Collaborative Knowledge Braiding for Restoration: Assessing Climate Change Risks and Adaptation Options at Wuda Ogwa in Southeastern Idaho, United States

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Running head: braided knowledge for climate-adapted restoration

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SK, WM, LC, DP, BP, SCK, MB, NH conceived the research; SK, WM, LC, TT, DP compiled focal species lists; WM, TT conducted vegetation surveys; SK analyzed data; SK, WM, SCK wrote the manuscript. All authors edited the manuscript.

Abstract

The restoration of culturally significant landscapes pose formidable challenges given more than 160 years of settler-colonial land use change and a rapidly changing climate. A novel approach to these challenges braids Indigenous and western scientific knowledge. This case study braids Indigenous plant knowledge, species distribution models, and climate models to inform restoration of the Bear River Massacre site in Idaho, now stewarded by the Northwestern Band of the Shoshone Nation. MaxEnt species distribution models were used to project the future spatial distribution of culturally significant plant species under medium (SSP2-4.5) and high (SSP5-8.5) emissions scenarios. These results support revegetation priorities and approaches, identified by tradeoffs between each species' current and future suitability. This research contributes to a knowledge-braiding approach of the analysis of climate risks, vulnerabilities, and restoration possibilities for Indigenous-led restoration projects by using the Wuda Ogwa ecological restoration site as a case study.

Key Words

Climate-adaptation, restoration, Indigenous, collaborative capacity, knowledge braiding, species distribution modeling

Implications for practice

- Advancing Indigenous-led climate adaptation efforts requires meaningful partnerships, interpersonal relationships, and built collaborative capacity to operationalize a knowledge "braiding" approach with Indigenous Knowledge and western scientific knowledge.
- Considering both the past and future suitability of culturally important species for Indigenous-led restoration efforts can create a prioritization scheme to weigh the most salient vegetation-outcomes against cultural values and contexts.

Introduction

Given global concern about biodiversity loss and a resurgence of Indigenous-led land and water restoration efforts, there are ethical and practical reasons to braid Indigenous and scientific ecological knowledge to manage land in ways that achieve conservation goals and support Indigenous sovereignty (Satterfield et al. 2013; Posner et al. 2016; Tengö et al. 2017). Braiding different types of knowledge can help affected parties reach legitimate, credible, and salient natural resource management practices (Kimmerer 2013; Posner et al. 2016; Reid et al. 2020). A growing number of case studies illustrate how to operationalize this knowledge braiding, particularly in the context of Indigenous-led restoration efforts in the American West (Reyes-García et al. 2019; McElwee et al. 2020; Marks-Block et al. 2021). Indigenous people have been an integral part of the American West landscape for thousands of years (Grayson 2011), and there are growing movements to reclaim management of their lands and food systems (Mihesuah & Hoover 2019; Dickson-Hoyle et al. 2022).

This project is a case study of co-producing actionable science to support an Indigenous-led restoration project that centers Indigenous history, sovereignty, and climate change vulnerabilities at a site situated in an agricultural matrix that reflects over a century of settler-colonist occupation. More than 150 years after the dispossession of their traditional winter camp, the Northwestern Band of the Shoshone Nation (NWBSN) acquired the land along the Bear River where, in 1863, more than 400 Shoshone were massacred by settlers and volunteers led by the US Cavalry (Parry 2019). The site of one of North America's most egregious massacres of Indigenous people will become a cultural and interpretive center where NWBSN tribal educators can share the tribe's history and restore the area as closely as possible to the habitat that existed at the site prior to the massacre. The Shoshone name of the site and subsequent ecological restoration project is Wuda Ogwa, meaning Bear River.

Vegetation in the Great Basin, a semi-arid cold desert in the interior western United States, had been relatively static since the Pleistocene Era (Nowak et al. 1994a, 1994b). However, land use and vegetation composition were altered when European settler-colonists arrived in the Great Basin in the 1850s (Young et al. 1972) and since then, the rate of change in land cover and condition has been unprecedentedly high (Miller & Wigand 1994; Grayson 2011). The introduction of cattle and sheep grazing (Belsky et al. 1999; Batchelor et al. 2015), combined with water diversion for agricultural and residential consumption (Sidle & Hornbeck 1991), beaver (*Castor canadensis*) extirpation (Gibson & Olden 2014), and introduced invasive riparian woody species, like Russian olive (*Elaeagnus angustifolia*; Katz 2016) has led to degradation of many riparian areas in the Great Basin (Macfarlane et al. 2017).

