Conversion of Siberian Larch Forests in Response to Climate Change

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Introduction

The Siberian boreal forest may affect the Earth's climate through temperature driven changes in the regional forest composition and resultant changes in surface albedo. Siberia's forests are dominated by the deciduous conifer larch (*Larix spp.*) and a warmer climate may accelerate succession from larch to evergreen conifer forest. Because larch is a deciduous conifer, this shift to evergreen dominance would lead to a significant decrease in albedo, particularly in winter, when evergreen trees tend to mask underlying snow relative to deciduous species (Betts and Ball 1997). This implies a positive feedback where warmer climate accelerates succession to evergreen conifer, which in turn leads to further warming through a change in albedo. It is possible that a human-mediated introduction of European Larch (*L. decidua*), which has higher tolerance for warmer conditions than the native larch, would mitigate the effects of climate change in Siberia by slowing the rate of conversion from deciduous to evergreen conifer forests.

The individual based dynamic forest gap model FAREAST (Yan and Shugart 2005) has been validated against inventory data across Russia (Shuman 2010, Shuman and Shugart 2009) and is ideal for exploring the feedback between climate and forest composition. FAREAST is used to simulate species and biomass dynamics across Siberia and the Russian Far East. Climate sensitivity analysis quantifies changes in response to altered climate and the inclusion of *L. decidua*. In sites identified as vulnerable to early replacement of larch by evergreen conifers, albedo data is analyzed for representative evergreen and larch stands, and the local radiative forcing associated with this transition is calculated.

Methods

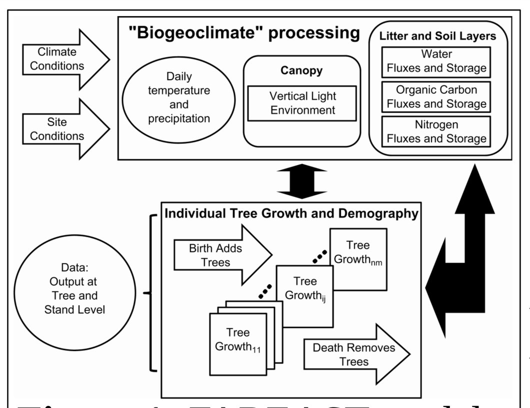


Figure 1: FAREAST model subroutines and interactions.

Forest simulation

FAREAST was run at 372 sites across Siberia and the RFE with species unique to each site from 58 potential species. At each site, 200 independent twelfth-hectare plots were simulated for 500 years and biomass values were averaged for each species in each year producing a landscape-level view of succession (Figure 1).

Climate sensitivity analysis

A non-parametric factorial ANOVA was performed at 10 year intervals and used to assess differences in total forest, *Larix* spp., and evergreen conifer biomass (tC ha^{-1}) between model runs that employed one of the 11 different climate and *L. decidua* treatments and the base climate scenario (Table 1). Base scenario is derived from historical climate data (NCDCa,b). Remaining climate scenarios use linear increase in temperature or precipitation or both from year zero to year 200 followed by 300 years with climate stabilized around conditions attained in year 200. The *L. decidua* treatment allowed European Larch into the potential species pool for all sites.

Table 1. Treatments used in climate sensitivity analysis

Change in temperature	Base + 4 °C
Change in precipitation	Base 10%
Introduction of *Larix decidua*	Base + *L. decidua*

Analysis was completed at the continental scale for a total of 372 sites, and for six regional subsets including northwest Siberia (NW Siberia), Central Siberia, two sets from southern Siberia (E Irkutsk, and W Irkutsk), and two sets from the Amur region of the Russian Far East (N RFE and SW RFE). Within the regional subsets, local scale results were evaluated for changes in successional dynamics resulting from treatments.

