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6 **Dryland Bounty:**
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8 **Improving Arizona Agriculture with the Silvopastoral Management of Piñon-Juniper Woodlands**
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Abstract

Piñon pines face climate challenges in Arizona and throughout the Southwest but provide a valuable and nutritious seed which has been valuable to humans for millennia. Piñon pines form Piñon-juniper woodlands: complex ecosystems which comprise a significant portion of the landscape in Arizona and the Southwest. Gaps in scientific understanding and uncertain management outcomes for piñon-juniper woodlands bring us to explore alternative management for these ecosystems. Arizona faces poverty and poor outlooks for rural livelihoods, with both likely to worsen through systemic pressures in the coming decades. Silvopastoralism, a type of agroforestry, promises to improve stakeholder outcomes, overall systems productivity, and utilization of non-timber forest products. Silvopastoralism has not emerged as a common land-use type in Arizona, but evidence suggests significant benefits for this management and agriculture type. We investigate the value of piñon-juniper on the landscape through the lens of pine nut-cattle silvopastoral management via a targeted review of published metrics. We also examine regional systems for evidence of presence of common hinderances to the sustainable development of a stronger pine nut industry through an adapted framework and review of publications. We found that silvopastoral management of piñon-juniper woodlands has advantages in productivity and income which require more knowledge to incorporate into economic planning, and that systemic barriers to the development of Arizona's piñon nut likely exist. We present specific guidance for researchers, managers, and policy makers to capture the potential of Arizona's piñon-juniper woodlands through silvopastoral management.

1. Introduction

1.1 Piñon Pine and Piñon Pine Nuts

Piñon pines are a group of tree species which produce an edible seed, also called a nut, at irregular intervals (Wion et al. 2019). There are several species of piñon pine in the western U.S. which typically live between 4,500 and 9,000 feet in elevation and are slow maturing conifers (Richardson and Rundel 1998). Arizona's primary piñon species, two-needle piñon (*Pinus edulis*) takes between 25 and 75 years to reach seed-bearing age, and 75 to 100 years to reach full seed yield potential (Ronco 1990; Fisher 1988).

Piñon pines mast, producing seeds in synchronous events in geographic clusters, at irregular intervals, with some stands masting yearly, and others producing infrequent crops (Ronco 1990). Piñon literature typically characterizes production years as good or bad and suggests that some piñon stands produce large amounts of seed with high frequency while some piñon stands rarely produce substantial seed crops. Aridity, precipitation, nutrient depletion, and site-specific factors may influence this type of productivity (Wion 2019; Zlotin et al. 2018; Phillips 1909). Throughout this paper, we use "productive piñon" and "piñon productivity" to refer to piñon trees and stands with high intensity and frequency of seed masting.

Piñon pine nuts are nutritious, providing roughly 1600 calories per pound, and containing 15% protein, 15% carbohydrate, and 24% fat by weight (USDA 2019). Piñon pine is valuable to many wildlife species for food and shelter (Evans 1988), and perhaps most notably the piñon jay (*Gymnorhinus cyanocephalus*) which symbiotically assists in piñon regeneration and depends on piñon seed production for a food source (Fair et al. 2019). Piñon pine's value to human society is demonstrated through its historical and modern significance for tribal cultures in the Southwest (Lanner 1981). Piñon was likely a primary food and protein source for humans in this region for millennia, and archaeobotanical evidence suggests that it was both harvested nomadically and intentionally cultivated by indigenous civilizations (Berkebile et al. 2015).

Current utilization of piñon nuts as a non-timber forest product (NTFP) has declined substantially from historical levels with the most recent significant economic activity occurring in the early 20th century (Lanner 1981). The current U.S. piñon pine nut industry is small, with little data available, and utilization of pine nuts in a modern commercial context is made difficult by irregular masting and recent declines in piñon nut yields (Friggins et al. 2020).

1.2 Piñon-Juniper Woodlands – Current Understanding

Piñon species typically live alongside juniper species, another group of slow-maturing conifers, to form piñon-juniper woodland (hereafter: P-J) ecosystems (Richardson & Rundel 1998). Across the southwestern U.S. P-J is a major landscape component, with approximately 11 million acres of P-J in Arizona (Shaw et al. 2018). However, not all P-J contains piñon, or productive piñon, and recent piñon mortality events have likely increased the percentage of juniper-dominated P-J (Shaw 2005).

Species of piñon pine and juniper form different versions P-J communities across its range, with varying suites of understory species composition, increasing the difficulty of understanding and managing these systems (Falco & Waring 2020). In Arizona, two-needle piñon (*Pinus edulis*) is the most common piñon pine, and alligator juniper (*Juniperus deppeana*), one seed juniper (*Juniperus monosperma*), and Utah juniper (*Juniperus osteosperma*) are the most common juniper components (Christie 2009). Other

significant P-J species include western juniper (*Juniperus occidentalis*) and Rocky Mountain juniper (*Juniperus scopulorum*), Mexican piñon (*Pinus cembroides*) and one-needle piñon (*Pinus monophylla*) (USDA 1997).

Scientific understanding of P-J ecosystems remains limited despite an increased recent focus (Hartsell et al. 2020). Successional dynamics (Hartsell et al. 2020), influences on piñon mast seeding patterns (Wion et al. 2019), and even recent wide-scale mortality among piñon pine (Meddens et al. 2014) are areas where future projections are difficult with current knowledge. P-J successional dynamics vary with species composition and differing successional models have been suggested to describe this complex behavior (Pieper 2008).

The theory of encroachment, that P-J has extended its range into grasslands and shrublands throughout the western U.S. as a result of changing climate and unsustainable grazing, is a key driver in current P-J management strategies (Miller et al. 2019). However, several studies have contradicted the encroachment narrative (Amme 2019; Barger et al. 2009; Romme 2009), and historic range determination may be impossible due to a lack of historical records before significant 19th century piñon removal for mining (Lanner 1981). Balancing existing narratives and scientific understanding to drive effective management will be an ongoing challenge for Arizona's P-J stakeholders.

