

Mapping landscape suitability for forest thinning to reduce evapotranspiration and enhance groundwater recharge in Arizona

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Abstract

Literature on the relationship between forest thinning and water yield was used to develop suitability criteria to map where forest treatment is most likely to enhance groundwater recharge across the Mogollon Rim Ranger District in the Coconino National Forest. Recharge in the region is ephemeral and focused in periods of snowmelt and locations of enhanced permeability when soil moisture exceeds threshold levels. Our approach combines thematic maps of criteria such as average precipitation, snow dominance, slope, aspect, landscape morphology, forest density, lithology and hydrologic soil type into a GIS-Multi-Criteria Decision Making model. Pairwise comparisons were made between criteria, and Analytic Hierachy Process was used as a weighting method.

Keywords: suitability mapping, Forest thinning, Water yield, groundwater recharge, GIS-MCDM, AHP

1. Introduction

Since 2000, the Colorado River Basin has been in the midst of a historic drought [1, 2]. Average temperatures increased by 0.9°C from 2000 - 2014, and streamflow in the Colorado River has declined by 19% below the 1906-1999 average [3, 4]. Extreme hydroclimate events such as droughts, heatwaves, and floods have more than doubled in frequency since 2010 [5]. Simultaneously, like much of the inter-mountain west, Arizona has experienced rapid population growth, increasing the demands on already strained water supplies. Reductions in streamflow have increased reliance on groundwater pumping, while groundwater levels have declined for decades in much of the state [6].

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Concurrently, western forests are at increasing risk from catastrophic wildfires—an emerging driver of runoff change that will increase the impact on the water supply [2]. Forest structure in the Ponderosa Pine forests of Northern Arizona and New Mexico has changed significantly post-Euro-American settlement due to grazing, logging, wildfire exclusion, and other factors [7, 8]. As a result, many forests are overstocked relative to pre-settlement conditions, increasing the risk of catastrophic wildfire [9]. Rising temperatures and related droughts have contributed to extensive tree mortality from wildfire, disease, and insect infestation [10]. Warming temperatures have tripled the frequency and quadrupled the size of wildfires in recent decades [2]. Increasing heat has pushed many low-elevation conifer forests past climate thresholds, creating conditions less suitable for tree regeneration [11].

Landscape-scale forest restoration efforts have been planned or implemented across much of Arizona. For example, the Four Forest Restoration Initiative (4FRI) includes plans for restoration across over 1 million hectares of Arizona’s forests [12]. The primary goal of restoration efforts is to reduce wildfire risk [9, 8]. However, numerous studies have linked forest treatments to increased water yields in semi-arid forests and have emphasized the role of forest restoration in improving hydrologic services and increasing water availability [13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24].

The connection between forests and water supplies is well documented. Around 65% of surface water in the western states originates from forested lands, which cover just 29% of the land area [25]. The average annual precipitation in the Lower Colorado River Basin is about 330 *mm*, and only about 10 *mm* of that precipitation becomes streamflow, while much of the rest is lost to evapotranspiration [17]. Regional studies have found that up to 90% of annual precipitation in semi-arid forests is lost evapotranspiration [26, 27, 28, 24]. Sublimation has been shown to remove 10 - 90% of snowfall in the Colorado River Basin, while the remaining snowmelt provides over 80% of streamflow to the Colorado River [29]. Over half of streamflow from the Upper Colorado River basin comes from groundwater sources primarily recharged by snowmelt [30]. Therefore, small reductions in evaporative losses could have out-sized impacts on available water supplies, particularly enhancing groundwater recharge in terrains underlain by karst lithology [24, 31].

While the connection between forest treatment and water yield is well documented, the response of forests to treatments is complex and non-linear and differs across forest types, with treatment level, and along aspect and elevational gradients [32, 33, 17, 24, 34]. Regardless of the potential for increased water yield the enhancement of groundwater recharge rarely, if ever, ranks among the primary motivations for forest treatment [35, 36, 9, 8]. This study examines forest restoration through the lens of groundwater recharge enhancement and identifying potential recharge zones. All else held equal, we map suitability for forest thinning with the goal of enhancing recharge. Suitability maps like these may complement (or supplement) existing frameworks for prioritizing

landscape-scale forest management.

