Assessing Impacts of Forest Disturbances on Future Colorado River Flows under Climate Change – A Stakeholder-Engagement Modeling Process

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Abstract

Accelerated climate change and forest disturbances (e.g., wildfire, drought-related mortality) are anticipated to significantly impact water resources in the Colorado River Basin (CRB), and the need for actionable information from hydrologic research is growing rapidly. We designed a stakeholder engagement and modeling process to assess the impact of these changes on the CRB hydrology. We used the Variable Infiltration Capacity model to simulate alternative climate futures (a "top-down" structure) with scenarios of incremental forest disturbances (a "bottom-up" assessment). Forcings were derived from climate model outputs that represent 'warm and wet' (Warm/Wet) and 'hot and dry' (Hot/Dry) future climate bookends. During the process, we incorporated feedback from water managers to capture a range of perspectives on modeling scenarios and to create decision-relevant analyses. Results showed improved streamflow conditions with forest disturbances by end of century (basin-wide mean annual streamflow up to 12% larger than without disturbance) due to lower snowpack reductions and evapotranspiration losses. Larger forest reductions reversed warming impacts in the Warm/Wet case but could not fully offset the more water-limited conditions of the Hot/Dry future.

1. Introduction

Climate change is anticipated to accelerate forest disturbances across the western U.S., including drought-related stress (McDowell *et al.*, 2016), wildfires (Stavros *et al.*, 2014; Gergel *et al.*, 2017), bark-beetle infestations (Bentz and Jönsson, 2015), and the co-occurrence of these factors (van Mantgem *et al.*, 2009; Williams *et al.*, 2013; Hicke *et al.*, 2012). This could pose major consequences to ecosystems that provision streamflow (Q; Anderegg *et al.*, 2013; Sun *et al.*, 2017; Goeking and Tarboton, 2020), in particular for the Colorado River Basin (CRB; Fig. 1). Evidence is also mounting that climate change will intensify droughts and reduce water supplies in the CRB (Lukas and Payton, 2020; Milly and Dunne, 2020). As a result, quantifying the hydrologic responses to forest disturbances under climate change is important for informed planning of long-term water operations in the CRB (Zou *et al.*, 2010; Hallema *et al.*, 2018a).

Studies have found mixed hydrologic responses to forest disturbances. For example, reductions in forested areas can increase bare soil evaporation and understory transpiration leading to decreases in runoff (Biederman *et al.*, 2014b, 2015; Bennett *et al.*, 2018; Chen *et al.*, 2015). Conversely, runoff may also increase from reductions in overstory transpiration and canopy evaporation (Buma and Livneh, 2015; Bart, 2016). Tree loss also modifies snow processes, causing changes in snow duration, melt, and sublimation (Biederman *et al.*, 2014a, 2022; Bennett *et al.*, 2018). The aggregated Q response depends upon the net change in evapotranspiration (Goeking and Tarboton, 2020). Forest disturbance impacts can also be modified by local climate conditions and diluted in large watersheds with spatial variations in these conditions (Zhang *et al.*, 2017; Li *et al.*, 2017; Wang *et al.*, 2020; Penn *et al.*, 2016). As a result, post-disturbance hydrologic changes in the spatially-variable landscapes and climatic settings of the CRB will likely result from the complex interactions of various factors.