The ancestors of Northwestern Shoshone interacted with and moved on the landscape in a seasonal pattern: fishing for salmon, hunting large ungulates, and gathering pines nuts and grass seeds (Parry 2019). The Wuda Ogwa site was a permanent wintering home of the Northwestern Shoshone. The land along the Bear River provided hot springs, plentiful fish and game, and willows that served as wind and snow breaks during the winter months. Settler colonialism degraded Shoshone food sources and seasonal movement and this conflict resulted not only in the Bear River Massacre, but significant ecological impacts to the landscape ecology such as habitat connectivity, beaver extirpation, introduction of invasive annual grasses and the associated altered fire regimes that remain to this day. Restoration that restores riparian function and vegetation diversity provides ecosystem services at short time scales also supports long-term resilience in the face of changing climate (Falk 2017). As such, restoration can be a climate adaptation strategy (Falk 2017; Simonson et al. 2021) but restoring a site for climate adaptation requires an understanding of the potential local impacts of climate change on the long-term success of restoration (Simonson et al. 2021).

The goal of the NWBSN's Wuda Ogwa restoration project is to create a site that looks and feels like pre-massacre conditions while empowering NWBSN members to reconnect with their land and culture. While the NWBSN was violently dispossessed of their land for generations, their presence and stories persist and reflect strong connections to the land (Parry 2019; R. Pacheco 2022, NWBSN, personal communication). Caring for and restoring the land at Wuda Ogwa is an opportunity for reciprocal restoration:

> *"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"* (Kimmerer 2011).

In ecological restoration, the "reference site" is a goal state upon which restoration success is based (Clewell et al. 2013). In this study, the reference site is pre-massacre and pre-colonization site conditions. However, the reality of the site conditions (the surrounding matrix of development, highways, and agriculture) and emphasis on reciprocal restoration and cultural connection require more consideration than this simple definition of a reference site. Borrowing terminology from Aronson et al. (1993), restoration *sensu stricto* aims to emulate the structure, functioning, diversity, and dynamics of a given site, which is not possible at Wuda Ogwa given site disturbances and developed environs. Restoration at Wuda Ogwa is guided by the alternative framework to *sensu stricto*, which is *sensu lato* (Aronson et al. 1993). *Sensu lato* restorationseeks to "simply" stop degradation and redirect a degraded site's trajectory towards a goal state that was presumed to have prevailed prior to disturbance, with less focus on ecosystem structure and function. An additional consideration paid to the goal state at Wuda Ogwa is the reality of a changing climate and the need to incorporate current knowledge about how global ecosystems are responding to climate change (Pörtner et al. 2022) to plan and design a more resilient restored site. Additionally, a “successful” restoration at Wuda Ogwa may appear different from a “conventional” restoration project because of the values-laden success criteria for the restoration of Wuda Ogwa: a multi-part goal that balances and incorporates ecological integrity, cultural revitalization, and critical historical storytelling.

The challenge for the Wuda Ogwa site is to establish a culturally meaningful landscape considering more than 160 years of land use change and a changing climate. This case study describes a transdisciplinary approach that braids Indigenous knowledge, contemporary restoration practice, and models of future climate into a risk analysis for NWBSN leadership as they work to create a climate-adaptive stewardship plan. Species distribution models (SDMs) project the anticipated impact of climate change on the distribution of culturally important species and can inform which native species may be successful under two future climate change scenarios (2061-2080, the longest-range CMIP6 projections) to identifythe range of risk. By identifying which species are most at risk from climate change and how future suitability differs from historic suitability, we provide unique and actionable information to support the NWBSN in devising a restoration plan to address these risks and uncertainties. More broadly, and uniquely in the literature, we offer a case study for how ecologists and restoration practitioners can support Indigenous knowledge and goals to collaboratively apply modeling approaches that support long-term stewardship of land and water.

Methods

We formed a team of NWBSN leaders, academic researchers, and restoration practitioners that collaborated to braid Indigenous knowledge, contemporary restoration science, and climate modeling to inform restoration of the Wuda Ogwa site. The team reviewed NWBSN archives, oral histories, and ethnobotanical collections to understand the pre-colonial ecology and ethos of the Wuda Ogwa site. Two of the co-authors are leaders of the NWBSN, one is a private-sector restoration practitioner, and the other members of the team are part of the Climate Adaptation Science program at Utah State University. Our team repeatedly met with NWBSN leadership to understand the goals for restoration at this site and to learn about tribal history. We also conducted a review of local environmental histories, archeological site reports, and a geomorphologic reconstruction of tributaries on the site. We used these knowledge sources to identify key plant species and historical geomorphology. These plant species were analyzed using species distribution models to anticipate which plants are most likely to experience increases, no change, or decreases in habitat suitability under future climate scenarios.