Suitability mapping, and particularly GIS-based Multi-criteria decision making (GIS-MCDM), is widely used to map potential recharge zones and areas suitable for Managed Aquifer Recharge (MAR), but to our knowledge, it has not yet been implemented to map recharge enhancement potential through forest thinning [37, 38]. Pairwise comparisons were made between criteria including average precipitation, snow dominance, slope, aspect, landscape morphology, forest density, lithology, and hydrologic soil type, and the Analytic Hierarchy Process (AHP) was used as a weighting method.

Forest treatments such as thinning and burning can significantly impact the hydrologic cycle of forests [32]. For example, forest thinning in Arizona has been associated with increased snow cover days [39, 40, 41], greater soil moisture [42, 43], and greater forest canopy moisture [44]. However, the response of forests to treatments is complex and non-linear and differs across forest types, with treatment level, and along aspect and elevational gradients [32, 33, 17, 24, 34].

Water yield can decrease with reductions in forest cover in drier forests with little topographic shading or SW aspects due to increased water use by remaining vegetation and increased snow sublimation or direct evaporation of soil moisture [45, 46]. Biederman and others [33] found that low-elevation forests in Arizona may produce less streamflow following reductions in canopy cover due to wildfire, highlighting the importance of elevation and particularly water-energy asynchrony to water yield [47]. The effects of forest treatment appear to have little or no effect on water yield in areas receiving less than 500mm of annual precipitation [33, 48, 49, 17, 24].

**** Papers on how thinning works primarily in snow-dominated systems****

This research aims to develop criteria for areas suitable for thinning to enhance groundwater recharge. It focuses primarily on regional studies to determine suitability criteria, which are likely the best predictor of hydrologic response to treatment [18].

1.1. Regional Hydrologic Responses to Treatment

Several regional studies link forest treatment to changes in stand-level ecohydrology, including increased tree growth in Ponderosa Pines greater soil moisture and total ecosystem moisture leading to increased drought resilience [44, 43], increased snow retention [50, 51], greater streamflow [14], water table rise [Denver et al in Prep][[16]][23] and increased springflow [23][Hart prarie and hoxworth in prep].

1.1.1. Water Yield/Runoff

Several regional studies link forest treatment to increased streamflow [52, 33, 50]. However, there appears to be a threshold response, with water yield increasing only in treated forests receiving over 500mm of annual precipitation or in snow-dominated forests [33, 48, 49, 17, 24].

1.1.2. Soil Moisture and Drought Resilience

A synthesis of several treatment types across Northern Arizona, including thinning at various levels and prescribed burning, found that treated sites had significantly greater total ecosystem moisture, making forests more resilient to drought [44, 43]. Treatments were shown to increase tree growth, improving resilience to drought in Ponderosa Pine forests [53]. Thinned Ponderosa Pine forests have higher soil moisture for two to eight years post-thinning, a result also found in semi-arid forests around the Mediterranean [42, 32, 54, 55].

1.1.3. Justification

- regional studies are the best predictor of hydrologic response to thinning in Arizona forests [18]
- A synthesis of all 4FRI treatments found that thinned and burned forests have significantly greater total ecosystem moisture and are thus more resilient to drought and wildfire [44]
- Thinned forests are better buffered against drought impacts in terms of both soil moisture and tree health [43].
- Soil moisture and ET may be affected by thinning for 3.6 - 8.6 years [32].
- Prescribed burning or thinning can increase tree growth, improving resilience to drought in ponderosa pine forests [53].
- Thinned forests (around Flagstaff) have higher soil moisture at 25 and 50cm in the first two years post-thinning [42].
- Thinning in semi-arid forests around the Mediterranean increased antecedent soil moisture and below ground hydrologic processes and increased deep soil moisture by 50mm/year over the control [55].
- a review of 35 studies published from 1971 to 2018 found that thinning was more effective than clear-cutting in terms of increasing groundwater recharge due to reduced sublimation and evaporation. Springs can effectively monitor groundwater recharge effects in arid lands [23].
- A review of studies on forest mgmt effects on groundwater resources found that a rise in the water table can generally be expected following forest thinning in all forested landscapes [16].