1.3 Piñon-Juniper Woodlands – Current Management

Overall management trends for P-J involve removal and thinning to achieve objectives of increased grass and fodder productivity, increased water availability and infiltration, and reduced fire hazard (Miller et al. 2019; Evans 1988). However, P-J biophysical influences on those desired conditions are not well understood, and current management methods may not meet those goals completely or effectively, as described below.

Hydrologic impacts of P-J on the landscape are unclear, with some studies finding reduced infiltration and water storage due to tree-soil interactions (Lebron et al. 2010), and other studies indicating that P-J expansion improves soil infiltration (Leite et al. 2020). The combined effects of treatments and P-J ecosystem effects are likely complex, and Johnson et al. (2020) found highest infiltration in untreated P-J stands, as compared to treated stands where infiltration decreased and surface runoff increased for up to 13 years after treatment.

Fire regimes in P-J and the hazards of P-J wildfire are also complex issues. Fire danger to communities prompts treatments to reduce fire hazards while some studies have found that P-J typically exhibits low-severity fire (Reemts et al. 2020). Degradation of forested ecosystems is often linked to increased fire risk and fire management in Arizona (Miller 2014), but P-J has been shown to maintain historical fire regimes even when degraded (Floyd et al. 2000). Huffman et al. (2009) provide an excellent review of the complications in fire management and fire behavior for P-J systems.

Additionally, many treatment techniques have been shown to be ecologically damaging and ineffective at accomplishing management objectives, as described here. Chaining, a common treatment for large-scale P-J removal, encourages the growth of invasive grass species, fails to prevent juniper regeneration, and can be ecologically damaging (Redmond 2013). Mastication treatments are likely less ecologically damaging than chaining but may bring reductions, rather than increases, in grass cover (Jones et al. 2013) and may increase invasive species cover above pre-treatment levels (Rubin & Roybal 2018).

Much of available management literature focuses on the Great Basin region, where P-J expansion is most noted, and conservation of Greater Sage Grouse is a frequent objective of restoration (Coates et al. 2017; Miller et al. 2019). Arizona faced among the highest levels of piñon mortality during recent drought-related die offs (Shaw 2005) and has relatively little historical Greater Sage Grouse range (Schroeder et al. 2004), and therefore Arizona P-J management and treatment effects likely vary from national norms.

Overall, P-J management methods meet their goals most completely over small, well-studied landscapes, and tend to produce undesirable results over large or unstudied landscapes (Williams et al. 2020). Increasing management intensity and focus generally increases costs and the budgetary obstacles to favoring most-effective treatment methods and monitoring, despite potential benefits, are well-known to land managers (Rummer 2008)

1.4 Arizona Agriculture and Rural Livelihoods

Arizona faces poverty rates higher than national averages, which disproportionately affect indigenous communities, and which create socioeconomic issues expected to worsen with changing climate conditions (Wilder et al. 2016). The next several decades will bring food pressure from population growth, decreased yields, and increased irrigation requirements for agricultural systems (Berardy & Chester 2017), and increased pressure on Arizona's aquifers, many of which are not managed sustainably (Kyl Center for Water Policy 2019).

Challenges to food security and livelihoods in the coming years might be best met by focusing on alternative land use and agricultural-ecological strategies (Mora et al. 2020). Current understanding of arid landscapes and rural livelihoods suggests that focus on sustainable development strategies can greatly improve outcomes for rural stakeholders (Vergles et al. 2015). Dryland systems, which are often viewed as less agriculturally useful than other ecosystem and climate types, can specifically benefit from development approaches that encourage socioeconomic considerations to build sustainable production (Ffolliott et al. 1995).

Cattle systems are a promising target for agricultural improvement, as a significant portion of Arizona's overall agricultural productivity is based on beef cattle grazing and fodder production and approximately 21% of Arizona's 19,000 farms focus on beef production (NASS 2019; Kerna et al. 2014). Although ranching and beef production bring significant food, cultural, and economic value to the region (NASS 2019; Kirner 2015), there is real concern that modern cattle industry mechanisms result in declines in regulatory capacities for grazed ecosystems (Pogue 2020) and encourage cycles of poverty for rural farmers (Sadhu 2021).

1.5 Pine Nut-Cattle Silvopastoralism as an Alternative

Agroforestry is a range of combined land-use systems which include trees and agriculturally significant species to maximize systems performance (Jose 2009). Silvopastoralism is a specific form of agroforestry involving grazing of livestock in forested ecosystems and which has been shown to provide ecological and economic benefits in the United States (Clason 1999).

The economic potential for general silvopastoral management of P-J has been discussed (Kline 1993) but studies of practical applications are mostly relegated to a New Mexico project which focused on harvesting wood products from trees and did not explore pine nut production (Gottfried 2004). Managing P-J for pine nut production has been addressed by past studies which projected favorable

1 incomes for pine nut-based management compared to grazing use and the highest income potentials for
2 multi-use systems (Van Hooser & Casey 1987). Piñon nuts have significant and inelastic commercial
3 values, and despite the significant quantity of piñon pine in the United States, most pine nuts sold here
4 are imported, suggesting potential for U.S. production (Sharashkin & Gold 2004).

5 Current research suggests an ecological suitability of P-J for silvopastoral management, as explained
6 here. Existing but limited literature shows few negative interactions of sustainable grazing on P-J tree
7 growth (Van Auken 2014) and suggests that grazed P-J may have fodder productivity similar or higher
8 than average Arizona rangeland (Evans 1988). Tree density effects on piñon nut yield are not fully
9 understood, but preliminary findings suggest that low P-J densities can improve pine nut yields in arid
10 landscapes (Lightfoot et al. 2016).

11 Silvopastoral management focused on pine nuts would require combining pine nut management with
12 existing range management systems. The Bureau of Land Management (BLM) and United States Forest
13 Service (USFS) both sell grazing leases to private farmers and ranchers, typically for 10-year periods
14 (BLM 2021; USFS 2021). Private range ownership is significantly smaller by area than federal ownership
15 (Kerna et al. 2014). Management of these grazed areas typically focuses on fodder production for
16 livestock and wildlife (Smith et al. 2012). Pine nuts collection is primarily managed by the BLM and
17 includes both by-weight licensing and bidding on specific parcels (USFS 2020), but little analysis has been
18 done on these systems. Silvopastoral systems are widely studied as a means for sustainable
19 development, and published methodologies and case studies are available for other geographic areas
20 (Chara et al. 2019).

