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Conservation Issues

Traditional Ecological Knowledge Used in Forest Restoration Benefits Natural and Cultural Resources: The Intersection between Pandora Moths, Jeffrey Pine, People, and Fire

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ABSTRACT

Collaborative efforts between indigenous peoples and government land managers are gaining recognition as important elements of forest restoration. Unique land allocations, such as the Research Natural Area (RNA) system of the US Forest Service, necessitate novel approaches to achieve desired outcomes among stakeholders. We describe a Traditional Ecological Knowledge (TEK) framework that integrates efforts among resource managers, tribal representatives, scientists, and a tribal youth intern program to conduct ecological restoration in a Jeffrey pine (*Pinus jeffreyi*) forest ecosystem of the western United States with a history of frequent fires. Reintroduction of TEK-based practices provided some moderation of fire effects during an unplanned wildfire event, benefiting both ecological conditions and a traditional Paiute Indian food source, piagi, the larvae of the Pandora moth (*Coloradia pandora*). Tribal youth learned about traditional food collection and land management practices, and federal managers discovered that TEK helped achieve ecological restoration goals. Our collaborative framework increased confidence in the mutual benefits of western science- and TEK-based forest management practices, creating a foundation for long-term partnership in ecosystem restoration.

Index terms: fire severity; forest restoration; Jeffrey pine; Pandora moth; Research Natural Areas; Traditional Ecological Knowledge

"*Besa wunudu mahunnedu*"
–Translated as "Those that take good care of trees" in Kutzadika (Mono Lake Northern Paiute)

INTRODUCTION

Integration of TEK with natural resource planning on public land provides benefits ranging from better understanding of ecosystem history to development of novel management actions, and effective outcomes require creative, site-specific collaborations (Senos et al. 2006; Charnley et al. 2014; Reyes-Garcia et al. 2019). Definitions of Traditional Ecological Knowledge (TEK) are diverse and often abstract (Berkes 1999; see review by Hoagland 2017), and we adopted a broad meaning intended to provide guidance for our restoration collaboration: TEK as a type of indigenous knowledge, guiding stewardship of the natural world that is dynamic, interactive, and respectful. Perhaps most importantly, TEK is a participatory, ongoing process, rather than a collection of facts or events as they occurred in the past (Houde 2007). Integration of TEK with natural resource planning is most likely to succeed when based upon field experience, active participation among collaborators, and upon equal recognition of indigenous and western science–based knowledge (Hoagland 2017). However, challenges to integration may stem from divergent viewpoints and cultural values, institutional barriers, and differences in communication and knowledge transmission systems (Menzies and Butler 2006). These challenges underscore the need for robust knowledge-based frameworks that incorporate both TEK and western science in natural resource management planning. Such a framework would include active tribal engagement (including youth engagement), bidirectional communication, collaboration-based goals, and explicit recognition of cultural context and the value and limitations of local knowledge (Whyte 2013; Kretser et al. 2018).

We illustrate a framework integrating TEK with natural resource planning, developed through a multi-year collaboration between land managers from the US Forest Service (USFS), local tribal representatives, and research scientists to plan and conduct forest restoration. The overarching goal of this collaboration was to integrate western science–based land management goals, academic research, and a tribal youth internship program in the design and implementation of forest management practices originally rooted in and intended to sustain the continuity of TEK. The nexus for this collaboration was a site in the Research

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Figure 1.—Summary of Pandora moth natural history, traditional use of piagi, and relation to fire. Numbers indicate sequence of life cycle events. Center photo is a characteristic large-diameter Jeffrey pine tree in Indiana Summit. Inset 2: Feces are scattered among pine needles. Inset 3: Interns learn traditional method from tribal elder (author Raymond Andrews); arrow indicates mountain mahogany digging stick for shaping the trench.

Natural Area (RNA) system, a nationwide network of designated areas on National Forest lands established to protect exemplary ecosystems while promoting research, education, and monitoring. The Indiana Summit RNA, hereafter referred to as Indiana Summit, was the first RNA designated in California (1932), and established in part to protect the ecological and cultural resources of the representative Jeffrey pine (*Pinus jeffreyi* Grev. & Balf.) ecosystem, including the traditional harvest area of piagi larvae by Paiute Indians.

Piagi, the larvae (caterpillars; Figure 1) of the saturniid moth *Coloradia pandora* (Blake), or Pandora moth, is a native defoliator, and is considered by some to be a modern silvicultural pest, although the moth has caused minimal tree mortality in the Indiana Summit vicinity (Bulaon and MacKenzie 2014). For the local Bishop Paiute and Mono Lake Kutzadika (Northern Paiute Tribes), however, piagi are considered an important traditional food resource, and the harvest itself has cultural importance (Aldrich 1921; Fowler and Walter 1985). During one phase of their biennial life cycle, piagi descend tree trunks to pupate in the ground, a behavior that led to the tribal practice of capturing larvae in circular trenches, or piagi rings, dug around the bases of large trees (typically >76 cm diameter at breast height, or dbh) throughout Jeffrey pine forests as far north as Oregon. Piagi rings are abundant and still evident in Indiana Summit as a signature of traditional knowledge and practice (Figure 1). The harvest practice has gradually declined over the past few decades as western agriculture and commercially available foods have largely replaced the local, native harvest. Some families do continue the practice, and tribal members are seeking ways to ensure that traditional knowledge and practice are passed on to future generations.

