



Restoring a forest keystone species: A plan for the restoration of whitebark pine (*Pinus albicaulis* Engelm.) in the Crown of the Continent Ecosystem

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ABSTRACT

The precipitous decline of the keystone species whitebark pine (*Pinus albicaulis* Engelm.) has resulted in dramatic changes to many high elevation ecosystems in the western U.S. and Canada. To restore these ecosystems, there is a need to establish populations of whitebark pine that will persist in the face of both natural and anthropogenic disturbances (e.g. climate change, white pine blister rust [*Cronartium ribicola* J.C. Fisher]). The listing of whitebark pine as endangered in Canada and its recent proposed listing as threatened in the U.S. reinforce the urgency of the need to act. This paper presents a six-step methodology for whitebark pine restoration planning in a GIS environment, that was developed as a pilot on a 5-million-acre (2-million-hectare) subset of the Crown of the Continent Ecosystem (CCE). The methodology synthesizes the best available datasets and science into a flexible, data-informed decision-making process that can be applied consistently across large geographic areas. The end-product is an action plan that guides implementation of treatments with a high likelihood of success at an appropriate scale to address the enormous need for restoration. The methodology begins by mapping where whitebark is capable of existing, then quantifies the priority conservation values it provides, the stressors affecting those conservation values, and how those stressors could affect the likelihood of restoration treatment success. Based on those results, priority core areas for restoration are identified. Finally, a restoration plan assigns and prioritizes site-specific actions that protect and restore genetically diverse, evolutionarily stable populations of whitebark pine that are well-distributed across the area of interest. This methodology can be scaled up as demonstrated by its use to identify core areas in Region 1 of the USDA Forest Service. It can also be applied to other species as demonstrated by the addition of limber pine (*Pinus flexilis* James) when the methodology was used to develop a restoration strategy for the full 18-million-acre (7-million-hectare) CCE (Summary Report in progress).

Abbreviations: CCE, Crown of the Continent Ecosystem; CSKT, Confederated Salish and Kootenai Tribes; CV, Conservation Value; FNF, Flathead National Forest, USDA Forest Service; GNP, Glacier National Park, USDI Park Service; MPB, Mountain Pine Beetle; N_e, Effective Population Size; NWPRP, National Whitebark Pine Restoration Plan; Tech Team, High Five Working Group Technical Team; WBP, Whitebark Pine; WPBR, White Pine Blister Rust.

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1. Introduction

Restoration planning is a cornerstone of implementing actions to conserve and restore threatened and endangered species, and species whose existence or habitat are in jeopardy (Canada Species at Risk Act, 2002; U.S. Endangered Species Act, 1973). Restoration plans provide an outline of the site-specific treatments required to restore self-sustaining populations.

Establishment of evolutionarily stable populations that are self-sustaining is an important goal in many restoration plans (Frankham et al., 2014). When the number of individuals in a population becomes too low, inbreeding can lead to a downward spiral of reduced genetic diversity (Frankham et al., 2017; Tomback and Kendall, 2001). While the term “population” is commonly used in restoration plans, it often lacks a definition that is well-quantified (e.g. Aubry et al., 2008; Greater Yellowstone Coordinating Committee, 2011; Perkins et al., 2016). The quantification of evolutionarily stable population goals for genetic diversity, size, distribution, and connectivity, is necessary to adequately determine whether a restoration plan can meet its objective of species restoration, and to effectively guide restoration planning and actions.

Restoration planning is urgently needed for whitebark pine (WBP; *Pinus albicaulis* Engelm) due to its dramatic range-wide decline caused by a combination of mountain pine beetle (MPB; *Dendroctonus ponderosae* Hopkins), effects of fire suppression, and the nonnative pathogen *Cronartium ribicola* J.C. Fisher, which causes white pine blister rust (WPBR), all of which have the potential to be exacerbated by climate change (Keane et al., 2017b; U.S. Fish & Wildlife Service, 2020). This decline has led to WBP being listed under the Species at Risk Act in Canada (Government of Canada, 2019) and to its recent proposed listing under the Endangered Species Act in the U.S. (U.S. Fish & Wildlife Service, 2020). The decline has also spurred a U.S. range-wide planning effort; the National Whitebark Pine Restoration Plan (NWPRP) (Tomback and Sprague, 2022; Whitebark Pine Ecosystem Foundation, 2018).

WBP is a foundation and keystone species at high elevations in the western U.S. and Canada (Tomback et al., 2001; Tomback and Achuff, 2010) and its loss would lead to cascading ecosystem changes (Tomback and Kendall, 2001). WBP provides a host of ecological functions, including regulation of snowmelt and streamflow, nurse tree functions that allow other less tenacious species to exist in the harsh conditions near treeline, and early tree establishment in large-scale disturbances due to long-range seed dissemination by the primary disperser of WBP seed, the Clark’s nutcracker (*Nucifraga columbiana* Wilson) (Tomback, 1978; Tomback et al., 2001). Perhaps WBP’s greatest ecological impact comes from its calorie-rich seeds held tightly in indehiscent cones that are highly sought after by many bird and mammal species, including the threatened grizzly bear (Hutchins and Lanner, 1982; Mattson et al., 1992).

Nowhere has the decline of WBP been more severe than in the Crown of the Continent Ecosystem (CCE) (Fig. 1) where >90% mortality has been documented in some areas (Retzlaff et al., 2016; Shepherd et al., 2018; Smith et al., 2013). The CCE spans an 18-million-acre (7-million-hectare) area in northwestern Montana, southeastern British Columbia, and southwestern Alberta. Internationally known for its biodiversity, the CCE is one of North America’s most ecologically intact ecosystems with no known extinctions since Lewis and Clark’s exploration of the area in the early 1800’s (Flathead Transboundary Network, 1999). It is a

jurisdictionally complex landscape, overlapping two countries, one U.S. state and two Canadian provinces; administered by multiple federal, provincial, state, tribal and First Nations governments, and private lands. Each of these jurisdictions has its own missions, mandates, and capacities that vary widely.

In response to the dramatic decline of high elevation 5-needle pines (WBP and limber pine [*Pinus flexilis* James]) in the CCE, the CCE High Five Working Group was formed in 2016 (Crown Managers Partnership, n.d.). With a mission to protect and restore functional WBP and limber pine ecosystems in the CCE, the group prioritized the development of a restoration plan and the improvement of coordination between the diverse jurisdictions. Due to the complexities of developing a restoration plan for two species in such a large and jurisdictionally diverse area, a decision was made to first develop a proof of concept methodology for WBP in a pilot study area. The purpose of this paper is to provide a detailed description of the methodology that was developed through the pilot so that the process can be applied by others. The pilot was con-

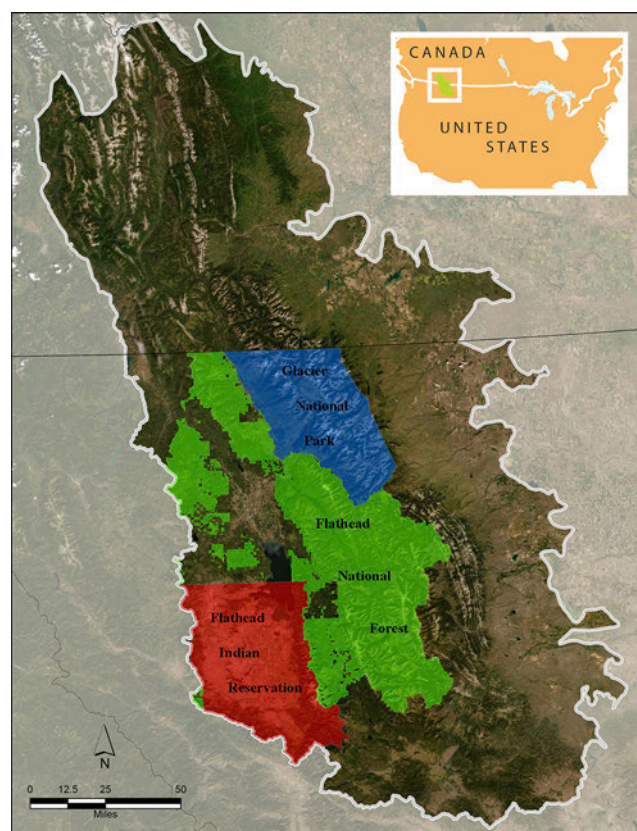


Fig. 1. The Pilot area was composed of three jurisdictions in the Crown of the Continent Ecosystem (CCE): Glacier National Park (blue), Flathead National Forest (green), and Flathead Indian Reservation (Confederated Salish and Kootenai Tribes) (red). The overall white border defines the CCE. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

ducted on a five-million-acre (2-million-hectare) subset of the CCE in the U.S. that includes the Confederated Salish and Kootenai (CSKT) tribal lands, Flathead National Forest (FNF), and Glacier National Park (GNP) (Fig. 1; CCE High Five Working Group, 2019). These three jurisdictions were selected because they were adjacent, had relatively consistent and robust data sets, and provided a reasonable representation of the wide breadth of missions and mandates in the CCE.

