

DECADAL SCALE VARIABILITY--20TH CENTURY RESPONSES

I. PINE INVASION OF MEADOWS & SNOWFIELDS

Throughout the Sierra Nevada, conifers are increasing in density in forests and colonizing previously treeless habitats, such as subalpine meadows or openings left by early melting of persistent snowfields. This effect has often been considered to result from human impacts of fire suppression, trampling, overgrazing, exotic plant invasion, and watershed deterioration. In many cases, restoration goals seek to reverse the effect and reduce tree biomass. The implications of climate as a natural process and its influence on ecological dynamics have been little studied.

OBJECTIVES Investigate 20th century demographics of meadow and snowfield slope invasion by pines in the high Sierra Nevada and their relationship to climate.

METHODS

- 9 meadows (2600-3050m); 6 snowfields (2700-3100m)
- Sites located east and west of the Sierran crest
- Diverse fire and grazing histories among sites
- Varied environmental contexts (forest types, substrates, elevations)

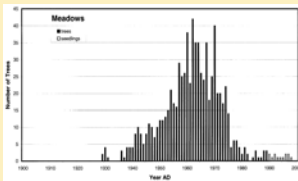
At each site, we established 3m circular plots at 15m intervals along line transects from the forest borders into the openings, and for trees within plots we calculated tree age by counting rings and branch whorls.

- N (meadows) = 926 trees (*Pinus contorta*)
- N (snowfields) = 608 trees (*P. contorta*, *P. monticola*, *P. albicaulis*)

RESULTS

Meadows:

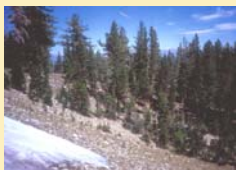
- Single, multi-decadal pulse of tree invasions in each meadow: 1945-1975
- Meadow trees, mean age = 35 yrs (SD = 8.5 yrs)
- Forest border trees, mean age = 142 yrs (SD = 65.2 yrs)



Snowfields:

- Gradual invasion throughout 20th century, starting in late 1890s
- Older trees near forest, younger trees near center of slopes
- Accelerated invasion periods: 1925-1945; 1975-2000

- Snowfield trees, mean age = 52 yrs (SD = 20.6)
- Forest border trees, mean age = 153 yrs (SD = 69.6 yrs)



II. WHITEBARK PINE KRUMMHOLZ GROWTH

Treeline populations of whitebark pine (*Pinus albicaulis*) in the Sierra Nevada typically grow in low shrubby forms (*krummholz*) that are entrained by desiccating winds and freezing temperatures. Occasionally, upright branches (*flags*) establish above *krummholz* crowns. Horizontal extent of the crown is determined by branch growth rates, which are presumably influenced by growing-season conditions. Associations of upright branch recruitment and annual branch growth rate with specific 20th century climate conditions have not been studied.

OBJECTIVES Investigate trends of upright branch establishment and annual branch-growth rate in whitebark pine *krummholz* trees at treeline in the Sierra Nevada and their relationship to 20th century climate.

METHODS

- 6 branch-growth sites (3430-3565m)
- 5 flag sites (3300-3445m) crest
- Granitic and metamorphic substrates
- Sites located east and west of Sierran crest

We measured release dates on upright branches (flags) by taking increment cores from stems at the point of emergence above the *krummholz* crowns and cross-dating against master tree-ring chronologies developed locally from whitebark pine augmented with regionally synchronous frost- and marker-ring events (King & Graumlich 1998). To measure annual branch growth, we cut branches around *krummholz* crowns, and cut thin branch sections at 25cm intervals, using the stem tip as the start point. On each branch section, we calculated the pith date by cross-dating as above. We estimated annual growth increments by assuming an average growth between the pith dates of consecutive stem samples.