1.1.3.1. Snow retention.

- The effects of forest thinning and subsequent snowmelt are highly variable, with responses depending on forest structure and local climate, where thinning in dense and taller vegetation generally increases snow retention, thinning in shorter, less dense forests may decrease retention [56].
- In semi-arid forested watersheds, thinning can influence streamflow variability by modifying snowpack accumulation and melt, particularly in wet-

ter years where thinning can either reduce or increase snow retention based on site-specific conditions.[50].

- Thinning in semi-arid forested watersheds can significantly impact streamflow by altering snowmelt timing, with reduced forest cover tending to delay snowmelt at warmer sites while advancing melt at cooler, snowpack-persistent sites [52].
- Thinned forests around Flagstaff have greater snow persistence at 25%-35% canopy cover [40]
- Thinned forests in Northern Arizona have more snow and soil moisture [54]
- Found that thinned and burned vs. control forests had varying rates of snowmelt and snow persistence. Canopy cover is most predictive of snow persistence [41].

1.1.3.2. *Thresholds in literature.*

- A review of 94 catchment studies showed that significant changes in water yield are correlated to forest growth in forests that receive 600-1200 mm of mean annual precipitation Bosch and Hewlett, 1982 The caveat being there were not many coniferous forests studies in that precipitation range [13].
- [49] hypothesized that where annual precipitation exceeds ~500 mm or water yield is dominated by snowmelt, watershed will experience significantly decreased evapotranspiration and increased flows if canopy cover is reduced by over 20%. However, their recent observations suggest that in dry forests, water yield may decrease. More research is needed. This paper was focused on tree-die off not thinning.
- [48] found a threshold hydrologic response when evaluating the thinning of a snow-dominated semi-arid Pinyon-Juniper community in the Great Basin. They found that a positive water yield in thinned plots was only observed when precipitation exceeded 400mm annually (wet years)
- [33] suggests that disturbance will positively impact streamflow for a minimum of several years following disturbance in areas where mean annual precipitation exceeds ~500mm. “Presumably because below 500 mm, most precipitation is evaporated regardless of forest condition (Hibbert, 1979)[@]
- [57] evaluated 250 worldwide catchment studies and found that the differences in ET between forested and non-forested catchments diminish in areas with annual rainfall less than 500 mm

1.1.4. *thinning decreases ET in some circumstances*

- Reductions of canopy cover can increase ET of existing trees, and solar radiation increases ET @biederman_recent_2015

- Decreases in post-disturbance ET may be offset by increased soil evaporation, increasing net ET (Reed et al., 2016)
- [46] reviewed the hydrologic response of stand-replacing and non-stand-replacing disturbances and found that post-disturbance streamflow may increase, not change, or even decrease. Non-stand replacing fires—because of increased evaporation from higher sub-canopy radiation and increased transpiration from rapid post-disturbance growth can reduce water availability in some cases.

1.2. Data & Methods

1.2.1. Weighted Suitability Workflow

1.2.1.1. Define.

“define the goal, supporting criteria, and evaluation metrics for the weighted suitability model.”

Here we define the goal of this suitability map—to locate areas on the Mogollon Rim Ranger District in the Coconino National Forest where thinning may increase groundwater recharge based on modeling of criteria found in the literature quantifying the impact of thinning on water yield in Regional studies of Semi-arid forests.

1.2.1.2. Suitability Criteria.

1.2.1.2.1. Aspect

Aspect has a large impact on solar radiation.

