San Francisco Estuary & Watershed Science: Science & Policy for the Delta

Changing Paradigms of Knowledge Production: Interweaving Traditional Knowledge and Predominant Science in the Delta

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SFEWS Volume 23 | Issue 2 | Article 1

https://doi.org/10.15447/sfews.2025v23iss2art1

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ABSTRACT

Scientists, policy-makers, and Tribes are increasingly recognizing the profound insights that diverse knowledge systems can provide in a process of interweaving, for both the global ecocultural landscape and the Delta specifically. Traditional Knowledge (TK) is a holistic approach of place-based knowledge, practices, and ethical beliefs of Indigenous peoples that has historically been under-represented in decision-making. Many struggle to understand how to meaningfully interweave knowledge systems together. We discuss approaches to interweaving knowledge systems, where to find interweaving opportunities, and under what governance structures. Collaborative knowledge production is illustrated through three examples in the Delta: (1) cultural burning practices, (2) ecological restoration, and (3) species management. We acknowledge ongoing barriers and solutions to interweaving TK, by: challenging misperceptions of TK; protecting Indigenous data; reforming funding structures; and preserving and using TK. Creating meaningful space for Indigenous voices and worldviews is just the first step in a broader process of empowering Tribes and scientists to co-produce knowledge and create policies to co-manage resources.

KEY WORDS

Indigenous, Native American, Tribes, Traditional Knowledge, co-production, co-management

INTRODUCTION

Traditional knowledge (TK) has been the bedrock of Indigenous cultures and societies for time immemorial, defining their connections with the natural world. Often called a “way of knowing,” TK is a dynamic body of knowledge that combines knowledge, practice, culture, and ethics (Berkes et al. 2000; Cajete 2000),

and is applied for sustainable land management, watershed management, and agriculture (Kimmerer and Lake 2001; Kagawa and Vitousek 2012; Johnson et al. 2022). Despite its depth and richness, TK has historically been misunderstood, marginalized, and excluded by scientists and decision-makers as inferior or irrelevant (Huntington 2000), while those same scientists often disregard the inherent human biases present in their own work. This systemic disregard and active suppression have led to a cultural loss for Indigenous peoples and a general loss of valuable insights into biodiversity, restoration, and sustainable futures (Simpson 2001). Still, many Indigenous peoples continue to practice TK in support of diverse and flourishing landscapes and communities. Increasingly, scientists and decision-makers have become interested in interweaving TK as a deep, culturally bound source of place-based knowledge and associated land-stewardship practices to tackle "wicked" societal challenges (Williams and Hardison 2013; Hosen et al. 2020).

BOX 1

Traditional Knowledge

Traditional Knowledge (**TK**) is defined by Robin Wall Kimmerer (2002) as "the knowledge, practice, and belief concerning the relationship of living beings to one another to the physical environment." (p. 432). Roy Dudgeon and Fikret Berkes (2003) recognize that Indigenous knowledge "evolv[es] by adaptive proc esses and [is] handed down through generations by cultural transmission" (p. 2). **Traditional Ecological Knowledge** (**TEK**) is often used to focus on their place-based ecological knowledge. We use TK here because it is more inclusive of knowledges beyond ecological knowledge. However, there are many different definitions of TK, depending on context, history, and perspective. That means TK should serve as an entry point for "non-indigenous parties to learn more about how particular [I]ndigenous communities approach fundamental questions of the nature of knowledge and how it fits into their visions of environmental governance" (Whyte 2013, p. 10).

Climate change, in particular, represents an existential threat to society (Steel et al. 2022), and fossil fuel emissions, deforestation, land-use changes, and biodiversity loss are ongoing and unlikely to slow (IPCC 2022). In this context, scientists have observed that "[D]espite being the worst affected by climate change, Indigenous people's TK responses to local-level climate variations make significant contributions to adaptation" (Hosen et al. 2020, p. 2). While the natural sciences provide a wealth of data, the problem of climate change cannot be solved with the predominant science paradigm alone (Herman 2016). Also called "Western Science" to recall the provenance of scientific inquiry (Lindeberg 2010), the predominant science paradigm foregrounds its dominance over other knowledge systems. Yet, working together with Indigenous peoples to interweave knowledge is critical in developing new approaches to achieving a resilient future for the planet (DSC 2024a).

Interweaving knowledges can be compared to how musical harmonies work. You can play a single melody line, and it might be lovely. When you add harmony lines—complementing it, sometimes seeming to clash before resolving—you create something richer than any single line could achieve; creating depth and resonance to the entire piece. In other words, it's not just about adding different perspectives together, but about how they can dynamically interact to transform each other. When done well, it doesn't diminish any of the individual voices. For example, in the Arctic, Inuit hunters' knowledge of sea ice, animal migration, and weather has helped climate scientists better understand how regional climate affects polar bears (Gagnon and Berteaux 2009).

Crucially, interweaving goes beyond just data integration—it centers the relationship with knowledge-holders themselves. Through a relational process that prioritizes ethical standards, there is great potential to strengthen governance by incorporating other ways of knowing (David–Chavez et al. 2024). To advance a vision of knowledge co-production—both within and outside the Delta Stewardship Council (DSC)—we conducted a review and narrative synthesis of literature describing: (1) participatory approaches to interweaving knowledges; (2) potential applications of TK within and adjacent to the Sacramento–San Joaquin Delta (Delta) for species management and restoration through practices like Traditional Fire Management and cultural burning; and (3) ongoing barriers and solutions to interweaving knowledges.

HISTORICAL CONTEXT

Understanding historical context is essential for building meaningful partnerships today. Euro-American and Spanish colonization of the American West in the early 1800s devastated Tribal communities through disease, displacement, slavery, and forced assimilation (Dillon 2022; Sze et al. 2009; Zedler and Stevens 2018). In California, this started with the Gold Rush. Until 1968, Indian boarding schools separated children from their families and communities, disrupting the transmission of TK across generations (Turner et al. 2000).

