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Using science management partnerships to develop landscape level indicators and assessments to measure vulnerability of Piñon-Juniper woodlands

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ABSTRACT

The process of identifying tangible actions to conserve important resources in the face of climate change is challenged because of uncertainties regarding future conditions. There is also a lack of existing methods for evaluating the effectiveness of proposed management actions for mitigating negative impacts. For piñon-juniper (PJ) ecosystems within the Southwest U.S., efforts are further hampered by a lack of information on the direction and drivers of changing population trends. PJ ecosystems, while ecologically important, have been the focus of eradication efforts due to perceptions that they are encroaching into important grasslands. However, recent impacts of drought, insect outbreaks, and fire increasingly threaten these ecosystems. It is unclear at this time where and to what extent PJ ecosystems are vulnerable to climate change and other disturbances, challenging management. To develop a method for determining the current and future status of PJ ecosystems, we engaged with local land managers to identify key indicators and drivers of PJ population change and developed a vulnerability assessment approach based on these indicators. Our goal was to use this process to create data products that would assist resource managers dealing with rapidly changing landscapes. Borrowing from other successful assessments strategies, we used Adaptation Forums to facilitate stakeholder input to vet potentially relevant indicators of PJ status and response to climate change and other stressors. Through multiple iterations, we finalized a list of indicators that could be used to quantify vulnerability of PJ ecosystems. We then developed a vulnerability assessment framework that can systematically quantify risks to PJ based on these indicators and applied this framework to two landscapes in the southwestern U.S. This process allows us to support decision making processes by generating information on future PJ status even when data are incomplete.

1. Introduction

Natural resource managers must balance the need to provide ecosystem services in the near term with the development of long-term strategies to maintain ecosystem function and reduce ecosystem degradation. Additional complexities that arise as a result of historic land management practices, inherent variation in ecological systems, and climate change further challenge the conservation of ecosystems. To successfully manage diverse landscapes under an uncertain future, scientists and managers must engage in collaborative approaches to develop methods for resource evaluation and to design management strategies that are effective across multiple jurisdictions (Beier et al., 2017). A prime example can be found in the western U.S. where there is an urgent need to identify how piñon-juniper woodlands will respond to climate and other disturbances in order to inform woody species management.

Increased abundance and density of woody plants into what were formerly grassland and shrublands has been a major concern in many areas of the western U.S. (e.g. Coates et al., 2017; Carroll et al., 2017). These shifts have been attributed to recovery from disturbance, natural

Abbreviations: SRLCC, Southern Rockies Landscape Conservation Cooperative; RMRS, Rocky Mountain Research Station; CNHP, Colorado Natural Heritage Program; SWAP, State Wildlife Action Plans; FC, Four Corners; URG, Upper Rio Grande; VA, Vulnerability Assessment; E, Exposure; S, Sensitivity; AC, Adaptive Capacity

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range expansion, livestock grazing, climatic variability, elevated CO_2, and fire suppression (Neely et al., 2001; Romme et al., 2009; Swetnam et al., 2016). Woody plant encroachment has long been considered a problem by ranchers who want to maximize forage production and conservationists who want to maximize grassland diversity. As a result, historical management practices for rangelands includes deliberate removal of trees, by means of mechanical, chemical, or fire treatments. Native piñon–juniper (PJ) woodlands have often been a target of these efforts. However, it is not clear that methods for woody species removal fully achieve management goals and discrepancies between short- and long-term flora and fauna responses to treatment call for additional research (Archer, 1996). In addition, there is increasing push back on the notion that PJ ecosystems are undesirable or have negative impacts where they occur (e.g. Davenport et al., 1998; Madsen et al., 2008; Jacobs, 2015). A lack of consensus in the scientific literature as well as a general lack of information for PJ in some parts of its range, challenges resource managers who must plan for changing landscapes under changing climate.

Uncertainty exists regarding the drivers and direction of PJ expansion. Notable examples of PJ expansion have been observed for shrublands in the Great Basin (Neely et al., 2001) and, since 1850, PJ is estimated to have increased by 20% in the Colorado Plateau (Tuhy et al., 2002) and by 10% in the lower southern Rockies (Neely et al., 2001). Since the early 1950's, many PJ woodlands have also experienced infilling, increased tree density, and increased canopy cover within its existing range (Romme et al., 2008; Carroll et al., 2017). However, within the Southwest, several recent analyses show significant declines in existing PJ stands and, in particular, piñon trees. Marked contractions of PJ have been noted for areas in Colorado, New Mexico, and Arizona (Manier et al., 2005; Shaw et al., 2005; Clifford et al., 2011; Arendt and Baker, 2013) due to a combination of drought induced stress, outbreaks of piñon Ips bark beetle (*Ips confuses*) (Breshears et al., 2005), and cheatgrass invasions that have shortened fire return intervals (Arendt and Baker, 2013). Mortality in the Colorado Plateau (Coconino National Forest) during the 2002–2004 drought exceeded any gains in canopy cover from the preceding decades (Clifford et al., 2011) and mortality rates of piñon has been particularly high (30–65%) in the Four Corners region (Shaw et al., 2005). Some observed contractions may relate to increased tree density as a result of infill, which has left piñon stands more prone to drought related die-offs (Floyd et al., 2015). However, recent evidence does not support an entirely density dependent mechanism (Meddens et al., 2015).

Research is also mixed on the ecological role of PJ in western ecosystems. On one hand, PJ expansion and increased tree density are associated with undesirable declines in understory cover of shrubs and native perennial grasses, and associated changes in wildfire regimes, soil stability, and species composition (Jacobs and Gatewood, 1999; Jacobs, 2015; Carroll et al., 2017). Accelerated rates of soil erosion (Davenport et al., 1998) and reduced subsurface available water have also been attributed to increases in piñon and juniper vegetation (Carroll et al., 2017, though see Madsen et al., 2008). On the other hand, PJ is known to play an important role for both plant and animal communities. Piñon and juniper trees create islands of high fertility soils by accumulating soil moisture, organic material, and nutrients beneath their canopies (Barth, 1980; Nielson, 2009) and may increase water retention in some areas (Madsen et al., 2008). Additionally, piñon-juniper woodlands provide valuable cover, food, and nesting sites for many wildlife species (Gallo et al., 2016; Bombaci and Pejchar, 2016) supporting high wildlife diversity comparable to that found in riparian and aspen forests (Bombaci and Pejchar, 2016). In Colorado alone, PJ woodlands support 67 species of greatest conservation need and 39% of species that use PJ are obligate or semi-obligate (Paulin et al., 1999; CO SWAP, 2015).