Before fire suppression efforts began in the mid-1900s, Jeffrey pine forests were characterized by frequent, predominantly low-severity, surface fires with an average fire return interval of 7–15 y (Safford and Stevens 2017). However, vegetation management, including prescribed fire, is generally prohibited in RNAs by

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policy (US Forest Service 2005), although the potential benefits of fire—and consequences of fire exclusion—in California's RNAs have been acknowledged (Skinner 2005; Taylor et al. 2009; Coppoletta et al. 2019). As a result, Indiana Summit has been largely unburned since its establishment in 1932, and long-term fire exclusion has led to fuels accumulation and created a risk for high-severity wildfire, threatening the ecological and cultural resources that the RNA was designed to protect (Meyer et al. 2014). Recent severe drought in California heightened concern among federal land managers and Tribes regarding the sustainability of ecological conditions in Indiana Summit. Both parties were also concerned about potential unintended negative effects on resources that might result from using prescribed fire, even if intended to mitigate the risk of future catastrophic wildfires.

To address these concerns, we aimed to develop a collaborative TEK-forest restoration model under the umbrella of multiple paradigms, with the following goals:

1) Foster a TEK-based, multidisciplinary partnership, involving land managers, Tribes, and research scientists.
2) Protect Indiana Summit's cultural and ecological resources from uncharacteristic high-severity fire through proactive fuels treatment, striving concurrently to meet goals of multiple stakeholders.

We report on our steps toward meeting these goals, which were largely realized despite, and because of, an unexpected wildfire (2016 Clark Fire) in the midst of our restoration work and studies. The quantitative analysis that emerged as a result of the wildfire, evaluating the interrelationships among TEK practices, piagi, Jeffrey pine trees, and fire, deepened a mutual understanding among partners of both ecological and cultural resources.

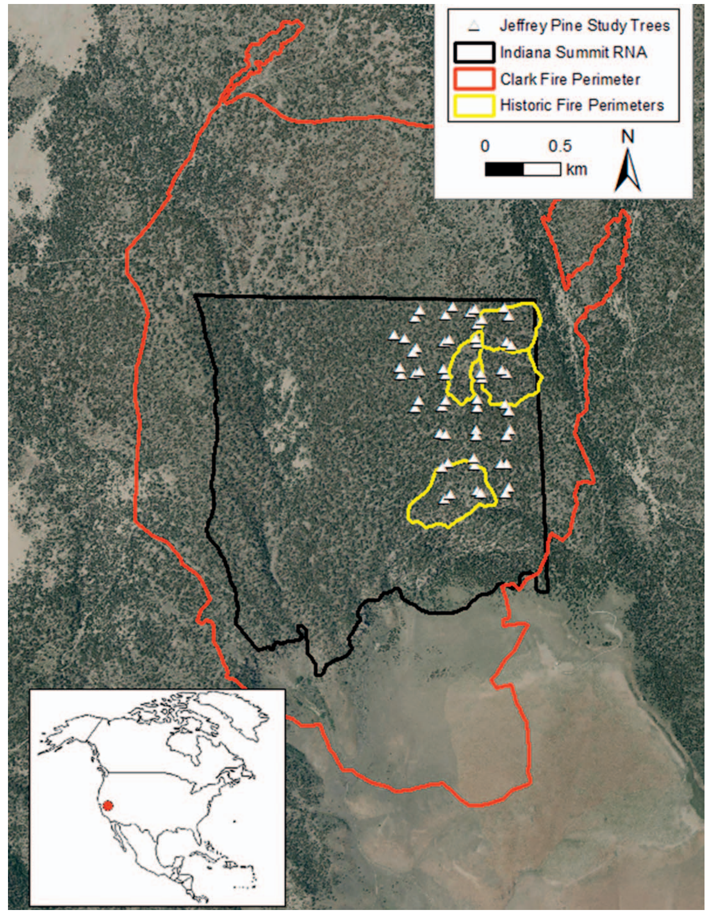

Figure 2.—Pre-fire satellite image of Indiana Summit Research Natural Area, indicating the jurisdictional boundary and historic and Clark Fire perimeters. Pairs of study trees are indicated; symbols representing closely co-located trees have been jittered for distinction.

METHODS

Site Description

Indiana Summit, in the Glass Mountains of California on the Inyo National Forest, is dominated by Jeffrey pine forest (Figures 1, 2), and includes some lodgepole pine (*Pinus contorta* Loudon), white fir (*Abies concolor* (Gordon & Glend.) Lindl. ex Hildebr.), and shrub- and herb-dominated clearings. The forest is characterized by dry, volcanic soils, and is situated at 2350–2600 m elevation, with comprehensive site descriptions given by Taylor (1977) and Meyer et al. (2014). Prior to Euro-American settlement, this forest was generally characterized by lower tree density, especially in smaller size classes. The denser stand structure that has since developed, coupled with effects of recent drought, indicated that mature Jeffrey pine trees are especially vulnerable to climate and fire stressors. Indiana Summit is noteworthy as a relatively "pristine" late-seral forest ecosystem that was never harvested for timber, adding to the contrast in forest density with the surrounding national forest lands, as evident in satellite imagery (Figure 2).

The lightning strike density is among the highest in the state (Sugihara et al. 2006), underscoring the importance of reintroducing fire to restore stand structure and increase ecosystem resistance and resilience to stressors. Tribal burning for cooking and warmth was practiced traditionally at Indiana Summit, and smoke was sometimes used to coax piagi from trees (R. Andrews, pers. obs.; Carolin and Knopf 1968). Therefore, it seems likely that at least some ignitions may have resulted from traditional uses in the area. Only one wildfire has been recorded at Indiana Summit, in 1986, which was suppressed. In the 1990s, the Inyo National Forest conducted small prescribed burns in the northeast corner of Indiana Summit (Figure 2). We targeted initial work in this same area (115 ha), where previous burns had reduced fuels to the extent that fire specialists and RNA managers felt confident that an additional low-severity burn could be conducted with positive outcomes for forest resilience.