- Annual growth, N = 175 branches; 850 thin sections
- Flag establishment, N = 152 branches

RESULTS

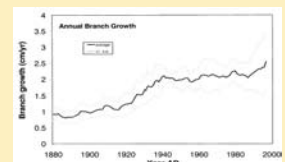
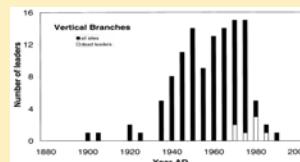
Vertical Branch Development (Flags)

- Flag ages at all sites concentrated (85%) in single period: 1945-1976
- Oldest branch dated to 1902, youngest to 1990
- 7 dead leaders near end of pulse; all others alive



Annual Growth of Horizontal Branches

- Mean annual growth more than doubled over 20th century, from 0.9cm/yr in 1890 to 2.4cm/yr in 1996
- Accelerated growth on all sites 1920-1940 and 1976-1996, plateaus in growth 1880-1900 and 1945-1975



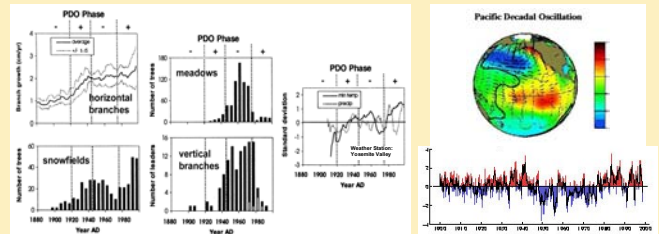
III. CORRELATED RESPONSES TO 20TH CENTURY CLIMATE VARIABILITY

Correlated responses within and across these four independent studies suggest regional influences on conifer growth. Four multi-decadal time periods characterize conditions of growth response in our studies:

- 1) 1900-1925
- 2) 1926-1945
- 3) 1946-1975
- 4) 1976-2000

These correspond to multi-decadal periods of the Pacific Decadal variability (also called Pacific Decadal Oscillation, PDO). PDO is a long-lived El Niño/Southern Oscillation-like pattern of climate variability defined by North Pacific Ocean temperature anomalies that persist 20-30 years. Positive (El Niño-like) phases occurred between 1920-1945 and 1976-1998 and negative (La Niña-like) phases occurred between 1900-1919, 1946-1975, and after 1998.

Growth also correlated with locally observed weather trends, as recorded at longterm weather stations in the Sierra Nevada. Minimum temperatures increased significantly over the 20th century, with dominant multidecadal patterns within the century. Precipitation varied decadal but without significant change in mean over the century. Interannual variability in precipitation and temperature had multi-decadal patterns as well. For the 20th century, the period from 1945-1975 had the lowest annual variability, while the period from 1976-2000 had the highest variability.



Potential climate influences on growth include:

- Dry period in mid-century with low interannual variability favored establishment of trees in meadows and flags on *krummholz*
- Accelerated warming decades in early and late 20th century hastened early snowmelt in persistent snowfields and favored establishment of conifer seedlings
- 20th century warming increased growing season at treeline and favored greater annual growth in *krummholz* branches

ABSTRACT

We present results from ongoing studies of pine ecosystems in the high Sierra Nevada and Great Basin ranges that demonstrate forest response to past climate change at decadal to century time scales. Using standard tree-ring and ecological plot analysis methods, we document growth responses and meadow/snowfield invasions of whitebark and lodgepole pines (*Pinus albicaulis*; *P. contorta*) correlated with multi-decadal climate patterns in the 20th century. Century-scale growth variability of limber pine (*Pinus flexilis*) forests over the past 3500 years correlates with major temperature and precipitation patterns as derived from independent climate indicators. Repeating extirpation and recolonization events at the watershed scale in limber pine correlate with century-scale climate variability. Climate variability as a primary driver of ecological shifts at these scales has not been fully recognized as a significant natural force of change, nor have implications been integrated into conservation analysis and planning.