Several WBP restoration plans have been written that detail treatments needed in specific areas of interest, in addition to a publication on range-wide restoration principles (Aubry et al., 2008; Greater Yellowstone Coordinating Committee, 2011; Keane et al., 2012; Perkins et al., 2016; Shoal et al., 2008). The CCE Pilot WBP Restoration Strategy built upon these planning efforts, synthesizing many of the restoration guiding principles and management considerations into a restoration decision-making process that leverages available spatial data and improves objectivity in assigning treatments. The end-product is a restoration plan with site-specific actions designed to protect and restore genetically diverse, evolutionarily stable populations of whitebark pine across the area of interest.

Minimum Viable Population size (i.e. the smallest size at which a population can exist without unacceptable probability of extinction), which is sometimes used in restoration planning (Brook et al., 2006; Soulé, 1987; Thomas, 1990; Traill et al., 2007), has not been estimated for WBP to our knowledge. Estimation of Minimum Viable Population size was not attempted here because it is data intensive and complex (Brook et al., 2011; Nunnery and Campbell, 1993) and the results can have a high level of uncertainty for species like WBP with long projection timeframes (Fieberg and Ellner, 2000). In the absence of more refined population threshold estimates such as Minimum Viable Population size, we define an evolutionarily stable population, that if created, can maintain adequate genetic diversity over time and provide a strong foundation to build on as additional information becomes available (Spielman et al., 2004; Traill et al., 2010).

This paper describes the details of our methodology for WBP restoration planning and project implementation, the resulting products, unique findings, and the primary lessons learned. The steps in the methodology are:

1. Establish WBP's potential and existing ranges within the area of interest.
2. Quantify the ecosystem services (USDA Forest Service, n.d. -a.) that WBP provides, and its biological capability to occupy habitat (i.e. establish, survive, and reproduce) (Hall et al., 1997).
3. Quantify current and future stressors that could affect the capability of WBP to provide ecosystem services and occupy habitat.
4. Assess the likelihood of restoration treatment success based on current and future stressors.
5. Establish core areas where restoration priority is highest.
6. Assign and prioritize treatments within core areas based on likelihood of treatment success and genetic principles designed to achieve evolutionarily stable populations that will persist and evolve over time.

2. Materials and methods

2.1. Overview

A CCE High Five Working Group Technical Team (Tech Team) of scientists, local managers, and GIS analysts collaborated closely to develop the CCE Pilot WBP Restoration Strategy methodology and implementation planning process. The Tech Team developed a six-step

approach to guide the identification and prioritization of restoration actions that would support long-term persistence (i.e. evolutionarily stable populations) and function of WBP in the CCE (Fig. 2). The strategy accomplished this by identifying “core areas” on 20–30 percent of WBP potential habitat where conservation value (CV) (Section 2.3.2) was highest and treatment success was likely, and then spatially delineating areas where treatments would be most effective within the core areas. The target of having 20–30 percent of potential habitat in designated core areas came from guidance in the NWPRP (Tomback and Sprague, 2022). The end-product was a plan to restore functional WBP ecosystems with evolutionarily stable populations in the long-term (see Box 1, Genetics and restoration) by identifying treatments necessary to create or maintain populations of sufficient size, genetic diversity, connectivity, and distribution (see Box 2, Component populations), along with treatments to protect existing high-value trees not within a component population.

2.2. Spatial analysis

The CCE Pilot WBP Restoration Strategy integrates existing data sources, knowledge of local experts, and modeling within a GIS platform utilizing 30 m pixels as the base resolution. GIS data were selected based on quality and applicability (scale, accuracy, reliability, relevancy, and extent). The GIS spatial analysis was conducted by Mapmonsters GIS, Inc., Victoria BC, Canada (www.mapmonsters.com). Publicly available data sources that were used in the analysis are mentioned where applicable.

2.3. The six-step methodology for restoration planning

A six-step methodology was developed by the Tech Team to generate the set of GIS layers necessary to delineate core areas and plan restoration actions within those core areas (Fig. 2).

2.3.1. Step 1: Establish WBP potential range and existing range

The first step was to establish the potential range for WBP within the area of interest, and within that potential range, predict where WBP currently exists.

Potential range was defined as the area **where the species is capable of existing** under current climate conditions. It provided the boundary for all subsequent analyses. The potential range was designed to be inclusive, depicting all areas where WBP is capable of growing. While the effects of climate change are an important consideration in restoration planning (Keane et al., 2017a and b), climate niche modeling was not used in establishing the potential range because it would limit the analysis area based on uncertain model predictions (Keane et al., 2017a). Climate change effects were instead incorporated in Step 3-Stressors and considered when determining location of restoration treatments. An additional option for incorporating climate change effects has been provided in Section 3.3, Lessons Learned.

Four potential habitat modeling products, Remote Sensing Application Center (Housman et al., 2014), Landfire Biophysical and Existing Vegetation Type (Landfire, n.d.; Rollins, 2009), Montana Natural Heritage Spatial Analysis Lab (Montana Natural Heritage Program, n.d.) and a WBP habitat suitability layer created by the CSKT for their tribal lands, were combined with existing plot and stand data to determine potential range. Each pixel that fell within any of the four inputs was considered part of the potential range. A hard cutoff of 5200 feet (1585 m) was used based on field observation and preponderance of evidence of the lowest limits of WBP habitat in the area. There was no upper elevational cutoff, because WBP in the CCE often grows to the highest elevations present or

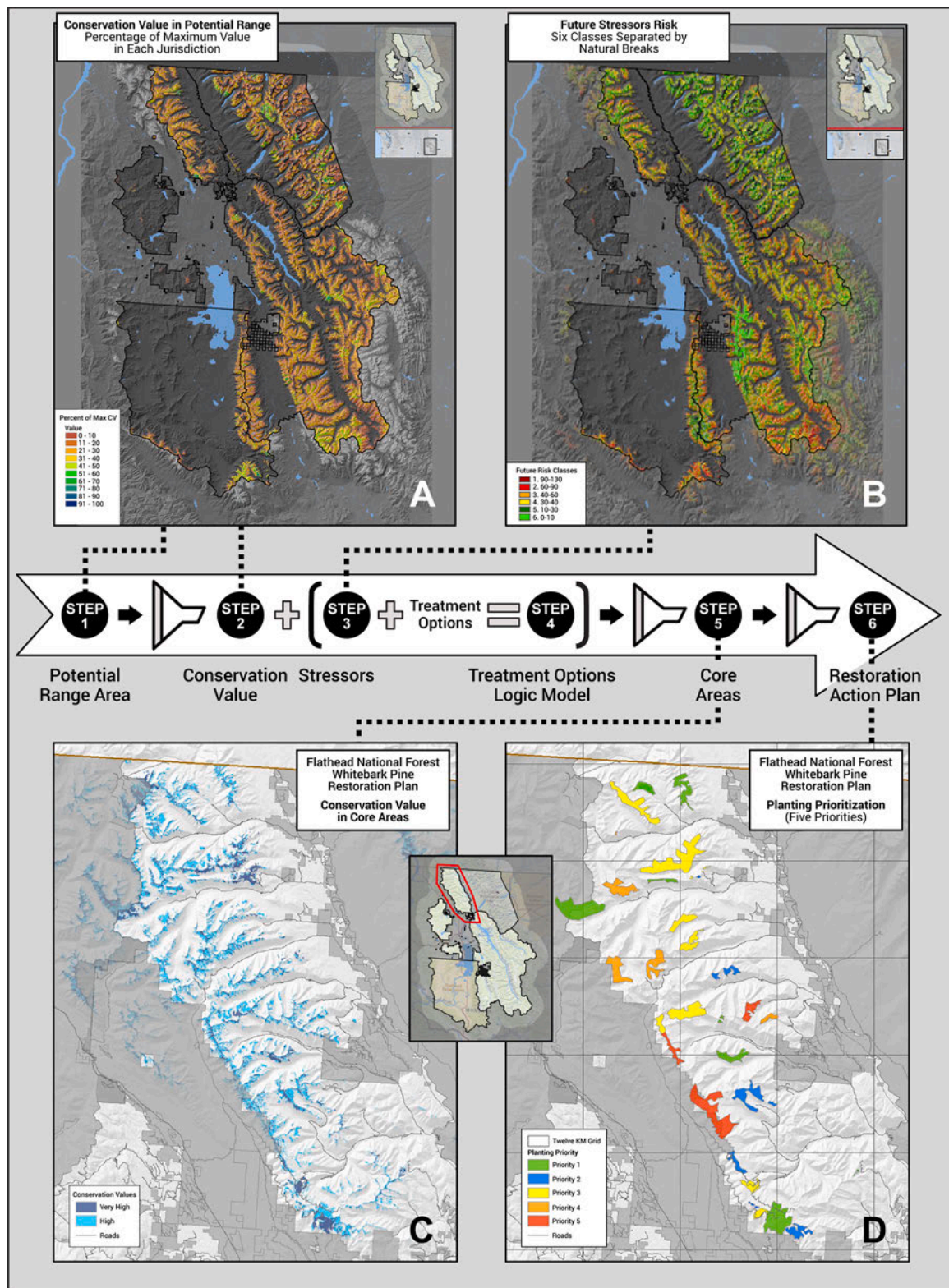


Fig. 2. A visual representation of the six-step methodology for restoration planning used to prioritize actions needed to create evolutionarily stable populations of whitebark pine (WBP) and support restoration of functioning ecosystems in the Crown of the Continent Ecosystem (CCE). Inset A: Step 1- Establish potential range and Step 2- Quantify conservation value. Inset B: Step 3- Quantify stressors (the map displays all future stressors ratings (i.e., wildfire hazard, MPB risk, and future climate risk) combined. Center of Figure: Step 4- Determine likelihood of treatment success based on stressor effects; considered in Step 5 and 6. Inset C: Step 5- Identify 20–30% of potential range with highest CV as core area. “Very High” (i.e. CV1) and “High” (i.e. CV2) CV displayed within core areas (North Fork area of the FNF). Inset D: Step 6- Implementation plan; planting treatment prioritization example with an overlaid 12 km grid (maximum distance recommended between component populations). A detailed description of the six steps is provided in [Sections 2.3.1 through 2.3.6](#).