21 *1.6 Focus of Study*

22 We focus on pine nut-cattle silvopastoral management (hereafter: PNCSM) of P-J because of its
23 relevance to the issues described in this introduction, and in particular its potential to defray increased
24 management costs and improve agricultural stakeholder outlooks with increased income potential.
25 Arizona, facing disproportionate climate-induced loss of piñon pine (Shaw 2005) and worsening outlooks
26 for agricultural systems (Berardy & Chester 2017), may benefit from adopting PNCSM for P-J.

27 However, our understanding of the potential for PNCSM sits at odds with the currently small United
28 States piñon industry and a lack of spontaneously developed silvopastoral focus for Arizona P-J
29 management. We consider and explore two potential explanations for this apparent contradiction
30 through a targeted review of available literature. First, we consider that actual food yield and income
31 potential for pine-nut-based management of P-J may compare unfavorably to cattle-centric
32 management, and extract and analyze available values related to yield and income for these systems to
33 investigate the relative potentials of these systems in Arizona P-J. Second, we consider that systemic
34 barriers may be hindering the development of the United States pine nut industry and investigate
35 available literature for evidence of obstacles to development in regional systems.

36 **2. Methods**

37 We conducted a targeted review of scientific and grey literature relevant to P-J, piñon pine, pine nuts,
38 and cattle, focusing on economic, ecological, and social factors. Searches were conducted over Web of
39 Science, Google Scholar, and Google Search to ensure a breadth of identified resources. Information
40 extracted from this review powered two separate analyses, described in the sections below. Although
41 two-needle piñon is most relevant to Arizona's landscapes, we also considered metrics for one-needle

piñon due to poor availability of data for all piñon species. Our review of PNCSM component values mostly relied on scientific studies and industry publications for yield potentials and market and scientific data for income potentials. Our analysis of hinderances relied on stakeholder and NGO publications and letters, with occasional support from peer-reviewed scientific literature.

2.1 PNCSM Component Value Review

Our first analysis employed a novel approach to extract values for food yields and income potentials for pine-nut and cattle management of P-J in order to provide context for potential PNCSM values [Table 1]. Landscape values such as these are useful for decision-making tools for land managers (Minang et al. 2020), but poor availability of data specific to silvopastorally managed P-J requires us to employ a broad review of metrics relevant to PNCSM. Although cattle are used for both beef and dairy production, over 80% of Arizona cattle are raised for beef (NASS 2019), leading us to focus on beef production for yield metrics.

We calculated food yield potential in units of expected yield in weight of food over a set area. Beef yield was calculated by comparing average cattle weight gain during range occupancy and per-area productivity of Arizona rangeland, using standard units of Animal Unit Months (AUM). Piñon yield was captured from published assessments of seed production per unit area. Food yields were normalized to annual rates. To convert monthly rates to annual rates, we assumed a three-pasture rotation, meaning that one AUM provides fodder for four out of twelve months of the year. Values for continuous grazing usage may differ in practical application but would require insights into site-specific ecology.

Table Reference	Calculated Value/Method
Table 4	Piñon pine nut annual yield (per unit area)
Calculated by:	Yield [High, Medium, and Low from Table 2-a] / [Average from Table 2-b] yield frequency
Table 4	Beef cattle annual yield (per unit area)
Calculated by:	(Yield [High, Medium, and Low from Table 3-b] * 365 [days per year]) / ([Average from Table 3-a] * 3 [three field rotation])
Table 5	Annual gross income potential (per unit area)
Calculated by:	Average annual yield per unit area * market price per unit weight
Table 5	Annual net income potential (per unit area) - pine nuts
Calculated by:	Average annual yield per unit area * market price per unit weight * expected percentage return from existing pine nut market
Table 5	Annual net income potential (per unit area) - beef cattle
Calculated by:	Average net income per cow adjusted to per acre income based on [High, Medium, and Low from Table 3-b]

Table 1. Calculations for PNCSM component value review in Tables 2 to 5. Beef yield calculation requires consideration of daily animal weight gain on rangeland and a range of extracted rangeland carrying capacities adjusted to a yearly average figure which is divided by a factor of three to adjust for three-field grazing rotation.

Profitability was calculated as potential gross income, using yield and market prices, and potential net income, using established economic analyses (Teegerstrom & Tronstad 2016; Moreno et al. 2011). Beef income potential was calculated by comparing expected profit per cow to cow carrying capacity of Arizona rangeland, and by comparing food yield to market prices for beef cattle. Piñon income potential was calculated by comparing food yield potential to market prices for pine nuts, and by applying the profitability of pine nuts in the Mexican industry (Moreno et al. 2011) to market prices as a proxy for potential U.S. market behavior.

2.2 Pine Nut Development Barriers Review

Our second analysis examined potential barriers to the development of the U.S. pine nut industry by adapting results from Rodrigues de Mello et al.'s (2020) meta-study of sustainable economic development of non-timber forest products. We selected the five hinderances for which Rodrigues de Mello et al. (2020) found the most support in their systematic literature review and searched for evidence of presence of those barriers in information available from pine nut-specific sources, sources from Arizona, and sources from across the Southwest.

Our criterion for evidence was binary, either identifying a source supporting the existence of each barrier or not, and we intended the three levels of focus (pine nut-specific, Arizona-specific, and Southwest-specific) to provide greater resolution to our findings. We also considered circumstances where a barrier would be de facto present in one of those systems based on evidence from a separate system.

3. Results

3.1 PNCSM Component Values

Our results suggested considerable income potential for land uses which include pine nut collection as a focus as compared to use for beef production alone [Table 5]. We also see that the degree of productivity of piñon is a controlling factor in pine nut food production, and that the current uncertainty about piñon pine yield creates a wide range of potential incomes for pine nuts [Table 2; Table 4].

Income potential for beef cattle was lower than income for piñon pine nuts for both net and gross estimates [Table 5]. We found a current market price for beef cattle of \$120 per 100 hundredweight (Tridge 2021) which was supported by an average 10-year price of \$120 per hundredweight in domestic beef markets (Iowa State University 2021). Current piñon prices are variable depending on source country and species with recent wholesale market prices of \$21 per pound (Tridge 2021), which were generally supported by literature on piñon markets in the European Union, suggesting wholesale market prices between \$10.90 and \$14.50 per pound (Awan & Pettenella 2017).