Closer to 0 or 360 is desired, low suitability scores for closeness

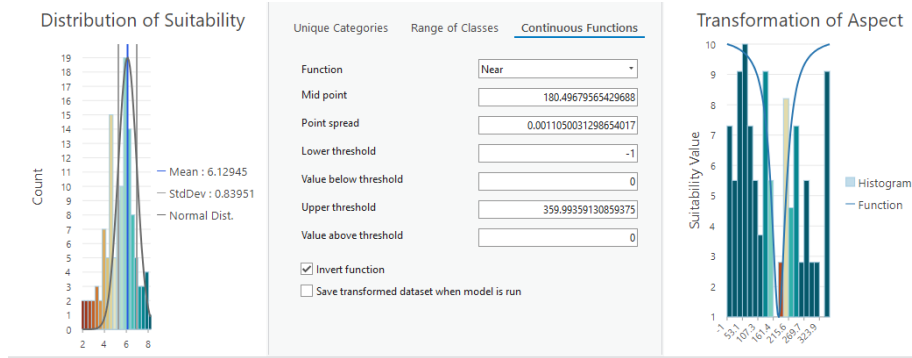
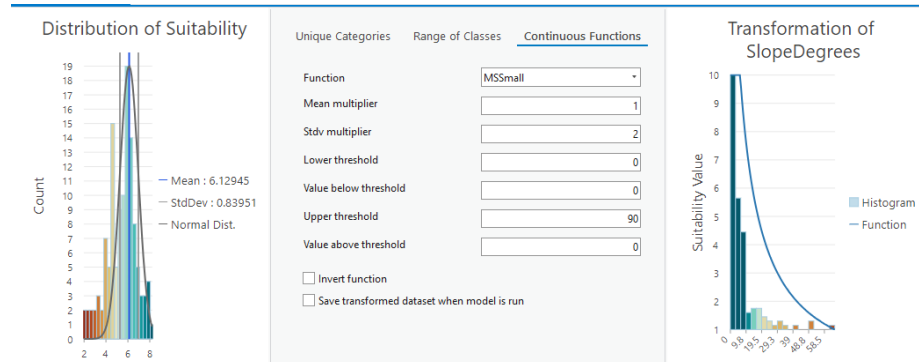


Figure 1: Screenshot of Transfer function for Aspect Suitability

1.2.1.2.2. Slope

Higher slopes are less suitable because thinning is both more expensive, and more precipitation will end up as runoff.

Lower slopes have higher suitability scores



1.2.1.2.3. Elevation

Water yield in lower elevation watersheds will be less responsive to changes in forest structure due to asynchrony between snowmelt and transpiration [58]

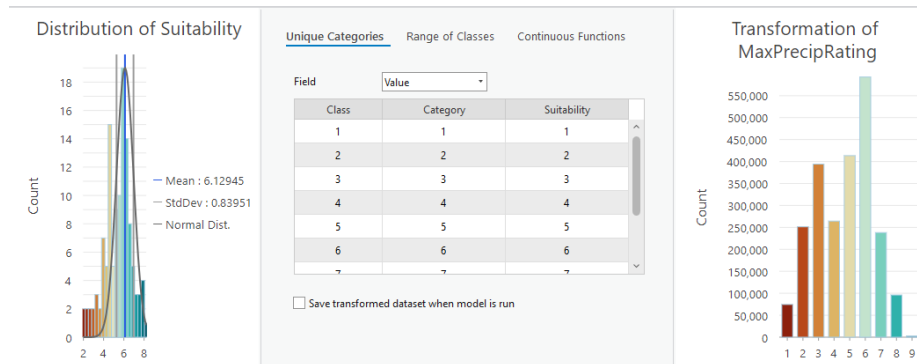
Winter precipitation mainly falls as snow at elevations above 1800m in Arizona [8]

1.2.1.2.4. Precipitation

Ideal: Mean annual precipitation must be higher than 500mm 1990 - 2020

Marginal: (benefits only expected in wet years or during some events) Max precipitation higher than 500mm but Mean annual precipitation < 500mm

