

1 Mapping suitability for thinning to reduce atmospheric  
2 losses and enhance groundwater recharge in Arizona

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## Abstract

In semi-arid forests such as Arizona, over 90% of annual precipitation may be lost to evapotranspiration. Forest structure has changed significantly post-Euro-American settlement due to various factors, including grazing, logging, and wildfire exclusion. As a result, many forests in Arizona are overstocked relative to pre-settlement conditions, increasing the risk of catastrophic wildfire. In recent years, the growing frequency and severity of drought and wildfires have resulted from warming associated with anthropogenic climate change. Landscape-scale efforts to restore forests to near historic densities are underway throughout Arizona. Mechanical thinning has increased water yield for several years following treatment in some forests. However, the response of forests to treatments is complex, site-specific, and varies with elevation, aspect, treatment level, and climatic conditions. As Arizona grapples with increasing water insecurity due to historic drought, demographic changes, and increased hydroclimatic variability, policymakers are searching for ways to bolster water supplies statewide, particularly groundwater, which has been declining across much of the state. Here, we review the literature on the effects of forest thinning on water yield throughout Arizona and map areas where mechanical treatment has the highest potential for increasing groundwater recharge.

## Plain Language Summary

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## 1 Introduction

This research synthesizes the myriad studies examining the effects of forest treatment on water yield in semi-arid forests and compiles a list of relevant variables. Our approach combines thematic maps of average precipitation, elevation, slope, aspect, forest type, forest density, depth to bedrock, and soil type into a GIS suitability model to highlight areas where forest treatment will most likely enhance recharge statewide.

Since 2000, the Colorado River Basin has been in the midst of a historic drought (Meko et al., 2022; Williams et al., 2022). 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 (Hogan & Lundquist, 2024; Udall & Overpeck, 2017). Extreme hydroclimate events such as droughts, heatwaves, and floods have more than doubled in frequency since 2010 (Bennett et al., 2021). Simultaneously, Arizona has experienced rapid population growth, increasing the demands on already strained water supplies. Reductions in streamflow have increased reliance on groundwater, while groundwater levels have declined for decades (Tadych et al., 2024). The *Arizona Tri-University Recharge and Water Reliability Project* (ATUR-WRP) has been tasked with identifying ways to protect water supplies and enhance recharge by identifying where landscape management practices can reduce atmospheric losses. Average annual precipitation in the lower Colorado River Basin is about 330mm, and only about 10mm of that precipitation becomes streamflow while much of the rest is lost to Evapotranspiration (Zou et al., 2010). Sublimation has been shown to remove 10 - 90% of snowfall in the basin; the remaining snowmelt provides over 80% of streamflow to the Colorado River (Lundquist et al., 2024). Therefore, small reductions in evaporative losses could have outsized impacts on available water supplies.

Around 65% of surface water in the western states originates from forested lands, which cover just 29% of the land area (Brown et al., 2005). However, western forests are increasingly at risk from catastrophic wildfires, an emerging driver of runoff change that will increase the impact on the water supply (Williams et al., 2022). Increasing temperatures and related droughts have contributed to extensive tree mortality from wildfire, disease, and insect infestation (Berner et al., 2017). Warm-

ing temperatures have tripled the frequency and quadrupled the size of wildfires in recent decades (Williams et al., 2022). Increasing heat has pushed many low-elevation conifer forests past climate thresholds, creating conditions less suitable for tree regeneration (Davis et al., 2019). This increased risk of wildfire and forest loss is driven by climate and overstocked conditions resulting from over a century of forest management practices since euro-american settlement (Allen et al., 2002; Covington & Moore, 1994).

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 2.5 million acres of Arizona’s forests (Schultz et al., 2012). The primary goal of restoration efforts is to reduce wildfire risk. 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 (Baker, 1986; Bosch & Hewlett, 1982; Gottfried, 1991; Moreno et al., 2015; O’Donnell et al., 2018; Schenk et al., 2020; Simonit et al., 2015; Smerdon et al., 2009; C. Wyatt et al., 2015; C. J. W. Wyatt, 2013; Zou et al., 2010). Forest treatments such as thinning and burning can significantly impact the hydrologic cycle of forests (Del Campo et al., 2022). 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 (Biederman et al., 2022; Del Campo et al., 2022; Moore & Wondzell, 2005; Zou et al., 2010). This research aims to develop criteria for areas suitable for thinning to enhance groundwater recharge. It focuses primarily on regional studies that are likely the best predictor of hydrologic response to treatment (C. J. W. Wyatt, 2013).