Traditionally, at Indiana Summit, Paiute Indians maintained trenches 25–40 cm deep and 60–90 cm wide around the bases of select trees in mid-summer, when piagi caterpillars were descending trees to pupate in the ground (Figure 1). Entrapped larvae were collected several times a day, sometimes with yields of over 100 larvae per collection. Preparation typically involved roasting the live caterpillars, followed by boiling. Those not consumed immediately were dried and stored in a cool place, such as a lean-to (Fowler and Walter 1985). Unpublished archaeological records indicate that a Paiute couple and their

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grandson worked 18 trees at Indiana Summit during a 1963 harvest; such practice was common, though precise numbers and frequency of trees worked is unknown. More comprehensive background on piagi as a traditional food resource and as a silvicultural pest can be found in the literature (e.g., Carolin and Knopf 1968; Fowler and Walter 1985; Speer and Holmes 2004); in this paper, we focus on linking the traditional practice to current land management efforts through a restoration partnership.

Developing a TEK-Based Partnership

Our partnership stemmed from the common recognition among land managers and tribal members that the ecological and cultural resources of Indiana Summit faced significant risks. The risk of high-severity wildfire was so great that loss of the large trees, the piagi resource, and cultural features such as trenches and storage shelters seemed inevitable without restoration action (Meyer et al. 2014). However, typical USFS restoration tools to reduce fuels accumulation and the risk of high-severity wildfire—prescribed fire and mechanical reduction of fuels—are generally prohibited in RNAs. Any viable action required an innovative and collaborative approach.

The Inyo National Forest assembled an interdisciplinary team, including fire specialists, archaeologists, tribal members, and researchers, to develop a proposed action under the National Environmental Policy Act, designed to protect resources. RNA managers—who would need to approve any potential action—were involved from the outset in project development. The team began by conducting an ecological assessment of stand structure and function (Meyer et al. 2014).

Our solution required a TEK mindset; by viewing management practice as a fundamental component of the Indiana Summit ecosystem, rather than an undesired or unnatural manipulation under RNA policy, we would collaboratively meet the goals of RNA managers and Tribes alike. We thus proposed a TEK-based approach as described in more detail in the following sections: first design a restoration and monitoring framework that implements traditional practices to mechanically rearrange fuels, thereby reducing fire risk to trees and cultural resources, then reintroduce fire to the RNA to restore ecosystem structure and function. During each phase, we planned to engage tribal youth in the restoration work and in the investigation of western science–based questions, as developed by research ecologists. We envisioned eventually conducting restoration (TEK-based mechanical work followed by prescribed fire) throughout Indiana Summit over a decade or more, but recognized that the scope of our initial project should be limited to a smaller area to (1) ensure our approach was feasible, and (2) build and foster our framework for project implementation and monitoring with RNA managers and the Tribe.

A multi-partnered tribal intern program was initiated in 2015 to give youth practical fieldwork experience across resource management disciplines (e.g., botany, vegetation management, wildlife biology, archaeology) in a variety of settings, including Indiana Summit. Five interns were selected in 2016–2017 to learn about cultural tradition from Paiute elders and to perform cultural resource preservation work at piagi collection trenches (Figure 1). The internship curriculum aimed to dispel the notion that indigenous knowledge is inherently at odds with western science, and to replace this perceived dichotomy with a multicultural partnership to ensure long-term success (Bala and Joseph 2007; Gamborg et al. 2012).

Protecting Cultural and Ecological Resources

We planned to conduct a fuels treatment to achieve our goals of protecting the RNA's cultural and ecological resources from uncharacteristic high-severity fire and of restoring resilience of the Jeffrey pine ecosystem (Meyer et al. 2014). Although traditional cleaning of piagi trenches was primarily conducted to maximize the larval harvest, we hypothesized that the practice would provide additional benefits of reducing nearby fuels and thereby fire-related injury to large trees during fires (Kolb et al. 2007). The cleaning of the trenches would provide immediate restoration of those cultural features, and protecting the trees themselves would allow for the continued use of existing trenches in harvesting piagi. We also planned to provide protection to nearby wooden storage structures for piagi by removing duff and litter. We envisioned that this initial mechanical work would set the stage for an eventual prescribed fire that would burn at low severity. Half of the sample trees with trenches were randomly selected for cleaning, creating three analysis groups (no trench, treated trench, untreated trench).

Archaeological surveys conducted by our team for one-third of the study area documented over 120 piagi trenches, suggesting that three times this number may be present in the Indiana Summit study area. Most trenches were filled with pine litter and duff and were barely discernable except as slight depressions; fire later revealed a higher density of trenches than evident pre-burn. In 2016, our team began cleaning trenches, following the traditional method using a mountain mahogany (*Cercocarpus ledifolius* Nutt.) digging stick, with additional modern rakes utilized for efficiency. Litter and duff were transported at least 10 m from the bases of trees and dispersed. Hand tools and digging sticks were used to reshape trenches, retaining the estimated original structure, and removing material accumulated since last use (Figure 1).

In addition to protecting the trees and trenches, the Tribe was interested in ensuring the persistence of piagi in the forest following potential prescribed fire. They had reported relatively low numbers of moths in recent years, and to encourage reestablishment, we collected over 200 piagi from three separate localities 8–30 km from Indiana Summit and transported the larvae inside the RNA for release in early 2016. Interns participated in the collection, and we were guided in finding the larvae by TEK: by looking for the feces dropped by caterpillars from the canopy, and by listening for the droppings falling to the ground as we walked, we learned an effective way to detect piagi, a method that had been practiced traditionally (R. Andrews, pers. obs.; Figure 1).

Treatment Effectiveness Monitoring Design

In preparation for a potential prescribed fire, we established a study design to enable evaluation of the effectiveness of our TEK-based treatment to reduce negative fire effects. Fifty-six Jeffrey pine trees (>76 cm dbh) were selected to ensure that our sample was limited to the largest trees in Indiana Summit, these

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trees being a significant resource as identified by RNA managers. Earlier surveys also indicated that trenches were most common surrounding larger-diameter trees. The 56 sample trees, which included 26 with trenches, were selected as the nearest trees to points stratified on a 300 m grid, with its point of origin in the northeast corner of the RNA (Figure 2). A grid of this scale allowed us to capture spatial variability in forest cover and density, while limiting tree numbers to what might be treated feasibly by the interns. Each tree was measured in 2014, and again in 2016, following the trench raking treatment—and unexpected wildfire, described below. Tree health and structural metrics were selected from an established US Forest Service (2015) protocol, designed to quantify fire effects relevant to stand health.