Unsuitable: Max annual precipitation < 500mm

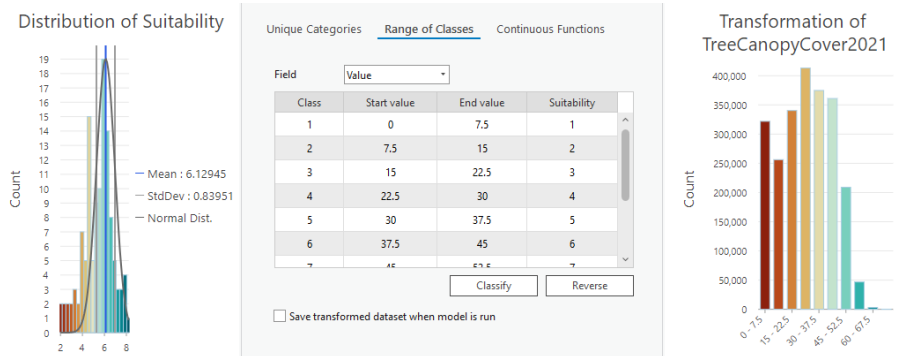


1.2.1.2.5. Vegetation Characteristics

Higher vegetation density, when thinned, will yield more water, so focus on areas of high vegetation density and high departure from historic conditions.

NLCD 2021 Total Canopy Cover (% Cover)

Canopy cover % below 30 were considered low suitability (1) while increases in canopy cover about 30% increase in suitability.

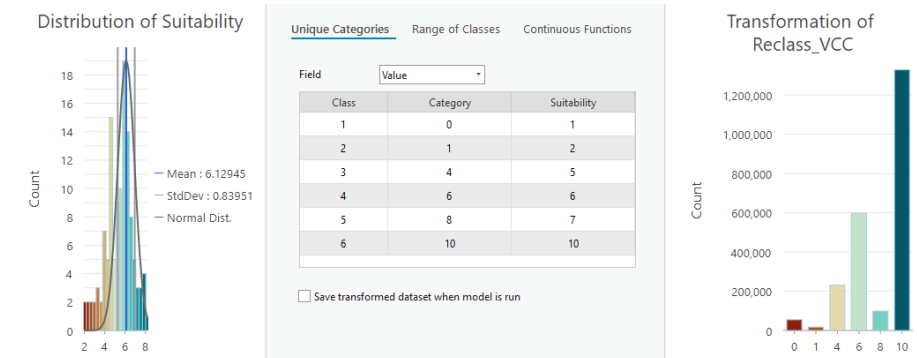


Landfire 2022 Vegetation Condition Class 3rd update to the 2016 remap.

Variation from modeled historic conditions. Forests that have deviated significantly from their modeled historic conditions are more suitable for thinning than forests that have not deviated from their historic condition.

Vegetation Condition Class (VCC) represents a simple categorization of the associated Vegetation Departure (VDep) and is a derivative of the VDep layer. It indicates the general level to which current vegetation differs from the estimated modeled vegetation based on past reference conditions. VDep and VCC are based upon methods

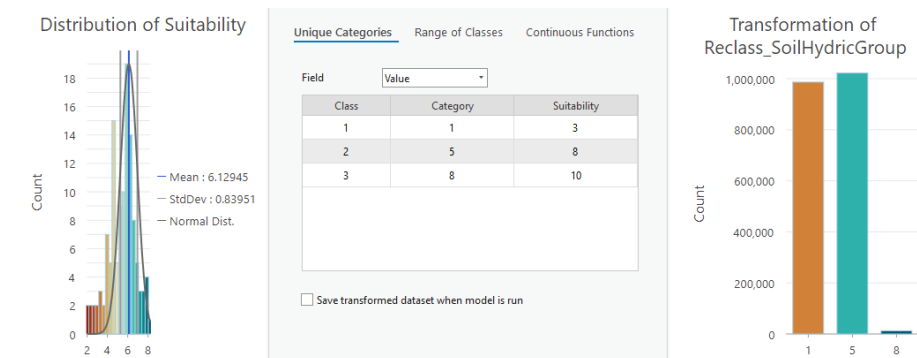
originally described in the Inter-agency Fire Regime Condition Class Guidebook but are not identical to those methods. They should not be considered as a replacement data set. Full descriptions of the techniques used can be found in the VDep product description. Note that the LANDFIRE (LF) team feels it is very important for users to review the VDep methods before comparing VDep or VCC values across LF versions. [info PDF](#)