Albedo methods

Larch and evergreen sites were identified using a combination of the 2005 Type 1 IGBP global vegetation classification scheme, visible satellite imagery, and regional vegetation maps. Collocated pairs of sites were used to control for snow depth and albedo. MODIS shortwave albedo was extracted for all 11 available years (2000-2010) and averaged over the maximum area of coherent, undisturbed forest. Shortwave radiative forcing was calculated as the change in reflected shortwave radiation at the surface and scaled to top of the atmosphere (TOA) using a spatially explicit atmospheric compensation factor (12% for this region; Winton, 2005). Incoming radiation data from NASA's Surface meteorology and Solar Energy (SSE) dataset (eosweb.larc.nasa.gov/sse/) were averaged over the 21 available years (1984-2004) to develop a representative climatology of local incoming radiation for use in the radiative forcing calculation.

Regional Results

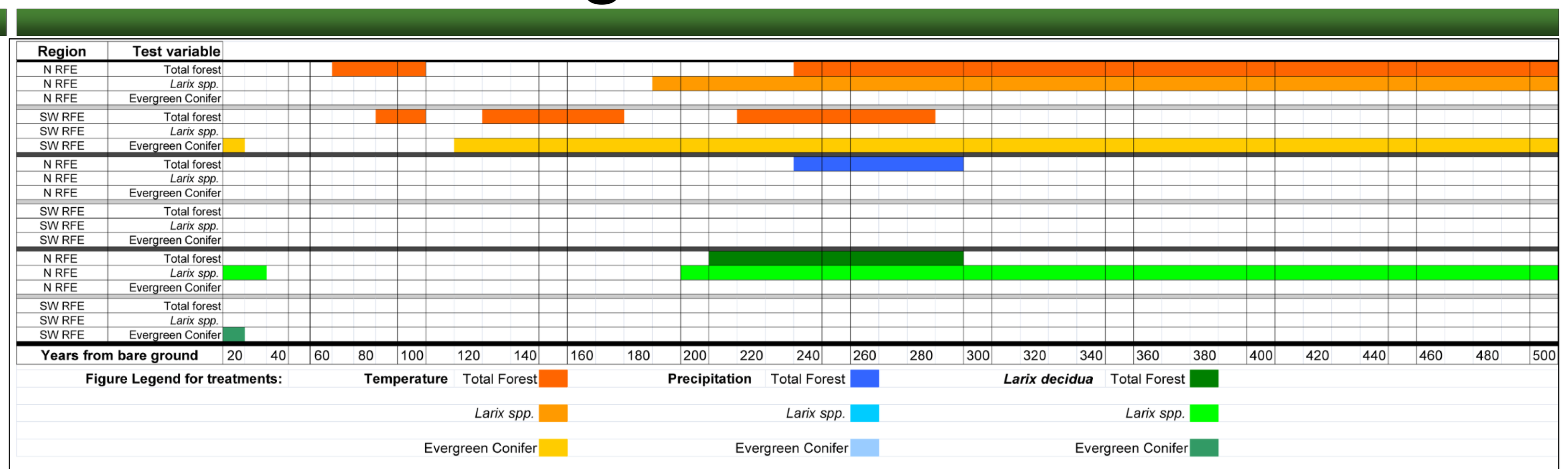
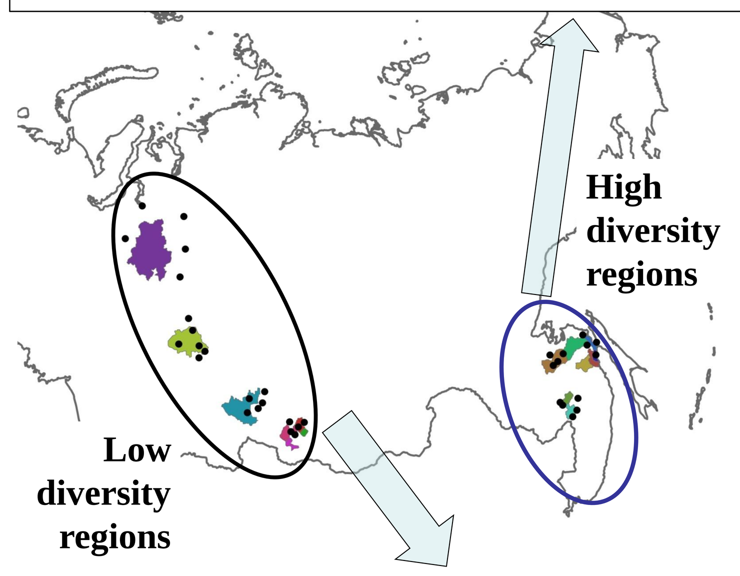