Identification of Existing and Future Conditions

The first step in restoration is explicitly stating the goal (Meffe & Carroll 1997). NWBSN leadership's goal was to "restore the site to pre-massacre conditions while thinking of climate change impacts." In doing so, NWBSN restores their relationships with their traditional territories by creating a *sensu lato* restored system (Aronson et al. 1993) that evokes the ethos of pre-colonization and pre-massacre conditions.

The Wuda Ogwa site is in southeastern Idaho in northern Cache Valley, at the edge of the Northern Basin and Range Ecoregion (Omernik & Griffith 2014). The site receives 427 mm of precipitation on average, falling primarily as snow in the winter, with annual mean monthly temperature of 8.1°C (1991-2020 30-year normals; (PRISM Climate Group 2014). The site is embedded in a mosaic of privately owned lands, irrigation canals, and powerlines. The built environment around the site is a legacy of the more than 160 years since colonists began settling the valley. Wuda Ogwa is divided into two main areas: an upland area with loamy and sandy soils and a semi-wet meadow with a seasonally shallow water table (Fig. 1; Soil Survey Staff USDA-NRCS 2022). Wuda Ogwa is located at the confluence of the Bear River and Battle Creek where oral history and geomorphic reconstruction identifies a historical alluvial fan characterized by willow habitat, anabranching dynamic channels, and semi-wet meadows. Currently, Battle Creek carries high sediment loads and hasinvasive species populated banks (tamarisk [*Tamarisk ramosissima*] and Russian olive)and it is channelized along a highway to its confluence with the Bear River. Vegetation was surveyed using a combination of unmanned aerial vehicles (UAV) and field verification by BIO-WEST, Inc., between August 18 and September 16, 2021. A DJI Phantom 4 RTK UAV with a 1-inch CMOS sensor was flown at an average elevation of 60 m above ground level. The imagery was post-processed with Aerotas software (Aerotas 2018). After vegetation communities were identified from the imagery, a field crew mapped the outer perimeter of the communities, which were delineated based on the dominant species present according to the United States National Vegetation Classification Standard (Jennings et al. 2009).

Our primary source of Indigenous ecological knowledge was publications from Shoshone elders (Parry 2019, R. Pacheco 2022, NWBSN, personal communication). This knowledge included oral history, descriptions of where culturally important plants were traditionally found, how those plants were used, how some were harvested, and their Shoshone names. Some Shoshone descriptions of plants present and used pre-colonization (see Parry 2019) did not include grass species, which are a critical ecosystem component in the Great Basin (Pyke et al. 2002).Grasses were conceptualized by Northwestern Shoshone as a taxonomic group but were not specified to genera and species in written and oral histories (Spykerman 1977). We used records of vegetation composition in Cache Valley at the time of colonization (Hull & Hull 1974; Hansen 2013) for specific grass species.

Species Distribution Models Under Climate Scenarios

We used species distribution models (SDMs) to identify the impact of climate in 2070 on the species identified as culturally important (Spykerman 1977, Parry 2019, R. Pacheco 2022, NWBSN, personal communication) and present at the time of colonization (Hull and Hull 1974, Hansen 2013). These SDMs model how suitable the habitat at Wuda Ogwa is for each species under historic climate normal and climate change scenarios, allowing land managers to incorporate suitability into restoration planning. The models (MaxEnt; *dismo* Hijmans et al. 2017) were created using downloaded presence data from the Global Biodiversity Information Facility (http://www.gbif.org/). These observations were cleaned to remove observations with coordinate uncertainty greater than 1000 m and observations with coordinates within two kilometers of known herbaria using the R package *CoordinateCleaner* (Zizka et al. 2019). We used the 19 bioclimatic variables from the WorldClim version 2.1 data from historic 30-year normals (1970-2000; Fick & Hijmans 2017) and projected data for 2061-2080 under two emissions pathways (SSP; shared socio-economic pathways) in the most recent Coupled Model Intercomparison Project 6 (CMIP6; Wyser et al. 2020). We used SSP2-4.5, representing a “lower”, “better-case” emissions scenario and SSP5-8.5, representing a “higher”, “worse-case” emissions scenario at 2.5 minute resolution. We used EC-Earth3-Veg multi-model ensemble because it is among the best-performing CMIP6 models in North America with the finest spatial resolution (Almazroui et al. 2021). MaxEnt uses maximum entropy to estimate a species niche and spatial distribution using presence-only data, is easy to use, and produces robust results with sparse, irregularly sampled data (Elith et al. 2011). We corrected for sampling bias inherent in presence-only datasets using bias files (Fourcade et al. 2014) and pseudo-absences (Hijmans 2012). We averaged historic and future suitability values over the Cache and Malad Valleys EPA Level IV Ecoregion (Omernik and Griffith 2014).