Despite these histories, Indigenous resilience and defiance of colonialism have meant Tribes are re-discovering and re-connecting with their Native places and identities (Kondrashova 2020). For example, the California Indian Basketweavers' Association (CIBA) has grown into a solidarity movement for Native Americans to reconnect to traditional basketry techniques and access cultural resource sites and species (CIBA n.d.). When cultural uses have been threatened, as they are in the Delta, Tribes acquired legal representation to challenge state government decisions (Delta Tribal Environmental Coalition 2024). Similarly, Tribes have filed legal complaints for failing to protect water quality in the Bay–Delta and excluding tribes from policy-making, violating Title VI of the Civil Rights Act of 1964 and US Environmental Protection Agency (USEPA) non-discrimination regulations. So, the USEPA investigated the State Water Resources Control Board (SWRCB) for impingements to flow, temperature, and harmful algal bloom (HAB) criteria (USEPA 2023).

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States across the US are taking progressive steps to recognize Tribal sovereignty and implement co-management practices. For instance, thirty Tribes across Alaska, Idaho, Oregon, and Washington (EPA Region 10) have authority to review and certify projects that affect their water quality, under Section 401 of the Clean Water Act (USEPA 2020). Despite California's slower progress, Indigenous-led decolonizing and anti-colonial resistance—by reclamation of land and knowledge—continues to grow in the state (Middleton Manning et al. 2018). Early successes like the Timbisha Shoshone's co-management agreement of 2000 in California's Death Valley National Park set an important precedent. The agreement transferred almost 8,000 acres back to the Tribe, representing the culmination of a 65-year struggle (Stringfellow 2016).

By 2020, Governor Newsom released an Executive Order encouraging every California state agency to support Tribal co-management of lands, facilitating Tribal access to Native lands (Exec. Order N-82-20 2020). Then, in 2022, the Biden–Harris administration released guidelines on Indigenous Knowledge for federal agencies that changed the paradigm for all federal agencies, specifically mandating they start "Understanding Indigenous Knowledge; Considering, including, and applying Traditional Knowledge in Federal research, policies, management, and decision making" (White House 2022, p. 1). That information has since been removed from the White House website.

PARTICIPATORY APPROACHES TO INTERWEAVING KNOWLEDGES

How Do We Develop Trusting, Respectful Relationships?

Developing relationships characterized by trust and respect is fundamental for any collaboration with Tribes (Fernandez–Gimenez et al. 2008). Allowing sufficient time to earn trust and build meaningful relationships means that Tribal collaborations may operate on a slower timeline. Building trusting and respectful relationships requires understanding how historical power dynamics and governmental maltreatment of Indigenous individuals and Tribes interact with research practices (Dotson 2014). Research provides insights into the importance of representation and meaningful participation. For example, people often feel most comfortable speaking up when there is a critical mass of individuals with a shared interest or other commonality (Agarwal 2010).

This meaningful collaboration goes beyond representation alone. Holders of TK must be able to trust that their insights will genuinely affect scientists' and decision-makers' thinking, action, and follow through (Seigerman et al. 2023). Building effective partnerships requires context-specific support guided by Indigenous peoples; active reflection on institutional and historical context; recognition of different worldviews and knowledge systems; and commitment to addressing inequities in decision-making processes (Irlbacher–Fox 2014). Building respectful relationships demands being clear about who benefits, and being honest about inherent risks or harms.

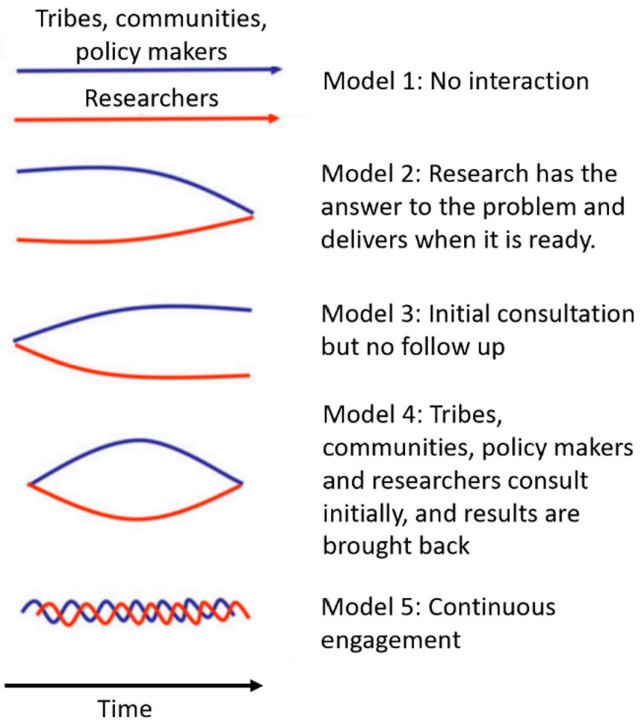

Figure 1 Models of engagement between researchers and tribes, communities, and policy makers over time. **Model 1** illustrates no interaction between researchers and communities. **Model 2** represents a unidirectional approach, where researchers independently produce knowledge and deliver findings at the end. **Model 3** involves initial consultation without sustained collaboration. **Model 4** shows early co-design of research with findings later shared back. **Model 5** depicts continuous engagement, characterized by ongoing, reciprocal collaboration. Adapted from Reid et al., (2009) to illustrate differing levels of knowledge co-production in support of interweaving knowledge systems.

Literature recommends that collaborations between scientists and holders of TK should begin at the earliest stages of project creation and continue through to sharing the final product with wider communities and audiences (Kondrashova 2020). Traditionally, science has operated on a "loading dock" model, where scientists deliver research results to Tribes, decision-makers, and communities only when a project is completed—what Robin Reid and colleagues (2016) typify as model 2 in their research (Figure 1). While alternative collaboration models exist (e.g., models 3, 4), their research found that continuous engagement throughout the research process (model 5) leads to more effective social and ecological outcomes.

Whose Knowledge Do We Engage?

Having a single individual or Tribe participate may not empower others to voice their opinions, and there are crucial distinctions to consider. Specially, Tribal members and holders of TK represent different types of expertise and authority. Although all Tribal members can access and use TK, only TK holders recognized by Tribal leaders have the authority to share culturally sensitive information. White House guidance directs agencies to engage "only with such individual knowledge holders designated by Tribal leadership" (OST and CEQ 2022, p 10). Tribal members or representatives are not necessarily knowledge-holders, and conversely, not all knowledge-holders are enrolled members of federally recognized Tribes.