HIGH-ELEVATION CONIFERS TO PAST CLIMATE VARIABILITY



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CENTURY SCALE VARIABILITY--THE LAST 3500 YEARS

I. MEDIEVAL CLIMATE WARMTH & LITTLE ICE AGE EFFECTS ON FOREST COMPOSITION

A volcanic eruption of the Glass Creek vent (Inyo Craters chain, eastern Sierra Nevada) during medieval times buried forests in the adjacent region under several meters of tephra. Large, mostly downed, dead trees on nearby Whitewing Mtn (3052m) and San Joaquin Ridge (3105m) appear to have been killed by the eruption and preserved in arid, cold environments; tentative radiocarbon analysis (Univ AZ, Lab of Tree Ring Research, 1980) gave dates in the eruption era. The presence of these stems suggests a tall forest existed at the time the trees were alive. Conditions at this time were warm with two 150-200 year dry periods between AD 900-1350 in the Sierra Nevada (Stine 1994). The dead stems contrast with current conditions of these habitats, which are treeless or have only occasional krummholz whitebark pine. Live forests of whitebark pine downslope suggest cycles of shifting treeline in more recent centuries, during the cool centuries known as the Little Ice Age. No previous studies have examined the paleoecological, climatic, or eruptive-sequence implications of the downed logs or downslope contemporary forests.



OBJECTIVES Determine species composition and ages of dead logs and live trees on Whitewing, San Joaquin, and North Point (3047) Mts and use this information to date the eruption, estimate paleoclimates, and evaluate climate influences on vegetation.

METHODS & RESULTS

- Standard tree-ring, ecological, and wood identifications methods for dating live trees and dead wood & identifying dead wood to species

Species identified from summit dead wood (currently krummholz *P. albicaulis*, rarely *P. flexilis*):

Pinus albicaulis (37), *P. monticola* (20), *P. flexilis* (7), *P. contorta* (7), *P. jeffreyi* (6), *P. lambertiana* (2) (spp currently exotic east of crest), *Tsuga mertensiana* (1)

Size and Growth of Summit Dead Logs (N = 1295):

mean stem length = 4.6m
 (SD = 2.5m, max = 14.5m)
 mean stem diameter = 26.2cm
 (SD = 22.3cm, max = 110cm)

Date Ranges of Whitebark Pine Downslope of Whitewing Mtn:

- Upper forest border (2900m) live whitebark pine invading current barren uplands.
- Mid-slope (2800m) live whitebark pine in current western white pine, whitebark pine, and red fir forests.
- Lower-elevation (2700m) dead whitebark pine stems in current lodgepole pine and red fir (*Abies magnifica*) forests.

CONCLUSIONS

- Medieval-age (AD 900-1350) forest composition, structure, and growth on summits were typical of forests currently 300-500m lower, suggesting an effectively warmer climate during medieval times
- Relative to present, sugar pine has been regionally extirpated and species diversity declined from 7 to 1; crown form altered from upright, straight stems to stunted krummholz, growth rates declined significantly, conditions went from forest to mostly barren
- 500 years ago (AD 1500, Little Ice Age), whitebark pine grew 100m below its current optimum; this zone has been moving upslope since, and at present whitebark is colonizing barren slopes above 2900m. Alternating zonal decline and increase may reflect response to Little Ice Age cool/dry climates and warming of the 20th century.
- Best estimate Glass Creek Vent eruption: AD 1350 (~650 years ago)
- Vegetation trajectories in this area likely influenced by combined climate change and volcanic effects

II. WATERSHED-SCALE EXTIRPATIONS & COLONIZATIONS IN LIMBER PINE

Limber pine (*Pinus flexilis*) is a wide-ranging upper-elevation conifer of the eastern Sierra Nevada, Great Basin, and Rocky Mtns. Like bristlecone pine (*P. aristata*), limber pine growth and demographics are highly sensitive to climate. In its arid, high elevation habitat, dead wood preserves well, making it desirable for tree-ring analysis of historic conditions, although the species has been little studied in the western part of its range. At Pleistocene time scales (~10⁵ yrs), limber pine's range shifted repeatedly as much as 1500m with large changes in distribution extent as a response to glacial/interglacial climate variability. Major demographic shifts appear to occur also over much shorter times in the late Holocene, suggesting that extirpation and colonization are significant natural processes relevant to management time scales.