We withheld 20% of observations to check model validity and all models were well fit (Table 1). An AUC score of 0.5 means that the model correctly classifies known presences with 50% accuracy, while an AUC score of 1 means that a model always correctly classifies presences, and an AUC score of 0 means the model never classifies presences correctly. There are criticisms of using AUC as the sole statistic, but it remains the most common means for measuring model performance (Lobo et al. 2008; Jiménez-Valverde et al. 2013).

We defined suitability based on four suitability classes used by Khafaga et al. (2011) and Remya et al. (2015): very low (< 0.1), low (0.1-0.4), medium (0.4-0.6), or high (0.6), based on mean pixel value within the Cache and Malad Valleys EPA Level IV Ecoregion. We classified changes in suitability between historic (1970-2000) and future conditions (SSP2-4.5 and SSP5-8.5 for 2061-2080) in four categories: no change-high/medium suitability, decreasing suitability, increasing suitability, no change-low/very low suitability. Species in the no change-high/medium and no change-low/very low categories were in the same suitability class between the historic and SSP5-8.5 SDMs; species in the increasing suitability and decreasing suitability categories increased or decreased suitability classes, respectively, between historic and SSP5-8.5 scenarios. Data and code are available at https://doi.org/10.4211/hs.8aa14e6af1fc4f8e89d325f55c08bcb7 (Koutzoukis et al. 2024).

Results

Indigenous and Settler Historical Records

Historical records, oral histories, and geomorphic reconstructions provide evidence of dramatic changes in site conditions. Settler maps drawn after the massacre, as well as geomorphic reconstructions, show that the channels of the Bear River and Battle Creek have shifted (Reid et al. 2017). Battle Creek historically meandered through the semi-wet meadow and met the Bear River far less directly than the currently shunted and incised channel.

Vegetation surveys revealed that some of the desired species are currently present in the site and surrounding watershed (Fig. 1). There are remaining populations of culturally important species. One of the ways we compared Indigenous knowledge and western science can be shown in the names of the species. The Northwestern Shoshone will often refer to all species of a lifeform or variety using just one name, whereas western sciences has several names for the types of plants on-site; for example Bah-sa-vee refers to both Fremont cottonwood (*Populus fremontii*) and narrow leaf cottonwood (*Populus angustifolia*). We include all known Shoshone names for the focal plant species (Table 1) The focal species currently found on site are: milkweed “San-Ah-Koo” (*Asclepias speciosa*), grey alder “Hoo-Zah-Ve” (*Alnus incana*), coyote willow “Su-He-Vee” (*Salix exigua*), peach leaf willow “Se-He-Ve” (*Salix amygdaloides*), Bebb’s willow “Se-He-Ve” (*Salix bebbiana*), yellow willow “Se-He-Vee” (*Salix lutea*), Fremont cottonwood “Bah-sa-vee”, narrow leaf cottonwood “Bah-sa-vee” , chokecherry “Do-nahm-bee”

(*Prunus virginiana*), Woods' rose "Tsia-Pin" (*Rosa woodsii*), and skunkbush sumac "Ittse-Ppeh" (*Rhus trilobata*).

In addition to Indigenous plant knowledge and UAV surveys, we examined local historical documents to compile an integrated plant palette for restoration (Table 1). In Cache Valley in the 1860s, settler-colonists describe grass "taller than a man" in places and in such abundance that livestock were grazed in the foothills in the summer and fed on cured grasses throughout the winter (Hansen 2013). The most abundant grasses included bluebunch wheatgrass (*Pseudoroegneria spicata*), followed by thickspike wheatgrass "Pia Soni-Ppeh" (*Elymus lanceolatus*), Great Basin wild rye "Pia Soni-Ppeh" (*Leymus cinereus*), and western wheatgrass (*Pascopyrum smithii*; Hull & Hull 1974). In sandier soils, the most common grasses were Indian ricegrass "Wye" (*Achnatherum hymenoides*), needle and thread (*Hesperostipa comata*), and sand dropseed (*Sporobolus cryptandrus*; Hull & Hull 1974).