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Each holder of TK and elder has a different perspective and decision-making authority. As one elder from the Canadian Mi'kmaw Nation put it: "We need to acknowledge that elders and knowledge holders … each one of us … has certain expertise, yes, but none of us knows everything. This is also why TK is collective knowledge" (Bartlett et al. 2012). This diversity of place-based knowledge makes it inappropriate to assume that one Tribe's participation can represent others' views (Singleton et al. 2023). Holders of TK also exist in a complex landscape of tribal recognition—including federally recognized Tribes, non-federally recognized Tribes, and individuals who are descendants of multiple Tribes or geographically displaced from their Tribe—creating additional layers of consideration for meaningful engagement. For example, the Winnemem Wintu Tribe in Northern California are not federally recognized, so are often treated as a "public stakeholders," without the respect and legal deference given to sovereign nations (Middleton Manning 2018).

In California, the history of tribal recognition is riddled with non-ratified treaties dating back to the Gold Rush in the 1850s, during which the then-Senate imposed an injunction of secrecy until they were unearthed in 1905 (Miller 2013). The struggle to gain legal status and recognition through the Federal Acknowledgment Process is ongoing for many non-federally recognized Tribes (Chilcote 2024). They continue to maintain robust concepts of cultural sovereignty that are distinct from political sovereignty and deserve recognition. These nuances underscore the importance of developing inclusive, culturally appropriate engagement processes that recognize and respect these distinctions in meaningful collaboration.

Where Do We Look for Opportunities to Interweave Knowledges?

Scientists and holders of TK are well-positioned to co-create research and co-produce knowledge where "each approach is assumed valid within its own set of rules" (Carmack and Macdonald 2008, p. 266). Both are committed to understanding the world through systematic and repeated observation, prediction, inference, and verification (Kimmerer 2011; Mason et al. 2012; Hoagland 2017). Where interweaving is most apparent is at the scale of human experience and perception—spanning several inches to several hundred miles—rather than at the microscopic or global scales which are the strengths of science (Thornton and Scheer 2012). This includes scales to monitor species abundance, evaluate the extent of sea ice, or detect harmful algal blooms (Huntington 2000). In this shared pursuit of knowledge, TK and predominant science can often emerge not as conflicting narratives but as complementary threads.

Interweaving knowledge systems, though, is not always appropriate, or even desirable. As Thornton and Scheer (2012) note, TK and predominant science are "not [of] a different nature but rather a different focus" which keeps these two schools of thought "looking in different directions" (p. 10). Predominant science excels at global and microscopic scales while TK excels at localized, multi-generational observations—expressed through the perpetuation of living culture. For example, gathering basket-weaving materials after a cultural burn simultaneously maintains and strengthens material culture and human–plant

relationships. These traditions and worldviews are kept alive through oral tradition, with stories that "hold water" (Aldern and Goode 2014; Vinyeta and Lynn 2013). Oral traditions are not mere narratives, but powerful tools of Indigenous-based inquiry that encourage listeners to ask questions, build relationships with the narrative, and facilitate meaning-making (Wilcox et al. 2012).

What are Some Research Methods for Interweaving Knowledges?

How can these two knowledge systems work together to steward the landscape? The two paradigms might best be considered together using collaborative methodologies (Johnson et al. 2016). For example, community-based, participatory research (CBPR) designs are often well-suited for inquiry or research contexts that seek to bring together knowledge traditions by building relationships and empowering Indigenous communities (Cunsolo Willox et al. 2013). CBPR has long been used in the field of health, and more recently been applied in environmental research to develop community-defined research questions through a collaborative research process with outcomes meaningful to Indigenous communities (Mulrennan et al. 2012).

Any CBPR project that engages Tribes must honor Tribal sovereignty and their data sovereignty (Carroll et al. 2020). Federally recognized Tribes, as sovereign nations, govern research on their land and sometimes have local protocols that are authorized by the Nation's government. For example, the Karuk Tribe of northwestern California has its own Resources Advisory Board that functions as an Institutional Review Board (IRB) that oversees ethical standards for Tribal cultural resources (Karuk Tribe 2015). Scientific researchers are also obligated to follow ethical standards for research with "human subjects," typically under university IRB oversight. However, researchers must understand that data for Tribes extends beyond traditional scientific definitions to include stories and testimonials. The podcast Intentional Fire, which documents Karuk stories on fire in their community, exemplifies how such narratives are necessary data for interweaving Indigenous voices with science and decision-making (Murveit et al. 2023).

Participatory methodologies can be effective frameworks for respectfully interweaving knowledges and centering Indigenous voices. A compelling example comes from a community-based research project in the Canadian Inuit community of Rigolet in Labrador, which used digital storytelling to illuminate how changing climates influenced community wellbeing. The project involved a week-long, facilitated workshop where participants learned to create a "first-person mini-movie of sorts" by illustrating personal narratives with photographs, artwork, music, voice overlay, videoclips and text (Cunsolo Willox et al. 2013, p. 132). The process began with brainstorming sessions where participants reflected on how changes to sea ice, snow, and land affected human health, creating concept maps on chalkboards. This initial stage sparked lengthy dialogue and participant-led storytelling that became the backbone of their digital storytelling narrative. Throughout the week, participants engaged in hands-on skill-building activities, including video editing, digital scanning of artwork, and recording and

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transcription of songs. The workshop culminated in a film screening "with evident pride, anticipation, and excitement" of participants (ibid). Such methods can help reveal previously hidden worlds, empower marginalized communities, and create a digital record that can inform research beyond the Indigenous community. But before such stories, songs, narratives, and observations can be created, researchers and community members must detail who owns the story, who hears the story, and who can repeat the story; questions that are central to Indigenous data sovereignty (see "Species Management" section). A more comprehensive list of methodologies can be found in Johnson et al. (2016).

What is the Role of Governance in Interweaving Knowledges?

