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PERSPECTIVE

Browning boreal forests of western North America

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The GIMMS NDVI dataset has been widely used to document a 'browning trend' in North American boreal forests (Goetz *et al* 2005, Bunn *et al* 2007, Beck and Goetz 2011). However, there has been speculation (Alcaraz-Segura *et al* 2010) that this trend may be an artifact due to processing algorithms rather than an actual decline in vegetation activity. This conclusion was based primarily on the fact that GIMMS NDVI did not capture NDVI recovery within most burned areas in boreal Canada, while another dataset consistently showed post-fire increasing NDVI. I believe that the results of Alcaraz-Segura *et al* (2010) were due simply to different pixel sizes of the two datasets (64 km^2 versus 1 km^2 pixels). Similar results have been obtained from tundra areas greening in Alaska, with the results simply due to these pixel size differences (Stow *et al* 2007). Furthermore, recent studies have documented boreal browning trends based on NDVI from other sensors. Beck and Goetz (2011) have shown the boreal browning trend derived from a different sensor (MODIS) to be very similar to the boreal browning trend derived from the GIMMS NDVI dataset for the circumpolar boreal region. Parent and Verbyla (2010) found similar declining NDVI patterns based on NDVI from Landsat sensors and GIMMS NDVI in boreal Alaska. Zhang *et al* (2008) found a similar 'browning trend' in boreal North America based on a production efficiency model using an integrated AVHRR and MODIS dataset.

The declining NDVI trend in areas of boreal North America is consistent with tree-ring studies (D'Arrigo *et al* 2004, McGuire *et al* 2010, Beck *et al* 2011). The decline in tree growth may be due to temperature-induced drought stress (Barber *et al* 2000) caused by higher evaporative demands in a warming climate (Lloyd and Fastie 2002). In a circumpolar boreal study, Lloyd and Bunn (2007) found that a negative relationship between temperature and tree-ring growth occurred more frequently in warmer parts of species' ranges, suggesting that direct temperature stress might be a factor in some species. Since warm growing seasons are also typically dry growing seasons, direct temperature stress and moisture stress could occur simultaneously. For example, 2004 was the warmest summer in over 200 years in boreal Alaska (Barber *et al* 2004) but it was also during a drought with less than 50 mm of summer precipitation recorded in Fairbanks. In Fairbanks, the length of the growing season, as defined as the period above freezing, has increased by 45 per cent over the past 100 years, with no significant increase in precipitation (Wendler and Shulski 2009). Regional winter runoff has increased, likely associated with permafrost thawing (Brabets and Walvoord 2009), while surface water has decreased, likely associated with increased evapotranspiration (Riordan *et al* 2006, Anderson *et al* 2007, Berg *et al* 2009). The mean annual air temperature in boreal Alaska has increased by over 1.5 °C during the past 50 years (Stafford *et al* 2000), and is projected to increase by 3–7 °C by end of this century (Walsh *et al* 2008). Thus, it would be surprising if a declining NDVI trend was not occurring in the western boreal region of North America as the climate continues to warm.

Insects and disease in the North American boreal forest may also affect the NDVI browning trends (Malmström and Raffa 2000), as the life histories of damaging insects may be linked to a warming boreal climate. For example, warmer temperatures contributed to the spruce beetle outbreaks in Alaska with a reduction in the beetle life cycle from two years to one year (Berg *et al* 2006).

Thus, as the boreal climate continues to warm, tree growth reduction and mortality from insects and diseases may become more substantial. In boreal Alaska, recent alder dieback and mortality is likely to be related to alder's susceptibility to a canker-causing fungus in drought years (Ruess *et al* 2009). Recent widespread and prolonged outbreaks of aspen leaf miner and a willow leaf blotch miner in boreal Alaska are likely to have resulted in decreased NDVI (Parent and Verbyla 2010).

The NDVI browning trend has expanded in area in boreal North America (Beck and Goetz 2011). If the trend towards a warmer and drier climate continues, these areas may represent a future tipping point where drought-induced mortality across a boreal region may occur. Such events have already occurred in the western United States (van Mantgem *et al* 2009) and the aspen parklands of the southern Canadian boreal forest (Michaelian *et al* 2010).

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