We consider our estimates of beef profitability per acre [Table 5] to be reasonable, considering the focus of modern ranching publications on three dollar per acre profits as a goal (Waggener 2017). Income for pine nuts varies significantly with yield, and though the potential of pine nut incomes could represent “100 times more revenue” than beef-only use (Kline 1993) for productive P-J, the data suggest that for less productive sites, modest increases in income should be expected. Data further suggest that even for unproductive P-J, a focus on pine nut collection could more than offset expected per-cow losses [Table 2-4].

2a. Yield of Pinon Pine Nuts in Productive Year (lb/ac)				
Values Extracted				Note
Source	Minimum	Maximum	Average	
Zlotin and Parmenter 2008	18.20	N/A	N/A	Highest yield over seven-year data set
Phillips 1909	N/A	300.00	65.13	N/A
	18.20	300.00	65.13	Productivity for Table 3

2b. Years Between Productive Yields for Pinon Pine Stands				
Values Extracted				Note
Source	Minimum	Maximum	Average	
Springfield 1976	3	7	N/A	N/A
Jeffers 1995	2	7	4.1	N/A
Zlotin and Parmenter 2008	N/A	N/A	7	Duration of data collection
Phillips 1909	N/A	N/A	5	More frequent yields are common
			5.37	Yield frequency for Table 3

Table 2-a and b. Piñon yield data for annual yield calculations in Table 4. Extracted metrics are given, with minim, maximum, and average values proposed by listed sources. Gray cells indicate averaged values used in Table 4. Values for yield frequency were more consistent across sources than values for per-acre yield, and we use only an average of proposed average frequencies in Table 4.

3a. Average Daily Gain for Beef Cattle on Rangeland (lb/day)				
Values Extracted				Note
Source	Minimum	Maximum	Average	
Augustine et al. 2021	N/A	N/A	0.78	Steers with enhanced range management
Currie et al. 1978	N/A	N/A	0.5	Cows under rotational grazing systems
Currie et al. 1978	N/A	N/A	0.79	Calves under rotational grazing systems
Ringwall 2012	N/A	N/A	0.81	Target weight gain for range management
			0.72	Per-animal yield for Table 4

3b. Animal Unit Months [AUM] per Acre on Arizona Rangeland				
Values Extracted				Note
Source	Minimum	Maximum	Average	
Teegerstrom & Tronstad 2016	N/A	N/A	0.25	Arizona range average
Stucky & Henderson 1969	0.08	0.21	N/A	P-J across Arizona
Clary et al. 1974	N/A	N/A	0.19	Utah juniper
Clary et al. 1974	N/A	N/A	0.52	Alligator juniper
	0.08	0.21	0.25	Carrying capacity for Table 4

Table 3-a and b. Beef yield data for calculations in Table 4. Extracted metrics are given, with minim, maximum, and average values proposed by listed sources. Gray cells indicate averaged values used in Table 3. Values for daily weight gain were presented as averages in most studies, and we use the average value from 3-a in Table 4.

4a. Average Yearly Yield for Piñon Pine Nuts (lb/ac)		
Low	Medium	High
3	12	56

4b. Average Yearly Yield for Beef Cattle (lb/ac)		
Low	Medium	High
7	18	22

Table 4-a and b. Annual food yield calculations for pine nuts and beef cattle, showing the formula for calculation, and using the low, medium, high, and average values identified in Tables 2 and 3.

A productive piñon nut yield of 300 pounds per acre is an established value in literature (Jeffers 1995, Fisher et al. 1988) but is almost entirely based on a single paper (Phillips 1909). Jeffers (1995) provided a value of 250 pounds per acre, which was originally presented by Fowler and Oliver (1988), who cited Dodge (1955), which was a non-reviewed travel article in Arizona Highway magazine which gave a value of 300 pounds per acre (not 250), which was likely based on Phillips (1909).

We identified two values in addition to the 300 pound per acre figure most-referenced in literature. Phillips (1909) also provided an additional yield average of 73 kilograms per hectare (65 pounds per acre) for larger geographic areas, which we consider an average value for PNCSM [Table 2-a]. Zlotin and Parmenter (2008) mainly investigated juniper fruit production, but provided data showing a maximum piñon yield of 20.4 kilograms per hectare (18.2 pounds per acre) over a 7-year period in arid P-J, which we consider an minimum value for PNCSM for unproductive piñon [Table 2-a].

Piñon yield frequency was also agreed upon and is more widely sourced. All sources proposed a minimum pine nut masting frequency of once in 7 years and a maximum frequency of once in 2-3 years (Jeffers 1995, Springfield 1976, Phillips 1909), except Zlotin and Parmenter (2008) who did not address piñon masting specifically, but from which we used the 7-year period over which seed production was studied as a minimum frequency. We used average pine nut yield frequencies to calculate annual yields [Table 2-b]. Values for cattle growth while grazing, productivity of Arizona P-J as rangeland, and market values were generally agreed upon in the literature [Table 3-a and b; Table 4].

Gross Income Potential					
Pine Nut Market Price (\$/lb)			Beef Market Price (\$/cwt)		
\$21			\$120		
Piñon Yield (Pounds per Acre per Year) (from Table 4)			Beef Yield (Pounds per Acre per Year) (from Table 4)		
Low	Medium	High	Low	Medium	High
3	12	56	7	18	22
Expected Gross Income for Pine Nuts (\$ per acre per year)			Expected Gross Income for Beef (\$ per acre per year)		
Low	Medium	High	Low	Medium	High
\$71.22	\$254.85	\$1,173.91	\$8.40	\$21.60	\$26.40
Net Income Potential					
Expected Pine Nut Profit for Collectors :		22.12%	Average Return on Arizona Beef Cattle (\$ per cow) (Teegerstrom & Tronstad 2016):		
(Moreno et al. 2021) (% market price of yield that collectors realize in income)			Low	Medium	High
Expected Net Income for Pine Nuts (\$ per acre per year)			-161	26.8	143.6
Low	Medium	High	Expected Net Income Assuming 5 acres per AUM (\$ per acre per year)		
\$15.75	\$56.37	\$259.67	Low	Medium	High
			-\$10.73	\$1.79	\$9.57

Table 5. Gross and net income potentials for pine nuts and beef cattle. Gross calculations compare market price to yields presented in Tables 2 and 3. Market prices are based on observed wholesale prices are likely lower than retail. Net income potentials use separate methodologies described in the table and in the methods section of this paper. Green-colored cells indicate positive income potentials and red-colored cells represent negative income potentials.

