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Challenges to forest restoration in an era of unprecedented climate and wildfire activity in Rocky Mountain subalpine forests

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Unprecedented conditions in Rocky Mountain subalpine forests challenge contemporary approaches to forest restoration, requiring deep thinking across the science–management spectrum. Paleoecology can contribute to this endeavor by contextualizing ongoing change and revealing how ecosystem transformations unfolded in the past.

Fire and anthropogenic climate change in Rocky Mountain subalpine forests

Anthropogenic climate change is enabling increased fire activity across western North American forests by increasing fuel aridity (Abatzoglou and Williams 2016). Fire intensity and spread in dry fuels is more extreme, especially in high-wind conditions, evading fire control and often resulting in greater human and ecological impacts.

The pattern of increased burning is particularly evident in subalpine forests of the western US (Alizadeh et al. 2021). Subalpine forests are high-elevation, conifer-dominated ecosystems that span the ca. 1000 m just below treeline, across the Rocky Mountains. Wildfires have shaped subalpine forests for millennia, but emerging interactions among climate, fire, and society are transforming these fire-prone social-ecological systems.

Historically, fire in subalpine forests was limited by high fuel moisture and only occurred in unusually warm, dry conditions, with mean fire-return intervals of one to several centuries (e.g. Higuera et al. 2021). Contemporary climate change is promoting fire in subalpine forests by increasing the frequency and intensity of drought, making fuels dry enough to burn more frequently (Alizadeh et al. 2021).

Uncharted territory: subalpine forests now burning more than any time in recent millennia

After extraordinary burning across the western US in 2020 (Higuera and Abatzoglou 2021), we suspected that climate change may have pushed contemporary burning beyond the longstanding range of variability experienced in some Rocky Mountain subalpine forests.

We tested this hypothesis using a unique network of 20 paleofire records within a 30,000-km^2 study region in northern Colorado and southern Wyoming. We found that subalpine forests in the 21st century are now burning twice as often as they have over the past two millennia: estimated mean fire return intervals are now 117 yr compared to an average of 230 yr over the past two millennia (Fig. 1; Higuera et al. 2021). Additionally, the 21st-century rate of burning (e.g. area burned per unit time) is over 20% higher than the maximum rate estimated over the past two millennia, which occurred during the early Medieval Climate Anomaly (MCA; 770 to 870 CE), when Northern Hemisphere temperatures were ~0.3°C above the 20th-century average (Mann et al. 2009). The paleofire record thus highlights that 21st-century climate change has enabled fire activity that exceeds the range of variability that shaped these ecosystems for millennia (Fig. 1). We are clearly in uncharted territory.

Core insights from paleoecology in Rocky Mountain subalpine forests

The rich network of paleorecords in Rocky Mountain subalpine forests, including climate, fire, and vegetation histories, highlight three themes relevant to understanding contemporary change and informing forest-management decisions.

First, fire itself is not novel in these systems; rather, it is the frequency of burning that is unusual. For millennia, subalpine forests experienced high-severity wildfires—killing most trees—once every one to several centuries. Holocene pollen, geochemical, and charcoal data indicate that vegetation and ecosystem properties recovered in the decades after wildfire, exhibiting resilience to individual fire events (Minckley et al. 2012; Dunnette et al. 2014).

Second, paleorecords bolster our contemporary understanding of the climate controls of fire in subalpine forests. Tree-ring research reveals widespread burning during years of unusually warm, dry conditions in Colorado subalpine forests (Sibold and Veblen 2006), and lake sediments studies from the same region show that fire activity varies with centennial-scale climate variability (Calder et al. 2015; Higuera et al. 2021; Fig. 1).

Finally, the paleorecord reveals just how rarely wildfires caused state changes in the past, in subalpine forests and beyond (e.g. Crausbay et al. 2017), mainly when changes in climate and fire jointly drove ecosystem transformation. For example, extensive burning in northern Colorado during the MCA transformed some subalpine forests to "ribbon forests", narrow bands of trees separated by subalpine meadow communities. This lower tree density and forest extent was maintained afterwards by snowier conditions of the Little Ice Age (ca. 1400–1700 CE, Mann et al. 2009), and still persists today (Calder and Shuman 2017).