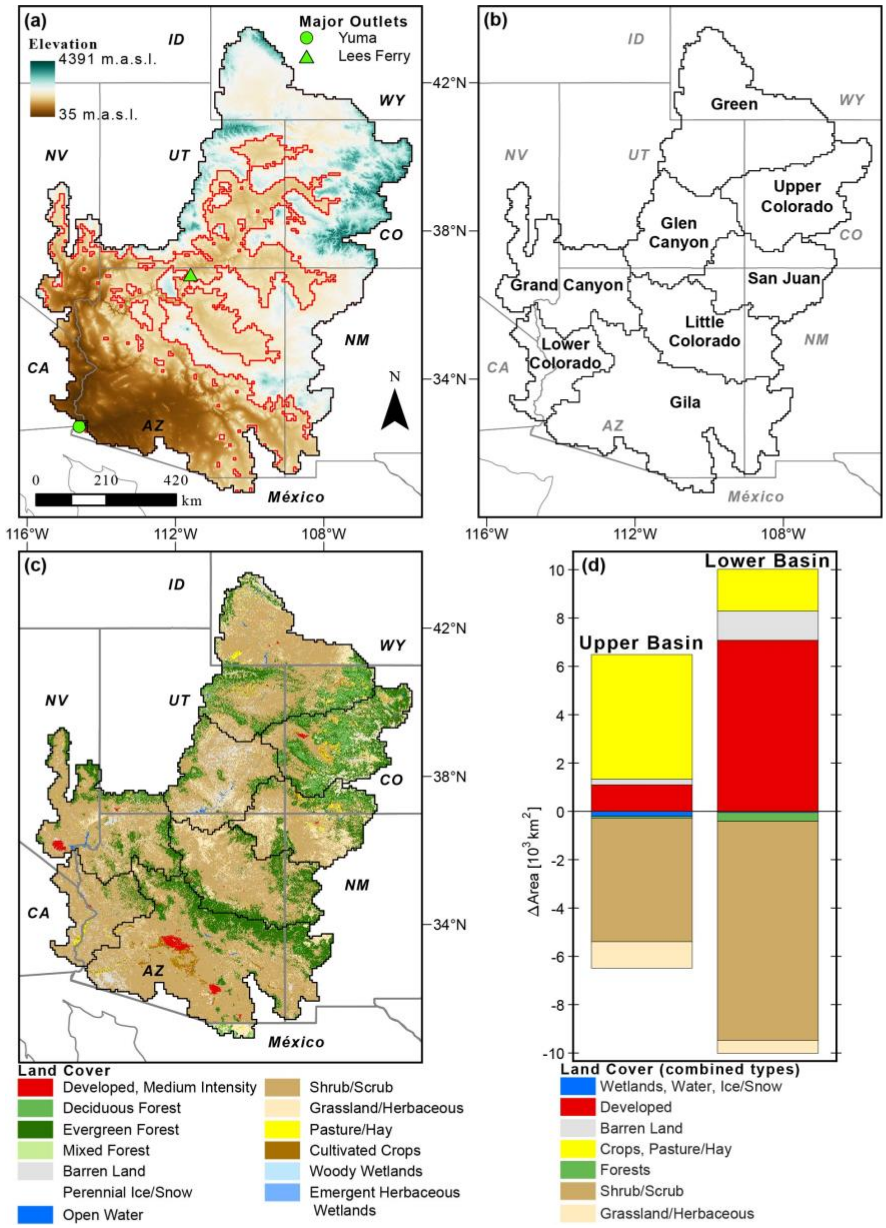

Fig. 1. (a) Elevation map of the CRB with location of Imperial Dam and Gila River outlet at Yuma, AZ, and the division of Upper and Lower Basin at Lees Ferry, AZ, from USGS (2016). Red line show elevations ≥ 1,800 m. (b) Subbasin delineations and names. (c) Land cover map from the FORE-SCE (Sleeter *et al*., 2012) and INEGI (2013) products. (d) Total area changes in Far-Future relative to Baseline across the Upper and Lower Basins.

Forest cover impact assessments in the CRB have been conducted at large subbasin (Fig. 1b) or small catchment scales (Table 1). Observational studies have found unchanged or even decreased mean annual Q in northeastern catchments following forest disturbance (Biederman *et al*., 2015). Model investigations in the same region showed opposite changes in mean annual Q (Livneh *et al*., 2015; Yates *et al*., 2015). Other investigations under historic climate conditions found contrasting water yield changes in various parts of the basin (e.g., Guardiola-Claramonte *et al*., 2011; Hallema *et al*., 2018b; Moreno *et al*., 2016; Wine and Cadol, 2016). Few studies

Table 1. Summary of research on the effects of forest disturbances to hydrology in the CRB.