Species Distribution Modeling

Under current conditions, most species have medium and high suitability at Wuda Ogwa (Table 1). The species expected to see no change in suitability between historic and future conditions, with suitability staying high or medium, are four forbs (common milkweed "San-Ah-Koo" [*Asclepias speciosa*], common yarrow "Patontsia" [*Achillea millefolium*], field mint "Pakwana" [*Mentha arvensis*], sego lily "Sikoo" [*Calochortus nuttallii*]), one grass (Great Basin wild rye), and one shrub (Wyoming big sagebrush "Poho-pin" [*Artemisia tridentata* ssp. *wyomingensis*]; Table 1, Fig. 2). The forbs and sagebrush are culturally important species and Great Basin wild rye was likely present in the 1860s in Cache Valley (Hull and Hull 1974). The species with no change in suitability between historic and future conditions, where suitability stayed low or very low, and are culturally important plants (Parry 2019): two forbs (bitterroot

“Gana” [*Lewisia rediviva*], camas “Pasikoo” [*Camassia quamash*]) and two woody species (Bebb’s willow, yellow willow; Table 1, Fig. 2). While mean suitability changes between SSP2-4.5 (lower) and SSP5-8.5 (higher) emissions scenarios, under both emissions scenarios, all species, except bitterroot, were in the same suitability class. Bitterroot suitability was low under SSP2-4.5 scenarios and very low under SSP5-8.5 scenarios (Table 1).

Most species were expected to experience a change in suitability between historic and future conditions. We found increasing suitability between historic and SSP5-8.5 scenarios for three grasses (Indian ricegrass, needle and thread, sand dropseed), all identified by Hull & Hull (1974) and five tree and shrub species, all culturally important species (coyote willow, Fremont cottonwood, peachleaf willow, skunkbush sumac, Utah serviceberry; Fig. 2, Table 1). We found decreasing suitability for two forbs, both of which are culturally important (arrowleaf balsamroot “Kusi Akken” [*Balsamorhiza sagittata*], yampah “Yampah” [*Perideridia gairdneri*]); four grass and grass-like species, two of which are culturally important (cattail [*Typha latifolia*], horsetail “Sebu” [*Equisetum hyemale*]) and two of which were historically found in Cache Valley (bluebunch wheatgrass, thickspike wheatgrass); and five culturally important shrubs and trees (grey alder, aspen “Senkapin” [*Populus tremuloides*], chokecherry, narrowleaf cottonwood “Bah-Sa-Vee" [*Populus angustifolia*], Woods’ rose; Fig. 2, Table 1). Bluebunch wheatgrass, chokecherry, Indian ricegrass, needle and thread, sand dropseed, coyote willow, Fremont cottonwood, peachleaf willow, and skunkbush sumac stayed in the same suitability class under both emissions scenarios (SSP2-4.5, SSP5-8.5; Table 1). For the species with different suitability classes between emissions scenarios (arrowleaf balsamroot, yampah, cattail, thickspike wheatgrass, grey alder, aspen, narrowleaf cottonwood, Wood’s rose, and Utah serviceberry “Team-Pih” [*Amelanchier utahensis*]) suitability was typically lower under SSP5-8.5 than SSP2-

4.5. Utah serviceberry is the exception to this pattern, with medium suitability under SSP2-4.5 and high suitability under SSP5-8.5 (Fig. 2).

Discussion

The knowledge-braiding research approach we used supports the design of a plant palette for cultural revitalization, ecosystem restoration, and climate resilience. Understanding the sensitivity of each species to historic conditions and site-specific climate change supports NWBSN leadership and restoration partners to allocate resources and deploy techniques to increase establishment and persistence.

Possible outcomes in habitat suitability

Species distribution modeling under historic and future climate elucidates four pathways to establishment with different tradeoffs between initial effort required for establishment and future persistence: (1) no change-high/medium suitability, (2) decreasing suitability, (3) increasing suitability, (4) no change-low/very low suitability. Conventional approaches to climate-informed restoration plans typically seek to identify species in the first category: no change-high/medium suitability (Padonou et al. 2015; Butterfield et al. 2017; Duarte et al. 2019). These species are sought-after because they are, based on historic suitability, easier to establish and based on future suitability, are likely to persist. The establishment of the species in this category may be relatively easy to achieve at Wuda Ogwa because they are currently on-site (milkweed), have weedy tendencies (yarrow, field mint), or establish at high rates under specific restoration techniques (sagebrush, Great Basin wild rye). For example, planting sagebrush seedlings rather than seeds results in higher establishment rates (Brabec et al. 2015) and transplanting field-collected small sagebrush results in even higher establishment rates than transplanting greenhouse-grown seedlings (Bailey et al. 2024). Selecting octoploid varieties of Great Basin wild rye may lead to higher survival rates with greater trait variation than tetraploid varieties (Johnson & Vance-Borland 2016).