Climate changes within the southwestern U.S do not appear to favor the persistence of PJ ecosystems. Climate conditions directly impact piñon and juniper survival and regeneration and indirectly influence PJ distributions via effects on fire regimes and beetle attacks (Rehfeldt et al., 2006; Keane et al., 2009; Romme et al., 2008). Models project both increasing and decreasing climate suitability for PJ in areas of the Southwest and a reduction of co-occurring piñon and juniper species in some areas (Rehfeldt et al., 2006; Keane et al., 2009; Romme et al., 2008; Appendix C). However, in general, widespread loss of trees is expected under warmer and dryer conditions (Allen and Breshears, 1998; McDowell et al., 2008; Park Williams et al., 2013; Anderegg et al., 2013; Allen et al., 2015; Clark et al., 2016) and climate models generally project warmer and more arid conditions in the SW (Seager et al., 2007; Park Williams et al., 2013). Though precipitation projections are less certain, models indicate that without significant increases in precipitation that can compensate for increased water usage associated with higher temperatures, there is likely to be a net reduction to surface water, soil moisture, and water availability (Dai, 2013) and with this decline, PJ is also likely to suffer (Ronco, 1990; Thompson et al., 1998; Pearson et al., 2002; Cole et al., 2008a,b; Redmond et al., 2012; Allen et al., 2015; CO SWAP, 2015; Floyd et al., 2015; Clark et al., 2016). Specifically, PJ is expected to decline under the interaction of warmer temperatures, drought, insect outbreaks, and fire disturbance (Ronco, 1990; Thompson et al., 1998; Pearson et al., 2002; Cole et al., 2008a,b; Redmond et al., 2012; Allen et al., 2015; CO SWAP, 2015; Floyd et al., 2015; Clark et al., 2016).

Uncertainty about patterns of PJ expansion and contraction and trends under future climate trajectories reflect the interplay between large scale top down processes and locally variable bottom up processes. The complexity of these systems and pressure to provide ecosystems services, challenges resources managers who must determine the most appropriate management actions for the arid rangelands of the western U.S. As a result, there is an increasing call for better information on the current status of PJ communities as well as a process for measuring future impacts that can directly inform management practices (Rondeau et al., 2017). In particular, managers need spatially explicit products that provide a rapid method for viewing relative impacts across large landscapes to determine where PJ is likely to persist into the future, as well as areas vulnerable to type change. Vulnerability assessments (VA) are a key step toward identifying effective management strategies and prioritizing specific management actions to conserve and restore natural resources, even under conditions of uncertainty (Füssel, 2007; IPCC, 2007). The most effective vulnerability assessments are tailored to address specific objectives of resource managers or others who will use the information for management decisions (Friggens et al., 2013). Therefore, to ensure research and assessment products are relevant to resource management decisions, early and consistent engagement with managers is necessary (Beier et al., 2017). With this in mind, we worked with a multi-agency partnership organized by the Department of Interior's Southern Rockies Landscape Conservation Cooperative (SRLCC), to identify a set of spatially explicit indicators that could be used to measure PJ ecosystem status and threats. Then, through an iterative process, we developed an assessment framework to estimate PJ vulnerability based on these indicators and applied this system to two landscapes within the SRLCC boundary. Given the nature of the uncertainties surrounding PJ ecosystems, our objective was to develop a set of PJ vulnerability indicators and assessment products that enable land managers to make decisions based on local conditions as well as regional climate change projections. These two case studies allowed us to test our application of indicators in a landscape scale assessment and assess the capacity of the vulnerability assessment framework to facilitate identification of cross jurisdictional management strategies. In this paper, we describe the collaborative process we used to identify and vet potential indicators of vulnerability, present a framework for using those indicators to assess PJ vulnerability, and demonstrate its application for predicting current and future PJ vulnerability within landscapes in the Southwest with the intent to inform resource management decision making processes.

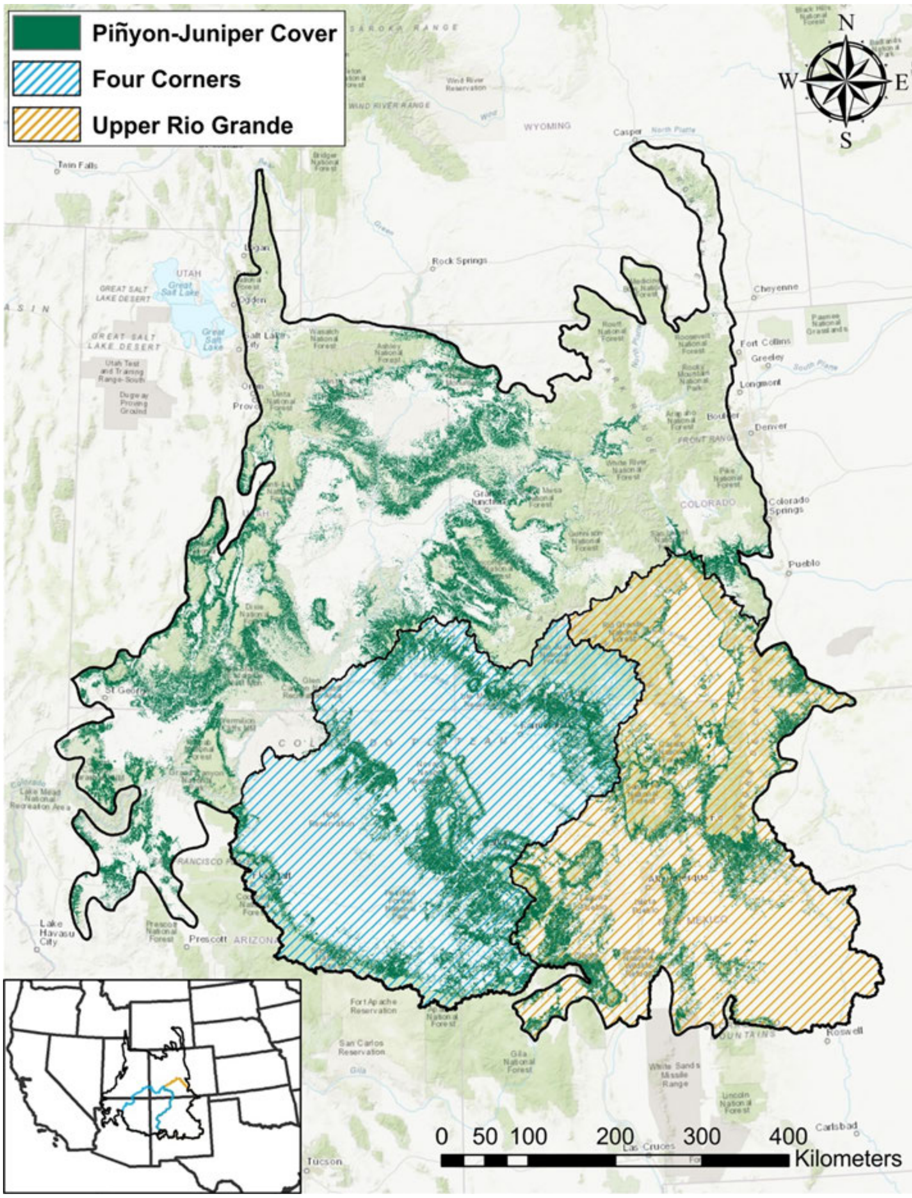

Fig. 1. Piñon-Juniper cover within the SRLCC boundary. PJ cover is estimated from LANDFIRE Existing Vegetation Layers. See Methods 2.4 for the specific plant communities used to create this layer. PJ vulnerability was assessed for two landscapes within this boundary, the Four Corners and the Upper Rio Grande.