Pre-treatment/fire measurements:

- Litter and duff depth at the tree base
- Crown base height (CBH)
- Compacted live crown ratio (CLC)
- Previous burn history (fire scar evident)
- Ladder fuels (tree branches less than 2 m from the ground surface, or live or dead seedlings or saplings within the dripline of sampled trees) scored as present or absent

Post-treatment/fire response variables:

- % Crown scorch: needles discolored or affected by directional needle "freeze," but not blackened. Needle freeze is the windswept appearance of foliage following fire that results from heat and wind (Simeoni et al. 2017).
- % Crown torch: near to complete foliage combustion as evident from needles missing or blackened
- % Bole base circumference blackened at intersection of bole with forest floor
- Bole scorch (char) top height

In addition, tribal interns counted the moth eggs (Figure 1) on sample trees in 2017 by performing a systematic grid-based search of the bark around the circumference of each tree from ground level to approximately 3 m height. Because unburned bark was relatively uncommon within the RNA, we searched an additional 242 large, unburned trees outside of, but within 1 km of, the RNA.

The Clark Wildfire

Before prescribed fire planning was completed, the Clark Fire ignited from a lightning strike on 4 August 2016, burning 1140 ha, including 99% of the RNA (Figures 2, 3). Over 80% of the fire burned at moderate to high severity, with almost all low-severity areas located outside the RNA where the forest had been thinned previously (using mechanical thinning and prescribed burning), or within our target restoration area in the northeast corner of the RNA, where previous prescribed fire had occurred (Figure 2; US Forest Service 2017; Coppoletta et al. 2019). The interns had completed raking and cleaning of nine trenches when the fire ignited, thus transforming our intended treatment effectiveness study for a prescribed low-severity burn into a study testing the effects of a TEK treatment in a severe wildfire.

Statistical Analysis

Statistical tests were performed in R Studio 3.5, using the packages spdep (Bivand et al. 2018), mvnormtest (Jarek 2015), dunn.test (Dinno 2017), dplyr (Wickham et al. 2018), and randomForest (Breiman et al. 2018). We computed Moran's index and found no evidence for spatial autocorrelation of values in any response variable ($p = 0.5$). Because the Shapiro-Wilk test indicated nonnormal distributions, we used Kruskal-Wallis ANOVA on ranks, and the Dunn test for pairwise comparisons among treatments, with the Benjamini-Hochberg adjustment for multiple comparisons. Where the Levene test indicated heteroscedasticity, we used the Brown-Forsythe test for comparisons. These methods met our needs for testing hypotheses regarding treatment effectiveness. However, we intended to further evaluate interactions between pre- and post-treatment/fire attributes, to improve our understanding of the ecosystem and to help shape further research questions. For this purpose, we used random forest modeling, an aggregate decision-tree technique that does not carry parametric assumptions and minimizes model over-fitting. Despite our limited sample size resulting from the unplanned wildfire, this technique provided an important tool to better understand and visualize interactions between variables.

RESULTS and DISCUSSION

Developing a TEK-Based Partnership

Our collaborative effort implemented a framework as modeled by Berkes et al. (2000), which aims to secure an interdependent system among partners. Questions and concerns of multiple stakeholders intersected uniquely in Indiana Summit, allowing many goals to be pursued collectively (Figure 4). Indeed, at an early meeting, it was agreed that we would not refer to our work as a "project"; our effort was a long-term endeavor, and not to be reduced to a limited-life event, nor a simple collection of words to be included in a report (Mason et al. 2012). Interns devoted 15 d in 2016–2017 to Indiana Summit, working alongside resource management professionals and tribal elders, thus gaining experience in career pathways and renewing exposure to cultural traditions. Our multidisciplinary team participated in four field trips to assess conditions and discuss objectives, including one California Fire Science Consortium workshop attended by scientists, managers, tribal members, and other stakeholders with interest in fire ecology (Joint Fire Science Program 2017).

Treatment Effectiveness Monitoring

The raking treatment, which completely removed duff and litter 1–2 m surrounding treated trees, resulted in smaller percentages of stem bases blackened by fire, and lower char heights on the bole, as compared to trees with no trenches or untreated trenches (Table 1, Figure 5). There were no significant differences between treatment groups for % crown scorch or torch. As expected, the treatment alone—rearrangement of relatively small proportions of litter and duff on the forest floor—did not result in a reduction of fire-related effects to the crown; crowns are generally influenced more by neighboring ladder fuels (e.g., shrubs, saplings, and short-statured trees).

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Figure 3.—The Indiana Summit Research Natural Area burns in the 2016 Clark wildfire (credit A. Taylor).

The initial limited sample size was further constrained by the unexpected wildfire. In addition, because measurements were taken shortly after the burn, more time will be needed to assess long-term tree survivorship. Nevertheless, the fire effects selected are useful proxies for desired outcomes, assuming that less bole char translates to greater likelihood of long-term tree survival (Kolb et al. 2007).

Synergy between TEK Treatment and Crown Characteristics

Fire effects were influenced by several site and crown characteristics aside from the treatment itself, and these relationships were characterized through random forest modeling (Table 2). For example, of the variables tested, the presence of ladder fuels and increasing duff and litter depths explained over 50% of the variability in char height. Crown scorch was greatest in the presence of ladder fuels, and when there was no evidence of previous fire near the tree. As expected, crown features (CBH and CLC) had a much smaller influence on measured fire effects as compared to surface features and ladder fuels (Table 2). The positive, though weak, relationship between CBH and % crown scorch was unexpected, and might be best explained by stand-scale and microsite wind and weather at the time of the fire; our small sample suggests complex relationships among crown variables and fire that require further investigation.