Indigenous peoples steward around 80% of the world's biodiversity, despite comprising less than 6% of the global population (World Bank Group c2023). Often, Tribes are more effective at managing lands despite limited resources, in part because of their relationships with and reliance on the lands (Washburn 2021). Tribes have improved salmon habitats (Breslow 2014), increasing the number of plant species needed for basket-weaving through selective harvest (Zedler and Stevens 2018), and sustainably managed waters and wetlands (Fox et al. 2017; Middleton Manning 2018).

The salient point is that interweaving has integral governance implications. Responsible co-production of knowledge must empower holders of TK to use their knowledge in an environmental policy or land-management context (Agrawal 1995); whether that be hiring a subject matter expert, developing a Tribal Advisory Committee, or engaging in nation-to-nation contracts for co-governance will depend on the scale and level of empowerment envisioned (Figure 2). Ensuring holders of TK are not only consulted but also actively engaged in leadership roles throughout the policy-making and implementation processes is one potential pathway for achieving effective environmental justice (Martinez, Middelton, et al. 2023).

Co-governance is just one formalized governance process that can effectively support ethical interweaving of knowledges. According to Wilson (2020), "Co-governance requires that both parties share authority or jurisdiction on a nation-to-nation basis." The legal authority for co-governance has developed over the last half century (Diver et al. 2019), starting with the US Indian Self Determination Act of 1974, which empowered Tribes to contract with federal agencies whose purviews affect Indigenous communities. For example, Tribes that have been approved by the USEPA to be treated as a state (TAS) and have authority to regulate and establish water-quality goals within their reservation under the Clean Water Act (USEPA 2016). There are hundreds of examples of Tribal nations successfully operating federal programs on Tribal reservations, demonstrating that Tribal nations are well-equipped for contracting with other land-management agencies (Washburn et al. 2021). However, these processes are often slow to form.

In 2003, the Mountain Maidu peoples began searching for ways to reclaim and manage their ancestral homelands in California's northern Sierras, then owned by

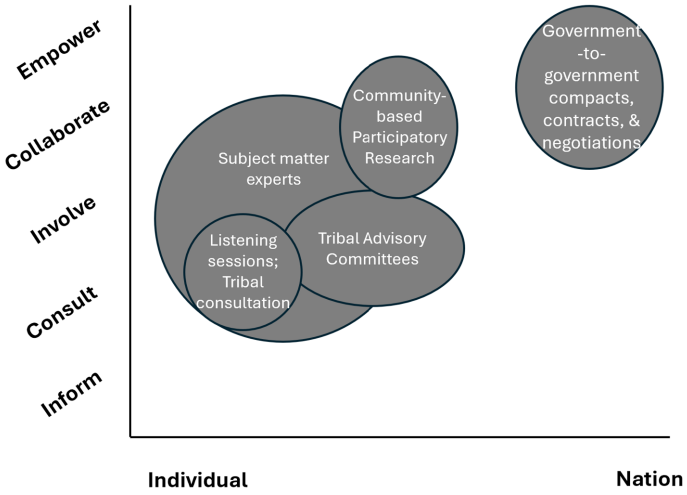

Figure 2 Forms of engagement with Tribes across a spectrum of relational scale and decision-making influence. The *vertical axis* reflects increasing levels of engagement and shared power, from informing to empowering (IAPP 2018). The *horizontal axis* spans engagement with individual Tribal members to formal nation-to-nation relations. Methods such as listening sessions, Tribal consultation, and subject matter expert engagement tend to focus on individuals with limited decision-making power, while government-to-government compacts and negotiations represent nation-level relationships grounded in Tribal sovereignty and co-equal governance.

Pacific Gas & Electric Company (PG&E). Like many Tribes in California though, the Mountain Maidu are not federally recognized so when their application to take back their land was rejected, they moved instead to form The Maidu Summit Consortium, a non-profit. In 2019, the consortium was finally granted five parcels, totaling 3,000 acres. To manage its lands, though, the Tribe must still co-manage lands with the Department of Fish and Wildlife and a local land trust. Slowly, their habitat-restoration crew has developed beaver-like dams to keep nutrient-rich sediment in the meadows as places for plants and wildlife to thrive. "[W]hat we are doing here will support opportunities for co-management throughout the rest of California" (Middleton Manning 2018, p. 189).

Beyond co-management initiatives between Tribes and agencies, a multitude of collaborative governance structures and processes can facilitate interweaving knowledges. These include seeking out and paying Tribal staff as subject matter experts; engaging in Tribal consultation or listening sessions; forming a Tribal Advisory Committee—ideally informed by elders or recognized knowledge holders—to include Indigenous voices in government, university, or organizational processes; or creating compacts, contracts, and Memoranda of Understanding (MOU) between nations (Long et al. 2018; Simpson 2001). Such agreements must be developed collaboratively with flexibility, recognizing Tribal land-management histories as well as advancing Tribal self-sovereignty (Casson 2015).

Indeed, one author argues that "...the only meaningful way to foster decolonization is through reconnection of People to their places (Kondrashova 2020, p. 10). This, in turn, requires acknowledging historical harms and asymmetries of power, and empowering holders of TK as experts to co-direct inquiry and management (Thornton and Scheer 2012). As observed by Agrawal (1995, p. 432), "The appropriate response from those who are interested in preserving the diversity of different knowledge might then lie in.. revers[ing] state policies...to permit members of threatened population to determine their own future." Creating structures and authorities to enhance power-sharing is arguably the most effective

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and ethical way to support Tribes in preserving their TK and using it to influence environmental policy and land management (Agrawal 1995; Thornton and Scheer et al. 2012; Diver 2017).

In California, and in the Delta specifically, Tribes are just beginning to employ biologists and restoration practitioners (e.g., Shingle Springs Rancheria's Scientist and Habitat Restoration Practitioner). Capacity building through funding will be important to meet the wildlife, water-quality, and restoration objectives, yet Tribes still face several barriers to reaching those outcomes and interweaving more broadly.