2. Methods

2.1. Study area and ecosystems

Occurring in the transitional zone between lowland grassland and shrubland ecosystems and mountain conifer ecosystems (1370–2290 m), piñon-juniper ecosystems (PJ) consist of evergreen pines and junipers with other shrubs, grasses, and forbs (Gori and Bate, 2007; Nielson, 2009). Our case study analysis focused on two landscapes, the Four Corners (FC) and the Upper Rio Grande (URG), within the Southern Rockies Landscape Conservation Cooperative (SRLCC) boundary (Fig. 1, See Section 2.2). Within our study landscape, the most common piñon tree, Colorado or two-needle piñon pine (*Pinus edulis, PIED*) is found with one-seed juniper (*Juniperus monosperma*), Utah juniper (*Juniperus osteosperma*), Rocky Mountain juniper (*J. scopulorum*), and alligator juniper (*J. deppeana*). Of the four PJ types present within our study area (Board et al., 2013), Colorado Plateau PJ Shrubland, Colorado Plateau PJ Woodland, Southern Rocky Mountain PJ woodland, and Southern Rocky Mountain Juniper Woodland and Savanna (U.S. Geological Survey (USGS), 2011 National Gap Analysis Program Land Cover Data), this assessment primarily focuses on the PJ woodland types, which are estimated to comprise nearly 40 million hectares in the western U.S. (Romme et al., 2009). For a more detailed description of piñon-juniper ecosystems within the study area, see Friggens et al. (2018).

2.2. Co-production method

We identified relevant indicators of PJ status and vulnerability in partnership with the Department of Interior's Southern Rockies Landscape Conservation Cooperative (SRLCC, https://lccnetwork.org/about/about-lccs). The SRLCC was formed to provide science capacity and technical expertise to meet the shared needs of stakeholders within the SRLCC boundary, which encompasses over 127 million acres and covers portions of Arizona, Colorado, New Mexico, Utah, and Wyoming (Fig. 1). As part of their goals, the SRLCC formed an interagency steering committee and coordinated meetings and discussions among federal, state, and local governments, tribes and first nations, and nongovernmental organizations to identify common priorities and needs within the region. From 2015 to 2018, the SRLCC facilitated several webinars and in-person meetings to gather SRLCC members for the purpose of identifying science based products to facilitate collaborative decision making among the various represented agencies. As part of the process to develop shared goals for local stakeholders in the SRLCC area, SRLCC staff and steering committee members identified focal resources, including PJ, within three focal landscapes. In 2016, the Rocky Mountain Research Station began to develop vulnerability assessment products for SRLCC focal resources in two of those landscapes: the Four Corners (FC) and Upper Rio Grande (URG) (Fig. 1). Resulting assessment products addressed two key goals of the LCC: 1) providing integrated science-based information about the implications of climate change and other stressors for resources; 2) facilitating the exchange of applied science in the implementation of conservation strategies. The RMRS identified relevant indicators, produced datasets, and developed a vulnerability assessment framework for five focal resources: this paper describes the efforts related to piñon juniper (PJ) ecosystems. The specific assessment approach used in the analysis of PJ was designed to provide SRLCC stakeholders with the capacity to identify shared conservation priorities and goals.

We used an iterative process based on engagement with stakeholders (local resource managers) to guide our selection of indicators and the development of an assessment framework that would translate those indicators into a meaningful and spatially explicit representation of vulnerability. The SRLCC held two series of Adaptation Forums attended by local stakeholders for each landscapes (Table 1) to further refine goals and inform the assessment process (Grunau, 2016, Friggens and Hawksworth, 2018). From an initial series of Adaptation Forums held in Durango, Colorado and Albuquerque, New Mexico in 2016 we were able to solicit stakeholder input on the utility of assessment products and begin to evaluate potential indicators representing threats and issues (Grunau, 2016). Participants listened to several presentations and then engaged in break out group discussions to identify and refine focal targets for assessment, key issues and threats within the landscape, and share relevant research and data produced by stakeholders (Grunau, 2016). It was at these Forums that piñon-juniper ecosystems were identified as an important resource needing additional assessment. Following these discussions, we formed a method to assess vulnerability of PJ based on current assessment processes (see Section 2.4) that could produce spatially explicit representations of vulnerability and also leverage existing data produced by SRLCC partners. We presented the preliminary assessment products via a series of webinars (recordings available here: https://www.fs.usda.gov/rmrs/science-spotlights/co-producing-landscape-scale-vulnerability-assessments) and used a second series of Adaptation Forums, held in Taos and Albuquerque, NM in 2017, to critique indicator datasets and assessment outcomes, and explore potential applications of assessment products (Friggens and Hawksworth, 2018). Through breakout group discussions and flip chart exercises, participants discussed and ranked individual indicators based on perceived urgency and importance of indicator (Friggens and Hawksworth, 2018, See Section 3.1). Feedback from SRLCC stakeholder input was incorporated into the final vulnerability assessments for each landscape.

Table 1
Number of individuals from local, state, federal and non-governmental agencies that participated in each of four Adaptation Forums. Federal agencies from the U.S. Department of Agriculture (USDA), Department of Defense (DOD), and U.S. Department of Interior are listed in alphabetical order. 2016 Adaptation Forums were facilitated by staff from the Colorado Natural Heritage Program (CNHP, Grunau, 2016). 2017 Adaptation Forums were facilitated by SRLCC and RMRS staff (Friggens and Hawksworth, 2018).

	Upper Rio Grande Forums		Four Corners Forums	
Affiliation	**2016**	**2017**	**2016**	**2017**
University	4	2	2	2
Non-Governmental Organization/ Consultants*	2	4	9	9
Native American Tribes	3	3	2	5
State	1	1	4	
Federal				
Agricultural Resource Center (USDA)			1	
Bureau of Indian Affairs (DOI)	1	1	3	
Bureau of Reclamation (DOI)	1	2		3
Bureau of Land Management (DOI)	2		3	
Fish and Wildlife Service (DOI)	3	1	2	1
National Park Service (DOI)	1	1	2	2
Natural Resource Conservation Service (USDA)			1	
U.S. Army Corps of Engineers (DOD)	2			
U.S. Forest Service (USDA)	2	6	3	3
U.S. Geological Survey (DOI)	8	1	4	3
USDA Climate Hub (USDA)	1			
Total	31	22	36	28

*e.g. Querencia Environmental, Chama Peak Land Alliance, ERO Resources.
**Includes (as listed by participant): Laguna Pueblo, Navajo Nation, Jicarilla Apache Nation, Kewa Pueblo, Pueblo of Acoma, Pueblo of Sandia, Pueblo of Tesuque, Southern Ute Indian Tribe, Ute Mountain Ute Tribe.