Interactions between surface fuels and other variables were especially informative, highlighting that small-scale treatments—that may be conducted feasibly by a collaborative such as ours—can provide synergy to achieve desired outcomes, especially when designed to exploit existing forest structure. For example, shallower litter and duff resulted in lower char heights when ladder fuels were present (Figure 6). Similarly, less litter and duff resulted in smaller proportions of stems blackened, an effect that was amplified for trees with previous fire exposure. This suggests that while previous burns may have reduced litter depth on average throughout the stand, the thorough raking at tree bases in the treatment provided an additional targeted benefit to individual trees. In areas that had not burned for an especially long time, such small-scale rearrangement did not provide as great a benefit.

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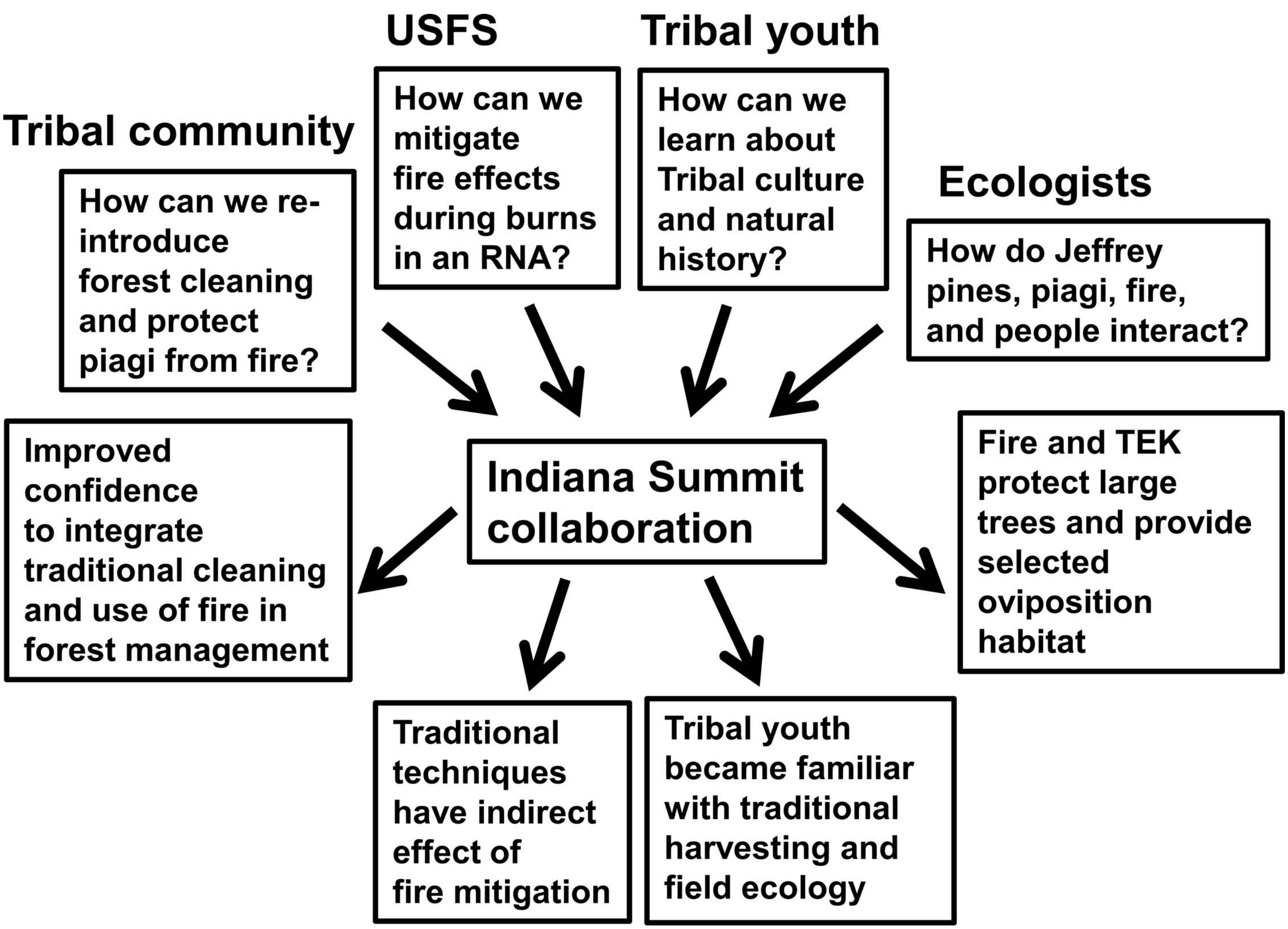

Figure 4.—A summary of inputs to, and results from, our collaborative model for restoration, integrating Traditional Ecological Knowledge (TEK) with federal land management practices.

Linking the Pandora Moth Resource to Fire

Moth eggs were found almost exclusively on burned bark (14 of 56 sample trees with char had eggs post-fire, $\bar{x} = 47$ eggs/tree, $\sigma_{\bar{x}} = 9$; Figure 1). We observed several additional burned trees with eggs that were not included in our sample. Only one of the 242 large-diameter, unburned trees was found with eggs (26 total eggs). Char height was the most important predictor for egg presence, explaining >20% of the variability in the random forest model (Table 2). Apparent moth preference for burned bark suggests that indirect benefits of fire may at least in part counterbalance direct negative effects of fire and smoke on moths, caterpillars, and eggs. The benefit of low-severity fire in particular seems evident, because while the char provides substrate for the eggs, surviving trees nearby will be needed to provide foliage for caterpillars in subsequent years.