WHERE TO BEGIN INTERWEAVING IN THE DELTA

The literature is replete with case studies about how TK and predominant science can be applied together, including but not limited to climate adaptation and mitigation, biodiversity conservation, and forestry. In the Delta, cultural burning, restoration, and species management are three common applications with great opportunity for interweaving knowledges to the potential benefit of Tribes and the Delta more broadly (Table 1). We see these tangible applications as logical starting points for scientists, agencies, and others interested in exploring possibilities of co-production with Tribes as prominent practices already within the Delta. Because of the paucity of research conducted on TK and with Tribes in the Sacramento–San Joaquin Delta, we at times draw from examples farther afield to help demonstrate the approach that agencies and scientists could take with Tribes.

Cultural Burning

Categorical differences in cultural understandings between predominant science and TK are perhaps best exemplified by examining how historical perspectives on fire, burning, and smoke have historically been understood. Predominant science and Western resource-management practices have largely considered fire as a threat to life and livelihoods, and smoke as an air-quality hazard and pollutant. In contrast, Tribes see cultural burning as a land-management practice that encourages plant growth, facilitates the summertime cooling of streams, attenuates peak flood flows, and prolongs streamflow during the rainy season (Zedler and Stevens 2018; Long et al. 2020). Research by David et al. (2018) further highlights that smoke-induced cooling creates localized thermal refuges for cold-loving salmonid fish. This demonstrates a complex interplay between fire regimes and aquatic ecosystems. Additionally, Indigenous burning practices allow for more precise timing and control of smoke, which can mitigate potential public-health concerns (Hankins 2021a).

For many millennia before colonial settlement, Native Americans in the Delta used periodic controlled burning for numerous applications, including maintenance of travel corridors, tending natural resources such as food and fibers, and enhancing biodiversity (Hankins 2021b). In modern applications, we most often see burning to reduce fuel load, and to reduce encroachment by conifers and shrubs (Wray and Anderson 2003). The Wukchumni Yokuts of the San Joaquin Valley, for example,

Table 1 Delta topics that can be informed by interweaving

DELTA TOPICS THAT CAN BE INFORMED BY INTERWEAVING		
Cultural Burning	**Restoration**	**Species Management**
▪ TK practices like cultural burning are well-positioned to help scientists explore questions about 'why' fire is good, for what species, when and where. ▪ Funding for cultural burning can be used for indigenous workforce development to manage lands and provide better data on species management.	▪ TK can help agencies and scientists promote watershed health and protect sacred waters for Tribal Beneficial Uses. ▪ Elders' Knowledge of local and longitudinal processes can help scientists plan restoration projects that are more effective and widely accepted.	▪ TK can help agencies and scientists learn about species of cultural importance to avoid disturbance and encourage growth. ▪ Tribes can provide early detection of spatially variable or cryptic species and provide insight into how management affects different Tribal activities.

historically burned marshes to clear out old growth, leaving space for waterfowl to move and nest, and room for growth of emergent tules—essential for basket-making, traditional rafts (known as tule balsas), and building material (Anderson et al. 1998). The application of cultural burning can fine-tune the landscape to create a "mosaic of vegetation" that improves biodiversity and cultural use (Hankins 2021b).

Federal and state fire-management policies have historically targeted the complete suppression of fire, which has paradoxically increased the risk and occurrence of catastrophic wildfires (Mason et al. 2012). These policies were founded on the misguided premise that burning destroyed ecosystems and that nature would restore itself "naturally" without human intervention. This approach led to an enormous fuel build-up and more intense mega-fires (Martinez 2003). The additive effects of anthropogenic climate change, industrial logging, and residential expansion into rural areas have also tipped the scales of fire intensity and prevalence in California (Martinez, Seraphin et al. 2023). California historically held Indigenous peoples liable for fire damages until Senate Bill 310 (CA SB 310 2023) removed this liability, allowing Tribes to engage in cultural burning for fire suppression. Collaboration between Tribes and agencies such as the California Department of Forestry and Fire Protection (CalFIRE) is gaining recognition for effective fire management (Marks–Block and Tripp 2021). For example, in 2024, Californians approved bond funding for fire-fighting organizations, including Native American Tribes.

Traditional Knowledge of fire practice and ecology extends to including how frequently to burn (e.g., annually), what season to burn (e.g., fall or spring), what direction to burn (e.g., upslope or downslope), and what plant communities should be burned or left alone. In the Pacific Northwest, fall burning has often been preferred to introduce new growth, stimulate seed germination, and support wildlife that browse those species (Senos et al. 2006). Elders recount the importance of considering seasonality, location, and vegetation types when managing waterways, particularly to "increase streamflow during critical

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migration phases of key fish species" (Senos et al. 2006, p. 397). Although various Tribes have long practiced cultural burning for many different reasons in Northern California (Marks–Block et al. 2021; Long, Lake, and Goode 2021), predominant scientific research has only recently begun to quantitatively document the spatial and temporal characteristics and benefits of cultural fire regimes (Greenler et al. 2024). Significant opportunities remain for rich, culturally grounded investigations led by local Tribes into the benefits of cultural burning in the Sacramento–San Joaquin Delta and its watershed.

Restoration

For Tribes, ecological restoration is often described as an act of reciprocity, where humans exercise care-giving responsibility for ecosystems, through a process that some have termed reciprocal restoration (Kimmerer 2011; Zedler and Stevens 2018; Long et al. 2020; Claire and Surprise 2022). Robin Wall Kimmerer (2011), an Indigenous scholar at SUNY–College of Environmental Sciences and Forestry, describes reciprocal restoration as "the mutually reinforcing restoration of land and culture such that repair of ecosystem services contributes to cultural revitalization, and renewal of culture promotes restoration of ecological integrity" (p. 279). In this way, reciprocal restoration can be thought of as the repair and renewed relationship with place (Claire and Surprise 2022). Such restoration moves beyond standard agency-led restoration efforts that focus on specific ecological objectives such as protecting endangered species, improving flow, or re-engineering habitat (Long et al. 2020). While reciprocal restoration may achieve some of these objectives, it manifests in restoration of subsistence activities, revitalization of traditional Indigenous diets, resurgence of language and culture, or a focus on cultural keystone species (Kimmerer 2011).