Figure 2: Non-parametric factorial ANOVA results for climate sensitivity analyses in two high diversity sites of the Amur region in the Russian Far East: northern Russian Far East (N RFE) and southwestern Russian Far East (SW RFE). Shown in colors are comparisons significant to p<0.001 for treatment effects on total forest, *Larix* spp., and evergreen conifer biomass.



Regional scale results:

- ***High diversity*** regions (average 38 trees species) are ***minimally responsive*** to 4°C increase
- ***Low diversity*** regions (average 9 tree species) are ***highly responsive*** to 4°C and *L. decidua* treatments
- Timing of response to precipitation in low diversity region of Central Siberia suggests connection between low annual precipitation and transition to moisture sensitive evergreen conifer dominance

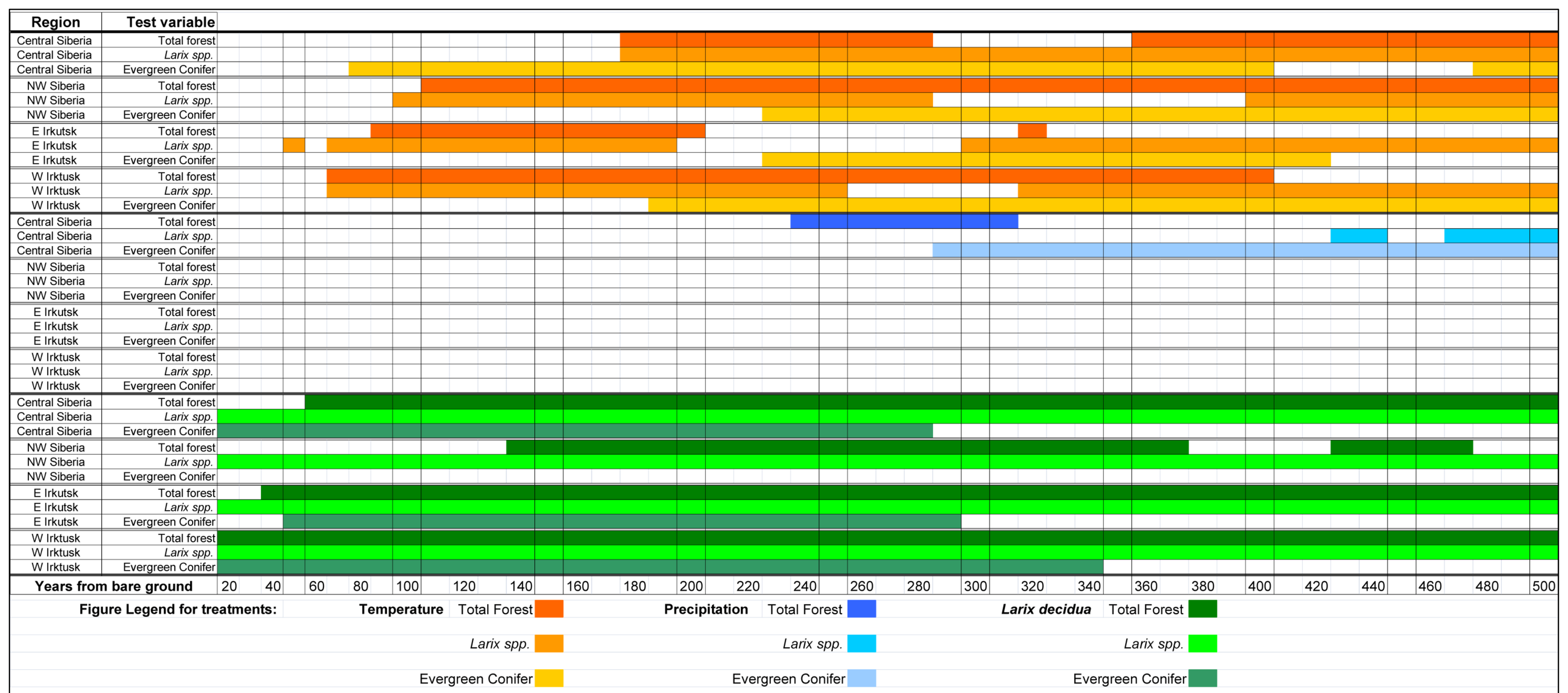


Figure 3: Non-parametric factorial ANOVA results for climate sensitivity analyses in low diversity sites of Siberia. Shown in colors are comparisons significant to p<0.001 for total forest, *Larix* spp., and evergreen conifer biomass. NW Siberia is the northwest Siberia region. E and W Irkutsk regions are in southern Siberia.