Understanding which species fall into the second and third categories- increasing and decreasing suitability- allows restoration practitioners and collaborators to better allocate resources over time. A "triage" approach to climate change conservation planning prioritizes establishing species that will persist at a given site under climate change scenarios but if that is not possible, intensive efforts should be taken at a given site to maintain current population sizes (Gilbert et al. 2020). Intensive efforts could be taken to first establish and maintain species with decreasing suitability by taking advantage of a still-favorable climate, then shifting to focus on establishing species with increasing suitability as the climate becomes more suitable. Cottonwood establishment is one example of operationalizing this triage approach at Wuda Ogwa while understanding and incorporating Shoshone conceptualizations of plant relationships. Narrowleaf cottonwood, for example, was expected to have low suitability at Wuda Ogwa under SSP5-8.5 but had high historic suitability and is currently on-site. It can have high survival rates when transplanted from commercially-grown cuttings (Clary et al. 1996), but is prone to drought-induced mortality (Tyree et al. 1994). Intensive efforts could be taken now to protect the remaining populations and establish a large population of narrowleaf cottonwood from cuttings by planting this species and supplementing water as necessary. Then, efforts can shift to establishing Fremont cottonwood, a species expected to have future increases in suitability.

The example of narrowleaf and Fremont cottonwood is an example of how Indigenous Knowledge and understandings of Shoshone plant associations can be braided with western restoration practice. We identified how CMIP6 projections can be used to evaluate suitability, but suitability alone is irrelevant without being couched in the cultural relevance to NWBSN. Narrowleaf and Fremont cottonwood are both Bah-Sa-Vee in Shoshone, referring in general to deciduous trees, used mostly for firewood (Spykerman 1977). Planting both, at different times, allows for continuous cultural use and relevance for NWBSN. Similarly, most grass species have the same Shoshone name, with the suffix "ppeh", referring to low-growing green plants that are not shrubs or trees (Spykerman 1977). While thickspike wheatgrass had decreasing suitability, Great Basin wild rye had increasing suitability. Both grass species are Pia Soni-Ppeh in Shoshone. Investing in establishing Great Basin wild rye may yield more established plants for the same investment as establishing thickspike wheatgrass, with a similar cultural use and utility.

In response to the climate change risks to riparian species like narrowleaf cottonwood, process-based restoration (PBR) techniques based around restoring processes capable of sustaining complex and healthy river ecosystems (Norman 2020; Jordan & Fairfax 2022; Skidmore & Wheaton 2022) can serve as proactive adaptation actions. Pre-colonization, beavers were an integral ecosystem engineer whose extirpation, in combination with the development of the highway next to Wuda Ogwa, likely led to the degradation of Battle Creek, the small tributary that meets the Bear River at Wuda Ogwa. However, local ranchers and producers are, for the most part, opposed to beaver reintroduction at Wuda Ogwa (Stocker 2021). PBR encompasses a range of stream rehabilitation practices typically initiated by the introduction of structural elements, like in-channel large woody debris capable of altering flow, beaver dams, beaver mimicry structures, and rock retention structures which are increasingly used to restore degraded streams in the Great Basin because of their relative cost-effectiveness and can act as a reservoir for surrounding vegetation, offsetting the negative effects of seasonal and longer-term drought (Fairfax & Small 2018; Pilliod et al. 2018; Norman 2020). Additionally, applying the ethic of process-based restoration and a plural knowledges approach including both traditional place-based knowledges and practices alongside scientific tools allows for a more complete and sustainable restoration approach (Brierley et al. 2023).

The last category, where suitability was historically low and will stay low, presents a challenge to the restoration of culturally important species to the NWBSN. Indigenous restoration practices can differ from Western restoration practices in their focus on “cultural keystone species" (Turner 2008; Kimmerer 2011), even if those species have low or declining suitability. Culturally important species like camas and bitterroot were identified as having low suitability at Wuda Owga. While NWBSN food harvest knowledge and oral histories suggest that camas and bitterroot were never part of the major food harvest at Wuda Owga, if their suitability was higher, there was interest from the NWBSN in establishing populations at Wuda Owga given the *sensu lato* restoration goal. However, the model results suggested that bitterroot and camas will be extremely difficult to establish and maintain at Wuda Owga and as such, NWBSN have chosen to prioritize the establishment of other species with greater suitability and and protecting the other species with low historic and future suitability that are already on-site (Bebb’s and yellow willows).

Incorporating uncertainty into revegetation planning

There is uncertainty in the future suitability of the species we have identified because of inherent model uncertainty and because the likelihood of SSP scenarios depends on collective action that could reduce or exacerbate the effects of climate change (Lemos & Rood 2010), especially imporant given that all species (but bitterroot) had lower suitability under SSP5-8.5 (the “worse-case” scenario) than under SSP2-4.5 (the “better-case” scenario). Incorporating risk-spreading or bet-hedging approaches to revegetating Wuda Ogwa may make the site more resilient to the many unknowns of climate change. Two potential risk-spreading approaches to mitigate the uncertainty of future SDM outcomes are planting diverse genotypes and diverse vegetation types, including those that engineer the local environment by providing shade. Planting multiple cultivars, varieties, or source populations of a given species can act as a bet-hedging strategy by facilitating capacity for adaptation to future climate conditions (Kettenring et al. 2014; Cochrane et al. 2015; Bucharova et al. 2019). Rather than establishing more individuals with genotypes that may not confer survival in a changing climate, blending multiple sources of genotypes, through for instance, using propagules collected on-site, from other similar sites, and from warmer, drier sites, may increase both initial establishment and future adaptive capacity and persistence (Bucharova et al. 2019).