Box 1**Genetics and restoration**

Here we outline some genetics considerations for restoration planning given that WBP has been declining dramatically and is nearly extirpated in some areas.

1. **Effective population size (N_e) can be defined as the number of individuals in a population that contribute pollen and seeds to produce the next generation;** it is not the same as the total census population, that is the total number of trees growing in a population.
2. **The proportion that N_e is of the total census population size for forest trees is estimated to be 0.2** (e.g. a census population of 5,000 would equal an N_e of 1,000) (Hoban et al., 2020; Wang et al., 2020).
3. **A smaller N_e results in greater inbreeding and loss of genetic diversity;** genetic diversity loss accelerates as N_e declines, and is especially rapid in very small populations (Hoban et al., 2020).
4. **An N_e of ≥ 1000 individuals is needed to maintain a level of genetic diversity that will allow the population to be evolutionarily stable** - to evolve over long time periods as new stressors arise (Frankham et al., 2014; Franklin and Frankham, 1998; Yanchuk, 2001).
5. **An N_e of ≥ 100 is considered effective at maintaining genetic diversity in the short term- five generations,** which for WBP can be estimated at 300-600 years (Frankham et al., 2014).

Box 2**Component populations**

A component population for purposes of this paper (see Step 6, Section 2.3.6) is a population of sufficient area, density, genetic diversity, and connectivity to be considered as contributing to an evolutionarily stable population (Box 1). The goal is to create a set of component populations that together form what will become at least one large evolutionarily stable population (e.g. a metapopulation, Olivieri et al., 1990) through the exchange of seeds and pollen across the entire CCE Pilot landscape. Given the size of the project area, it is possible that more than one evolutionarily stable population will be established.

A component population is defined as a population that:

1. **Has an N_e of ≥ 100 , census population of ≥ 500 mature (i.e. reproductive) trees** (Box 1). The goal is for the component population's N_e to be large enough that the metapopulation (Olivieri et al., 1990) it is contributing to has a combined N_e of $\geq 1,000$, census population of $\geq 5,000$ mature trees (i.e. is evolutionarily stable) (Box 1).
2. **Has ≥ 50 mature trees/ac (124/ha)** (See Table 1, example of planting density needed). While this density is less than the 100 trees/ac suggested in Scott and McCaughey, 2006, it is more than sufficient to attract Clark's nutcrackers (Barringer et al., 2012) and allow for pollen distribution (Adams and Birkes, 1991; Schuster and Mitton, 2000). It also establishes whitebark habitat on twice as much area, which has been suggested to be important for attracting Clark's nutcrackers (Schaming and Sutherland, 2020).
Densities as low as 10 mature trees/ac can be included if the ≥ 500 census population is met, however this density is less desirable because it risks going below Barringer's recommended threshold of basal area for attracting nutcrackers ($\geq 8.7 \text{ ft}^2 \text{ ac}^{-1}$ [$2 \text{ m}^2 \text{ ha}^{-1}$]), is less likely to provide adequate pollen distribution (Bramlett et al., 1993; Koenig and Ashley, 2003; Rapp et al., 2013), and would allow more ingrowth of competing vegetation (Shaw, 2006; USDA Forest Service, 2016). See number 4 below for area considerations.
3. **Is within 7.5 mi (12 km) of another component population.** This distance will facilitate exchange of genes, creating a network that is well distributed across the landscape (i.e., a metapopulation, reviewed in Olivieri et al., 1990). It is the distance that Clark's nutcrackers will reasonably fly to cache seeds (Lorenz and Sullivan, 2009; Lorenz et al., 2011; Tomback, 1978).
4. **Is ≥ 10 ac (4 ha), but preferably ≥ 100 ac (40 ha), assuming 50 trees/ac (124/ha) at reproductive maturity. If populations are only 10 acres (4 ha) in size, include at least three within 7.5 mi (12 km).** The larger size is preferred because it increases genetic diversity (Box 1), resilience to perturbations (Morgan and Murray, 2001; Nunney and Campbell, 1993), and production of seed for establishment of natural regeneration. If anticipated mature tree densities are 10 to 49 trees/ac (25 to 121 trees/ha), the minimum area would need to be increased proportionally to a size that supports a census population of ≥ 500 mature trees. For example, 10 trees/ac (25 trees/ha) = minimum 50 acres (20 ha).
5. **May be composed of planted seedlings only or include naturally occurring WBP within 0.6 mi (1 km) of the planting site.** Both will contribute to the N_e target. Most seedlings establish within this distance from a source population (Leirfallom et al. 2015; Tomback et al. 1990).
6. **A naturally occurring population that is estimated to meet criteria 1–4 above would also be considered a component population.**

is limited at higher elevations by unsuitable substrates for establishment which vary in elevation (USDA Forest Service, n.d. -c). Some small areas where WBP is known not to grow were removed.

Existing range was defined as the area where the species currently exists. This data layer combined estimated percent canopy cover (Housman et al., 2014) and the highest probability of predicted occurrence from the Landfire and Montana Natural Heritage models (Landfire, n.d.; Rollins, 2009; Montana Natural Heritage Program, n.d.) along with any documented WBP occurrences. A hard lower-elevation cutoff

of 5600 feet (1707 m) was used based on field observation and preponderance of evidence of where WBP is commonly found in the area. Small and isolated polygons within the Existing Range where WBP is known not to grow were removed.

2.3.2. Step 2: Quantify conservation value

Conservation Value (CV) was defined as the ability of the species to provide ecosystem services and occupy habitat, both presently and in the future.

Table 1

Eight restoration treatments were considered for implementation in this effort and their descriptions and objectives within the pilot analysis area are detailed here; a more broadly applicable description of potential restoration treatments can be found in [Keane et al., 2021](#), and [Tomback et al., 2022](#). The effect of stressors on the likelihood that treatments would meet objectives was evaluated in Step 4. WBP is whitebark pine; WPBR is white pine blister rust; MPB is mountain pine beetle.

Treatment (shorthand)	Description ^a	Objective
Planting (PLANT)	Remove competition by burning or hand scalping if needed. Plant containerized seedlings grown from rust-resistant seed sources with a goal of ≥ 50 trees/ac (124/ha) at maturity. FNF example of seedling density needed to meet ≥ 50 trees/ac (124/ha): Plant 250 seedlings/ac (618/ha) $\times$ estimated 20% mortality from non-WPBR related causes = 200/ac (494/ha) $\times$ estimated 75% WPBR caused mortality = 50/ac (124/ha) at maturity. When planting one area over multiple years, splitting it into subunits is more efficient than interplanting.	Create component populations (Box 2) by establishing new populations or supplementing existing ones. Increase genetic diversity and frequency of rust resistance. Increase proportion of area where WBP is present.
Direct Seeding (SEED)	Place seeds collected from rust-resistant seed sources directly in bare mineral soil approximately 1 in. (2.5 cm) deep (DeMastus, 2013 ; Tomback, 1982). Experience with large scale direct seeding projects is limited and protocols have not been established. Number of seeds needed will depend on site conditions and could be as much as five times higher than for planting (Pansing and Tomback, 2019). Generally implemented where planting is not feasible.	
Mechanical (MECH)	Use heavy equipment to remove large competing conifers and treat slash; may remove other competing vegetation and create site conditions conducive to seedling establishment and growth.	Reduce competing vegetation to increase tree vigor, cone production, and resilience to fire and MPB.
Thinning (THIN)	Remove some or all competing conifers across entire stand using chain saws or other hand-held equipment.	Create sites for natural regeneration establishment, planting, or direct seeding.
Rx Burn (RxFIRE)	Use hand crews, heli-torches, or natural ignition to create burns that reduce competing vegetation and create site conditions conducive to seedling establishment and growth.	
Daylight (DAYLT)	Remove competing conifers within a radius (e.g. 1–2 tree heights) around individual WBP using hand-held equipment. Generally used for plus trees (trees in WPBR screening trials) (Mahalovich and Dickerson, 2004), young stands, or mature stands with low density phenotypically rust resistant WBP.	Improve vigor, cone production and resilience of targeted WBP trees.
Cone Collection (CONE)	Cage cones in July, remove cages and collect cones in September. Follow established jurisdictional guidance for seed collections. Collect from trees that have shown high rust resistance in rust screening when possible (Mahalovich and Dickerson, 2004 ; Sniezko et al., 2018). At a minimum, collect from trees that are in the same stand as highly resistant trees, or are phenotypically resistant compared to other trees in the stand. Preferably collect cones during masting events that occur every 2–4 years (Crone et al., 2011).	Collect seed for planting, direct seeding, rust screening, or ex situ gene conservation.
Pheromone (PHER)	Apply antiaggregant pheromone or pesticides when there is potential for mountain pine beetle mortality. Emphasize protection of high value trees (e.g. plus trees).	In situ protection of trees from MPB attack.