3.2 Pine Nut Development Barriers

Reviewing the five most-supported hinderances to NTFP utilization from Rodrigues de Mello et al.'s meta-analysis (2020), we found direct piñon-related support for four of the five hinderances, considered support to be strong for four of the five hinderances, and over all factors, found the most evidentiary support from agency and stakeholder documentation [Table 6]. Overall, we found little data to support the presence or absence of the reviewed hinderances in the Arizona system.

3.2.1 Land-use change/deforestation/forest degradation

Deforestation has been an effect of the management of P-J since the 19th century, with significant deforestation events in the mid-late 20th centuries (Lanner 1981) and large-scale removals ongoing across P-J's range (Oldham 2019), and we consider this barrier present for pine nut stakeholders and for the Southwest. We did not identify large-scale P-J removal as a documented concern in the Arizona system, although removal occurs, but the significant mortality events affecting piñon, and particularly in northern Arizona (Shaw 2005), may be considered as forest degradation in that system for NTFP industry development purposes.

Barrier to Development (Rodrigues de Mello et al. 2020)	System Considered			Details
	Pine Nut	Southwest	Arizona	
Land-use change/deforestation/forest degradation	(Oldham 2020)	(Cunningham 2018)	No	P-J removal occurring in various forms across its range. Arizona shows less evidence of large-scale removal than other Southwest states
Poor/lack of appropriate infrastructure and/or transportation system	(Frazier 2017)	De facto	De facto	No buying and selling stands or other processing infrastructure for pine nuts; many P-J areas inaccessible by road
Lack of consistent regulatory control and enforcement	(Frazier 2017)	(USFS 2020)	No	Pine nut licensing varies between states; little information available for Arizona's pine nut system
Poverty	De Facto	(Wilder et al. 2016)	(Yeagley 2020)	The Southwest has high poverty rates; tribal communities have twice the poverty rate of the Arizona average
Regulations that hinder access to natural resources resulting in illegal harvest and trade	(Yeoman 2019)	(USFS 2020)	No	Illegal harvest is mentioned by agencies, but no data is available; regulations may hinder collection practices for tribal stakeholders

Table 6. A summary of the findings of our investigation into hinderances to piñon NTFP development using Rodrigues de Mello et al.'s (2020) meta-analysis on the subject as a framework for hinderance identification. Green boxes indicate that a hinderance was identified in the listed system (a source is given in parentheses). Gray boxes indicate that the hinderance was de facto identified, meaning that we consider it to be present for that system because of its presence or absence in another system. Red boxes indicate that the hinderance was not identified for the listed system.

Although the elements involved in current management trends are complex, some P-J removal is viewed negatively by ecological and cultural stakeholders and clearing of P-J has received specific criticism from environmental, cultural, and economic stakeholders (Cunningham 2018; Oldham 2020).

3.2.2 Poor/lack of appropriate infrastructure and/or transportation system

Most piñon nut economic activity is carried out by small companies for which current data is proprietary, and we found little evidence of any infrastructure beyond licensing and regulatory frameworks. The lack of infrastructure specific to externalizing processing services for pine nuts, such as buying and selling stands, necessarily increases the barrier to entry in the piñon nut industry. Stakeholder input highlights the specific disadvantages that current infrastructure arrangements have upon economic utilization of pine nuts (Frazier 2017). Because available infrastructure for pine nut processing does not exist, we consider lack of infrastructure de facto present for the Arizona and Southwest systems.

3.2.3 Lack of consistent regulatory control and enforcement

BLM and USFS commercial piñon licensing and bidding systems vary between states and regulations may impact NTFP usage for the Southwest in terms of consistency, and of cultural harvest as described in section 3.4.5, but we did not find evidence that consistency of regulation and enforcement specifically impact the development of NTFPs in Arizona. We did find evidence that piñon NTFP stakeholders find management agencies to be inconsistent, untransparent, and unreactive for other Southwest areas (Frazier 2017) and consider this hinderance present in the pine-nut stakeholder and general Southwest systems.

3.2.4 Poverty

Poverty exists at elevated levels in the southwestern United States (Wilder et al 2016), and even more so in tribal and communities where poverty rates are often over three times the rates of nearby non-tribal areas (Yeagley 2020). We found no specific document-based evidence for poverty as a hinderance to pine nut industry development but consider the hinderance de facto present in all systems considering the infrastructure gaps described in section [3.2.2].

3.2.5 Regulations that hinder access to resources resulting in illegal harvest and trade

Illegal harvest is of sufficient concern to be mentioned in agency press releases at the start of piñon nut harvest season (USDA 2020) and that it is likely present in the Southwest system, but figures on illegal harvest volume and frequency are not available. Pine nut stakeholders, including tribal community members, have noted that existing regulations hamper cultural collection patterns and prevent resource extraction (Yeoman 2019), but we found no evidence specific to the Arizona system.

4. Discussion

Our results generally suggested economic benefits to PNCSM for P-J in Arizona given sufficient insight into geographic distribution of productive piñon and supported that a combination of hinderances to the development of pine nut industries are present in Arizona and the Southwest. Although an effort to develop PNCSM in Arizona should increase food production and income potential, economic and regulatory hinderances identified in our results would likely preclude large-scale buy-in into a PNCSM system.

Despite recent increases in P-J ecological research (Hartsell et al. 2020), published knowledge guiding the practical agricultural management of P-J was mostly found in studies from the late 20th century and may not apply to current conditions considering changing climate factors (Berardy & Chester 2016). With the future of piñon mortality events in the region unclear (Meddens et al. 2014), and baseline metrics outdated or poorly understood, increasing knowledge of P-J-cattle yield interactions, and improving awareness in geographic trends of piñon performance are both key objectives to realize PNCSM.