CONCLUSIONS

The TEK management framework was essential to restoration success in the face of ecological surprises, namely an unplanned high-severity fire. By setting framework development as our ultimate *goal*, rather than a second-tier means to alternate

Table 1.—Means for key metrics compared between traditionally raked and untreated trees. †: Significant difference between groups indicated by letters, based on Dunn Test with Benjamini-Hochberg adjustment for multiple comparisons ($p < 0.1$). ‡: No significant differences using Brown-Forsythe test.

		Pre-fire conditions			Select fire effects				
Group	No. trees	Litter and duff depth (cm)	Crown base height (CBH; m)	Compacted Live Crown (CLC; %)	Char height (m)†	% Stem base black†	% Crown unburned‡	% Crown scorch‡	% Crown torch‡
No trench, not treated	29	6.2	10.3	55.3	12.6^{a}	99.5^{a}	26.6	60.4	13.4
Treated trench	9	0	9.6	57.8	5.3^{ab}	73.6^{ab}	40.4	50.6	9
Untreated trench	15	10.9	11.9	51.3	11.1^{b}	94.7^{b}	27.5	59.7	12.8

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Figure 5.—Two Jeffrey pine trees, one with a cleaned and raked piagi trench showing minimal char on the bark following the Clark Fire.

objectives, we believe that a long-standing restoration partnership was established. The foundation of the collaboration was multi-faceted and relied on intersection of three key pieces: (1) fostering relationships, including youth participation, by emphasizing mutual goals among stakeholders; (2) protecting ecological and cultural resources; and (3) investigating ecological interactions through a combined lens of western science and indigenous knowledge.

Table 2.—Results of four random forest models with response variables in rows, and predictors in columns. Values are the relative importance of the predictor in explaining variability of the response, or % increase in mean square error of predictions as compared to those resulting from permutation (random shuffling). Signs indicate overall directionality of relationships; "–" indicates <2.

	Char height	% Stem base black	% Crown scorch	Presence of moth eggs
Ladder fuels	36	–	33	9
Previous burn	−11	−3	−25	–
Litter and duff	15	10	12	–
CBH	−9	−5	9	–
CLC	−4	–	8	–
Char height	na	na	na	24
% Crown scorch	na	na	na	3

Our results demonstrate that even small-scaled TEK-based restoration provided benefits to ecological and cultural resources, through moderation of negative fire effects. Such outcomes were especially evident when work was conducted in areas with limited ladder fuels and a recent burn history (Figure 6). This knowledge can now be used to help guide where future piagi trench restoration might provide greatest benefit prior to a fire. The apparent preference of moths for blackened bark as an egg substrate also helps address long-standing questions about the effects of fire on the Pandora moth life cycle. This was an especially important finding for our collaborative group, because it emerged from joint observations of tribal members, youth, scientists, and land managers in the field together, providing a sense of mutual discovery that was reinforced through recognition of both western science and TEK. The finding fosters trust for future collaboration because it provides land managers

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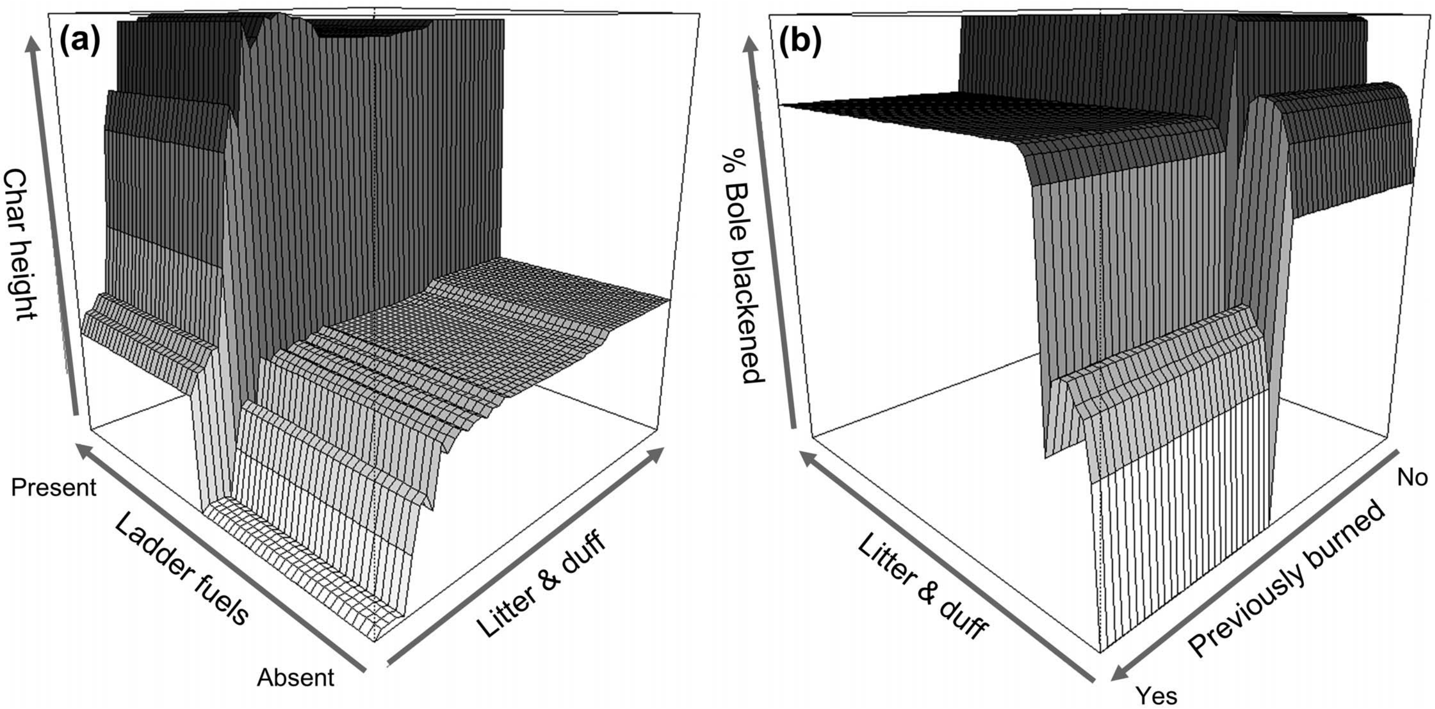