^a Monitoring treatment effectiveness is critical for adaptive management. CCE monitoring protocols are in development. Existing monitoring protocols were not included here because requirements vary by jurisdiction. See ([Tomback et al., 2022](#)) for guidance on monitoring.

Ecosystem services are the benefits that people receive from ecosystems ([USDA Forest Service, n.d. -a](#)). The Tech Team identified high priority ecosystem services subjectively based on factors that were important to the mandates and missions of the three jurisdictions in the pilot. Four priority ecosystem services were identified: Wildlife Food Source (included as a “cultural” human benefit [[USDA Forest Service, n.d. -a](#)]), Watershed Protection, Recreation Value and Cultural Uses. To account for differing mandates and missions of the three jurisdictions, each jurisdiction assigned their own weights for the value of ecosystem services, within a range of 0 to 50. Weights were assigned subjectively, relative to the value of other ecosystem services and relative to the weight of other jurisdictions.

WBP's role as a **wildlife food** source is important throughout the potential range, but areas where grizzly bear occupancy was predicted to be higher were given a CV weight of 10 because of the threatened status of the bear ([US Fish & Wildlife Service, 1975](#); [Great Northern Landscape Conservation Cooperative, 2016](#)). The CV in municipal **watersheds** and watersheds in impaired condition ([Brown and Froemke, 2010](#); [USDA Forest Service, n.d. -b](#)) was given an additional weight of 25 due to WBP's ability to slow runoff and reduce erosion ([Farnes, 1990](#)). Areas of concentrated **recreation** use such as ski areas, trails, and lookouts were given additional CV weight based on the importance of recreation and public education to each jurisdiction's mission (CSKT = 10, FNF = 20 and GNP = 30). Because WBP is a traditional food source of the Salish and Kootenai tribes ([American Forests, 2017](#)), an additional CV weight of 50 was given to areas designated as culturally significant by tribal members.

Biological capability factors that predict the ability of WBP to occupy habitat (i.e. establish, survive, and reproduce) ([Hall et al., 1997](#)) within the CCE were also quantified and weighted. Weights did not vary between jurisdictions because the value of biological capability factors was not affected by jurisdictional missions and mandates. The weights were

assigned subjectively, generally receiving higher value than ecosystem services because they were considered to have greater influence on likelihood of restoration success (i.e. restoring functional WBP ecosystems with evolutionarily stable populations). Four biological capability factors were identified: cone production, cone production potential, rust resistance, and regeneration potential. **Cone production** (areas currently containing cone producing trees) was assigned a weight of 30, 40 or 50 based on amount of WBP canopy cover ([Housman et al., 2014](#)), known WBP locations (plots, polygons, plus trees and other field observations), and presence within the Existing Range. Known locations and higher canopy cover received the higher weights. **Cone production potential** (areas where biophysical conditions were most likely to allow WBP to occupy habitat) was given a relatively low CV weight of 30 because the analysis was based strictly on modeling. **Rust resistance** (plus tree points, known concentrations of phenotypically resistant trees, and WBP plantations) was given a CV weight of 50. **Regeneration potential** (high and moderate severity fire areas that are likely to support seedling establishment [suitable planting conditions were estimated to persist 30 years post-fire]) was given a CV weight of 40.

The use of known WBP locations and areas with known rust resistance in the biological capability factors created bias toward those areas, however the scale of the impacts was limited when considered in context of the full analysis area. The CV weights of all biological capability and ecosystem services were added together at the pixel scale to calculate total CV ([Fig. 2A](#)). CV is the primary factor used to define core areas in Step 4.

Those who apply this process to other geographic areas would need to select their own ecosystem services, biological capability factors and assign weights that are appropriate for their area of analysis.

2.3.3. Step 3: Quantify stressors

Stressors were defined as **something that has reduced, or is likely**

to reduce, CV. Both current stressors (succession to shade-tolerant conifers, fire severity, WPBR hazard, and MPB mortality) (Keane et al., 2012) and future threats (wildfire hazard, MPB risk, and future climate risk) (Keane et al., 2017b) were evaluated (See Fig. 2B). Each of the stressors was broken into classes based on the level of effects (Table 2) (see Section 3.3, Lessons learned 2).

2.3.4. Step 4: Quantify likelihood of treatment success

Some restoration plans prioritize treatments in areas where the species has experienced the highest losses. While well-intended, this can result in a poor return on investments when treatments are concentrated in high stress areas where they may be less likely to succeed and where restoration costs are high (Keane and Schoettle, 2011; Schoettle et al., 2019). To increase treatment efficacy, managers can consider how environmental stressors affect the likelihood of restoration treatment success and refrain from investing in treatments that are unlikely to be successful (Schoettle et al., 2019).

Likelihood of Treatment Success is a **relative rating of the predicted success of a treatment** based on the proposed treatment type and the levels of stressors that are present. To incorporate stressors into the methodology, Step 4 uses a logic model that was developed by expanding the prioritization framework for regeneration decisions presented by Schoettle et al. (2019). The logic model facilitates the unique integration of treatment options (Table 1) and stressor conditions (Table 2) to generate a relative rating of predicted treatment success (i.e. meeting restoration objectives in Table 1).

The Tech Team recognized that low and high stress conditions do not always directly equate to likelihood of treatment success; that is, a treatment may be more effective in low stress conditions for some stressors while under high stress conditions for other stressors. For example, a thinning treatment to increase natural regeneration would be successful in meeting objectives for both the condition of low stress from future climate risk (remaining trees would likely persist under future climate), and the condition of high stress from succession (competing vegetation would be reduced). It was also recognized that focusing priority on high stress areas, or conversely, avoiding those areas for treatment would ignore instances where the same level of stressor can

have either a positive or negative effect on treatment efficacy depending on the type of treatment. For example, an area with high stress from high WPBR hazard has a low probability of success for planting (because high WPBR pressure can reduce probabilities of even rust-resistant seedlings surviving to maturity) (Schoettle et al., 2019; Sniezko et al., 2020), yet a high likelihood of success for identifying trees with superior genetic rust resistance for cone collection (Mahalovich and Dickerson, 2004). These complexities necessitated an approach where the efficacy of each treatment is evaluated for each stressor level. This enables development of recommendations based on a composite of treatment efficacy ratings for the unique combination of stressors at each location and avoids having to develop recommendations for every possible forest health condition scenario.

The stressor classes from Step 3 (Table 2) were simplified into binary impact levels (i.e., “lower” and “higher”). How the two levels were defined depended on the range of conditions for that stressor within the area of interest – the objective was to distinguish the two levels of impact that would best reflect the potential success of various treatments. Table 3A is a matrix with specific stressor conditions in the rows and treatment options in the columns; the scores in the intersecting cells reflect the efficacy of that treatment to mitigate the stressor and benefit WBP based on best available science and expert knowledge. If the treatment would mitigate the stressor and benefit WBP restoration, the entry was positive (yes) reflecting that the treatment had a high likelihood of success and was therefore recommended. If the treatment would not mitigate the stressor and the stressor level prevented the treatment from benefiting WBP, the entry was negative (no), and the recommendation was to explicitly avoid that treatment where that stress level exists. If the treatment would not mitigate the stressor and the stressor had no effect on the proposed treatment, the entry was neutral (-) to reflect that the treatment was not recommended or discouraged from being recommended.

The composite efficacy ratings for each treatment option at a location (i.e. pixel) with a suite of stressor conditions was the count of the number of times the treatment was and was not recommended for the benefit of WBP (yes and no, respectively; see example scenarios in Table 3B). If a negative designation (no) was in a cell for a stressor, the treatment was not recommended at that location, regardless of the

Table 2

In Step 3, current and future stressors were quantified into three, four, or five ordinal classes based on the level of stressor effects. Succession represents the amount of shading from shade-tolerant conifers in four classes of total percent canopy cover; WBP was included in total canopy cover, but its representation was typically very low (Housman et al., 2014; USDA Forest Service, n.d. -c). Fire severity was divided into four classes based on the degree to which the site had been altered or disrupted by fire; reduced competition from higher severity favors WBP survival and growth (Monitoring Trends in Burn Severity, 1984 to present). WPBR hazard was represented by four classes of soil moisture based on wetness index that was used to describe saturated air conditions conducive to rust production and spread (British Columbia Ministry of Forestry, 1998; Tarboton, 2005; Van Arsdell et al., 2006). MPB mortality is represented by three classes of cumulative mortality from 1909 to 1945, 1999–2015 and 2016 and 2017 quantified by percent of canopy killed (%) based on Forest Health Protection aerial detection surveys (Jenne and Egan, 2019). Wildfire hazard potential is defined by five classes of relative potential for wildfire that would be difficult for suppression resources to contain (Dillon, 2018). MPB risk is defined by five classes of percent of basal area predicted to be lost 2013–2027 (Krist et al., 2018; USDA Forest Service, 2012- revised 2018). Future Climate Risk is represented by five classes combining predictions from three different predictive models; future climate refugia (Mahalovich et al., 2017) and two future species distribution models (Keane et al., 2017a and b; Keane et al., 2018; Crookston et al., 2010). The reliability of the predictive models was considered to improve as model specificity to the analysis area increased (Mahalovich > Keane > Crookston). Decreasing model overlap was assumed to equate to increasing future climate risk.