2.3. Data

We identified indicators that could be used to estimate vulnerability by quantifying the collective impact of exposure and sensitivity weighted against potential adaptive capacity (Friggens et al., 2018, Fig. 2, See Section 2.4). To be useful for application in a spatially explicit vulnerability analysis, we outlined these additional required criteria for indicators: 1) Indicator information was available for the full extent of the study area and could logically be summarized at a HUC12 unit; 2) Empirical evidence or stakeholder input (expert opinion) linked indicator to PJ condition or response; 3) A threshold value of effect vs no effect could be determined within the range of indicator values. Our final indicator data set is based on an extensive review of primary literature, other assessments and reports (AZ SWAP, 2012, CO SWAP, 2015, NM SWAP, 2016, Rondeau et al., 2017), and limiting factors discussed by managers at the 2016 Adaptation Forum workshops. The

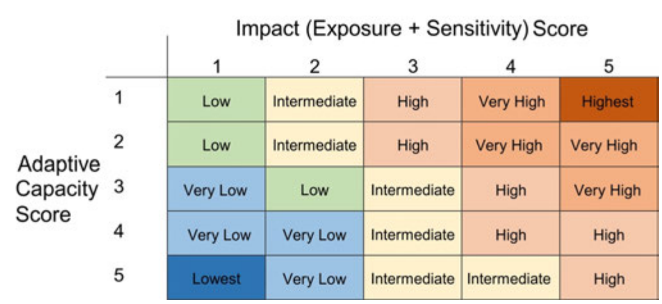

Fig. 2. Methodological Framework for Estimating Pinon Juniper Vulnerability. A matrix is used to link Impact and Adaptive Capacity Scores and determine HUC12 Vulnerability Class. Indicators (See Section 3.1 Table 3) are summed to give total scores for Exposure (E), Sensitivity (S), and Adaptive Capacity (AC). Exposure and Sensitivity are added together to represent Impact (I) and all values are rescaled to a 1–5 range. Impact increases as values increase along the horizontal and Adaptive Capacity increases as values increase along the vertical. Vulnerability is determined by the relative I versus AC of PJ according to these potential combinations. For instance, a HUC12 with I = 1 and AC = 5 is classified as having the lowest vulnerability, whereas a score of I = 5 and AC = 1 would result in that HUC12 being classified as having the highest vulnerability.

final dataset includes indicators that represent both threats to PJ ecosystems as well as traits or conditions that might influence how PJ will respond (positive or negative) to stressors (see Section 3.1). Each indicator was summarized by the HUC12 (hydrologic unit code) watershed unit because this provided a local sub-watershed level of analysis that was considered to have practical applications to management decision making processes (see Appendix A).

We created a spatial datalayer of all HUC12 within the two study landscapes that had at least 10% combined cover of one of the following LANDFIRE Existing Vegetation Types (EVT) representing PJ plant communities: 3011 – 'Rocky Mountain Aspen Forest and Woodland', 3016 –'Colorado Plateau Piñon-Juniper Woodland', 3019 – 'Great Basin Piñon-Juniper Woodland', 3025 – 'Madrean Piñon-Juniper Woodland', 3049 – 'Rocky Mountain Foothill Limber Pine-Juniper Woodland', 3059 – 'Southern Rocky Mountain Piñon-Juniper Woodland', 3115 – 'Inter-Mountain Basins Juniper Savanna', 3116 – 'Madrean Juniper Savanna', 3119 – 'Southern Rocky Mountain Juniper Woodland and Savanna'. A total of 1,630 HUC12 within the study areas fulfilled this criterion and were the focus of this vulnerability assessment.

In anticipation of additional assessments within the SRLCC boundary, indicator data were created for the entire SRLCC area and are available as maps or individual shapefiles at: https://www.sciencebase.gov/catalog/item/5693e56ee4b09c7f9a21a41d

2.4. Assessment framework

Vulnerability assessments take a wide range of forms and approaches (Glick et al., 2011). Assessment of climate change vulnerability typically considers three elements: exposure, sensitivity, and adaptive capacity (Glick et al., 2011; Table 2). Our PJ assessment framework is based on a set of definitions and criteria that are inclusive and adaptable to multiple scales of assessment (Table 2) reflecting stakeholder desires for products that are amendable to multiple uses and objectives.

We used a multistep process to translate spatial indicator datasets into quantified maps of vulnerability for each of the 1,630 HUC12 containing at least 10% PJ cover (Section 2.3). First, we determined whether each indicator dataset more appropriately measured exposure, sensitivity, or adaptive capacity (Table 1). We assigned each dataset a specific role as either contributing to (through exposure or increased sensitivity) or reducing (via adaptive capacity) vulnerability of PJ. These decisions were made based on our understanding of where a particular measure would provide the most meaningful output as well as input from Adaptation Forum participants.

Second, we assigned each HUC12 within our study landscape a value of 1 (effect) or 0 (no effect) based on whether a predetermined threshold of effect was reached (Table 3, Section 3.1). A threshold of effect was based either on observed impacts or using a method that would distinguish between most and least affected HUC12 (e.g. percentiles) (Appendix A). For instance, previous research has determined drought related mortality increases substantially where soil available water storage values are less than 150 mm (Peterman et al., 2013; see Appendix A). Therefore, if a HUC12 contained any soils with low Available Water Content (AWC), it was assigned a value of 1, indicating greater sensitivity. Individual maps showing the distribution of affected (=1) HUC12 for each indicator can be found in Appendix B. Discussions during the 2017 Adaption Forum that focused on indicator importance did not provide consensus that could be translated into a weighting scheme and, thus, all indicators are considered equally important. Third, cumulative scores for each exposure, sensitivity, and adaptive capacity were generated by summing the individual HUC12 1/0 scores (see Friggens et al., 2018 for more details). Total impact was estimated by adding together sensitivity and exposure scores (E + S = Impact) and rescaled to a 1–5 value. Adaptive capacity scores were similarly rescaled to 1–5.

Finally, vulnerability classes were assigned to each HUC12 by visually comparing the impact scores with adaptive capacity scores using a matrix (Fig. 2).