Incorporating vegetation that produces shade can improve establishment and persistence, affecting both immediate and long-term outcomes. In addition to their cultural value, larger woody species provide shade for understory plants and increase establishment and survival by increasing soil moisture (Liu et al. 2021). Shade provided by woody plants can facilitate seedling emergence and growth (Callaway 1992; Semchenko et al. 2012). Over longer time-frames, shade at the microsite scale can mitigate the effects of a future warmer and drier climate (Pausas & Bond 2021). Operationalizing this at Wuda Ogwa, under the framework of historic versus future suitability, could mean prioritizing the establishment of woody species that have medium suitability that is expected to increase, like Utah serviceberry, to create a shaded canopy that would persist into the future, and then planting co-occurring species with decreasing or low suitability, like yampah, underneath those woody species.

Braiding knowledge for restoration: addressing adaptive capacity

Cost-benefit tradeoffs are strongly influenced by cultural and societal values, and centering those values is critical to positive, salient outcomes of collaborative, braided projects such as Wuda Ogwa where costs and benefits are both cultural and financial (Choy 2018). The results from the SDMs present actionable science that the NWBSN can use to consider how to allocate resources accordingly to establish culturally important species. Planning and planting decisions ultimately reflect the values and priorities of the NWBSN, like the decision to not establish camas and bitterroot. While conventional restoration projects may ignore species with low suitability, the cultural value to NWBSN may justify the investment towards species with low suitability but high cultural value.

A growing body of literature describes the need and practice of engaging different knowledges to support ecological restoration. From knowledge braiding (Kimmerer 2013), two-eyed seeing (Smith et al. 2023), walking on two legs (Dickson-Hoyle et al. 2022), knowledge co-production (Norström et al. 2020), and knowledge weaving (Tengö et al. 2017), several emergent frameworks provide ways of conceptualizing and carrying out this complicated task. Incorporating diverse knowledge systems is increasingly recognized as important for creating robust restoration plans that support Indigenous sovereignty, goals, and improved restoration outcomes. The Wuda Ogwa case study fills a large gap in this body of literature by providing an example of how to center Indigenous knowledge sources of autecology, ecology, and history to better understand how potential restoration designs can address Indigenous goals amidst a changing climate. This work aims to support restoration managers as they work to adapt a culturally critical site to future climate risk by anticipating which species are more likely to thrive as the climate changes and creating revegetation plans to match anticipated future environments.

The urgency of reviving damaged ecosystems globally is highlighted in the UN designation of 2020-2030 as the decade on ecosystem restoration, which many argue will be more successful using explicitly social-ecological rather than only ecological approaches (Fischer et al. 2021). Insights from our social-ecological methods at Wuda Ogwa are relevant at a global scale. Our project highlights the critical need to build trust across an Indigenous group, restoration practitioners, and scientists. This trust is fundamental for enabling context-specific Indigenous ecological knowledge to inform climate adapted restoration efforts. We also seek to emphasize the need for restoration project participants to recognize not only the historical context but also intergenerational nature of restoration. Honoring Indigenous knowledge and leadership was also key to this project's success and we see this as fundamental for many restoration projects globally.

Braiding together history and knowledge from the NWBSN with settler-colonist records informed the focal plant species for species distribution and climate modeling. While species distribution modeling provides unique insight into long-term ecological risk, putting that information into action leads to additional considerations for Indigenous-led climate adaptation practice. In a recent Bureau of Indian Affairs and US Geological Survey report (Avery et al. 2022), Indigenous climate resilience leaders identified a lack of consistent funding, Tribal staff capacity, and shared perspectives on climate change as main issues facing Tribes as they build adaptive capacity for climate resilience. The report identified successful adaptation efforts as benefiting from diverse sources of expertise, community buy-in, and communicating adaptation planning efforts. As the NWBSN leads a multi-partner team to plan and implement the Wuda

Ogwa project, attention to how modeled ecological risk is translated into on-the-ground implementation practice will further provide insight into how a knowledge braiding approach to climate adaptation might further address these wider challenges.