Current stressor	Stressor class and description				
	1	2	3	4	NA- only four classes
Succession (% canopy cover)	10–25	25–40	40–60	>60	NA
Fire severity	Unburned	Low severity	Moderate severity	High severity	NA
WPBR hazard (soil moisture group)	Very xeric to submesic	Mesic	Subhygric	Subhygric-hygric	NA
MPB mortality (% mortality)	1–10	11–29	30–50	NA-only three classes	NA
Future stressor	1	2	3	4	5
Wildfire hazard potential	Very low	Low	Moderate	High	Very high
MPB risk (% basal area loss)	0–15	15–30	30–45	45–60	60–80
Future climate risk	Meets Mahalovich genetic refugia model	Meets Keane and Crookston A1B climate models	Meets Keane climate model only	Meets Crookston A1B climate model only	Does not meet any climate model

Table 3

A: The Likelihood of Treatment Success Logic Model produced a relative rating of the predicted success of a treatment based on the proposed treatment type and the stressor class. Stressors and their stressor classes (values of 1 to 5) are detailed in Table 2. We created an Impact class that simplified Stressor classes from Table 2 into binary impact levels (i.e., “lower” and “higher”), defined depending on the range of conditions for that stressor; the objective was to distinguish the two levels of impact that would best reflect the potential success of various treatments. Stressor classes are the values 1 through 5 listed in the Stressor class and description column in Table 2. Treatment type (PLANT or SEED, MECH, RxFIRE, THIN or DAYLT, CONE, PHER) was defined in Table 1. Yes, no, or neutral in the treatment type columns was assigned based on best available science and expert knowledge. A “yes” indicates the treatment would mitigate stressor, “no” indicates treatment would not mitigate stressor, and “-” (neutral) indicates neither a positive or negative effect. Table 3B: Stressor Scenario Examples: Examples showing how the designations “yes”, “no”, or “-” were combined to rate treatment success at the pixel scale. The cumulative count of yeses and noes was summed for each pixel. Any treatment with a “no” would not be recommended. The count of yeses indicates the efficacy of the treatment for mitigating stressors with the higher number of yeses equating to a higher likelihood of treatment success. Because the number of possible yeses varies by treatment type, the number of yeses needed for a treatment recommendation also varies: **Very Good = One yes for pheromone, two yeses for cone collection and three yeses for all other treatments; Good = One yes for cone collection and one or two yeses for all other treatments.** When the count of yeses and noes is zero, effects are neutral and treatments would be neither recommended nor not recommended.

Table 3A: Likelihood of Treatment Success Logic Model

Stressor (Step 3)	Impact class	Stressor classes (Table 2)	Treatment type (see definitions in Table 1)					
			PLANT or SEED	MECH	RxFIRE	THIN or DAYLT	CONE	PHER
Succession	lower	1,2,3	–	–	–	–	–	–
	higher	4	no	yes	yes	yes	–	–
Fire severity	lower	1	–	–	–	–	–	–
	higher	2,3,4	yes	–	no	–	–	–
WPBR hazard	lower	1,2	yes	yes	yes	yes	–	–
	higher	3,4,5	no	no	no	no	yes	–
MPB mortality	lower	1	–	–	–	–	–	–
	higher	2,3	yes	–	yes	yes	yes	–
Fire hazard	lower	1,2	–	–	–	–	–	–
	higher	3,4,5	–	yes	yes	yes	–	–
MPB risk	lower	1,2,3	–	–	–	–	–	–
	higher	4,5	–	yes	yes	yes	yes	yes
Future climate risk	lower	1,2,3	yes	yes	yes	yes	–	–
	higher	4,5	–	–	–	–	yes	–

Table 3B: Stressor Scenario Examples

		PLANT or SEED	MECH	RxFIRE	THIN or DAYLT	CONE	PHER
(1) higher Succession + higher Fire Hazard + lower other stresses	Composite efficacy rating	2 yes 1 no	4 yes	4 yes	4 yes	–	–
	Treatment recommendations	No	Very Good	Very Good	Very Good	Neutral	Neutral
(2) higher Fire Hazard + higher WPBR Hazard + higher MPB risk + lower other stresses	Composite efficacy rating	1 yes 1 no	3 yes 1 no	3 yes 1 no	3 yes 1 no	2 yes	1 yes
	Treatment recommendations	No	No	No	No	Very Good	Very Good
(3) higher Fire Hazard + higher Future Climate Risk + lower other stresses	Composite efficacy rating	1 yes	2 yes	2 yes	2 yes	1 yes	–
	Treatment recommendations	Good	Good	Good	Good	Good	Neutral

number of positive yeses for other stressors. The number of yeses, in the absence of any noes, reflected the number of stressors that treatment would mitigate – thus the higher the count of yeses for the location, the more likely that treatment would be efficacious at mitigating multiple stressors and improving WBP condition. See the example scenarios in Table 3B; note that the number of yeses that equate to a “Good” or “Very Good” recommendation vary by treatment type.

Logistical and potential regulatory limitations (i.e. accessibility, slope, and wilderness designation) (Table 4) were applied to the data layers generated by the Likelihood of Treatment Success logic model (Table 3A and 3B). Reserving these limitations until Step 4 allowed an accurate depiction of where the highest CV was located (Step 2) and prevented areas where restoration actions could be most beneficial from being excluded from consideration. For example, it would be important to know if high CV areas were concentrated in areas that are inaccessible or in protected areas (e.g. wilderness). Because CVs were assigned without considering regulatory limitations to treatment options, we knew that approximately 80 percent of core areas in the pilot area are in recommended wilderness or designated wilderness. This would be important information for wilderness specialists to consider when providing recommendations for a management framework in highly protected areas in the CCE (Aldo Leopold Institute n.d.; Cooke et al., 2018; Hahn and Landres, 2017).

For each of the treatment types a spatial layer was produced that displayed areas where likelihood of treatment success was rated “Very Good”, “Good”, “Neutral”, or “No” based on the number of yeses and noes in the pixel. These likelihood of treatment success layers were used in Step 5 (Identify core areas) and Step 6 (Restoration action plan).

2.3.5. Step 5: Identify core areas

The NWPRP directs that 20–30% of the range of WBP be identified as core areas for restoration (Tomback and Sprague, 2022). Core area polygons were established by selecting approximately 30% of the potential range with the highest CV (Very High = CV1 and High = CV2 in Fig. 2C), at least 5 acres (2 ha) in size, and where treatment success was rated positive or neutral. Core area polygons were designated so that ≥ 70% of the pixels were CV1 or CV2; it was often necessary to include some lower CV pixels when grouping high CV pixels into polygons, but low CV pixels were not allowed to exceed 30% of the polygon area. Core areas were designated at the jurisdiction scale. Total core area by jurisdiction is shown in Table 5. See Section 3.3, Lessons Learned, for details on an option to designate core areas at the analysis area scale.

2.3.6. Step 6: Restoration action plan

Personnel with WBP management expertise from each jurisdiction used the data layers produced in Steps 1–5 to create their jurisdiction's

Table 4

Limitations were applied to likelihood of treatment success layers to aid in prioritization. Restoration treatments considered in planning are described in Table 1. Limitations were applied as boundaries to the likelihood of treatment success layers created from the Likelihood of Treatment Success logic model (Table 3A); treatments were generally not planned past those limits. In the Wilderness column, “N” indicates that the treatment was not considered as currently compatible in designated wilderness and “MRDG” indicates the Minimum Requirements Decision Guide would be recommended for use when considering treatments (Hahn and Landres, 2017). Note that interpretation of provisions in the Wilderness Act can vary by agency. The example here is for the FNF and CSKT; GNP had different limitations.

Treatment	Limitations		
	Max distance from road (miles/km) ^a	Max slope (%)	Wilderness ^b (N or MRDG)
Planting (PLANT)	4.0/6.5	60	N
Direct Seeding (SEED)	No Limit	60	MRDG
Mechanical (MECH)	0.5/0.8	40	N
Thinning (THIN)	2.0/3.2	60	N
Rx Burn (RxFIRE)	No Limit	No Limit	MRDG
Daylight (DAYLT)	No Limit	60	N
Cone Collection (CONE)	4.0/6.5	60	MRDG
Pheromone (PHER)	No Limit	60	MRDG

^a GNP allowed longer distances from roads and trails.

^b Use of the Minimum Requirements Decision Guide would be recommended when considering treatments within wilderness areas designated under the Wilderness Act of 1964 (Hahn and Landres, 2017).

Table 5

The acres (hectares) of core area designated within each of the three jurisdictions in the pilot (CSKT, FNF and GNP) and the percent of the potential range (Step 1) that it represents.