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## 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 (Rodman et al., 2024) greater soil moisture and total ecosystem moisture [], increased drought resilience [], Increased snow retention, greater streamflow [], water table rise and increased spring flow []

### 1.1.1 Water Yield/Runoff

Several regional studies link forest treatment to increased streamflow (Biederman et al., 2022; Broxton et al., 2023; Dwivedi et al., 2024). However, there appears to be a threshold response, with water yield increasing only in treated forests receiving over 500mm of annual precipitation or snow-dominated forests (Adams et al., 2012; Biederman et al., 2022; Carroll et al., 2016; Zou et al., 2010).

### 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 (Sankey et al., 2021; Sankey & Tatum, 2022). Treatments were shown to increase tree growth, improving resilience to drought in Ponderosa Pine forests (Rodman et al., 2024). 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 (Belmonte et al., 2022; Del Campo et al., 2019, 2022; O’Donnell et al., 2021).

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## 1.2 Justification

- regional studies are the best predictor of hydrologic response to thinning in Arizona forests (C. J. W. Wyatt, 2013)

- 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 (Sankey et al., 2021)
- Thinned forests are better buffered against drought impacts in terms of both soil moisture and tree health (Sankey & Tatum, 2022).
- Soil moisture and ET may be effected by thinning for 3.6 - 8.6 years (Del Campo et al., 2022).
- Prescribed burning or thinning can increase tree growth improving resilience to drought in ponderosa pine forests (Rodman et al., 2024)
- Thinned forests (around Flagstaff) have higher soil moisture at 25 and 50cm in the first two years post-thinning (Belmonte et al., 2022).
- Thinning in semi-arid forests around the mediterranean increased antecedent soil moisture and belowground hydrologic processes and increased deep soil moisture by 50mm/year over the control (Del Campo et al., 2019).
- 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 be effective at monitoring groundwater recharge affects in aridlands (Schenk et al., 2020).
- A review of studies on forest mgmt effects on groundwater resources found that a rise in water table can generally be expected following forest thinning in all forested landscapes (Smerdon et al., 2009).

### 1.2.1 *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 (Lewis et al., 2023).
- In semi-arid forested watersheds, thinning can influence streamflow variability by modifying snowpack accumulation and melt, particularly in wetter years where thinning can either reduce or increase snow retention based on site-specific conditions.(Broxton et al., 2023).
- Thinning in semi-arid forested watershed can significantly impact streamflow by altering snowmelt timing, with reduce forest cover tending to delay snowmelt at warmer sites while advancing melt at cooler, snowpack-persistent sites (Dwivedi et al., 2024).
- Thinned forests around Flagstaff have greater snow persistence at 25%-35% canopy cover (Belmonte et al., 2021)
- Thinned forests in Northern Arizona have more snow and soil moisture (O'Donnell et al., 2021)
- Found that thinned and burned vs control forests had varying rates of snowmelt and snow persistence. Canopy cover is most predictive of snow persistence (Donager et al., 2021).

### 1.2.2 *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 (Bosch & Hewlett, 1982).

- (Adams et al., 2012) 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.
- (Carroll et al., 2016) found a threshold hydrologic response when evaluating 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)
- (Biederman et al., 2022) suggests that disturbance will have positive impacts on 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)[@]

### 1.3 thinning decreases ET in some circumstances

- Reductions of canopy cover can increase ET of existing trees, and solar radiation increasing ET [Biederman et al. \(2015\)](#)
- Decreases in post-disturbance ET may be offset by increased soil evaporation increasing net ET (Reed et al., 2016)
- (Goeking & Tarboton, 2020) 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. Nonstand replacing fires—because of increased evaporation from higher subcanopy radiation and increased transpiration from rapid post-disturbance growth can decrease water availability in some cases.