In California, Tribal engagement in restoration has played out on a case-by-case basis. For example, the Cosumnes River Preserve collaborates with Tribes to protect a mosaic of floodplains, wetlands, vernal pools, and grasslands (Stevens and Zaloza 2015). This localized approach could be expanded to encompass the thousands of acres of planned restoration in the Delta (DSC n.d.). Government agencies in the Delta have already recognized and engaged with Tribes as experts in restoration. For example, the DSC has proposed a co-management approach that goes beyond ecological outcomes, to improve Tribal access to their homelands (DSC 2024b). Similarly, the SWRCB's draft Bay–Delta Plan updates demonstrate a significant step forward by proposing the inclusion of Tribal beneficial uses, thus recognizing Tribal Tradition and Culture and Tribal Subsistence Fishing (SWRCB 2024). The success of these initiatives, though, ultimately depends on early, often, and meaningful engagement with Tribes throughout policy- and decision-making processes.

Species Management

Scientists have already called on decision-makers in the Delta to restore Tribal culturally significant plant assemblages in the Delta (Zedler and Stevens 2018). This restoration is in line with the Delta Plan's goal to protect and improve the unique cultural values of the region (DSC 2013). Such culturally significant plant

(and animal) assemblages could be identified by local Tribes with target priority locations for continuous monitoring. In such a system, TK could be interwoven with predominant science to understand which species can out-compete invaders, and what regions should be prioritized to foster sensitive species of concern, while adapting to climate change (Laughlin 2014). Some of the culturally significant plant assemblages that have already been suggested include White root (Carex barbarae), Willow (Salix spp.), Deer grass (Muhlenbergi rigens), and Tule (Shoenoplectus acutus), among many others that provide materials for basketweaving, food, and medicine (see Zedler and Stevens 2018). Since every Tribe is unique, any culturally significant plant species assemblages should be locally tailored, designed, and implemented together with trusted agencies and scientists, in a way that respects sacred and ceremonial sites.

Scientists have much to learn from Tribal fisheries and wildlife research, and land management too. The Karuk and Yurok Tribal fishery program of northwestern California has for years sampled substrates for fish spawning and conducted reproductive surveys of Pacific lamprey. They have paired this research—grounded in predominant scientific methodologies—with interviews of Tribal elders on where and how Pacific lamprey live and spawn, with critical insights on why they have declined and how it has affected Indigenous diets (Senos et al. 2006). Replacing diverse, locally grown diets—including lamprey—with highly refined and mass-produced foods that are high in fat is negatively affecting the health of Indigenous Peoples around the world. Research with members of the Karuk Tribe in northern California show that such dietary shifts have fundamentally disrupted traditional food systems, with profound implications for community health. Specifically, the replacement of traditional fish and acorn-based diets with processed foods has directly contributed to increased diabetes rates and nutritional challenges in Karuk communities (Norgaard 2019). When left untreated, diabetes can be fatal (Batal et al. 2023). So the benefits of this work are material not only for Pacific lamprey and the ecosystems where they live, but for Tribal community members themselves.

Effective species management has ramifications beyond human health—to spiritual and cultural wellbeing that nurtures all of us. For example, the Yurok Tribe has been working to reintroduce the critically endangered California condor populations through its Yurok Condor Restoration Program. In the 1980s, the condor population had dwindled to only 30 individuals when the US Fish and Wildlife Service launched a program to breed them in captivity, away from powerlines and poisons. Some believed that captive-raised condors would never be able to live in the wild. But the Yurok see themselves as having an integral role in rebalancing the world, so they built their own condor facility, deep in Redwood National Park. There they hosted their first adult condor to mentor four juveniles; research shows condor adults play a pivotal role in instilling a social order and ensuring survival. In May 2022, these juvenile birds took flight to become the founders of a new condor society in Yurok country and can be seen today on the Yurok's Condor Cam Live Feed (*https://www.yuroktribe.org/yurok-condor-live-feed*).

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Condors are considered sacred to the Yurok people, playing an essential role in carrying their prayers to the heavens, and honored through dance and with ceremony. Keeping condors alive and well will continue to be hard work, borne by scientists and Tribes working together.

ONGOING BARRIERS TO INTERWEAVING KNOWLEDGES AND POTENTIAL SOLUTIONS

Challenging Misperceptions of TK Rigor

Validation of TK by recognized community elders and knowledge holders is essential, and such concerns are shared by Tribes and elders: "[A]s Elder Albert points out, there is great temptation today for some people to 'just make it up' and so 'validation, by recognized community Elders and Knowledge Holders, of that which is brought forward is exceedingly important'" (Bartlett et al. 2012). In the predominant scientific paradigm, ideas are questioned and tested to increase the rigor and accuracy of ideas and results, where a hypothesis is never "proven,"—rather, it has not been *disproven*. Authors Anthony Davis and Kenneth Ruddle (2010) argue that the same treatment of rational skepticism must also accompany TK to increase its rigor. Neglecting to question the validity and strength of TK (or science) is potentially a sign of confirmation bias, where an author can select information to affirm prior conclusions.

This does not mean scientists can or should continue to ignore or discount TK, which is validated in part through the wide array of elders and holders of TK who converge on certain information, as well as the "massive set of scientific experiments [conducted by Tribes] continuing over generations" (Ramos 2018). Interweaving knowledges requires self-reflexively examining all the ways in which values, identities, and other ingrained worldview assumptions influence the production of knowledge (Zanotti and Palomino–Schalscha 2016). Like other forms of knowledge, predominant science cannot be free of the biases introduced by those who practice it. This inherent subjectivity in scientific practice creates specific challenges when attempting to integrate TK with predominant scientific approaches.

Huntington (2000) defines two main barriers to interweaving TK and predominant science: inertia and inflexibility. With inflexibility, scientists and institutions question the reliability and utility of TK. This inflexibility may stem, in part, from underlying, prevailing worldviews and beliefs established by years of academic training, socio-political systems that enforce dominant worldviews and beliefs, and discomfort with cross-cultural interactions in general. Those individuals, institutions, and systems that perpetuate prevailing social, institutional, and cultural conditions need to step back to reflect and recognize how their ways of thinking and knowing limit opportunities for Indigenous peoples (Dotson 2014). Including diverse voices and representation not only validates different cultural identities but also provides strategies that promote meaningful engagement (Parsons et al. 2021).