Jurisdiction	Potential range acres (hectares)	Core area acres (hectares)	Percent of potential range in core area (%)
FNF	941,470 (381,000)	268,810 (108,800)	28.6
CSKT	101,620 (41,130)	29,120 (11,780)	28.7
GNP	348,040 (140,800)	97,430 (39,420)	28.0

restoration action plan. Core areas were used as the boundary of where treatments would occur (see Supplementary Material A, FNF process for 10-Yr Implementation Planning). Treatments needed to create or protect component populations (Box 2 and Box 3) were assigned and prioritized

based on CV, likelihood of treatment success (Step 4) and site conditions such as presence of existing cone bearing trees or proximity to other populations. Restoration treatments that are not related to component populations such as cone collection, protection of high value trees or stands, and plus tree identification (Mahalovich and Dickerson, 2004; Snieszko et al., 2018) were also assigned and prioritized. The highest priority treatments up to the maximum 10-year capacity of the jurisdiction were included in a 10-Year Implementation Plan (Section 2.3.6.4; Supplementary Material A).

Connectivity and distribution of populations are key considerations when developing restoration plans; they are important to the resiliency, representation and redundancy principles used in species status and recovery assessments under the Endangered Species Act (U.S. Fish and Wildlife Service, 2016) and are emphasized in the NWPRP (Tomback and Sprague, 2022). The unprecedented high levels of WBP mortality in the CCE make achieving adequate connectivity and distribution of populations a particular challenge. Intact WBP stands are uncommon, with most WBP existing in scattered clumps or individuals, primarily near ridgetops (Retzlaff et al., 2016; Shepherd et al., 2018; Smith et al., 2013). The concept of component populations (Box 2) addresses the concern that reduced effective population sizes in the CCE may lead to increased inbreeding and a downward spiral of reduced genetic diversity (Frankham et al., 2017; Hoban et al., 2020; Tomback and Kendall, 2001). Component populations would need to be large enough that they are not easily extirpated (Morgan and Murray, 2001), with sufficient density to provide adequate pollen distribution (Adams and Birkes, 1991; Schuster and Mitton, 2000) and attract the primary vector of seed dispersal, the Clark's nutcracker (Barringer et al., 2012). The goal is for the component populations to eventually provide enough seed for natural regeneration establishment over successive generations to restore functioning ecosystems. The network of component populations would allow for some component populations to fail, while the overall meta-population thrives (see Box 2).

2.3.6.1. Step 6.a: Identify focus areas for treatment. Within the 268,000 acres of core area designated on the FNF (Table 5), local managers identified areas where treatments would be focused with emphasis on creating or protecting component populations (Box 2). These “Treatment Focus Areas” were drawn around areas where: 1) CV was the highest with preference on contiguous areas of CV rather than long narrow “fingers” (Fig. 3.2), 2) the size and conditions of the area could support a component population, 3) there were concentrations of high likelihood of treatment success from Step 4 - especially planting or seeding (Fig. 3.5), or 4) restoration investments were already present or planned. The establishment of Treatment Focus Areas did not preclude treatments occurring outside of those areas (e.g. cone collection).

Box 3

Genetic considerations in establishing component populations

Here we outline some genetics considerations when establishing component populations through planting or seeding. To maximize genetic diversity ($N_e \geq 100$; Boxes 1 and 2) we provide the following guidance:

1. **Use only WBP seed lots composed of seeds collected from at least 20 maternal trees separated by ≥ 200 ft (61 m) (USDA Forest Service, 2008; Mahalovich et al., 2006; Yanchuk, 2001).** Ideally these maternal trees would have high levels of rust resistance.
2. **Use seed from at least 20 maternal trees (one seed lot), preferably 60 or more (three seed lots), in a planting area of 10 ac (4 ha). In larger planting areas, increasing the number of maternal trees is advised. For example, in a 100 ac (40 ha) planting area, increase the number of maternal trees to at least 60, preferably 100 (five seed lots) or more.** Select as many seed lots as possible under applicable seed transfer guidelines to maximize both the number of maternal trees represented, and the number of source populations sampled. Sampling multiple source populations will increase the genetic diversity of the planting stock more effectively than collecting from more individuals from a single population (Hoban, 2019).
3. **If there are not enough seed lots immediately available, plant the area over multiple years using different seed lots each year of planting as new collections become available (see Table 1, Planting description).** While seedlots from different source populations are preferred, seedlots from the same collection site collected in different years can also be used since the genetic composition of the collection changes from year to year.

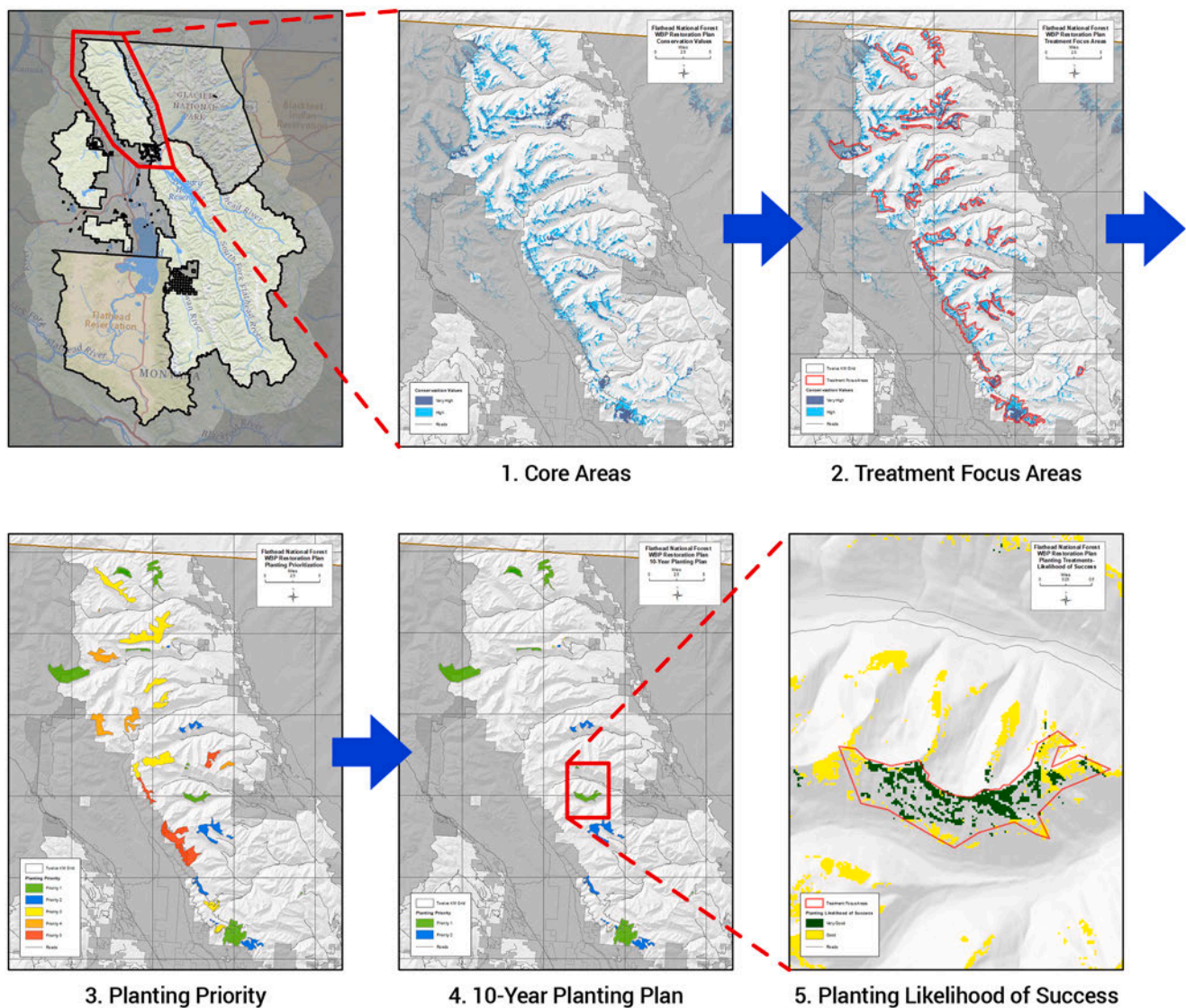


Fig. 3. Process for designating restoration treatments and 10-year planning; North Fork area of the FNF planting treatment example. Map 1- The delineated core areas developed from Step 5. Map 2- The delineated Treatment Focus Areas whose boundaries were defined by overlaying high/very high CV, core area boundaries, likelihood of treatment success layers, and planned and previous treatment polygons to identify where to focus successful treatments with emphasis on creating component populations. Map 3- A display of the designated and prioritized treatments that are to occur in each focus area (planting example; five priorities). Map 4- The high priority planting treatments included in the 10-year implementation plan; treatments were limited to the maximum capability of the jurisdiction during the planning period. Map 5- An example showing the Coal Creek area Likelihood of Planting Treatment Success layer and corresponding Treatment Focus Area designation.

2.3.6.2. Step 6.b: Designate treatment type and location. The next step was to designate treatment type and location, emphasizing treatments that would establish, maintain, or enhance component populations. First, treatments that had been planned prior to the pilot methodology but not yet implemented were reviewed to confirm they had high likelihood of success and fell within core areas. Next, the need for supplemental treatments to protect or enhance previous treatments was evaluated. For example, where plus trees had been identified, we evaluated the need for pheromones (Kegley and Gibson, 2011), cone collection, and thinning or daylighting (Rocky Mountain Research Station, n.d.). In previous plantings, we considered additional planting if needed to meet component population requirements, and thinning or daylighting. Where there were no known past or proposed treatments, likelihood of treatment success spatial layers (Step 4) were overlaid with CV (Step 2) and core area (Step 5) layers, to assign treatments. Treatment appropriateness was often verified with National Agriculture Imagery Program (NAIP) imagery and sometimes refined with knowledge

of conditions on-the-ground (e.g. presence of competing tree regeneration).