1.2.1.2.6. Soil Hydrologic Conditions

Soil types A,B,C,D are mapped for the USA, There are no A soil types in the study area, so they were given the following suitability values

B = 10 out of 10 C = 8 out of 10 D = 3 out of 10

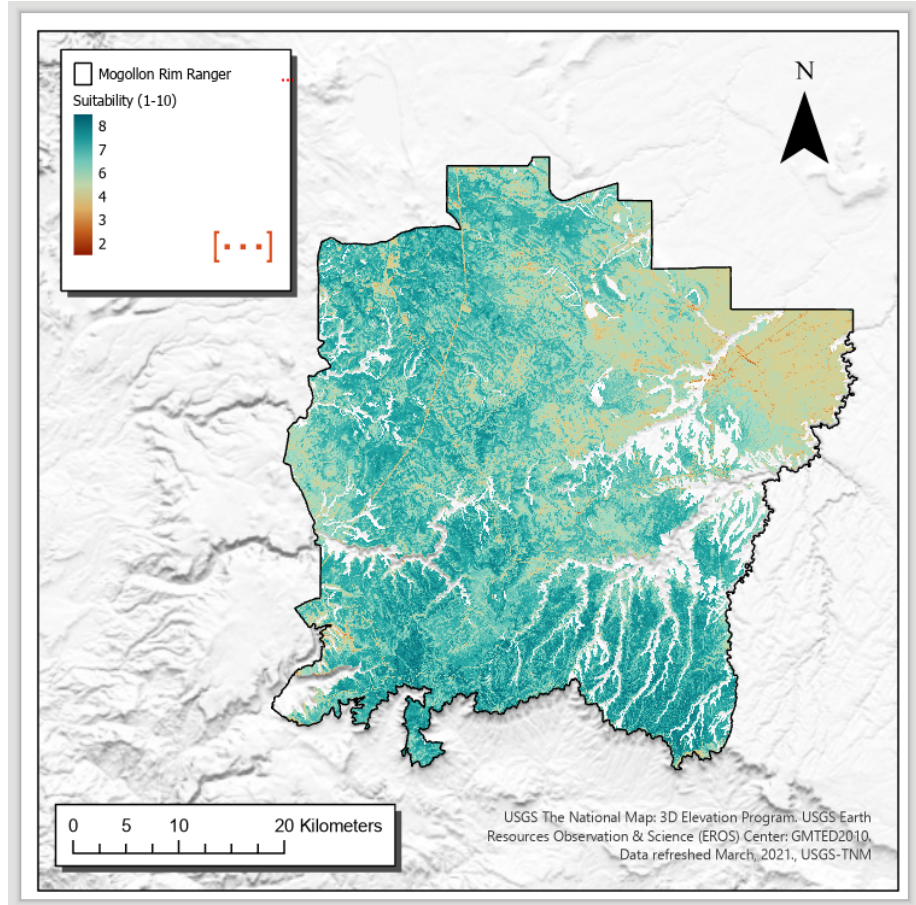


1.3. Preliminary Results

1.3.1. Weighting

Tree Canopy Cover = 20% Vegetation Condition Class = 20% Slope = 20%
Aspect = 20% Max Precipitation = 15% Soil Hydrologic Group = 5%

1.3.2. Overall Suitability



1.4. Acknowledgments

Phasellus interdum tincidunt ex, a euismod massa pulvinar at. Ut fringilla ut nisi nec volutpat. Morbi imperdiet congue tincidunt. Vivamus eget rutrum purus. Etiam et pretium justo. Donec et egestas sem. Donec molestie ex sit amet viverra egestas. Nullam justo nulla, fringilla at iaculis in, posuere non mauris. Ut eget imperdiet elit.

1.5. Open research

Phasellus interdum tincidunt ex, a euismod massa pulvinar at. Ut fringilla ut nisi nec volutpat. Morbi imperdiet congue tincidunt. Vivamus eget rutrum purus. Etiam et pretium justo. Donec et egestas sem. Donec molestie ex sit amet viverra egestas. Nullam justo nulla, fringilla at iaculis in, posuere non mauris. Ut eget imperdiet elit.

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