We propose that addressing these issues and increasing stakeholder buy-in would best be accomplished by a coordinated approach between managers, researchers, and policy makers. Frameworks like the sustainable livelihoods framework (Scoones 1998) show us the importance of considering the combined effects of management, policy, and research on livelihoods, and the ability of those areas to effect considerable positive change with coordinated action. Using integration between stakeholders and institutions with data sharing and policy mechanisms should increase buy-in and improve technical and ecological systems in sustainable agricultural systems (Bowler 2002) like PNCSM. We present suggested areas of focus for researchers, policymakers, and managers to facilitate operationalization of PNCSM [Figure 1]. We also provide a list of future research needs for PNCSM [Table 7].

4.1 Limitations of Methodology

Limited data are available for the U.S. pine nut industry and for ecological factors related to piñon and P-J, requiring generalization of data from across Arizona and the Southwest. Because of this generalization, values which we calculated may not be realized over any given section of the landscape for any length of time and should be supported by local assessments for application in specific areas. Similarly, beef economics are complex, and we attempt to provide reasonable estimates with established ranching economic reports.

Our review of barriers relied heavily on stakeholder-created documents and may be influenced by source bias. Whereas we hold that the challenges of studying marginalized and under-researched communities and resources often require consideration of non-peer-reviewed materials, we submit that our analysis is not a replacement for locally specific stakeholder input and more nuanced research approaches.

4.2 Policy and Incentive Mechanisms

Although the development of PNCSM without policy intervention is possible given expected income levels, policy incentives for stakeholders may be a useful pathway towards building sustainable agricultural systems like PNCSM (Rodrigues de Mello et al. 2020). Financial incentives can form an important part of improving agricultural outcomes and processes (Hemming et al. 2018), and we expect this general principle to apply to PNCSM.

New and established agricultural systems alike benefit from agricultural subsidies to increase stakeholder buy-in and improve knowledge and methods (DeBoe et al. 2020). Arizona paid 10 million dollars in agricultural livestock subsidies, mostly to ranches, in 2018 (EWG 2020), suggesting a systemic acceptance of subsidy pathways to improve beef production in this state. Considering the expected income and food production performance of PNCSM, subsidizing early adopters could provide a cost-neutral path to state-wide improvement.

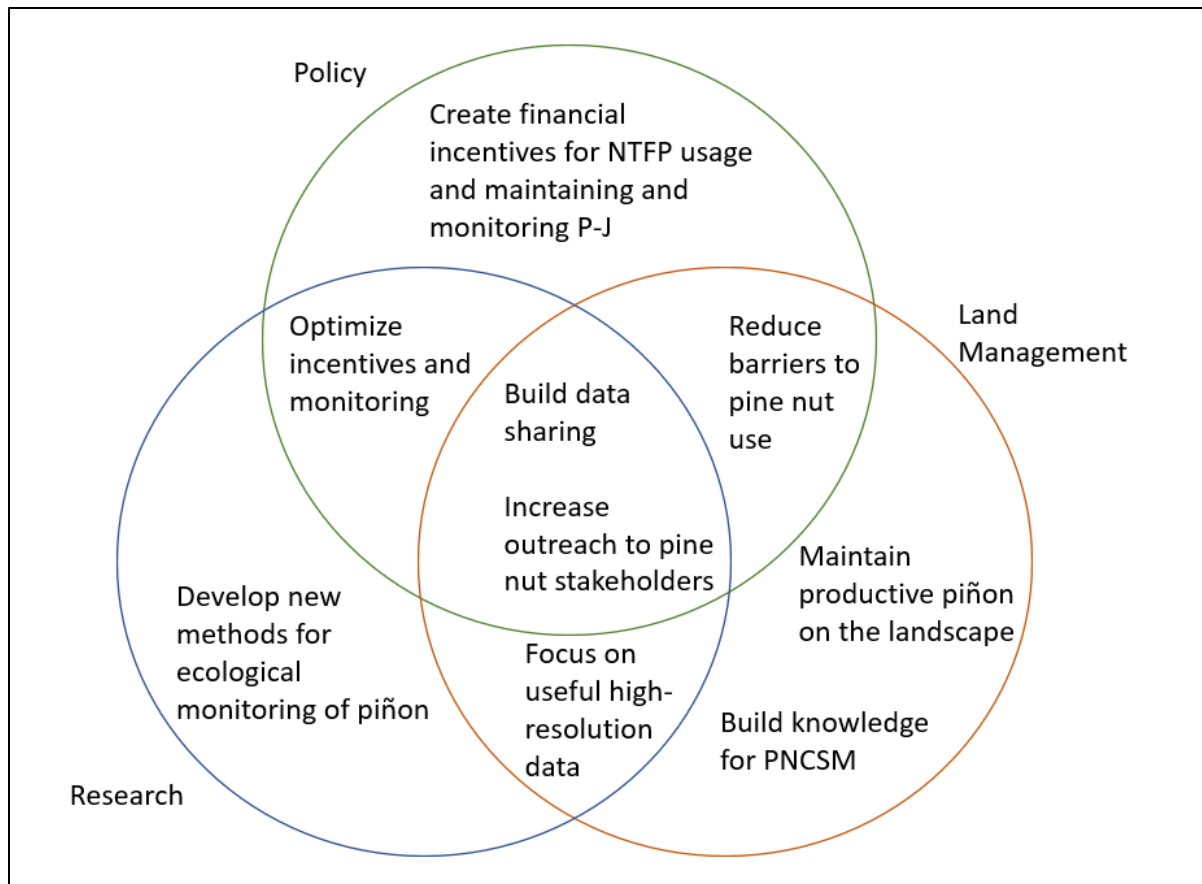


Figure 1. Relative areas of focus which might best meet current challenges to operationalizing silvopastoral management of P-J. Divisions in area of responsibility are not intended to preclude involvement between groups, but to encourage the conceptualization of multi-group cooperation in developing PNCSM.