3. Results

3.1. Indicators

Seventeen indicators fit our criteria for use as metrics of piñon-juniper vulnerability (Table 3). Our final indicator dataset represents outcomes of both literature based investigation and SRLCC stakeholder input from the second series of Adaptation Forums (Table 4, Friggens and Hawksworth, 2018). Exposure considers the proximity or percent area of known sources of disturbance or threats as well as the degree to which a watershed might be affected by a disturbance agent (Table 3). Sensitivity considers the presence of disturbances, associated species richness, current cover of PJ, and soil available water storage capacity (Table 3). Those areas with the highest value are considered most sensitive to disturbances that may cause declines in PJ or PJ related attributes. Adaptive capacity considers measures that indicate increased coping capacity (Table 3). Appendix A provides a comprehensive review of the literature and processing steps for each of these indicators.

3.2. HUC12 vulnerability

Overall, across the study areas, most HUC12 (50%) were classified as having low cumulative Exposure (E), Sensitivity (S), and Adaptive Capacity (AC) (Fig. 3). Approximately 20% of HUC12 had moderate or

Table 2
Framework based on Exposure-Sensitivity-Adaptive Capacity for assessing vulnerability of PJ in the Southern Rockies Landscape Conservation Design.

Definition	Examples	Indicators
Exposure		
External threat to the target species, system, or place	Human ImpactsNatural disturbancesClimate change	Urbanization Wildfire potential Magnitude departure in temperature
Sensitivity		
Qualities that make the target more susceptible to negative impacts from disturbance or threat	Traits associated with increased negative response Indicators of potential cost of disturbance	Narrow physiological threshold Current departure from reference condition Presence of threatened and endangered species High value watersheds
Adaptive Capacity		
The ability of the target to cope with disturbance or threat	Traits/conditions associated with resilience Potential for successful management intervention	Wide physiological tolerance Diverse prey base Capacity to implement conservation action (e.g. land ownership profile) Effective management options available (e.g. thinning can alter wildfire outcome)

Table 3
Description of 17 indicators used to estimate piñon-juniper vulnerability. Indicator data values were calculated for 1,630 HUC12 watersheds in the study. Data was generated for current and, when available, two future time periods (2030, 2060). Threshold values were used to assign each HUC12 a value of 1 or 0, which were then combined to estimate vulnerability. Percent of HUC12 within each focal area, Four Corners (FC) and Upper Rio Grande (URG), designated as "1" for a given indicator are given in the right most columns.

Description	Threshold values used in case studies	% FC	% URG
Exposure Indicators			
1. Change in the mean maximum temperature in the warmest month 2030, 2060 (Rehfeldt, 2006)	Increase > 1.8 degrees C° = 1	82	19
2. Change in the percent of total normal winter precipitation (Nov-Feb) 2030, 2060 (Rehfeldt, 2006)	< 100 percent = 1	82	31
3. Change in Development, 2040 (U.S. Geological Survey, 2005)	Increase present within HUC12 = 1	46	42
4. Road Density (U.S. Census Bureau, 2016)	> 25th percentile = 1	16	38
5. High to Very High Fire Potential (Dillon, 2015)	High or Very High present = 1	20	26
6. High Risk of Insect and Disease (Weidner and Todd, 2011)	> 0 = 1	34	39
7. Change in Suitable Climates for Great Basin Conifer Woodlands, 2030, 2060 (Rehfeldt et al., 2012)	Loss > 30 percent = 1	24	3
Sensitivity Indicators			
8. Energy (oil & gas wells, solar) (FracTrackerAlliance, 2015; New Mexico State Land Office, 2017)	Present = 1	20	6
9. Medium to High Intensity Development (Homer et al., 2015)	Medium or High Present = 1	38	36
10. Mechanically Disturbed Forest (USGS LULC cover, accessed in 2018)	Present = 1	9	20
11. Current Cover of Piñon-Juniper Woodlands (LANDFIRE, 2014)	< 30 percent = 1	48	64
12. Wildlife Diversity, n = 17 (U.S. Geological Survey, Gap Analysis, 2018)	> 12 species = 1	6	49
13. Available Water Storage Capacity less than 0.10 (Peterman et al., 2015)	> 0 km^2 = 1	28	9
Adaptive Capacity Indicators			
14. Change in Suitable Climates for Great Basin Conifer Woodlands (Rehfeldt et al., 2012)	Increase > 30 percent = 1	31	23
15. Current Cover of Protected Areas (U.S. Geological Survey, Gap Analysis Program, 2016)	> 30 percent = 1	37	51
16. Current Cover of Piñon-Juniper Woodlands (LANDFIRE, 2014)	> 60 percent = 1	14	8
17. Low to Very Low Fire Potential (Dillon, 2015)	Low or Very Low = 1	8	5

high E and S. Less than 2% were considered to have high AC. Still, 2/3 of the HUC12 were classified as having intermediate or greater vulnerability to future decline (Fig. 3). These patterns were driven by the interplay of E and S which drive increased vulnerability and AC, which decreases vulnerability. High or Very High E and S scores were most commonly associated with High vulnerability designations. Concurrent low S, E, and AC cumulative scores for a given HUC12 typically resulted in a vulnerability classification of intermediate. No HUC12 had concurrent high or very high scores for S, E, and AC. Among HUC12 with an AC score of high or very high, most were classified as having very low vulnerability).

Significant variation in scores for exposure, sensitivity, adaptive capacity, and vulnerability existed across the study areas (Fig. 3). The FC area generally had higher exposure scores and the URG had higher sensitivity scores. In general, URG watersheds scored as having lower expected impact (exposure + sensitivity) than watersheds within the FC. The result was that both areas had a similar number of highly (high, very high, highest) vulnerable watersheds though the URG had more

Table 4
Summary of outcomes of discussions for Piñon-Juniper indicator data at the 2017 Adaptation Forums held in the Four Corners and Upper Rio Grande Focal Areas. E, S, and AC indicate exposure, sensitivity and adaptive capacity variable, respectively. During each Forum, participants were asked to assess each indicator based on the importance and the urgency of the issue represented by the indicator. From this, participants discussed which indicators should be dropped (Column A), added (B), kept (C) or reassessed (D; e.g. to change threshold effect value). Changes implemented are noted in bold print. A lack of suitable data prevented the addition of many suggested indicators (Column C, See Section 4.1 for discussion). For further information regarding the preliminary products assessed during the forum and final decisions for follow-up action, please refer to Friggens and Hawksworth (2018).