With 21st-century climate change accelerating beyond the bounds of the past, we

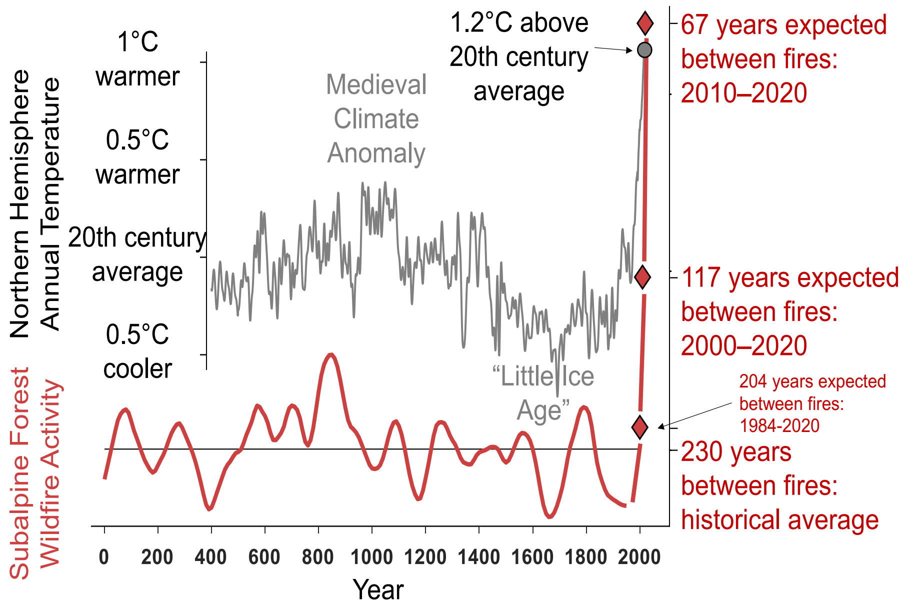

Figure 1: Northern Hemisphere climate history (from Mann et al. 2009) and subalpine forest-fire history from 20 lake-sediment records spanning a 30,000-km^2 region in northern Colorado and southern Wyoming (Higuera et al. 2021). The red line reflects the fire rotation period, equivalent to the average time between fires at any one lake, or mean fire return interval. Red diamonds reflect contemporary burning in the study region. Figure reused under CC license from TheConversation.com, modified from Higuera et al. (2021).

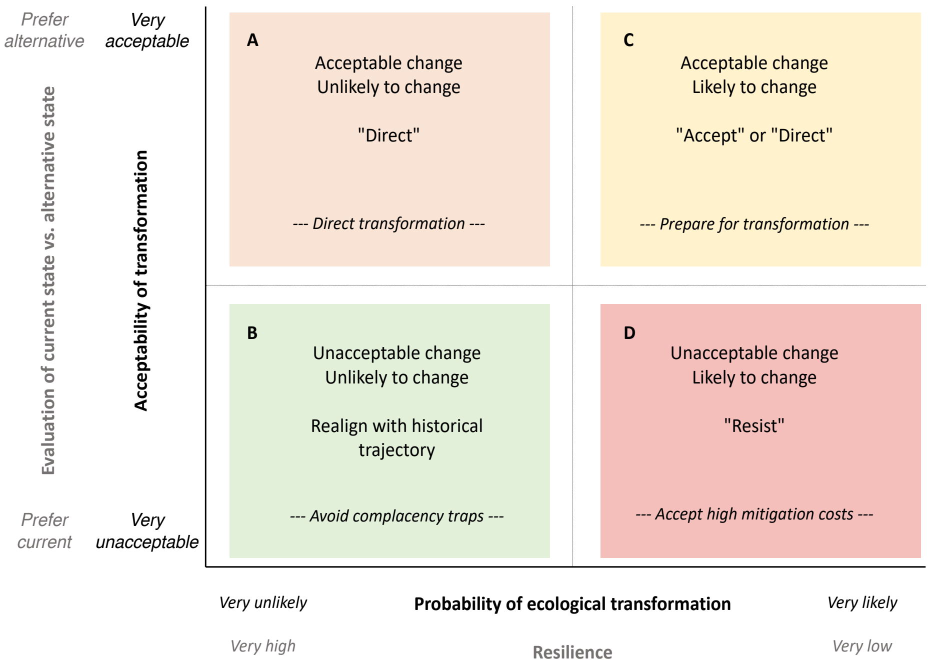

Figure 2: Managers face challenges that require understanding both the probability of ecological transformation and the acceptability of such changes. The "resist, accept, direct" framework can help decision making when transformation is **(C, D)** likely or **(A)** desirable; when transformation is **(B)** unlikely and undesirable, restoration goals remain appropriate and feasible. Modified from Higuera et al. (2019).

expect that events that were exceptional in the paleorecord will become increasingly common, altering the trajectory of ecosystems and their longstanding resilience to wildfires.