Much scholarship on TK has largely been dominated by non-Indigenous authors—including us—who know about TK and are regarded as experts by other scientists and policy-makers, but who do not have a lived understanding of TK (McGregor 2005). Scientists or policymakers who can "code switch"—i.e., alternate between different languages or ways of speaking—are often the ones primarily involved in the study or research of TK, and generally focus on TK at an abstract or conceptual level, rather than engaging with the TK of specific Tribes. While this serves to protect sensitive or confidential knowledge from appropriation (see "Protecting Indigenous Data" section), it is also somewhat ironic that scholars would "abstract" TK given that, as many of them write, TK is indelibly embedded in specific places and relationships. In other words, TK is inherently a local knowledge. This creates a paradox, whereby even well-intentioned efforts to engage with TK in a de-contextualized manner occupy morally ambiguous territory (McGregor 2005).

Once we recognize that all knowledge is socially and culturally situated, it becomes possible to open productive collaborative spaces in which TK and predominant science and TK can complement each other. For example, in 2004, Parks Canada launched an investigation to understand and include Inuit TK in parks and wildlife management in Nunavut (Gagnon and Berteaux 2009). Arctic wildlife research is generally limited to summer months, but winter records of seals, walruses, and polar bears can be readily collected by Arctic residents, who are often Indigenous peoples. By combining knowledge from wildlife researchers in summer months and holders of TK in winter months, Parks Canada compiled a rigorous estimate of the abundance, distribution, and behaviors of Arctic wildlife, while simultaneously acknowledging areas of **disagreement** that required further inquiry. For example, while scientists documented a steady decline in the polar bear population, Inuit hunters reported multiple winter sightings and were skeptical of research that suggested populations were in decline. Instead, the **disconnect** was attributed to "incomplete data collection and synthesis among Inuit observers, or of scientific data collection that is too narrowly confined in a geographic area" (Thornton and Scheer 2012, p. 6). In short, the two knowledges can complement each other to build a more complete understanding of the phenomenon in question.

Protecting Indigenous Data

While predominant science is centrally owned and distributed by scientists, TK can only belong to and be used by Indigenous peoples as part of their cultural heritage, which means that once it is distributed it runs the risk of being exploited and appropriated by non-Indigenous peoples. Once TK is in non-Indigenous hands, it is in danger of commodification, where "newcomers learn the plant knowledge and then ask, "What money can I make from this knowledge?" (Gonzales 2020, p. 84). For example, Tribes in the Pacific Northwest traditionally used the Pacific yew tree as a medicinal aid for strength and wounds; when scientists discovered its anti-cancer properties (now synthesized into Taxol), interested pharmaceutical industries invested in harvesting it to the point of extinction, putting it on the endangered species list (Williams and Hardison 2013). Over-harvesting of yew

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trees is just one of many examples from the literature of what can happen when communally generated TK is shared, exploited, and misused.

One reason the risk of exploitation and misappropriation is so high is that proper standards for protecting Tribal data sovereignty are not in place. Tribal data sovereignty ensures that Indigenous Peoples have the right to control the collection, ownership, and use of data about their communities and lands (Kukutai 2023). Its historical roots come largely from international Indigenous-rights movements and scientific ethics: the 1988 Declaration of Belém in Brazil, at the First International Congress of Ethnobiology, marked an early formal recognition of Indigenous peoples' rights regarding their TK and resources (Posey and Dutfield 1996). By 2007, the UN Declaration on the Rights of Indigenous Peoples declared in Article 31 that: "Indigenous peoples have the right to maintain, control, protect and develop their cultural heritage, traditional knowledge and traditional cultural expressions" (UN General Assembly 2007, p. 22). Ensuring Indigenous Peoples have complete and independent ownership and control over their cultural and intellectual property is, first and foremost, necessary for protecting their intellectual property. Scientists and TK practitioners including Robin Wall Kimmerer and Dennis Martinez have spent most of their lives promoting ecological and cultural restoration while ensuring Indigenous ownership of data.

In the current legal system, individual knowledge is protected through vehicles such as patents. However, TK is generally regarded, from a legal perspective, more like a public good. While a few people, often Elders, are the stewards of TK, the assumption is that once TK is more broadly shared it is owned by many: Indigenous and non-Indigenous. Unlike statutory protections such as the Native American Graves Protection and Repatriation Act (NAGPRA), other forms of TK are not, by law, considered intellectual property (Gervais 2003). Intellectual property laws are largely designed to protect individual property rather than communal property, which is how TK is often characterized. The Western legal system does not uphold protections or intellectual property for a collectively created Indigenous story, which has no clear "owner"; and standards for scientific publishing do not attribute authorship rights to Indigenous ancestors (Gervais 2003).

Tribal intellectual property and data sovereignty can conflict with FAIR (findable, accessible, interoperable, and reusable) open-data requirements (which are increasingly common in scientific research); with public agencies' contractual data rights and intellectual property requirements; and with Public Records Act requirements. All of these which apply to the work of public agencies. One way to address these conflicts is to apply the CARE (collective benefit, authority to control, responsibility, and ethics) Principles for Indigenous Data Governance (Carroll et al. 2020; Jennings et al. 2023). This literature suggests Indigenous data-governance protocols should be written into contracts and agreements for projects that involve TK or Tribal Nations, ensuring Indigenous control, ownership, security, and access to data and data protocols (DSC 2024b).

Reforming Funding Structures

Traditional Knowledge relies on relational and experiential observations conducted over multiple lifetimes of Tribal observers (Dudgeon and Berkes 2003). These time-scales differ greatly from governmental-agency funding cycles, which typically span no more than 2 or 3 years. Additionally, the logistics and costs for the co-production of knowledge can be quite high, and science is almost always slower than usual when knowledge is co-produced (Thornton and Scheer 2012). Both predominant science and TK practitioners have been frustrated by these constraints that limit the investigation of long-term processes, including climate change and ecosystem restoration (Mason et al. 2012).