Continental Results

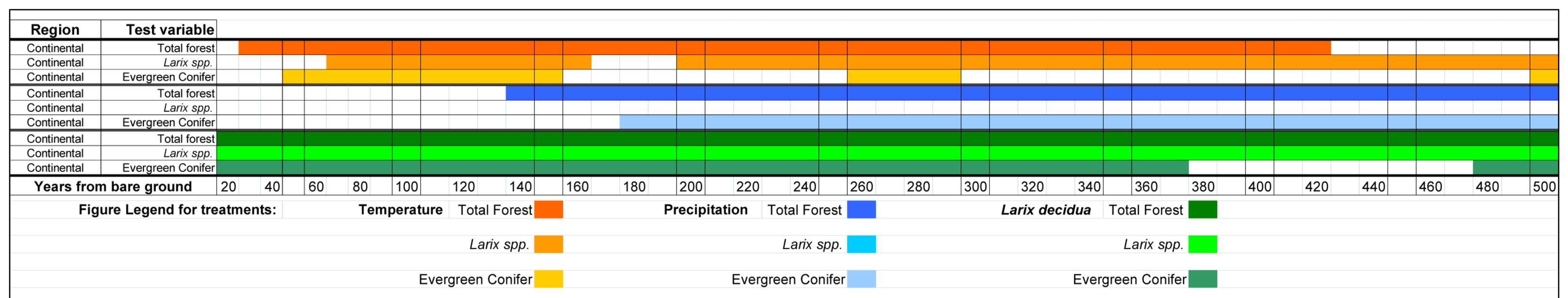


Figure 4: Non-parametric factorial ANOVA results for climate sensitivity analyses for 372 sites across Siberia and the Russian Far East. Shown in colors are comparisons significant to p<0.001 for treatment effects on total forest, *Larix* spp., and evergreen conifer biomass.

Continental scale results:

- Biomass of all classes across 372 sites highly responsive to 4°C increase
- Effect of precipitation change on biomass of total forest and evergreen conifers suggests connection to successional transition to evergreen dominance
- *L. decidua* establishes strongly thereby affecting all biomass classes
- System behaves as a ***low diversity area*** with ***low resilience*** to altered climate
- Shift from deciduous larch to evergreen conifer forest is accelerated across Siberia under warming conditions (Figure 6)