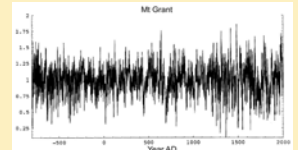
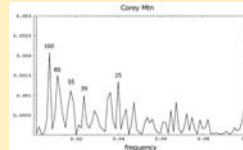
We report here a substudy on watershed-scale response of limber pine in the Wassuk Range to climate variability over the last 3500 years. Limber pine now grows only in remnant groves on mostly north-facing slopes of Mt. Grant (3415m) and scattered locations on other peaks. Dead wood, however, is abundant in all major drainages and aspects of Mt. Grant where no live trees now exist, and at elevations extending above current treeline.

This work is part of a more comprehensive study on limber pine paleoecology and paleoclimatology in the eastern Sierra Nevada and western Great Basin.

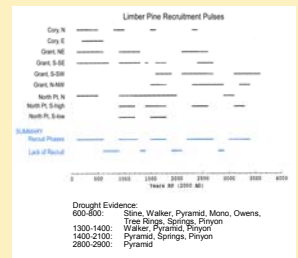
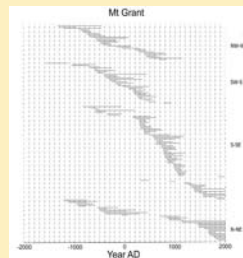
OBJECTIVES Describe the demographics and biogeography of extirpation and colonization of limber pine populations in the Wassuk Range, western Nevada, and their relationship to past climate variability.

METHODS & RESULTS

- Standard methods for cross-dating limber pine live trees and dead wood (COFECHA) enabled development of master chronologies and dating of dead wood to 1700 BC (~3700 years ago)
- Spectral analysis indicates decadal (25-30 year) and century scale (85-100 year) variability in tree-ring growth



- Distinct pulses of tree ages on different slopes, spatially synchronous
 - Extirpation events: 3200-2900 ybp (years before present), 2300-2100 ybp, 1600-1300 ybp, 1000-700 ybp
 - Colonization events: 3500-3200 ybp, 2900-2300 ybp, 2100-1800 ybp, 1300-1000 ybp, 700 ybp – present
 - Some slopes likely treeless for periods of several hundred years
- Northwest, west, southwest, south, and southeast slopes final extirpation 800 years ago
- No evidence for fire as stand-terminating events
- Dead wood elevation range extends 200m higher than current treeline (2960m)
- Synchronies with demographic pulses of limber pine populations in other western Great Basin and Sierran populations; extirpation associated with extensive droughts & colonization to hydric periods identified from other regional climate proxies



REFERENCES

- King, J.C. and Graumlich, L.J. 1998. Stem-layering and genet longevity in whitebark pine. A final report on cooperative research with the National Park Service (CA 8000-2-9001)
- Stine, S. 1994. Extreme and persistent drought in California and Patagonia during Medieval time. *Nature* 369: 546-549

CONCLUSIONS & MANAGEMENT IMPLICATIONS

The natural process of climate change has been largely ignored in our attempts to understand and manage natural resources, much as the importance of fire was unappreciated until relatively recently. Our studies here contribute to the growing realization that natural climate variability has influenced diverse and significant ecological responses at decadal to century time scales in the last 100-3500 years in Sierran ecosystems. Successful integration of this knowledge may challenge traditional management and conservation approaches and stimulate rethinking of policies. Because climate change can trigger responses similar to other natural processes (e.g., fire, insects, disease) and anthropogenic effects (e.g., fire suppression, harvest, grazing), it may often be overlooked and causality misinterpreted. Climate change should be considered along other disturbance events as a potential driver of significant ecological change at management scales. Relevant management contexts include diagnosing causes of change, monitoring, developing restoration goals and strategies, setting timber harvest and fuel reduction goals, anticipating ecological responses under landscape-scale land management or policy practices, and estimating responses to future global changes.