As of now, few solutions—beyond extending funding time-lines to accommodate the governance structure of Indigenous community partners—are obvious (Latulippe and Klenk 2020). However, grants that engage in co-production can and should focus on technical assistance and capacity-building for Tribes, with flexible and sustained funding opportunities that enhance Tribal-identified needs and interests (Jennings et al. 2023). Funding calls should apply the CARE Principles and could include sections that bring attention to the issues relevant to the needs of Indigenous communities that seek funding (Carroll et al. 2020).

Preserving and Using TK

US and Canadian boarding schools for Indigenous children actively suppressed and attempted to eliminate languages other than English (Turner et al. 2000). Against these odds, TK is often still expressed in Indigenous languages. The translation of concepts from Native languages into scientific terms is unlikely to fully capture the depth and nuances of the original knowledge. Indigenous languages often have specialized vocabulary and discourse associated with people's relationships with the land and each other (Kimmerer 2011). One researcher reflected that this was "exemplified in what is perhaps one of the most perplexing results of [our] research; there is no word or concept for "wildlife" in the Yurok language that has the same meaning as commonly used in the wildlife profession," because wildlife is not considered a resource that one can own (Ramos 2022, p. 18).

Literature suggests that agencies and scientists should engage in the preservation and use of Indigenous language whenever possible (Claire and Surprise 2022). Indigenous place names can serve as "conscious acts of cultural regeneration" (Louis 2004, p. 9), reconnecting Indigenous communities to their ancestral landscapes and traditions. For instance, place-based oral histories and place names in the language of the Yup'ik Indigenous Peoples of Alaska serve to reconnect its people to places (NSF Awards # 2032419, 1513438, 1231130, 0856634, and 0632345). The Atlas is part of a broader effort called Exchange for Local Observations and Knowledge of the Arctic (ELOKA) (*www.eloka-arctic.org*). This community-based research project partners with Indigenous organizations and researchers to manage, visualize, and share TK ethically, all while contributing to training, education, and leadership opportunities for Indigenous peoples.

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Many colleges and universities in California—including the University of California (UC) and California State University (CSU) systems—are also developing programs to train students in Indigenous methods like Traditional Fire Management (e.g., CSU–Chico's Wildland Management Program). Field trips, courses, or partnerships can be opportunities for non-Indigenous allies to visit Indigenous communities to listen, learn, and share knowledge through direct engagement. For example, California's Cache Creek Conservancy has a 2-acre Tending and Gathering Garden in Wintun homelands, which is a collaborative demonstration project of native and traditional land-management techniques (CCC c2025).

CONCLUSIONS

Interweaving knowledge systems requires respectful and trusting relationships, strengthened through transparency, accountability, and decision-making power. Relationships that start small may deepen and strengthen, especially if the collaborations reveal shared interests and advance mutually beneficial objectives through sustained partnerships (Simpson 2001). History has shown that trust is earned in droplets and lost in buckets. While there are many great projects and things to be learned from both sides, authentic relationship building is a long-term process (Mason et al. 2012; Craig 2021), so researchers and practitioners in this space should be fully committed. "Revitalizing our human connection and responsibility to this land" through a relationship-based approach is well understood by Tribes (Middleton Manning 2023, p. 149–150).

Community-based, participatory research methods are particularly promising approaches to interweaving that can foster relationships between research teams, Tribal collaborators, and their communities (Hoagland 2017; Ramos 2022). However, the insights gained by interweaving are indelibly situated in the co-production context and cannot be transferred or generalized outside the spaces and relationships in which they are generated (Whyte 2013; Latulippe and Klenk 2020). To avoid setting up expectations that lead to unethical appropriation or de-contextualization of TK, scientists should be aware of this before interweaving.

Scaling up from the interpersonal to the governance level, relationships start with government agencies that acknowledge federally recognized Tribes as sovereign governments. That said, we cannot ignore the voices of non-federally recognized Tribes either. Meaningfully including all Tribes early and often is important for building trusting, respectful relationships; we must strive to formalize TK as an equally valid way of knowing the world. In practice, this may mean pursuing governance processes such as co-management, which empower Tribes to use their TK to influence environmental policy and land management. In the Delta, interweaving is already underway for cultural burning, species management, and restoration, but more work remains.

Science has not solved the "wicked" problems of the Delta on its own (Zedler and Stevens 2018; Lee et al. 2024). Many Tribes have a long history of accumulating adaptive practices, tested by trial and error (Hosen et al. 2020); it will take more

than just one way of knowing at the table to invent, adapt, and experiment our way into a sustainable future for more than just humans. The time is ripe for scientists and managers in the Delta to heed this advice to forge not only a more sustainable future, but also a more just and equitable one.

POSITIONALITY STATEMENT

The team of researchers is composed of non-Indigenous scholars trained in the field of ecology and natural-resource management, embedded within the Delta Science Program at the Delta Stewardship Council. Our academic training in predominant science and professional experiences have contributed to our perspectives on TK and how it can be applied within land and watershed management. We acknowledge the privilege and responsibility inherent in our roles, as well as the limitations of our understanding of Indigenous ways of knowing. As researchers working within a colonial framework, we acknowledge the historical and ongoing impacts of colonization on Indigenous communities and their knowledge systems. Our research seeks to contribute to decolonizing practices for agencies involved in managing land, water, and wildlife by elevating TK as a valuable source of wisdom and insight. However, we recognize the importance of building reciprocal and respectful partnerships based on trust and mutual understanding. We acknowledge the complexities of colonial legacies, prioritize building equitable partnerships that center the agency of the Indigenous communities, and aim to honor Traditional Knowledge through this research.

ACKNOWLEDGEMENTS

We are deeply grateful for the contributions of others to developing the literature review including Grace Auringer, Allegra La Ferr, Sarah Hayroyan, Chris Klier, Karen Gutierrez, and Jennica Moffat. We would also like to thank Pascale Goertler, Dylan Chapple, Rachael Klopfenstein, Margot Mattson, Meenatchi Odaiyappan, Megan Nguyen, and others who do not want to be named whose comments have improved the quality of this manuscript. Finally, this work would not have been possible without Dr. Chelsea Batavia whose initial work in this area charted the path for this exploration and research. *The views and opinions expressed are those of the authors and do not necessarily reflect the views and opinions of the Delta Stewardship Council.*

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