A. Drop	B. Add	C. Keep	D. Change/Assess
FC			
1. **Mechanical disturbance (E)** 2. **Impervious surfaces (S)**	1. Energy Development (E) 2. ID areas where proactive post-disturbance restoration has a higher probability of success (AD) 3. Probability of suppression success (AD) converse of fire risk	1. Development (E) 2. Loss of GB woodland (E) 3. Insect and disease (E) 4. Wildfire Risk (E) 5. Water capacity (S) 6. Current Intensity Development (S) 7. Gain in GB woodland (AD) 8. PJ cover (AD)	1. Road density 2. Mean max temp (E) 3. **Presence of associated wildlife species (S)** 4. **Mechanical disturbance (S)** 5. PJ cover(S)
URG			
1. **Fish and Wildlife Service Critical Habitat (S)**	1. How far departed is it from its "natural" (S) 2. Syro-stage (S or AD) 3. **Winter precipitation (E)** 4. Piñon Jay Nest Colony Presence (S)	1. Change in Mechanical Disturbance(E) 2. Change in Development(E) 3. Insect and Disease Risk (E) 4. Road Density (E) 5. Mean Max Temperature of Warmest Month (E) 6. Low Available Water Capacity (S) 7. Current Intensity Development (S) 8. Impervious Surfaces (S) 9. Mechanical Disturbances (S) 10. Percent PJ (AD) 11. Protected Areas (AD) 12. Gain in GB Woodland 2030 (AD)	1. Change in Development (E) 2. Loss of GB Woodland Climates (E) 3. Wildfire Risk (E) 4. **Presence of Associated Species (S)** 5. PJ Cover (AD)

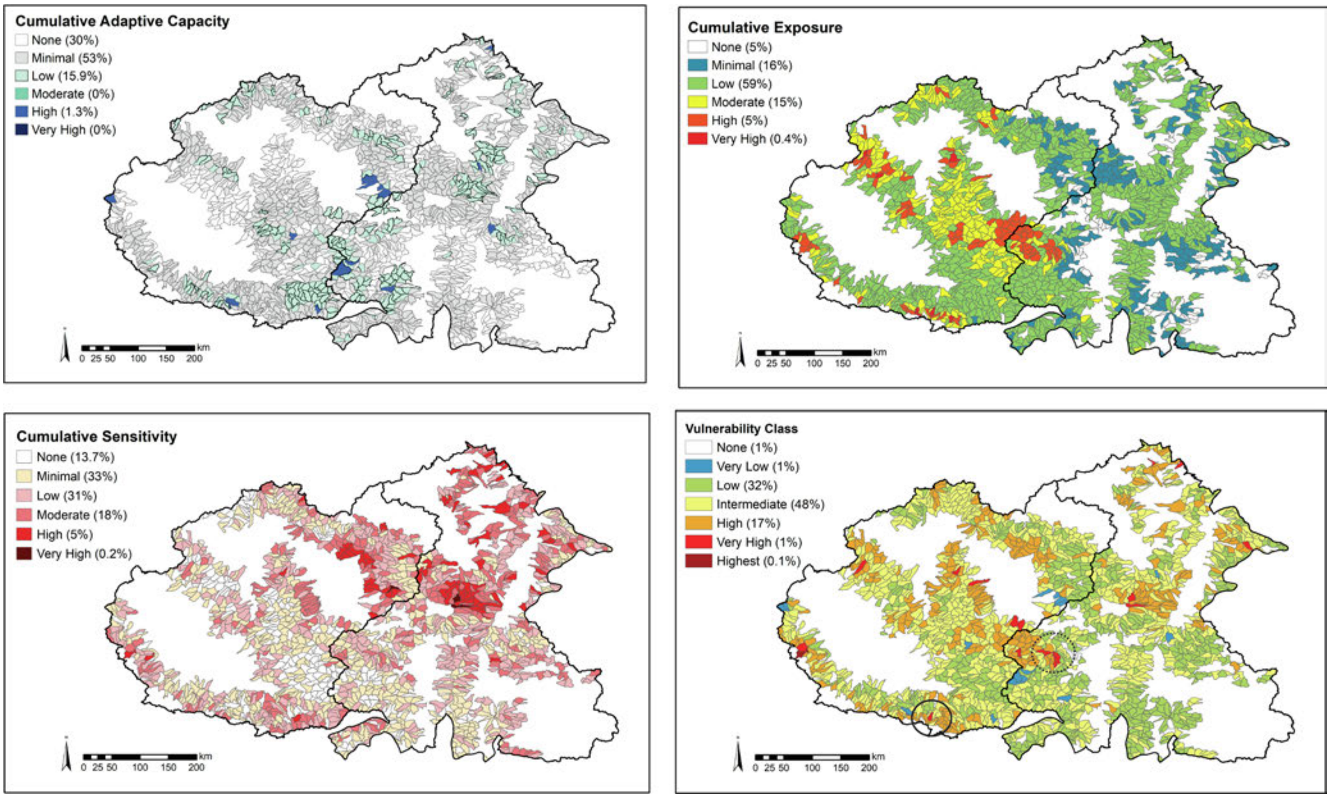

Fig. 3. Vulnerability Assessment Classes for PJ in 1,630 HUC12 watersheds in two study areas (black lines). Cumulative score category (with % HUC12 classified in that category) is shown for Adaptive Capacity (AC), Exposure (E), Sensitivity (S) and Overall Vulnerability. E and S are overlaid to create a measure of Impact (I, See Section 2.4) and is compared to AC using the vulnerability scoring matrix (Fig. 2) to generate the final Vulnerability designations seen here. HUC12 with less than 10% PJ cover (see Section 2.3) were not considered in this analysis and blank areas represent these low cover areas. Vulnerability panel indicates area surrounding Show Low, AZ (solid circle) and El Malpais National Conservation Area, NM (dotted circle).

HUC12 classified as having low vulnerability. The issues driving these trends were unique for the FC and URG. Climate changes, climate related declines in suitable habitat, and energy development were all greater threats for PJ within the FC, whereas URG vulnerability relates more to issues related to road density, relatively low total area of PJ, and high wildlife diversity (Table 2, Appendix B).

Within the URG, watersheds in the northern extent typically had higher sensitivity scores than those to the south. During the final report out to Forum participants, these results were overlaid with geographic references to identify specific landmarks at high risk or of potential conservation opportunity (Fig. 3). Overall, results were fairly localized to individual watersheds and it was not uncommon to find adjacent watersheds with different vulnerability classes. For instance, areas near Show Low, Arizona (solid circle, Fig. 3) contain HUC12 classified with very high vulnerability adjacent to HUC12 with very low vulnerability scores. Through examination of Fig. 3 and Appendix B, we see that different scores are driven almost entirely by different levels of exposure to threats and issues: all HUC have similar low or minimal AC scores, but highly vulnerable HUC12 have a greater number of potential E issues. Similarly, the watersheds near El Malpais National Conservation Area (dotted circle, Fig. 3) have some of the highest and lowest scores in the URG. Here differences are driven by factors relating to both higher E and higher S scores. Specifically, highly vulnerable HUC12 near El Malpais had higher road density and increased development and less PJ cover and publically owned land than less vulnerable neighbors (Appendix B).

Datasets, vulnerability analyses, recorded webinars and workshop presentations, and reports associated with the development of indicator datasets and vulnerability assessments are permanently housed here: https://www.sciencebase.gov/catalog/item/5693e56ee4b09c7f9a21a41d.