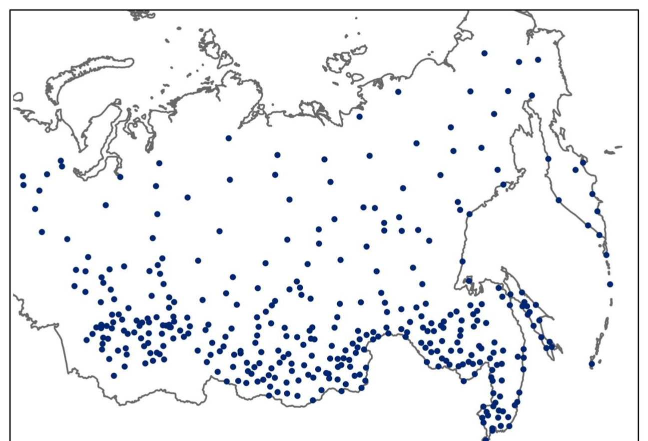


Figure 5: Location of 372 sites included in continental scale analysis

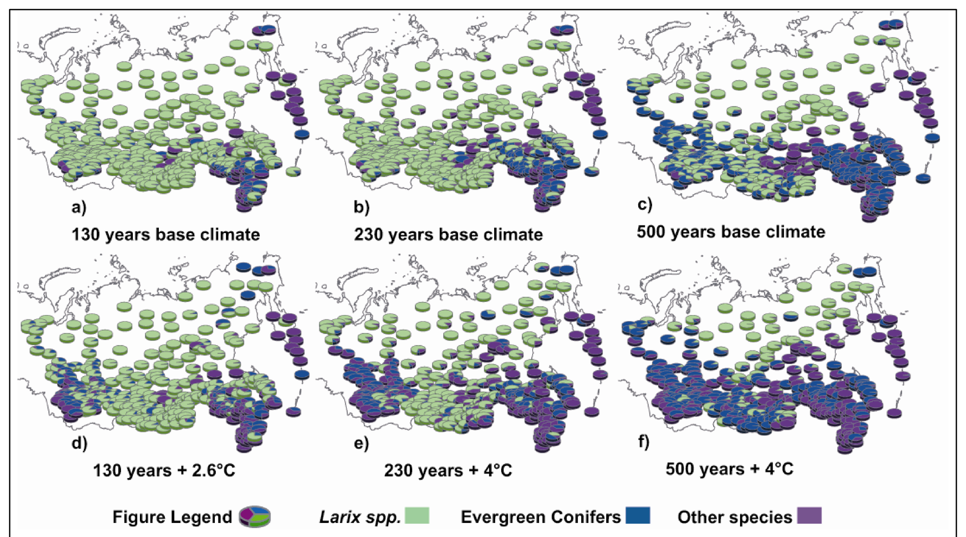


Figure 6: Species distribution for the baseline **(a, b, c)** and temperature increase **(d, e, f)** climates.