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## 2 Data & Methods

### 2.1 2.2 Weighted Suitability Workflow

#### 2.1.1 2.2.1 Define

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

##### 2.1.1.1 Criteria

#### Aspect

Closer to 0 or 360 is desired

#### Elevation

higher elevation is better; higher percentage of precipitation is snow, higher precipitation

#### Precipitation

Max precipitation must be higher than 450, mean precipitation should be higher than 400

#### Vegetation Characteristics

higher vegetation density, when thinned will yield more water, focus on areas of high vegetation density or high departure from historic conditions.

### 2.1.2 2.2.2 *Derive*

“Derive data that represents the model variables that are defined by the criteria. In this example, the criterion Far distances from streets defines distance from streets as a model variable. A raster that represents distance from streets is derived from street centerlines by using a geoprocessing tool.”

### 2.1.3 2.2.3 *Transform*

“Transform the values in each derived dataset into a common suitability scale by assigning each cell in the surface a suitability score (value on the suitability scale). For each dataset, assign the highest suitability scores to the variable values that are most preferred according to the associated criterion. In this example, the distance-from-streets raster is transformed into a 1-to-5 suitability scale. To represent the criterion Far distances from streets, the locations closest to streets are assigned a value of 1 (lowest preference) and the locations farthest from streets are assigned a value of 5 (highest preference).”

### 2.1.4 2.2.4 *Weight and combine*

“Weight and combine the transformed data, which represents the model criteria, into a single suitability surface that meets the model goal. In this example, three transformed rasters are combined to create the suitability surface.”

### 2.1.5 2.2.5 *Locate*

“Locate the phenomenon by using the suitability surface. In this example, a region that has the highest average suitability is identified.”

### 2.1.6 2.2.6 *Analyze*

“Analyze the result by visually evaluating the suitability surface and regions to ensure that the model goal has been met. Optionally, perform sensitivity and error analysis.”

## 2.2 **Environments:**

- ArcGIS Pro 3.3

### 2.2.1 *Unsuitable*

- Max Precipitation < 450mm
- Mean Precipitation < 450mm with low IAV interannual variability in precipitation
- Forest Cover Trees per Acre < 30
- Elevation < 900m
- EVC - Existing vegetation cover Landfire 2023: exclude values:
  - 9999: No data
  - 11-100: Open Water, Snow/Ice, Developed all, Barren, Cultivated, Sparse vegetation
  - 310 + (herb cover)
  - Existing vegetation cover Tree Cover < 30% 110 - 129
  - Existing Vegetation Cover Shrub Cover < 30% 210 - 230

- VCC - Vegetation Condition Class from Land Fire 2022

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 is different from the estimated modeled vegetation based on past reference conditions. VDep and VCC are based upon methods originally described in the Interagency Fire Regime Condition Class Guidebook, but are not identical to those methods and should not be considered as a replacement data set. Full descriptions of the methods 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](#)

#### Reclass\_LF23\_VCC\_1\_6

VCC Value 2022	New Class
Fill-NoData	NODATA
Fill-Not Mapped	NODATA
Veg Condition Class I, A	1
Vegetation Condition Class I, B	2
Vegetation Condition Class II, A	3
Vegetation Condition Class II, B	4
Vegetation Condition Class III, A	5
Vegetation Condition Class III, B	6
Water	NODATA
Developed	NODATA
Barren or Sparse	NODATA
Agriculture	NODATA
NODATA	NODATA

Higher numbers indicate departure from historical conditions, and indicate a need for forest restoration (CITATION NEEDED)

#### 2.2.2 Suitability Criteria Aspect

Closer to 0 or 360 is desired

#### Elevation

higher elevation is better

#### Vegetation Characteristics

Landfire 2022 VCC Higher is better 67-100 preferred Class II & III; A & B

Landfire EVC tree cover higher is better

Precipitation Higher is better

Wildfire Hazard POtential V2023 Higher is better

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### 3 Conclusion

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## References

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