Figure 6.—Partial probability, or dependence, plots for two random forest models showing the relative logit contribution of predictor variables to the likelihood of increased (1) char height and (2) percentage of bole base blackened by fire. The shape of the 3-D surfaces demonstrates interactions among predictors. Ladder fuels and previous burning represent discrete, dichotomous variables, whereas others are continuous. Arrows represent the direction of increasing values.

with improved understanding to implement prescribed burns that may avoid direct harm to moths or eggs in tribal harvest areas, while providing tribal members new insight about the benefit of fire for the Pandora moth eggs.

Our work also helped develop and prioritize ongoing and future research, creating additional support for the continuity of the collaboration. Further work to quantify the trade-offs between negative and positive interactions, and feedback mechanisms, between fire and each stage of the piagi life cycle (Figure 1) may enable forest managers to better plan the timing and arrangement of future prescribed burns to benefit both ecological and cultural resources. For example, how does the spatial patterning of fire, including fire size and severity, affect boundary dynamics and percolation (Stamps et al. 1987; Wiens et al. 1995, 1997) of moths and caterpillars throughout the forest? Does the defoliation caused by moths themselves help shape fire patterns, and does the piagi harvest counterbalance those effects by enhancing Jeffrey pine productivity (Speer and Holmes 2004)?

Additional work is already underway by the USFS comparing pre- and post-fire conditions at Indiana Summit, including tracking the trajectory of forest recovery (Coppoletta et al. 2019). The Tribe has expressed interest in continuing participation in the collaboration, and the USFS envisions the youth intern program to be an integral part of continued research and restoration efforts at Indiana Summit.

Finally, this study sets the stage for similar partnerships elsewhere, especially in RNAs, where a limited historical scope of forest management (e.g., fire exclusion in fire-adapted ecosystems) may have resulted in undesirable risks to the resources that these areas were designed to protect. Such demonstrations of TEK-based restoration may in fact help to reshape interpretation of long-standing management in RNAs. In this sense, results serve as an example of "translational ecology"—the identified needed shift in focus from simply gaining more data to ensuring it will be translated and conveyed (Safford et al. 2017).

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LITERATURE CITED

Aldrich, J.M. 1921. *Coloradia pandora* Blake, a moth of which the caterpillar is used as food by Mono Lake Indians. Annals of the Entomological Society of America 14:36-38.

Bala, A., and G.G. Joseph. 2007. Indigenous knowledge and western science: The possibility of dialogue. Race and Class 49:39-61.

Berkes, F. 1999. Sacred Ecology: Traditional Ecological Knowledge and Resource Management. Taylor and Francis Publishing Co., Philadelphia, PA.

Berkes, F., J. Colding, and C. Folke. 2000. Rediscovery of traditional ecological knowledge as adaptive management. Ecological Applications 10:1251-1262.

Bivand, R., M. Altman, L. Anseli, R. Assuncao, O. Berke, A. Bernat, et al. 2018. Spatial dependence, weighting schemes, statistics and models, version 0.8-1. <https://github.com/r-spatial/spdep/>

Breiman, L., A. Cutler, A. Liaw, and M. Wiener. 2018. Breiman and Cutler's random forests for classification and regression, version 4.6-14. <https://www.stat.berkeley.edu/~breiman/RandomForests/>

Bulaon, B., and M. MacKenzie. 2014. Pandora moth concerns in Three Creeks Jeffrey Pine Forest Health Restoration Project, North Zone, Inyo National Forest. USDA Forest Service State and Private Forestry, South Sierra Shared Service Area, Report No. SS14-02.

Carolin, V.M., Jr., and J.A.E. Knopf. 1968. The Pandora moth. USDA Forest Service, Forest Pest Leaflet 114.

Charnley, S., J.W. Long, and F.K. Lake. 2014. Chapter 9.6—Collaboration in National Forest management. Pp. 663-704 *in* J.W. Long, L. Quinn-Davidson, and C.N. Skinner, eds., Science synthesis to support socioecological resilience in the Sierra Nevada and Southern Cascade Range. General Technical Report PSW-247. USDA Forest Service, Pacific Southwest Research Station, Albany, CA.

Coppoletta, M., H.D. Safford, B.L. Estes, M.D. Meyer, S.E. Gross, K.E. Merriam, R.J. Butz, and N.A. Molinari. 2019. Fire regime alteration in natural areas underscores the need to restore a key ecological process. Natural Areas Journal 39:500-513.

Dinno, A. 2017. Dunn's test of multiple comparisons using rank sums, version 1.3.5. <https://cran.r-project.org/web/packages/dunn.test>

Fowler, C.S., and N.P. Walter. 1985. Harvesting pandora moth larvae with the Owens Valley Paiute. Journal of California and Great Basin Anthropology 7:155-165.

Gamborg, C., R. Parson, R.K. Puri, and P. Sandoe. 2012. Ethics and research methodologies for the study of traditional forest-related knowledge. Pp. 535-562 *in* J.A. Parrotta and R.L. Trosper, eds., Traditional Forest-Related Knowledge: Sustaining Communities, Ecosystems and Biocultural Diversity. Springer, Dordrecht, Netherlands.

Hoagland, S.J. 2017. Integrating traditional ecological knowledge with western science for optimal natural resource management. IK: Other Ways of Knowing 3:1-15.

Houde, N. 2007. The six faces of traditional ecological knowledge: Challenges and opportunities for Canadian co-management arrangements. Ecology and Society 12:17.