2.3.6.3. Step 6.c: Prioritize and sequence treatments. Once treatment types were designated, they were prioritized based on existing site conditions (Table 6). For the FNF Whitebark Pine Restoration Implementation Plan (Supplementary Material A), site conditions were grouped into three priority rankings: 1, 3 or 5 (Table 6). Rankings of 2 and 4 were purposely left blank to allow flexibility in assigning a priority when the site had multiple conditions. For example, when a Priority 3 condition and Priority 5 condition were present on the same site, managers could consider ranking the treatment as a Priority 4. Grouping conditions into five rankings provided an adequate distribution of treatment priority in the FNF WBP Restoration Implementation Plan, but future efforts ought to consider whether this number of priority rankings is adequate for their unique conditions. If the maximum work capacity (Table 7) for a jurisdiction is very limited, a finer scale of prioritization

Table 6

The planting treatment prioritization assignments (high, moderate, low, very low) from the Flathead National Forest Whitebark Pine Restoration Implementation Plan (Supplementary Material A) are provided here as an example. Site conditions that affect the ability of planting treatments to meet restoration goals were identified and separated into three priority rankings; 1, 3 and 5. Rankings 2 and 4 were left blank to allow flexibility when multiple conditions with different priority rankings were present.

High Priority Conditions (Priority 1)

- Site preparation complete (limited availability and limited window of suitability)
- Existing stands at or near the component population requirements that need supplementation to maintain or meet the requirements
- Educational opportunities or high-use recreation sites
- Priority areas designated by jurisdictional genetics specialist
- Landscape Connectivity/Distribution: No other populations meeting the component population criteria within 7.5 mi (12 km)

Moderate Priority Conditions (Priority 3)

- Cone-bearing trees present within 1 km that can supplement genetic diversity (at or near density of $\geq 8.7 \text{ ft}^2 \text{ ac}^{-1}$ [$2 \text{ m}^2 \text{ ha}^{-1}$] of basal area to attract Clark's nutcrackers preferred)
- Rated Very High CV (>50% of area) and no Priority 1 conditions
- Rated Very Good planting likelihood of treatment success (>50% of area) and no Priority 1 conditions
- Existing planted populations that need additional genetic diversity to meet recommendations for a component population (Box 2 and Box 3)
- Landscape Connectivity/Distribution: A Priority 1 planting condition that establishes a component population within 2.5 mi (4 km) of a population with more Priority 1 conditions

Low Priority Conditions (Priority 5)

- Rated Good CV (>50% of area) and no Priority 1 or 3 conditions
- Rated Good Planting Likelihood of Treatment Success (>50% of area) and no Priority 1 or 3 conditions
- Unable to establish a component population
- Low use recreation sites and no Priority 1 or 3 conditions
- Landscape Connectivity/Distribution: A Priority 2 or 3 planting condition that establishes a component population within 2.5 mi (4 km) of a population with higher priority conditions

Very Low Priority Conditions (Drop- No Priority Assigned)

- Landscape Connectivity/Distribution: A Priority 4 or 5 planting condition that establishes a component population within 2.5 mi (4 km) of a higher priority population

may be needed to identify a smaller amount of top priority treatments. Different conditions could also be added, or the priority of conditions could vary. For example, in jurisdictions where stand replacing fires have created favorable planting conditions over an extensive area, site preparation would not be limited and "site preparation complete" would likely not be considered a Priority 1 condition (Table 6).

Table 7

This table describes the Flathead National Forest (FNF) Maximum Work Capacity and 10-Year Implementation Plan. Treatment type is the name of the planned treatments; they are defined in Table 1. Unit is the unit of measure, acres or individual tree, used to quantify the capacity. FNF annual maximum capacity is the maximum amount of work the FNF could reasonably accomplish with no restrictions on treatment funding or personnel. 10-Year maximum capacity is the FNF annual maximum capacity multiplied by ten. Total planned is the number of units planned in the restoration plan. 10-Year plan is the number of units planned in the 10-year planning period. Planning cost is the cost per unit for project planning including required environmental analysis. Implementation cost is the cost of implementing one unit of the treatment. Total restoration plan cost is the total cost of planning and implementing the treatment type on all units in the "Total planned" column. 10-Year plan cost is the total cost of planning and implementing the treatment type on all of units in the "10-Year plan" column.

Treatment type	Unit	FNF annual max capacity (Unit)	10-Year maximum capacity (Unit)	Total planned (Unit)	10-Year plan (Unit)	Planning cost (\$/Unit)	Implementation cost (\$/Unit)	Total restoration plan cost (USD)	10-Year plan cost (USD)
Plant	Ac	300	3,000	4,930	2,900	\$100	\$800	\$4,437,000	\$2,610,000
Seed	Ac	100	1,000	2,450	1,000	\$100	\$900	\$2,450,000	\$1,000,000
Daylight/Thin	Ac	500	5,000	4,950	2,450	\$100	\$350	\$2,227,500	\$1,102,500
Rx burn	Ac	5,000	50,000	6,400	3,000	\$100	\$500	\$3,840,000	\$1,800,000
Mechanical	Ac	Access Limited	NA	660	660	\$100	\$1,200	\$858,000	\$858,000
Cone collect	Tree	200	2,000	375	375		\$350	\$131,250	\$131,250
Pheromone	Tree	1,250	12,500	3,750	3,750		\$30	\$112,500	\$112,500
Total Cost								\$14,056,250	\$7,614,250

Each of the possible restoration treatments (Table 1) were considered within the treatment focus area and if appropriate, assigned a Priority 1 through 5 based on the suite of possible conditions. When knowledge from field observations was adequate, the precise boundary of treatment areas was identified. When field knowledge was lacking, treatments were planned to occur within the treatment focus area where their likelihood of success was high, without a precise location.

Sequence of treatment was assigned when a treatment required another treatment to occur first. For example, if a Priority 1 rated planting treatment required a burning treatment to occur first, the burning would be classified as a P1-1 (priority 1, order 1) and the planting would be P1-2 (priority 1, order 2). If a treatment was unrelated to any other treatment, no order designation was given. The year of treatment was assigned where specific timing was appropriate. For example, daylighting (Rocky Mountain Research Station, n.d.) to reduce vegetative competition on planted trees was scheduled 15 years post-planting (see Supplementary Material A).

2.3.6.4. Step 6.d: 10-year implementation plan. The last step was to create an implementation plan that identified which treatments would be proposed in the budgeting and work-planning process over the next 10 years (the NWPRP suggests a planning timeframe of 10–15 years).

The planning unit (FNF) first determined the maximum capacity for each treatment type that could be accomplished over the 10-year planning period assuming that additional resources and personnel would become available (Table 7). The maximum capacity acres were then distributed to the highest priority treatments to determine which treatments to include in the 10-year plan. Unit costs were multiplied by both the number of treatment units in the 10-year plan, and by the number of treatment units planned for the entire restoration plan, to determine the total cost of each. Note: The 10-year plan acres for some treatment types in Table 7 do not meet the 10-year maximum capacity because they were part of a sequence and one of the treatments that came earlier in the sequence had already met its maximum capacity.

The 10-year implementation plan includes a spatial dataset that allows land managers to reassess proposed treatments annually, or as needed following landscape scale changes due to fire or MPB. By overlaying new disturbance boundaries, treatments in need of review could be easily identified. If the area of overlap was localized, treatment modifications (i.e. dropping, adding, or reprioritizing) could be done without further changes to the reference data. If disturbances were wide-ranging, it may be necessary to recreate the Likelihood of Treatment Success products to account for the changes in stressors.

3. Results and discussion

3.1. Products

Through a collaborative effort, land managers, scientists, and GIS analysts developed a methodology for planning the restoration of WBP that prioritizes restoration actions with the goal of establishing an evolutionarily stable population, and persistent and functioning WBP ecosystems over time. The best available science and datasets were synthesized in a flexible, data-informed decision-making process that can be used to plan treatments consistently across large geographic areas. The end-product is an implementation plan identifying the highest priority treatments that can be used to support funding requests and guide work-planning and budgeting (see example in [Supplementary Material A](#)). While following all six steps is recommended, flexibility within the steps provides opportunities for modification (e.g. individual CV factors, stressors, or treatment options could be modified or dropped if not applicable or when data is not available).

This work has contributed to the Whitebark Pine Ecosystem Foundation NWPRP; pilot core areas and planned treatments have been incorporated into the NWPRP (Tombach and Sprague, 2022; Whitebark Pine Ecosystem Foundation, 2018). The pilot approach can be used to guide other land bases outside of the CCE in identification of core WBP restoration areas (e.g. Karau et al., 2020). It can also be adapted to develop restoration plans for other species (e.g. CCE WBP and Limber Pine Restoration Strategy, Summary Report in progress).