4. Discussion

4.1. *Measuring Piñon Juniper vulnerability and resilience*

Despite a large number of papers describing studies of PJ (Miller et al., 2019), there is no consensus regarding current and future PJ trends. Piñon-juniper ecosystems have benefited from human related activities in the western U.S. though the degree to which these benefits have resulted in the establishment of new persistent woodlands varies according to the geographic region considered. Though recent expansion demonstrates resilience, PJ is recognized as facing multiple issues including wildfire, human disturbance, and invasive grass species, by states that considered PJ important wildlife habitat (Tausch, 1999; Gruell, 1999; AZ SWAP, 2012; CO SWAP, 2015; NM SWAP, 2016; Friggens et al., 2018). PJ ecosystems are also highly susceptible to widespread die-off due to the collective stress of drought and insect infestations, issues that are expected to increase under climate change (Seager et al., 2007; Dai, 2013). Though these impacts are not felt equally by the piñon and juniper species comprising these ecosystems (Redmond and Barger, 2013), recent research and this assessment indicate that the collective piñon-juniper woodland ecosystem within the southwestern U.S. is at risk under continued drought, climate warming, and other land use factors (Cole et al., 2008b; McDowell et al., 2016; Rehfeldt et al., 2012; Allen et al., 2015). Recent efforts to model climate suitability for PJ in the West and in our study areas cast doubt as to whether these ecosystems will persist into the future (e.g. McDowell et al., 2016; Rehfeldt et al., 2012; Allen et al., 2015). Other studies predict both positive and negative changes throughout the range of PJ (Cole et al., 2008b; Clark et al., 2016). Still others cite possible benefits for PJ woodlands from increased precipitation, earlier spring greening, longer growing season, and increased CO_2 (Miller and Wigand, 1994;

Miller et al., 2008; Allen et al., 2015; Settele et al., 2014). However, it remains unclear whether these drivers will favor PJ enough that they offset losses in some areas. What is clear is that potential declines in PJ due to range shifts and tree mortality could have long-term implications because once lost, the mature PJ woodlands critical to many wildlife species are unlikely to return in our lifetime (Cole et al., 2008a).

Through a collaborative process, we developed a system comprised of landscape-scale indicators and a flexible vulnerability assessment framework that can be used to prioritize and inform management actions even in the absence of perfect knowledge. This system was successfully applied to PJ within two landscapes where we show impacts from identified threats and issues will exceed potential adaptive capacity and result in high vulnerability. We also found many areas that appear to have relatively low risk of future decline in PJ and may represent potential refugia. Importantly, this assessment considers PJ ecosystems in the heart of an area that has experienced dramatic die-offs in recent years. Analysis of the underlying combination of indicators contributing to a high vulnerability score provides us with several observations (Fig. 3; Appendix B), and we note that the specific issues driving vulnerability in watersheds were unique to each of the study areas. While both areas are expected to experience similar increases in development and risk of stand replacing fire (Table 3, Appendix B), the Four Corners (FC) region is expected to experience more extreme climate conditions and contains a greater amount of soils with low Soil Available Water Storage Capacity (Table 3) indicative of low resilience and resistance (Chambers et al., 2014, 2017). Alternatively, PJ is relatively rarer within the URG and human related disturbances like mechanical disturbance and high road density are potentially greater. The issues and resiliencies we identify within PJ woodlands in our study areas are likely similar for other PJ stands in the southwestern U.S.

Our assessment system is able to guide the identification of tangible targets (watersheds and specific threats and issues) for management action using currently available data. This system is flexible and can be customized according to individual user needs by including or excluding individual indicators and is easily amended as new information becomes available. The final series of Adaptation Forums generated information on future research needs and preliminary actions to improve PJ conservation thus demonstrating the utility of this type of assessment for facilitating dialogue among diverse stakeholder groups to support landscape scale planning efforts.

Despite its strength as a decision support tool, specific weaknesses inherent to assessment systems like this need to be considered in any attempt to adapt or extrapolate these data to new efforts or landscapes. First, there are externally generated uncertainties related to the underlying indicator datasets. The goal of SRLCC project from which this assessment was developed was to generate products based on currently available data in order to provide information that could be used now when planning for future conditions. At this time, we do not know the degree to which uncertainties associated with individual datasets (described in Appendix A) influence final vulnerability designations. We minimize potential biases within any single data set by using multiple indicators and implementing a simple aggregate system where individual indicators either contribute to or reduce vulnerability. Second, there are several uncertainties driven by factors inherent to our assessment framework. One, uncertainty is introduced when we define specific threshold values to transform indicators into a 1 or 0 score. Transformation errors are a primary source of inherent instability in overlay mapping systems, which are analogous to our current assessment framework (Lodwick et al., 1990). A specific example within our assessment system is seen for indicators where any value > 0 (e.g. % area > 0) results in score of 1 (Table 3). Using this transformation formula can lead to different designations among watersheds that, in reality, have very similar values for a particular indicator (e.g. 0% vs. 1% cover). Alternatively, watersheds with very different values in underlying data (5% vs. 80% cover) will have identical scores of 1. It is likely that additional research of PJ ecology will highlight more appropriate thresholds for future assessment and these changes would be easily implemented using the current framework and available spatial data products. To some extent, we validate the thresholds used in this framework through discussions with stakeholders at Adaptation Forums. In particular, group discussions and our desire to identify potential management targets directly led to the adoption of a value $> 0 = 1$ formula for some indicators. The importance of capturing all potential issues and threats facing individual HUC12 outweighed the desire to quantify relative differences among watersheds. Two, we treat PJ as a unit of ecological importance and do not distinguish between relative impacts of climate and related disturbances for piñon and juniper species despite the fact that several indicators (e.g. Low Available Soil Water) relate to specific attributes of the piñon, *Pinus edulis* (see discussion in Appendix A). Three, indicators were sometimes drawn from studies conducted outside the current study area. Therefore, the results of these assessments may reflect more expectations for *P. edulis* than juniper components within PJ ecosystems and some indicators may be more or less relevant to a given study area. Four, we aggregate E and S into a composite representation of I, which reduces the relative contribution of E and S indicators to final vulnerability designations. However, our framework avoids some of the inconsistencies noted for other aggregate based systems (Choi and Huyun, 2019) because it does not use a purely additive or multiplicative equation to generate a vulnerability score. Instead, vulnerability is determined by the juxtaposition of I and AC. We should note that our effort identified relatively few AC indicators and, perhaps as a result of their lower frequency, AC indicators were often not present within our study watersheds. This shortcoming reflects both the availability of data and gaps in our knowledge of PJ ecology. Tellingly, many of the suggestions for further research derived from this assessment and discussions during the 2017 Adaptation Forums (Appendix D, Friggens and Hawksworth, 2018), focused on elements that improve our ability to identify and measure adaptive capacity in PJ ecosystems. Finally, we were not able to obtain adequate data to include indicators relating to two issues of known importance: grazing pressure and drought stress. Grazing data is available for BLM lands but is not consistently available for other lands, which prevented us from creating a reliable representation of grazing pressure across the study area. Measures of drought are available, but we lack research that provides a definitive response between these indices and PJ woodland response that could be used in this type of assessment (though Clifford et al., 2011 does identify precipitation thresholds). Collectively, uncertainties related to our process may mean that we have under- or overestimated vulnerability among watersheds. However, as currently constructed, this assessment system can reliably identify the relative vulnerability of PJ at the HUC12 scale based on the collective impact of various threats and issues and coping capacity.