We suggest incentives for maintaining piñon pine on the landscape. Productive piñon is valuable, according to our study results, but current knowledge of geographic distributions of productive stands and baseline knowledge on yield intensity is largely based on a single 1909 study (Phillips). Maintaining piñon pine on the landscape, to preserve overall productive piñon levels in future scenarios, could be accomplished with payments for ecosystem services (PES); an assortment of plans where landowners and farmers are provided payments to maintain valuable ecosystem components (Brouwer et al. 2011).

4.3 Data and Monitoring

We also suggest increasing the availability of geographically specific data for fodder production, pine nut yield, tree densities, and ecosystem composition. This goal could be achieved by providing incentive payments to stakeholders for the collection of desired data on local landscapes. Friggens et al. (2020) highlighted the importance of data sharing networks for P-J to enhance ecological knowledge and management of that ecotype. Increased knowledge sharing improves overall system performance and stakeholder outcomes in agricultural settings (Riley 2008), and investments made in incentivized monitoring now should provide returns with increased PNCSM focus across Arizona.

Yield-based and geographically specific data may be of most use to farmers and ranchers, but evolving research methods can also provide new insights to improve ecological management and agricultural productivity (Tittonell et al. 2020). Analysis driven by large data sets and machine learning have shown positive results in agricultural systems (Kamilaris & Prenafeta-Boldú 2018). Developments in aerial imaging methods, and their applications through deep learning systems can highlight trends in ecological patterns which may otherwise escape detection (Kalantar et al. 2020).

The existing USFS Forest Inventory and Analysis (FIA) program is a powerful tool for evaluating and assessing changes in forested landscapes (Smith 1987). FIA data has been shown to be useful for piñon-specific analysis (Shaw 2005), and Reimann et al. (2010) provided suggestions for increasing the usefulness of collected data for data-driven management. Focusing on developing these methods to detect trends in mortality and productivity across Arizona's P-J could power PNCSM with rich data and useful insights, and existing research in aerial detection of masting events has already shown useful for other tree species (Garcia et al. 2021). Increasing the utility of existing USFS aerial monitoring programs has been suggested to address other trends in tree ecology in this region (Wulder et al. 2012).

Monitoring and prediction of geospatial shifts in tree species due to climate change is a recent scientific focus, spurred on by ongoing drought- and heat-related mortality events (Allen et al. 2010). Current climate modeling of piñon pine shows high variation in potential range distributions due to differences in modeled climate circumstances and uncertainties around climate effects on piñon recruitment and mortality (Figure 2) (McCallum 2011; RMRS 2021). Increasing monitoring efforts to improve existing data sets and build understanding may sharpen our understanding of piñon pine's future range.

4.4 Outreach and Infrastructure

Our analysis of potential hinderances to the sustainable development of an Arizona pine nut industry suggested that several hinderances may be affecting this region but found little information specific to Arizona pine nut licensing, industry, or institutional focus. Modern understanding suggests that rural and marginalized communities suffer from a lack of outreach and involvement with the management and regulatory spheres (Scoones 2009). We suspect that low availability of Arizona-specific piñon nut information is evidence of a general lack of focus on this economic area which could be addressed with increased outreach and infrastructure. PNCSM-adjacent outreach should benefit existing cattle systems, as stakeholder outreach has already been identified as useful for improving ranching outcomes (Fernandez-Gimenez & Wilmer 2015).

Outreach may be particularly important for tribal communities who have a unique relationship with piñon pine (Lanner 1981), suffer disproportionately from poverty (Yeagley 2020), and are uniquely affected by land use issues due to a history of colonial occupation and oppression (McMichael 2014). Tribal stakeholders are therefore key to defining the acceptable bounds of any effort to shape P-J woodlands through management. Cultural and spiritual values cannot be captured through common metrics (Throsby 2003). Using outreach to identify areas of cultural significance and ensuring tribal access to P-J for culturally relevant collection would be crucial steps in the responsible administration of any PNCSM program.