3.2. Key advances

In the process of developing the six-step methodology, several key advances were made. First, the methodology accounted for institutional differences among jurisdictions by allowing each jurisdiction to weight the value of the ecosystem services they derive from WBP differently based on their individual mandates and missions. The unique ecosystem services weights for each jurisdiction were then combined at the pixel scale with biological capability weights common to all jurisdictions to calculate CV (Step 2). Biological capability factors are those necessary for WBP to occupy habitat (i.e. establish, survive, and reproduce) (Hall et al., 1997) and were given higher weight than ecosystem services because they were considered to have greater influence on likelihood of restoration success. Because ecosystem services had lower weighting, their use primarily refined where restoration ought to occur within areas where biological capability weight was high.

Further, the six-step methodology recognized the importance of establishing component populations in a landscape network to create evolutionarily stable populations (a metapopulation) when planning restoration of a species in ecosystems where high levels of mortality have occurred. The scarcity of seed resources coupled with the declining population sizes necessitated placing extra focus on conserving genetic resources. Guidance was provided on how to increase genetic diversity when designing reforestation efforts and how to connect component populations in a network so that gene flow could occur between them, resulting in evolutionarily stable populations.

Finally, the Likelihood of Treatment Success Logic model provided a solution for how to incorporate the effects of stressors (i.e., succession, MPB, fire, WPBR, and climate change) into the treatment prioritization process. The Tech Team recognized that treatments focused primarily in high mortality/high stressor areas would have a greater likelihood of higher costs and lower success rates. This approach addressed the logic complexity that a stressor can have both positive and negative impacts depending on treatment type (e.g. high WPBR hazard is negative for planting but positive for cone collection). Likelihood of restoration action success was rated by using individual stressors to evaluate the effectiveness of each treatment type and then treatment limitations (access, slope, and wilderness designation) were added. The best available scientific data was used as input for the logic model. The resulting

likelihood of treatment success layers (i.e. plant, direct seed, Rx burn, thin, daylight, mechanical, cone collection, and pheromone) were used to refine core area designation (Step 5) and were an integral part of the treatment planning and prioritization process (Step 6). As more restoration projects are implemented, results from monitoring of treatment success can be used to update the logic model.

3.3. Lessons learned

Lesson learned 1: The ability to prioritize treatments at scales larger than the jurisdiction is needed. The use of differing ecosystem services weights and datasets by jurisdiction prevented a relative comparison of CV across the full analysis area; core area establishment and treatment prioritization were therefore limited to the jurisdiction scale. The methodology could be modified to allow CV to be compared relatively across the entire analysis area by 1) using consistent datasets and 2) dropping the ecosystem services factors and basing CV on biological capability factors only. Dropping the ecosystem services factors can be thought of as dropping the “human benefits” from CV and including only the biological factors that affect the species’ ability to occupy habitat (i.e. establish, survive, and reproduce). Quantifying CV based on biological capability alone allows a relative comparison of core areas and the prioritization of treatments at the analysis area scale. Ultimately, defining core areas and prioritizing treatments at both the jurisdiction scale and the analysis area scale could be useful as was done for the CCE WBP and Limber Pine Restoration Strategy (Summary Report in progress). Resources that can be shared across jurisdictional boundaries could target accomplishment of the highest priority treatments at the analysis area scale (based on biological capability factors only), while individual jurisdictions would have the option to prioritize their resources in a manner that also considers their missions and mandates (based on biological capability factors and ecosystem services) in the context of the analysis area scale core areas. While it is likely that the jurisdiction scale core areas would have significant overlap with analysis area scale core areas due to the lower weights given to ecosystem services (e.g. 85% overlap between the two in the CCE WBP and Limber Pine Restoration Strategy), the scale and location of their differences would need to be considered when planning restoration treatments.

Lesson learned 2: To incorporate the effects of stressors, a method that combined three stressor classes with two CV classes into six “condition classes” was originally used. This method was eventually discarded because it did not have the ability to consider both positive and negative effects of stressors (CCE High Five Working Group, 2019). Instead, the Likelihood of Treatment Success Logic Model was used to incorporate effects of stressors, which required the three, four, or five stressor classes in [Table 2](#) to be reduced to two impact classes (i.e. lower and higher) ([Table 3A](#)).

Lesson learned 3: Effects of climate change could have been emphasized more by including climate modeling predictions as a biological capability factor. In the pilot methodology, climate change was only considered as a stressor that impacted likelihood of treatment success. It was not considered in CV, so climate modeling had no influence on core area establishment. While the reliability of climate modeling of species distribution is uncertain (Keane et al., 2017a), it would be useful to consider when prioritizing restoration locations. Including climate modeling as a low weighted biological factor, as was done in the CCE Whitebark Pine and Limber Pine Restoration Strategy (Summary Report in progress), would have allowed it to have some influence on where core areas were located while recognizing the uncertainty of future climate predictions.

Lesson learned 4: Prioritizing restoration actions by each treatment type produces better results and a better range of treatment priorities than prioritizing restoration actions by each existing site condition (Step 6- Restoration Action Plan). Prioritizing by eight treatment types is less complex than prioritizing by the almost limitless combinations of site conditions. In addition to being more complex, prioritizing by site

condition (e.g. site prep complete- wildfire) does not ensure a good range of priorities for a particular treatment; the most effective treatment would almost always be a high priority. For example, the planting treatment would be the highest priority treatment in most site conditions in the CCE because of the high levels of mortality. Knowing that planting is a high priority almost everywhere is not useful when trying to determine where to plant; prioritizing by treatment type resulted in a full range of planting treatment priorities and identified the highest priority areas to include in the 10-Year Implementation Plan.

3.4. Additional research needs

How much gene flow occurs between populations? How much gene flow occurs when populations are separated by 7.5 mi (12 km)?

Genetic monitoring of newly established component populations would allow for the detection of any declines in genetic diversity as the newly planted populations mature. In addition, the effective population size (N_e) could be more accurately estimated from the census population size (N_c) using molecular genetic data, rather than using standardized estimated values (e.g. $N_e = N_c * 0.2$; Wang et al., 2020). Currently the relationship between number of maternal and paternal trees used to establish a component population and the effective population size of that population is unclear for WBP. Collecting molecular genetic data would allow for understanding how the effective population size is changing over time- from the newly planted seedlings to saplings. This knowledge would help inform and plan future planting projects, as more will be known about how many maternal trees need to be represented and the density of trees needed to achieve the restoration genetic goals.

In addition, genetic monitoring of existing, mature, populations would allow for a determination of the level of gene flow between populations. Based on biology- particularly the flight distances of nutcrackers (Lorenz and Sullivan, 2009; Lorenz et al., 2011; Tomback, 1978) but also considering the possibility of long-distance pollen travel (Lanner, 1966; Schuster and Mitton, 2000; Smouse and Sork, 2004)- 7.5 mi (12 km) was selected as the critical distance between populations to ensure gene flow. However, molecular genetic studies between populations separated by smaller and greater distances would allow for the quantification of how much gene flow declines with increased distances between populations. This information would allow for the fine-tuning of minimum distances between component populations. It could also vary across the species range, as bird populations and wind patterns of pollen movement are not expected to be the same everywhere.

4. Summary

The methodology for whitebark pine restoration planning described in this paper can be adapted for use anywhere within WBP's range or to distributions of other high elevation five-needle pines. The resulting restoration plans target resource investments to priority areas that have been rigorously evaluated to have the greatest impact and highest likelihood of treatment success, and follow genetic diversity, connectivity, and distribution principles that support the goal of maintaining evolutionarily stable populations. The collaborative nature of the methodology development, with contributions from scientists, local managers, and GIS analysts, was key to its success.

When planning restoration treatments, it is important to follow principles that support the goal of maintaining evolutionarily stable populations. To help reduce inbreeding and promote genetic diversity, it is important to maximize the genetic diversity of planting stock while adhering to agency cone collection guidance. A network of "component populations" that are ≥ 100 ac (40 ha) with ≥ 50 mature trees/ac (124 trees/ha) and located within 7.5 mi (12 km) of another component population is recommended.

The proposed listing of WBP in the U.S. under the Endangered Species Act has brought increased attention to the urgent need for restoration of this keystone species. By following the principles presented,

land management agencies can optimize the benefit of their current investments, while creating a strong foundation to build on as resources become increasingly available and scientific advances are made.

CRediT authorship contribution statement

Melissa B. Jenkins: Conceptualization, Methodology, Resources, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration. **Anna W. Schoettle:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Jessica W. Wright:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Karl A. Anderson:** Methodology, Writing – review & editing. **Joseph Fortier:** Methodology, Software, Validation, Data curation, Writing – review & editing, Visualization. **Linh Hoang:** Conceptualization, Methodology, Data curation, Writing – original draft, Writing – review & editing, Project administration, Funding acquisition. **Tony Incashola Jr.:** Data curation, Writing – review & editing. **Robert E. Keane:** Methodology, Resources, Data curation, Writing – review & editing. **Jodie Krakowski:** Data curation, Writing – review & editing. **Dawn M. LaFleur:** Data curation, Writing – review & editing. **Sabine Mellmann-Brown:** Conceptualization, Methodology, Data curation, Writing – review & editing. **Elliott D. Meyer:** Methodology, Validation, Data curation, Writing – review & editing. **ShiNaasha Pete:** Methodology, Data curation, Writing – review & editing. **Katherine Renwick:** Conceptualization, Methodology, Data curation, Writing – review & editing, Visualization. **Robert A. Sissons:** Conceptualization, Methodology, Data curation, Writing – review & editing, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

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