Jarek, S. 2015. Generalization of Shapiro-Wilk test for multivariate variables, version 0.1-9. <https://cran.r-project.org/web/packages/mvnormtest>

Joint Fire Science Program Exchange Network. 2017. California Fire Science Consortium. Clark Fire in the Indiana Summit Research Natural Area: Field Trip, 2017 July 17. Accessed 11 May 2018 from <http://www.cafiresci.org/events-webinars-source/indianasummitfieldtrip>

Kolb, T.E., J. Agee, P.Z. Fule, N.G. McDowell, K. Pearson, and A. Sala. 2007. Perpetuating old ponderosa pine. Forest Ecology and Management 249:141-157.

Kretser, H.E., J.P. Beckmann, and J. Berger. 2018. A retrospective assessment of a failed collaborative process in conservation. Environmental Management 62:415-428.

Mason, L., G. White, G. Morishima, E. Alvarado, L. Andrew, F. Clark, M. Durglo, J. Durglo, J. Eneas, J. Erickson, et al. 2012. Listening and learning from traditional knowledge and Western science: A dialogue on contemporary challenges of forest health and wildfire. Journal of Forestry 110:187-193.

Menzies, C., and C. Butler. 2006. Introduction: Understanding ecological knowledge. Pp. 1-17 *in* C. Menzies, ed., Traditional Ecological Knowledge and Natural Resource Management. University of Nebraska, Lincoln.

Meyer, M.D., M. Slaton, and S. Farley. 2014. Indiana Summit Research Natural Area Ecological Assessment. Unpublished report, Inyo National Forest, Mammoth Ranger District.

Reyes-Garcia, V., A. Fernandez-Llamazares, P. McElwee, Zsolt Molnar, K. Ollerer, S.J. Wilson, and E. Brondizio. 2019. The contributions of indigenous peoples and local communities to ecological restoration. Restoration Ecology 27:3-8.

Safford, H.D, S.C. Sawyer, S.D. Kocher, J.K. Hiers, and M. Cross. 2017. Linking knowledge to action: The role of boundary spanners in translating ecology. Frontiers in Ecology and Environment 15:560-568.

Safford, H.D., and J.T. Stevens. 2017. Natural range of variation for yellow pine and mixed-conifer forests in the Sierra Nevada, southern Cascades, and Modoc and Inyo National Forests, California, USA. General Technical Report PSW-256, USDA Forest Service, Pacific Southwest Research Station, Albany, CA.

Senos, R., F.K. Lake, N. Turner, and D. Martinez. 2006. Traditional ecological knowledge and restoration practice. Pp. 393-426 *in* D. Apostol and M. Sinclair, eds., Restoring the Pacific Northwest: The

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Art and Science of Ecological Restoration in Cascadia. Island Press, Washington, DC.

Simeoni, A., Z.C. Owens, E.W. Christiansen, A. Kemal, M. Gallagher, K.L. Clark, N. Skowronski, E.V. Mueller, J.C. Thomas, S. Santamaria, and R.M. Hadden. 2017. A preliminary study of wildland fire pattern indicator reliability following an experimental fire. Journal of Fire Sciences 35:359-378.

Skinner, C.N. 2005. Reintroducing fire into the Blacks Mountain Research Natural Area: Effects on fire hazard. Pp. 245-257 *in* M.W. Ritchie, D.A. Maguire, and A. Youngblood, eds., Proceedings of the symposium on Ponderosa pine: Issues, trends, and management. General Technical Report PSW-198, USDA Forest Service, Pacific Southwest Research Station, Albany, CA.

Speer, J.H., and R.L. Holmes. 2004. Effects of Pandora moth outbreaks on ponderosa pine wood volume. Tree-Ring Research 60:69-76.

Stamps, J.A., M. Buechner, and V.V. Krishnan. 1987. The effects of edge permeability and habitat geometry on emigration from patches of habitat. American Naturalist 129:533-552.

Sugihara, N.G., J. van Wagtendonk, K.E. Shaffer, J. Fites-Kaufman, A.E. Thode, and J.K. Agee, eds. 2006. Fire in California Ecosystems. University of California Press, Berkeley, CA.

Taylor, A.H, C.N. Skinner, and B. Estes. 2009. A comparison of fire severity patterns in the late 19th and early 21st century in a mixed conifer forest landscape in the southern Cascades. Final Report JFSP Project Number: 09-1-10-7. University of Nebraska, Lincoln.

Taylor, D.W. 1977. Ecological survey of the vegetation of Indiana Summit Research Natural Area, Inyo National Forest, California. USDA Forest Service, Report 761-PSW-77.

US Forest Service. 2005. Forest Service Manual. FSM 4063, Washington, DC.

US Forest Service. 2015. Field instructions for the annual inventory of California, Oregon, and Washington. Forest Inventory and Analysis National Core Field Guide Version 7.1. PNW Research Station, Resource Monitoring and Assessment Program, Portland, OR.

US Forest Service. 2017. Rapid Assessment of Vegetation Condition After Wildfire (RAVG). Thematic Percent Change in Composite Burn Index. Washington, DC.

Whyte, K.P. 2013. On the role of traditional ecological knowledge as a collaborative concept: A philosophical study. Ecological Processes 2:7.

Wickham, H., R. François, L. Hentry, and Kirill Müller. 2018. A grammar of data manipulation, version 0.7.8. <http://dplyr.tidyverse.org>, <https://github.com/tidyverse/dplyr>

Wiens, J.O., T.O. Crist, K.A. With, and B.T. Milne. 1995. Fractal patterns of insect movement in microlandscape mosaics. Ecology 76:663-666.

Wiens, J.A., R.L. Schooley, and R.D. Weeks. 1997. Patchy landscapes and animal movements: Do beetles percolate? Oikos 78:257-264.

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