# Global Precipitation Part II: Ecosystem & Management Implications

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This bulletin is the second in a two part piece on changes in global precipitation. In it, we discuss how water availability shapes forests and recent observations of forest decline linked to drought and heat stress. We then turn our attention to the issue of drought, including the factors that contribute to drought risk and the management options for mitigating it. While there will be a mix of wetter and drier conditions in the future, depending on the region, the background trend of warming temperatures will exacerbate drying – making more frequent and severe drought one of the more obvious climate-related risks.

## Changes in Global Precipitation: A Recap

Predicting how global climate change will affect future precipitation is one of the most challenging and uncertain areas of climate modeling research. However, there are some consistent patterns that have emerged from model projections, as described in part one of this bulletin. These general rules-of-thumb are summarized here:

- Increase in total global precipitation
- Regional differences, i.e. changes will not be uniform – increases in mid and high latitudes; decreases in subtropics
- General pattern of wet-get-wetter, dry-get-drier
- Increased contrast between wet and dry seasons
- Increased winter precipitation in mid and high latitudes
- Increased frequency of heavy precipitation events
- A few areas of model agreement in terms of drying (soil moisture), including northeast and southwest South America and southwestern U.S.

## Why Water Availability Matters

Water availability is likely to change in the future, due to the combination of increasing average temperatures and changes in the total, timing, and intensity of precipitation events. Water availability, in terms of soil moisture, is a particularly important metric for forest management, since it can drive changes in forest structure and species composition over time. Water availability affects tree mortality, seedling recruitment, and resource allocation within individual trees (e.g. root-shoot ratio), and these factors ultimately influence competition between species.

### *Tree Species Migration*

Severe or long-term decreases in water availability can predispose forest areas to large-scale die-off that opens the door for colonization of new species. While climate-induced tree species movement is usually a gradual process, it can happen more rapidly when sporadic mortality events eliminate competition from established species – arguably the biggest immediate barrier to species migration. We have seen some examples of this mortality-facilitating-colonization pattern in places like the Green Mountains of Vermont, where there is evidence that the upslope migration of hardwood species was likely accelerated by canopy turnover after red spruce experienced dieback from acid rain in the 1960's and 70's (Beckage et al. 2008) .

### *Tree Resource Allocation*

Water availability, including the amount and timing of rainfall, is critical to forest structure because it changes how individual trees allocate their resources between the above and belowground portions of the stem. Under drier conditions, trees will generally respond by decreasing inputs to foliage and aboveground woody biomass while increasing fine roots, which improves their ability to draw on limited soil water resources. This is a helpful adaptation, but it reduces growth in the merchantable part of the tree. Likewise, in wetter areas, trees will put more resources into foliage and increase growth rate, with fewer fine roots. This capitalizes on growth potential and increases competitiveness, but it can also result in a shallower root system that increases risk of blow down and vulnerability to future drought conditions (Farrior et al. 2013; McDowell et al. 2008).

Different species have different amounts of plasticity in the degree and speed with which they can shift resources in response to changing conditions and, as with any adaptation, there are tradeoffs, e.g. it has been shown that this flexibility, while beneficial in terms of adaptability, can be detrimental in stressful environments (Richter et al. 2012).

## Water Stress and Forest Mortality

Recently, researchers have documented widespread tree mortality on a global scale that is at least partly attributed to drought and heat stress (see this map from Hartmann et al. 2015, which shows locations of substantial drought- and heat-induced tree mortality around the globe since 1970). The impacts were observed in wet areas, as well as semi-arid regions, which indicates that increasing temperatures may be playing a significant role – by increasing water loss through transpiration, reducing tree vigor, and accelerating insect development and reproduction (Allen et al. 2010; Hartmann et al. 2015).

There are many examples of forest impacts in the U.S. that have been linked to water stress, including aspen decline in the west (Worrall et al. 2013), increased mortality of pine and oak species in the Central Coast and Southern Sierra Ranges of California (USFS 2015), loss of big trees (>2 ft dbh) throughout California (McIntyre et al. 2015), and regional-scale die-off of piñon pine (Breshears et al. 2008). The ultimate consequences of forest die-off driven by drought and heat stress are unclear and researchers have highlighted the importance of investigating these implications (Anderegg, Kane, and Anderegg 2013).

At this time, we don't have sufficient data to know whether forest mortality is increasing globally. Although, these observations have sparked a huge body of research on the physiological mechanisms that influence how plants avoid, tolerate, and/or recover from drought stress. A better understanding of exactly how and why certain trees succumb to drought will improve predictions of global-scale forest impacts from climate change.

Presently, the understanding is that drought-related mortality happens via three interrelated pathways – carbon starvation, hydraulic failure, and biotic attack (Figure 1). Carbon starvation occurs when photosynthesis is reduced and trees are forced to use up their carbon reserves – a consequence of closing leaf stomata, which reduces water loss but does not allow CO2 uptake. Hydraulic failure occurs when plants dehydrate past the point of no return. Insects and pathogens can amplify or be amplified by both of these processes (McDowell et al. 2008), e.g. carbon starvation will reduce resin production and make it difficult for trees to pitch out an attacking beetle.