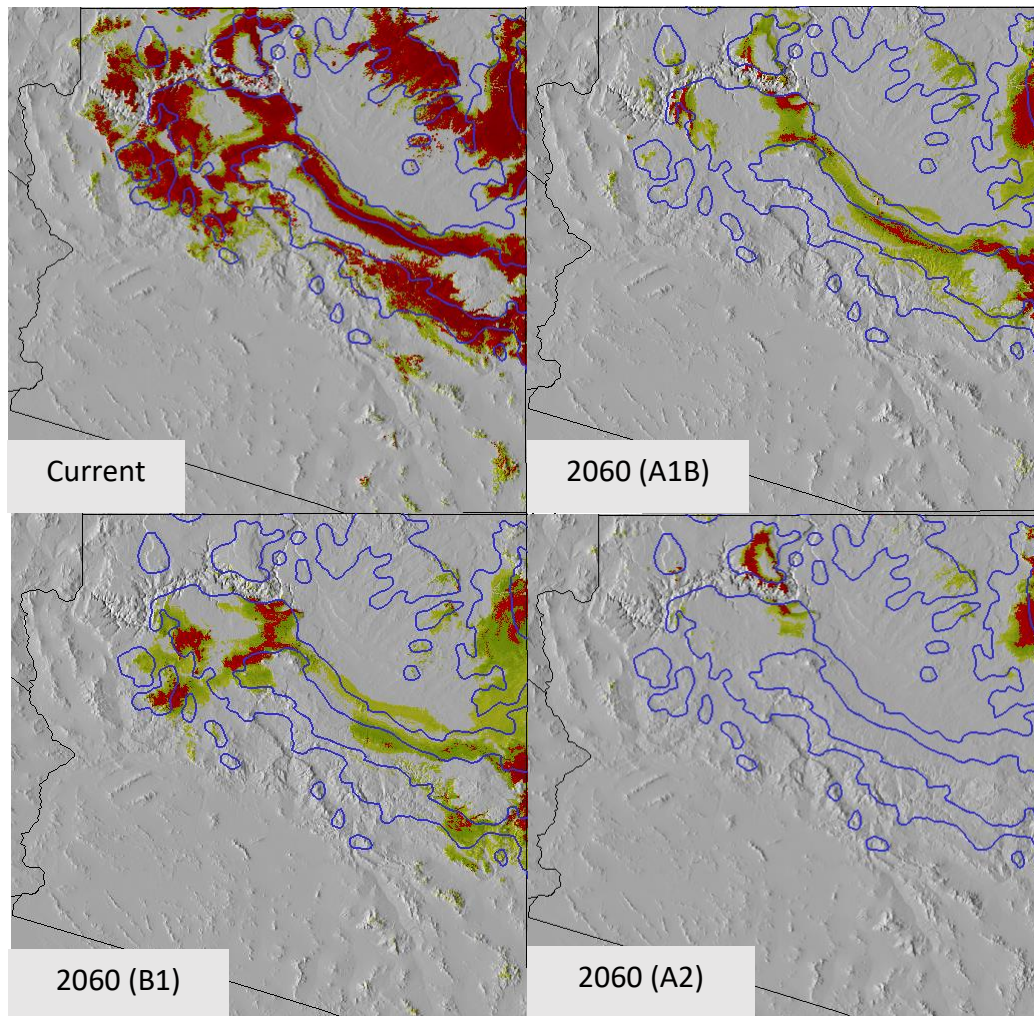


Figure 2. Current and projected (for year 2060) *Pinus edulis* range in Arizona under different climate scenarios (shown in parentheses; [A1B - balanced energy use with high global integration] ; [B1 – ecologically focused world with high integration] ; [A2 – divided world with high emissions]). Viability, the likelihood that piñon pine will survive in a particular area, is shown by color. Red areas show high species viability (.75 to 1.0) and green areas show lower viability (.5 to .75). Adapted from Coupled Global Climate Model analysis by Rocky Mountain Research Station (2021).

Lack of access to resources is damaging to industries and stakeholders alike (Singh 2021), and economic barriers to entry likely prevent access sufficiently to prevent sustainable agricultural development for some natural resources (Rodrigues de Mello et al. 2020). Reducing these barriers is partly an issue of the incentives and outreach described earlier in this section, but also of building systemic improvements to enable the growth of pine nut economic activity.

The lack of pine nut processing services in Arizona presents a practical barrier to potential PNCSM stakeholders in that pine nut processing requires additional investment. Increasing nut crop processing

could be achieved through policy intervention and has been suggested for other seed and nut crops to improve rural livelihoods, increase resource collection, and buoy industry consistency (Yan 2017). Walnuts are a well-developed seed and nut crop in the United States, with readily available commercial selling stands that allow independent collectors and small-hold farmers to profit from walnut crops without investment in processing equipment. We suggest that co-locating piñon pine nut processing centers with geographic centers of productive piñon, determined through increased monitoring described earlier, might provide optimal results, and note that spatial optimization of this sort is a well-studied issue in socioecological and data sciences (Egerer et al. 2020).

Future Research Questions for PNCSM	
Social	Will local food availability increase with greater piñon nut production?
	Is regional demand for piñon pine nut sufficient to support large-scale collection?
	Is increased economic activity in P-J compatible with tribal preferences?
	Could piñon pine become a part of the Federally Recognized Tribes Extension Program?
	Are PNCSM methods compatible with regional ranching culture?
Ecological	How much productive piñon will remain in Arizona with a warming climate?
	Will changes in climate and ecology produce areas of piñon refugia?
	Will relationships between fodder/seed production and tree density shift with PNCSM?
	Can big data analysis and deep learning explain trends in piñon range alterations?
	Is there a genetic component to piñon pine productivity?
Economic	What area of productive piñon would offset costs for large-scale investment in PNCSM?
	Will significant increases in regional pine nut production affect market prices?
	Can current technology and methods reduce costs for pine nut processing?
	What P-J densities result in highest fodder/pine nut yields for specific regions?
	Can non-cattle livestock bring higher returns to farmers under PNCSM?
	Can selection and breeding programs increase yields and reduce time to maturity?

Table 7. Future research needs for PNCSM identified over the course of this study.

We suggest alterations in the design of piñon commercial licensing. Current licensing is done by weight, and often by bidding on prospective collection plots (USFS 2020). Traditional methods of piñon pine nut collection emphasized community collaboration to create maximum group benefits from sporadic yield events (Lanner 1981). Exploring alternate licensing and pricing systems for non-timber forest products has been shown to improve performance for other sociological systems (Riley 2007), and we expect that it would apply to piñon pine nuts and PNCSM.

4.5 Current work and alternative components

Some current research addresses the issues of operationalizing PNCSM. Ciblis et al. (2008) have explored the landscape preferences of cattle in P-J, showing variations in climatic and temporal use cases. Continuing this line of inquiry may reveal controllable preferences that would encourage cattle grazing in traditionally less favored arid land types. Lightfoot et al. (2016) have explored density and seed yield relationships in piñon pine, with early evidence suggesting increased pine nut production at decreased tree densities. Lawson (2020) investigated the grafting of prolific seed-producing scions to speed and increase intensity seed production and had good success with graft survival. Grafting presents a unique way of increasing production without relying on the long maturation time of piñon.

This project focused on beef cattle and pine nut collection because of their relevance to current major agricultural uses of P-J, but other approaches to achieving PNCSM are readily available. Juniper species produce economically useful berries and extraction can yield usable amounts of a valuable wood protectant oil (Sichamba et al. 2012). While neither product may be useful for single-crop production in current technology and market conditions (Yesenofski 1996), either could further augment PNCSM incomes. Non-cattle livestock may also provide a path forward as changing climates shape agricultural systems. Goats, for example, are used commonly in national and international silvopastoral systems (Jose and Dollinger 2019), are well suited to arid landscapes (Skarpe et al. 2007), and have direct applications for sustainable agricultural development (Coffey et al. 2004).

5. Conclusion

The potential for greater agricultural and economic utilization of P-J has been promoted frequently in management and scientific literature. A rapidly changing landscape requires prudent investment in developing agricultural frameworks to ensure positive outcomes for system-wide production and rural livelihoods. Coordinated management, policy, and research efforts which prioritize data sharing and outreach to stakeholders may be vital to realize the agricultural potential of P-J in Arizona.

Achieving this goal will require significant scientific investigation, and answers to pressing research needs [Table 7] could drive development of PNCSM. We believe that the specific recommendations we provide to facilitate pine nut-cattle silvopastoralism would be of use to improve livelihoods, maximize landscape values, and increase the resistance of Arizona's agricultural system to existing issues and imminent challenges.

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