concepts and definitions.* In: Donald, A., Wilhite, Ed., Drought: A Global Assessment, vol. IRoutledge, New York, pp. 3–18 (Chapter 1).

Yang, F., and Coauthors, 2007: Developing a continental-scale measure of gross primary production by combining MODIS and AmeriFlux data through Support Vector Machine approach. *Remote Sens. Environ.*, **110**, 109–122, doi:10.1016/j.rse.2007.02.016.

Zeller, K.F., and N.T. Nikolov, 2000: Quantifying simultaneous fluxes of ozone, carbon dioxide and water vapor above a subalpine forest ecosystem. *Environ. Pollut.*, **107**, 1–20, doi:10.1016/S0269-7491(99)00156-6.

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