Challenges to ecological restoration

Climate change and increased area burned across western US forests adds urgency to the need for ecological restoration in many ecosystems. Ecological restoration is defined as the "process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed" (Society of Ecological Restoration (SER); ser-rrc.org/what-is-ecological-restoration). While the concept of recovery is central, the goal is to "return a degraded ecosystem to its historic[al] trajectory, not its historic[al] condition" (emphasis added). The emphasis on trajectories acknowledges non-stationarity (e.g. past climate variability), orienting restoration targets towards what an ecosystem would be like today in the absence of past degradation, damage, or destruction.

The goal of restoring past dynamics and trajectories is clearly applicable to many low-elevation forests across the western US, which, unlike subalpine forests, historically burned frequently in low-severity surface fires (e.g. mean fire return intervals < 10-50 yr). In these forests, fire suppression, policies preventing Indigenous fire stewardship, and high-grade logging since the 19th century have altered forest structure and composition (Hessburg et al. 2019). Restoration efforts here thus focus on reducing tree biomass and retaining thick-barked, fire-resistant species that dominated prior to fire suppression, to help ultimately reintroduce and sustain frequent low-severity fires.

Similar changes in tree density and composition are not as prevalent in subalpine forests, due to their historically long fire-free intervals (Fig. 1) and more limited land uses. Yet, contemporary climate change is increasingly altering disturbance regimes and ecological trajectories in these forests beyond the historical range of variability, even in the absence of past damage or degradation (Turner et al. 2019; Higuera et al. 2021). The combination of increased burning and warmer, drier post-fire conditions in subalpine forests requires a management framework that is more forward-looking in time, relative to the goal of ecological restoration.

Navigating uncharted territory

In a world experiencing rapid climate change, realigning ecosystems with historical trajectories may be inconsistent with expectations of climate-driven ecological change. The resist–accept–direct (RAD) framework has been developed to guide natural resource management when ecological transformation is likely (Schuurman et al. 2022). The RAD framework identifies three management responses to ecological transformation: resist, accept, or direct ecological trajectories. This adds options to the restoration-oriented goal of realigning systems with historical trajectories (Fig. 2). Paleoecology provides the long lens needed to contextualize contemporary ecological trajectories, and help inform choices among different RAD options if transformation is inevitable.

For example, the combination of climate change and increased burning in subalpine forests, now outside the range of variability in our study area (Fig. 1), suggests the likelihood of fire-catalyzed ecological transformation is high. Are there areas where dispersing seeds or planting seedlings in high-severity patches would help managers resist future forest loss, given reduced natural tree regeneration under warmer, drier conditions? Would planting different species help *direct* the ecological trajectory to a new community, with trees better adapted to future conditions? Or, are managers and stakeholders willing to accept the post-fire ecological trajectory, yet unknown and possibly novel, with minimal intervention?

Deciding among RAD options is complex and multidimensional, because consequences are social, cultural, and institutional, as well as ecological. Science that provides a better understanding of the likelihood of ecological transformation (i.e. *x*-axis in Fig. 2) is an important starting point for RAD decision-making (Crausbay et al. 2022), but assessing the acceptability of change (i.e. *y*-axis in Fig. 2) requires community input and extends beyond the science of ecology (Higuera et al. 2019).

Conclusions

Paleoecology is particularly well poised to inform RAD decision-making because the long historical perspective can help assess if, and when, contemporary conditions are unprecedented, and, thus, if transformation is likely. Paleoecology also offers opportunities to learn from past ecological change (Nolan et al. 2018), and hone in on the triggers, rates, and ecological trajectories that characterize the process of transformation. Integrating paleoecological knowledge with processes for making RAD decisions will be increasingly relevant when ecological restoration is not possible.

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