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PERSPECTIVE

Shrub expansion and climate feedbacks in Arctic tundra

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Arctic tundra ecosystems stand to play a substantial role in both the magnitude and rate of global climate warming over the coming decades and centuries. The exact nature of this role will be determined by the combined effects of currently amplified rates of climate warming in the Arctic (Serreze *et al* 2000) and a series of related positive climate feedbacks that include mobilization of permafrost carbon (Schuur *et al* 2008), decreases in surface albedo (Chapin *et al* 2005) and evapotranspiration (ET) mediated increases in atmospheric water vapor (Swann *et al* 2010). Conceptually, these feedback mechanisms are intuitive and readily comprehensible: warming-induced permafrost thaw will make new soil carbon pools accessible for microbial respiration, and increased vegetation productivity, expansion of shrubs in particular, will lower surface reflectance and increase ET. However, our current understanding of these feedback mechanisms relies largely on limited and local field studies and, as such, the quantitative estimates of feedback effects on regional and global climate require spatial upscaling and uncertainty estimates derived from models. Moreover, the feedback mechanisms interact and their combined net effect on climate is highly variable and not well characterized.

A recent study by Bonfils *et al* (2012) is among the first to explicitly examine how shrub expansion in tundra ecosystems will impact regional climate. Using an Earth system model, Bonfils *et al* find that an idealized 20% increase in shrub cover north of 60°N latitude will lead to annual temperature increases of 0.66 °C and 1.84 °C, respectively, when the shrubs are 0.5 m and 2 m tall. The modeled temperature increases arise from atmospheric heating as a combined consequence of decreased albedo and increased ET. The primary difference between the two cases is associated with the fact that tall shrubs protrude above the snow, thus reducing albedo year round, whereas short shrubs are completely covered by the snowpack for part of the year.

These results support evidence that shrub expansion in Arctic tundra will feed back positively to ongoing climate warming but, perhaps more importantly, illustrate the significance of shrub height in dictating the feedback strength. While differences in albedo associated with vegetation stature have been previously documented in these ecosystems (Loranty *et al* 2011, Sturm *et al* 2005a), the magnitudes of the feedbacks on regional climate were unknown. These findings highlight a pressing need to understand the rate and spatial extent at which shrub expansion is occurring. While increases in vegetation productivity inferred from satellite data have been observed across the Arctic (Bunn and Goetz 2006, Goetz *et al* 2005, Walker *et al* 2009), recent analyses suggest that the observed trends are a result of general increases in productivity across all vegetation types (Beck and Goetz 2011).

Another important finding reported by Bonfils *et al* (2012) is the positive correlation between shrub height and modeled active layer depth (i.e. permafrost thaw). Results from a field study (Blok *et al* 2010) showed that the shading effects of shrub canopies reduce ground heat flux, which in turn leads to a decrease in active layer depth. Bonfils *et al*'s (2012) results indicate that regional warming as a consequence of albedo and ET feedbacks will offset the local cooling effects of increased shrub cover, thus the net climate feedback associated

with shrub expansion could be greater than reported (owing to biogeochemical processes and related feedbacks). A similar study by Lawrence and Swenson (2011) found that snow redistribution to shrub covered areas (Sturm *et al* 2005b) simultaneously reduced the albedo feedback by covering shrubs with snow and introduced a soil warming feedback through insulation provided by additional snow cover, with a net result of increased active layer depth under shrubs. When shrub cover (1 m tall canopy) was increased by 20% and less snow was available for redistribution over a greater shrub covered area, the insulation effect was not great enough to offset the reduction in albedo, thus on average the effect of shrub cover on active layer depth was negligible. These results underscore the importance of shrub height, shrub cover and snow depth when considering how shrub expansion will influence net feedbacks to climate.

Uncertainties regarding the interacting effects of snow redistribution and albedo feedbacks on active layer depth make it difficult to predict how shrub expansion may ultimately mediate permafrost feedbacks to climate on annual to decadal timescales. Although both Bonfils *et al* (2012) and Lawrence and Swenson (2011) provide strong evidence that the albedo and ET feedbacks associated with a 20% increase in shrub cover, relative to the current distribution, will result in warming that more than offsets local cooling, the effects of a 5% or 10% increase in shrub cover are less clear. For example, it may be reasonable to assume that a 20% increase in shrub cover over the next 100 years will lead to a 1.84 °C regional temperature increase and, consequently, substantial permafrost thaw. But will a 0.46 °C increase over the next 25 years with a 5% increase in shrub cover significantly increase the active layer depth or melt permafrost? The regional warming associated with a 5% increase in shrub cover may not be strong enough to counteract the local cooling effects of shrubs (Blok *et al* 2010), in which case increased shrub cover could serve as a negative feedback to permafrost thaw in the near term, retarding the process, or even promoting permafrost aggradation. On the other hand, it is possible that the greater snow redistribution that would occur with less shrub cover (Lawrence and Swenson 2011) could lead to higher rates of winter warming that would offset the local cooling effects caused by shading during the growing season, thereby acting as a positive feedback to permafrost thaw. These feedbacks could either mitigate or exacerbate permafrost degradation associated with ongoing climate warming; thus research on this subject is essential and timely given the rates of shrub cover change documented by historical photographs (Tape *et al* 2006) and satellite imagery (Forbes *et al* 2010).

A complete understanding of the net climate feedback effects of shrub expansion in Arctic tundra will require improved knowledge of the factors controlling shrub distribution and the associated vegetation structure influences on the redistribution of snow. A recent synthesis highlights the myriad complex and interacting factors that are likely to govern shrub expansion, which include recruitment and dispersal mechanisms, species differences, topo-edaphic factors, and the role of disturbance and biotic interactions (Myers-Smith *et al* 2011). In the context of understanding climate feedbacks, it is imperative that future studies distinguish between instances of shrub expansion that include an increase in canopy height or extent that is biophysically relevant. Increased effort is needed to understand snow–shrubs interactions in the context of surface energy fluxes. This level of detail is necessary for accurate prediction of the rate and magnitude of shrub mediated climate feedbacks in the Arctic.

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