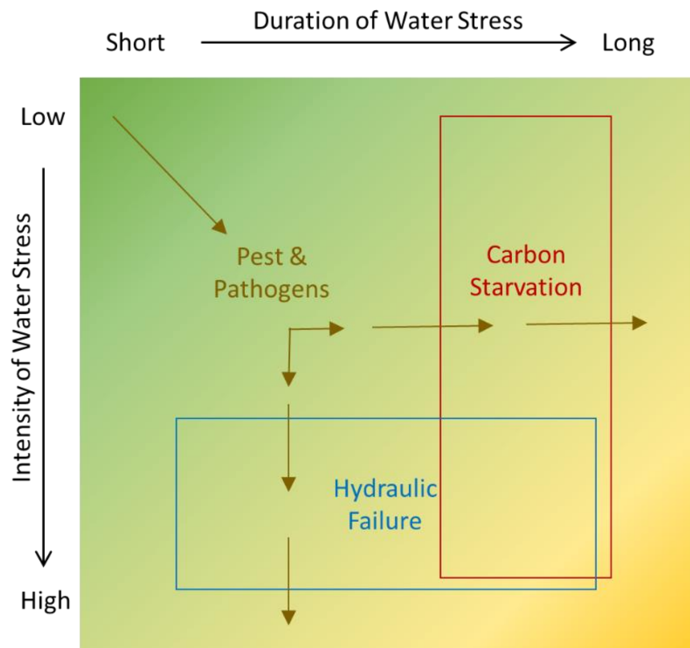


**Figure 1**: Theoretical relationship between the length and intensity of drought, and the three potential mechanisms underlying tree mortality. *Source: Adapted from McDowell et al. 2008.*

## Evaluating Drought Risk

Evidence suggests we will experience more frequent and severe drought due to climate change, but this risk is not universal and it varies with site characteristics and forest type. Determining whether it is a significant risk for your forestland involves considering all the factors that influence intensity, exposure, and vulnerability to drought.

### *Intensity*

Higher temperatures increase the intensity of individual drought events by water loss through direct evaporation and forest transpiration (collectively known as evapotranspiration). Additionally, as conditions dry, there is a feedback that exaggerates this process – less soil moisture means less cooling from transpiration and temperatures go up even further. This is similar to the way human sweat helps reduce body temperature – if you lose your ability to sweat when you are hot, your body temperature will begin to increase rapidly.

Including evapotranspiration in model simulations (rather than precipitation alone) increases the percentage of global land area that is projected to experience moderate drying by the end of this century (from 12 to 30%). Importantly, researchers found that this effect will even make relatively wet areas more drought prone: "Increased PET [potential evapotranspiration] not only intensifies drying in areas where precipitation is already reduced, it also drives areas into drought that would otherwise experience little drying or even wetting from precipitation trends alone" (Cook et al. 2014). This interaction with temperature has also been implicated in the severity of the recent California drought, where researchers have found that the occurrence of drought years has increased primarily because of the increased probability of warm-dry conditions, rather than a substantial change in the probability of a precipitation deficit (Diffenbaugh, Swain, and Touma 2015). The bright side is that these drying trends will be beneficial in some areas where conditions have historically been excessively wet – this will help alleviate issues of reduced productivity and limited access in these locations.

### *Exposure*

Site characteristics, including soil texture, depth to water table, and topography, have a big influence on the amount of drought exposure on a given site (i.e. the likelihood that a given location will experience drought conditions). These factors influence soil water holding capacity, run off, and evaporation rates, which all mediate the direct effects of precipitation change.

### *Vulnerability*

Vulnerability is primarily determined by the tree species mix on site, specifically the level of drought tolerance exhibited by each species. The variability in forest drought tolerance from region to region creates some unique advantages and disadvantages in terms of vulnerability. For example, the southeastern U.S. has a species mix with a relatively high drought tolerance compared to the northeast, which reduces the risk of negative drought impacts in that region. However, there is a much higher diversity in terms of the mix of drought tolerant and intolerant species in the Appalachian region and the northeast, which might be beneficial if future conditions are highly variable.

*Note: We recommend referencing [Russell et al. 2014] for maps of average drought tolerance and diversity of drought tolerance classes among tree species in the eastern U.S.*

### *Overall Risk*

Taken together, these factors tell us that sites that are projected to have large increases in temperature and decreases in precipitation, with low soil water holding capacity, and a drought-intolerant species mix will have the highest levels of drought risk (in terms of intensity, exposure, and vulnerability). In contrast, an area may have a high likelihood of intense drought in the future, but the risk may be mitigated by a drought tolerant species mix and better site conditions. The regions of greatest concern going forward will be places where all these factors overlap.

## Reducing Drought Risk through Management

From the perspective of an individual forest manager, there is not much that can be done to reduce the intensity of future drought conditions, but the following areas offer opportunities to reduce risk by reducing exposure and/or vulnerability:

- *Land base*
  - Focus resources on sites with soil and topographic characteristics that generally retain moisture
- *Species mix*
  - Use silvicultural techniques that favor regeneration of drought tolerant species
  - Plant genotypes from warmer and dryer areas of a species range
- *Reduce stocking*
  - A number of studies conducted in different forest types throughout the U.S. and Europe (primarily in pine-dominated systems) have highlighted the utility of thinning for moderating drought impacts on growth, increasing drought resistance, and improving the speed of recovery after drought events (D'Amato et al. 2013; Kerhoulas et al. 2013; Kohler et al. 2010; Slodicak, Novak, and Dusek 2011).
  - Although it is worth noting that thinning has been shown to have negligible effects on drought tolerance in sparse forest canopies (B. Law, personal communication, May 6, 2015), such as some dry western forests where self-thinning has naturally taken place.

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