Acknowledgements

Thanks to the many people involved in restoring Wuda Ogwa including Northwestern Band of Shoshone Nation elders, staff, and tribal council, BIOWEST Inc., Hansen, Allen & Luce, Trout Unlimited, and the Wildlife Conservation Society. Thanks to Britta Schumacher for additional help with data analysis. This project was supported by the National Science Foundation under Grant No. 1633756.

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Tables

Table 1: List of candidate restoration species for Wuda Ogwa identified by tribal history (Culturally Important.) or settler-colonist records (Historical Records). Shoshone names are included when available (Spykerman 1977; D. Parry, NWBSN, personal communication, 2023). Model area under the curve (AUC) was used to evaluate model accuracy.

Suitability Class	Functional Group	Species			Source	Model AUC
No Change-High/Medium Suitability	Forbs	Common milkweed	*Asclepias speciosa*	San-Ah-Koo	Culturally Important	0.92
		Common yarrow	*Achillea millefolium*	Patontsia	Culturally Important	0.87
		Field mint	*Mentha arvensis*	Pakwana	Culturally Important	0.85
		Sego lily	*Calochortus nuttallii*	Sikoo	Culturally Important	0.95
	Grass and Grasslike	Great Basin wild rye	*Leymus cinereus*	Pia Soni-Ppeh	Historical Records	0.94
	Shrubs and Trees	Wyoming big sagebrush	*Artemisia tridentata*	Poho-pin	Culturally Important	0.95
Decreasing Suitability	Forbs	Arrowleaf balsamroot	*Balsamorhiza sagittata*	Kusi Akken	Culturally Important	0.97
		Yampah	*Perideridia gairdneri*	Yampa	Culturally Important	0.97
	Grass and Grasslike	Bluebunch wheatgrass	*Pseudoroegneria spicata*		Historical Records	0.93
		Cattail	*Typha latifolia*	Toih-Ppeh	Culturally Important	0.88
		Horsetail	*Equisetum hyemale*	Sebu	Culturally Important	0.88
		Thickspike wheatgrass	*Elymus lanceolatus*	Pia Soni-Ppeh	Historical Records	0.88
	Shrubs and Trees	Grey Alder	*Alnus incana*	Hoo-Zah-Ve	Culturally Important	0.92
		Aspen	*Populus tremuloides*	Senkapin	Culturally Important	0.92
		Chokecherry	*Prunus virginiana*	Do-Nahm-Bee	Culturally Important	0.88

		Narrowleaf cottonwood	*Populus angustifolia*	Bah-Sa-Vee	Culturally Important	0.98
		Wood's rose	*Rosa woodsii*	Tsia-Pin	Culturally Important	0.89
Increasing suitability	Grass and Grasslike	Indian ricegrass	*Achnatherum hymenoides*	Wye	Historical Records	0.89
		Needle and thread	*Hesperostipa comata*		Historical Records	0.88
		Sand dropseed	*Sporobolus cryptandrus*		Historical Records	0.83
	Shrubs and Trees	Coyote willow	*Salix exigua*	Su-He-Vee	Culturally Important	0.92
		Fremont cottonwood	*Populus fremontii*	Bah-Sa-Vee	Culturally Important	0.95
		Peachleaf willlow	*Salix amygdaloides*	Se-He-Ve	Culturally Important	0.93
		Skunkbush sumac	*Rhus trilobata*	Ittse-Ppeh	Culturally Important	0.93
		Utah serviceberry	*Amelanchier utahensis*	Team-Pih	Culturally Important	0.95
No Change-Low/Very Low Suitability	Forbs	Bitterroot	*Lewisia rediviva*	Gana	Culturally Important	0.96
		Camas	*Camassia quamash*	Pasikoo	Culturally Important	0.98
	Shrubs and Trees	Bebb's willow	*Salix bebbiana*		Culturally Important	0.91
		Yellow willow	*Salix lutea*	Se-He-Vee	Culturally Important	0.92

Figures

Fig. 1: Map of current vegetation communities at Wuda Ogwa classified based on the dominant species present according to the United States National Vegetation Classification Standard (Jennings et al. 2009).

Fig. 2: Mean historic (1970-2000) and future (2061-2080) suitability under SSP2-4.5 and SSP5-8.5 scenarios within Cache and Malad Valleys ecoregion for species recognized as culturally important to the Northwestern Band of the Shoshone Nation or identified in historical records as present in the region. Points indicate mean and error bars indicate 95% confidence intervals for all pixels (2.5 minute resolution) in the Cache and Malad Valleys EPA Level IV Ecoregion. Suitability classes are as follows: < 0.1 very low suitability, 0.1-0.4 low suitability, 0.4-0.6 medium suitability, > 0.6 high suitability.