Local Results

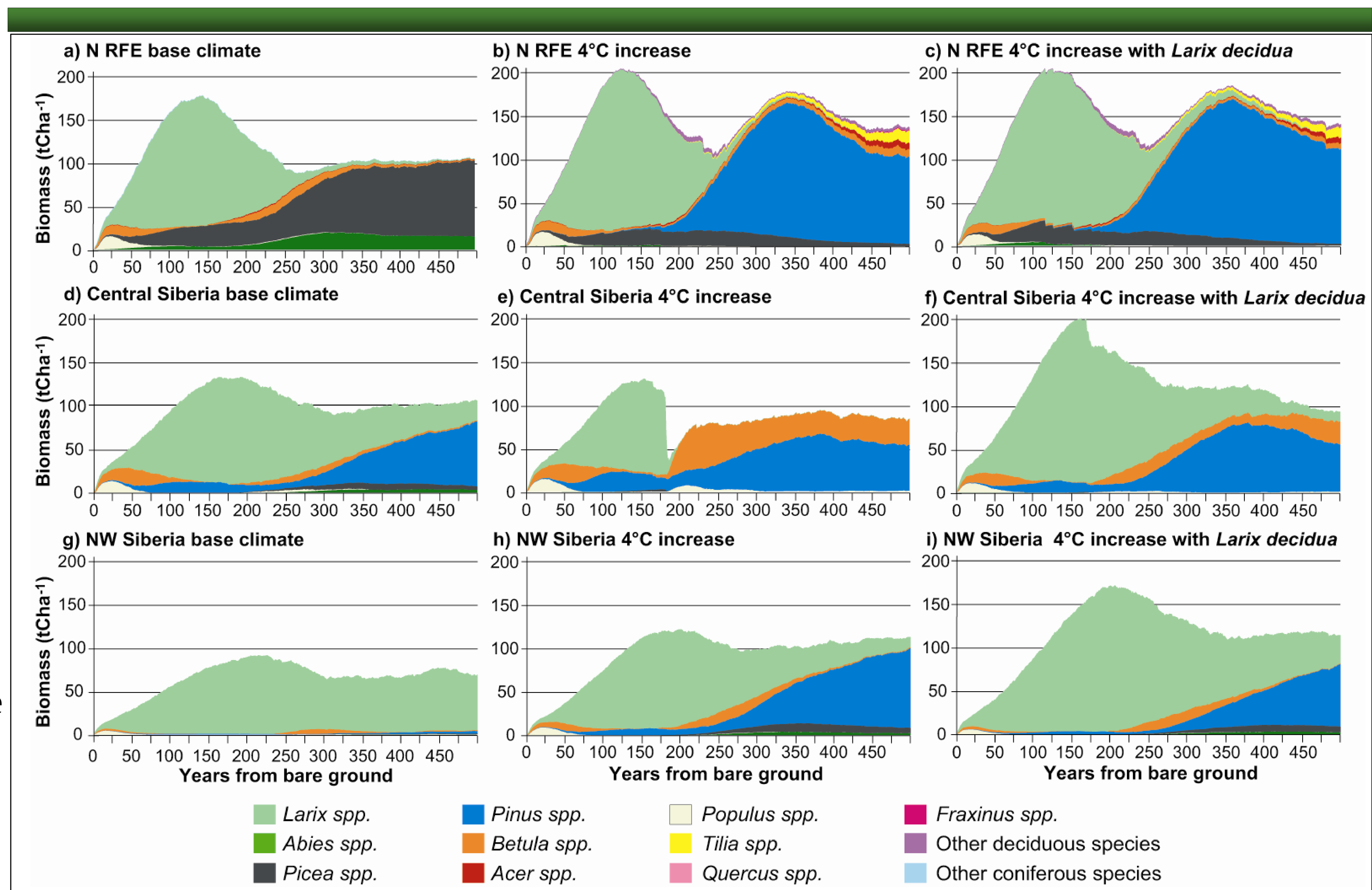


Figure 7: Cumulative species biomass (tC ha^{-1}) over 500 years from bare ground for 3 locations in Russia. Biomass dynamics for high diversity site in northern Amur region of Russian Far East **(a,b &c)**, low diversity site in central Siberia **(d,e &f)** , and low diversity site in northwestern Siberia **(g,h &i)** . Simulation results for base historical climate **(a,d &g)**, 4°C increase **(b,e &h)**, and 4°C increase with *Larix decidua* **(c,f &i)**.