4.2. Management considerations

Vulnerability assessments are used to guide the development of management strategies even in the absence of perfect knowledge. We have customized a process for estimating vulnerability of PJ that is designed to directly address management needs. Through an iterative process, we identified indicators of relevance to land managers that could be used in a vulnerability assessment of PJ. Our case study assessments demonstrate how these indicators and assessment framework provide the necessary first step toward developing management options for PJ within two focal landscapes. The maps produced from this analysis provide a backdrop that can be combined with maps of other important resources to identify areas that may need actions to reduce current or expected stressors and areas that are most likely to persist and present opportunities for conservation. The indicator datasets produced for our case studies, which include additional potential indicators and data from additional future time periods, can be recombined to create similar products for additional areas within the

SRLCC. Importantly, the methods applied here to two southwestern landscapes including vetted indicators and a framework for using them can be applied to estimate vulnerability of PJ in other areas where woodland management is a concern.

Adaptive strategies have been identified for PJ (Rondeau et al., 2017). Our vulnerability assessment maps provide a way to link those actions to specific watersheds. Watersheds with high productivity or PJ cover and low vulnerability can be managed to sustain wildlife and cultural needs. Where PJ is desirable, HUC12 with low vulnerability scores provide the best options for preservation. HUC12 with high vulnerability scores are likely to see a decline in PJ cover, which, depending on local manager needs, may facilitate a desired transition or could represent unwelcome loss. Perhaps more importantly, this assessment provides specific information on how, via presence or absence of individual indicators, each watershed is vulnerable and, thereby, a potential mechanism for management intervention. For example, future projections of suitable habitat could be used to reduce mechanical disturbance in critical areas (e.g. refugia) or help in efforts to triage actions within a landscape by allowing managers to focus on preserving PJ stands where they are most likely to remain viable into the future. Opportunities for conservation or potential intervention may focus on the individual indicators (e.g. road density, wildlife diversity) within a given watershed, may consider the collective impact of multiple indicators, or may identify issues common to a group of watersheds. The relative balance of vulnerability elements, exposure, sensitivity, and adaptive capacity, can also inform management approaches. For instance, lower vulnerability scores might be generated for areas when both impact and adaptive capacity are low or can arise when impact and adaptive capacity are high (thus balancing each other out) (Fig. 3). The need for management intervention is likely to be quite different between these scenarios depending on which of these situations apply to a particular management unit. Within our specific study areas, the results of the vulnerability assessment, combined with other recent assessments and outcomes from the 2017 Adaptation Forum formed the basis for several suggestions regarding PJ management strategies and research needs (Appendix D).

Within the SRLCC boundary, PJ ecosystems vary in tree and understory composition and structure and are found in sites that contain a wide range of climates, soils, and land use histories. Therefore, one of the most useful aspect of the VA may be to identify areas that require follow-up with 'ground truthing' to confirm watersheds with low or high vulnerability. The maps and data produced as part of this assessment take an important first step to distinguish areas by the specific threats and issues that are likely to impact the persistence of PJ woodlands. This is important as several recent studies have tried to tease out the relative impacts of climate and disturbance on PJ and the interaction of PJ with other ecosystems (e.g. Romme et al., 2003; Shaw, 2006; Gori and Bate, 2007; Allen, 2007; Margolis, 2014; Rocca et al., 2014; Redmond et al., 2015). However, information gaps identified in this assessment and during discussions held the 2017 Adaptation Forums indicate a need for far more research and management practices are needed that consider site and stand specific conditions (Appendix D).

5. Conclusion

The results of this assessment show that PJ ecosystems will continue to face numerous hurdles that are likely to contribute to further declines in important woodlands in at least some watersheds in the southwestern U.S. Our assessments also emphasize that PJ vulnerability is likely to vary according to local conditions as is demonstrated by the unique threats quantified for each HUC12 within this study. A primary result of our case study applications is that we can identify specific watersheds that are likely to experience declines in PJ as well as those that might provide refugia. By producing a spatially explicit representation of vulnerability, we are able to achieve our objectives to facilitate the identification of common issues and goals among the various land management organizations working in each landscape.

We now understand that applied science projects must be developed in partnership with the resource management audience to ensure that science outcomes are amendable to the needs of managers. Stakeholder input can be used to vet potential indicator datasets, to identify new data, and identify priority research needs. These partnerships require substantial investments from both research and management communities but the end result are products that achieve decision support goals. For the PJ assessment system, indicators were initially identified from the primary literature and then critiqued through a series of webinars and in person meetings involving stakeholders. This process took over two years to complete and, as new research becomes available, assessment products will need to be updated. However, as this effort shows, with sufficient support it is possible to successfully co-produce indicator datasets for use in management directed applications such as vulnerability assessments, thereby enriching the development process and greatly increases the utility of the resulting product.

We have produced a framework for assessing PJ vulnerability based on the best available science but through this process also identify important research needs. We found that it was easier to identify spatial data representing threats and issues within the landscape, essentially estimates of exposure, than it was to find information on ecosystems that could be used to measure sensitivity and adaptive capacity. This observation is likely to similar for other assessments as it is generally true that disturbance processes such as wildfire and land use change are measured at the landscape scale, whereas specific ecological information for a particular ecosystem is produced through more local studies. Better data on PJ response to environmental conditions, species specific information that can inform the determination of thresholds, and improved knowledge of PJ ecology are necessary in order that we can provide better estimates of potential vulnerabilities. In particular, future research that can better identify drought impacts in PJ could facilitate a method for conducting real- time vulnerability assessments (Meddens et al., 2015).

Vulnerability assessments are the first step towards the development of adaptive management plans designed to mitigate impacts from future disturbances. The next step to implementing collaborative management practices is to continue the dialogue started the Adaptation Forums and, using the assessment products produced through this effort, identify priority watersheds and management targets. Such progress requires coordination at the landscape scale and significant investment in terms of time on part of both science and manager partners but is also more likely to lead effective management strategies that address mutual priorities among local stakeholders.

CRediT authorship contribution statement

Megan Friggens: Conceptualization, Methodology, Project administration, Supervision. **Stephanie Mueller:** Data curation, Writing - review & editing. **Mary Williams:** Writing - review & editing.

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 data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2020.106830.

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