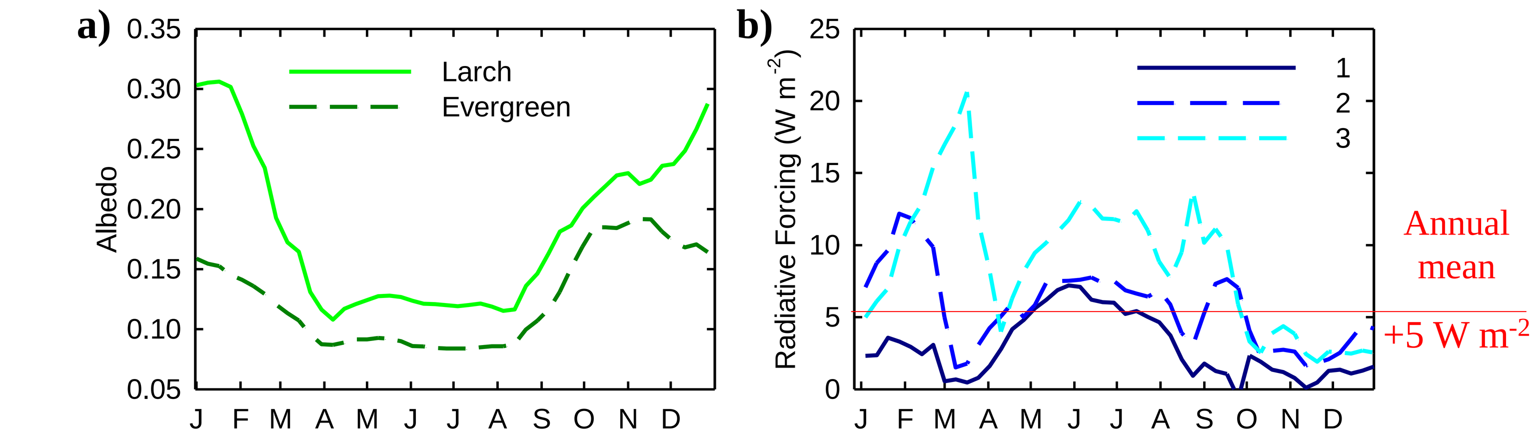


Figure 8: Seasonal albedo differences for larch and evergreen forests **(a)**, seasonal radiative forcing over 3 sites with latitude increasing from site 1 to 3 **(b)**

- Albedo differences are significant in summer and winter (Fig 8a). Winter differences are due to the deciduous nature of larch as the open canopy exposes underlying snow.
- The radiative forcing increased with increasing latitude over 3 sites (Fig 8b) because both the snowy and snow-free albedo difference was larger to the north.
- The instantaneous radiative forcing can be as high as +20 W m^{-2} in spring when snow is still lying and insolation is increasing.
- The average annual radiative forcing is +5 W m^{-2} for areas of complete conversion.

Conclusions

Local scale:

- **Low diversity sites:** *L. decidua* increases overall biomass, delays conversion of larch to evergreen conifer forest, and prevents collapse of larch in response to 4°C increase. *L. decidua* is uniquely adapted to establish and prevent positive feedback associated with a shift to evergreen conifer-dominance.
- **High diversity sites**: *L. decidua* does not significantly increase total biomass, nor does it prevent species shift in response to 4°C increase.
- **Albedo results:** A complete conversion from larch to evergreen would lead to a significant reduction in both snowy and snow-free local albedo. This would cause, on average, an extra 5 W m^{-2} of shortwave radiation to be absorbed at the surface over the year. This heating creates a positive feedback to the warming already projected to occur there. Spatial variability in this effect needs more research.

Regional scale:

- **Low diversity regions:** ***Low resilience and stability*** shown by strong response to 4°C increase, and strong effect of *L. decidua* for all classes of biomass across Siberia. Regional and local scale results suggest that areas of evergreen dominance and low annual precipitation are more responsive to altered precipitation.
- **High diversity regions:** ***High resilience and stability*** shown by minimal biomass response to 4°C increase, and *L. decidua's* inability to establish.

Continental scale:

- System behaves as a ***low diversity region*** with ***low resilience and stability*** shown by strong biomass response to 4°C increase, and significant effect of *L. decidua* on all classes of biomass. Further analysis is required to explain the timing of the precipitation effect, and its association with evergreen conifers.

Acknowledgements

Complete article available: Shuman, JK, HH Shugart and TL O'Halloran 2011 Sensitivity of Siberian larch forests to climate change *Global Change Biology* (Accepted Article) doi 10.1111/j.1365-2486.2011.02417.x We appreciate support from NASA grant Carbon/04-0231-0148, Larch Taiga/ NNX-07-A063G and Climate Change/09-IDS09-116.