Reference	Basin location*	Component studied	Method†	Effect of disturbance
Bennett *et al*. (2018)	San Juan subbasin	Effects of forest disturbance and climate change on hydrology	Sims.	Decreased water yields due to increased snow melt rates in late spring and summer, leading to higher transpiration rates.
Biederman *et al*. (2015)	Upper Colorado subbasin headwater catchments	Effects of beetle-infestation forest die-off on water yields	Obs.	No impact in most catchments, and decreased water yield in some catchments. Response dependent on precipitation, which must exceed a threshold to increase understory evapotranspiration before large streamflow loss occurs.
Biederman *et al*. (2022)	Gila subbasin headwater catchments	Effects of wildfire on water yields in drought and pluvial conditions	Obs.	No impact in higher/colder regions, and decreased water yield in lower/warmer regions due to greater sublimation rates.
Buma and Livneh (2015)	Upper Colorado subbasin headwater catchments	Effects of tree migration, disturbance, management and climate change on hydrology	Sims.	Increased water yields due to decreased transpiration rates; earlier peak flows; higher winter baseflow rates.
Guardiola-Claramonte *et al.* (2011)	Little Colorado, and catchments in the San Juan, Upper Colorado, Gila River subbasins	Water yield changes in forests affected by drought and mechanical thinning/harvesting	Obs.	Decreased water yields associated with drought-related mortality; Increased water yields associated with mechanical thinning.
Hallema *et al*. (2018b)	Headwater catchments in the San Juan, Green, and Gila subbasins	Effects of wildfire and climate change on water yields	Obs.	Water yield increases were attributed to wildfire impacts in all regions, despite precipitation decline in some regions of the Gila subbasin.
Livneh *et al*. (2015)	Upper Colorado subbasin headwater catchments	Effects of beetle-infestation forest die-off on water yields	Both	Increased water yields due to greater ground snowpack accumulation, but with dampened water yield increases after understory regeneration.

* See Fig. 1b for a map of the major internal subbasin locations listed in this table.

† Results based on observations (Obs.), simulations (Sims.), or both observations and simulations (Both).

Table 1. (continued)

Reference	Basin location*	Component studied	Method†	Effect of disturbance
Moreno *et al.* (2016)	Gila River subbasin headwater catchments	Effects of mechanical thinning and fire treatments on water yields	Sims.	Increased water yields due to decreased transpiration and infiltration rates, increased snow accumulation and melt.
Robles *et al.* (2014)	Gila River subbasin headwater catchments	Effects of mechanical thinning and fire treatments on water yields in drought and pluvial conditions	Sims.	Increased water yields, regardless of whether treatments occurred during drought or pluvial conditions.
Williams *et al.* (2022)	Upper Basin subbasins and internal catchments	Effects of wildfires on water yields	Both	Increased water yield that scaled with fire extent (larger fires produced more water).
Wine and Cadol (2016)	Gila River subbasin	Effects of wildfires on water yields	Both	Increased water yields.
Yates *et al.* (2015)	Upper Colorado subbasin	Impacts of beetle-infestation forest die-off and climate change on water yields	Sims.	Decreased water yields due to faster snowmelt rates, reduced interception and increased evaporative rates.

* See Fig. 1b for a map of the major internal subbasin locations listed in this table.

† Results based on observations (Obs.), simulations (Sims.), or both observations and simulations (Both).

have examined streamflow responses to the combined impact of climate change and disturbances that lead to changes in land use land cover (LULC) types. While studies found that forest fires can lead to increased water yields in southern areas of the CRB (Robles *et al*., 2014; Williams *et al*., 2022), process-based models show opposite responses to forest disturbances under warming in the northeast (Bennett *et al*., 2018; Yates *et al*., 2015; Buma and Livneh, 2015). Basin-scale efforts are thus needed to assess the combined impact of climate and LULC changes to water budgets in the CRB and to provide perspectives on competing water balance processes.

Several modeling approaches are used for determining the hydrologic impacts of climate and LULC change. Traditional efforts are based on "top down" schemes driven by outputs from general circulation models (GCMs, Bennett *et al*., 2018) and LULC change projections (Sohl *et al*., 2016). "Bottom-up" modelling approaches can complement these when a specific water resources challenge needs to be addressed (e.g., Bhave *et al*., 2014; Whetton *et al*., 2012; Cazares-Rodriguez *et al*., 2017). Often designed with stakeholders through a participatory exercise, a combination of "top-down" and "bottom-up" approaches can be used to transform modeling objectives from predicting all possible outcomes towards identifying critical conditions under which the water resource system is more vulnerable or robust, and allow managers to plan for situations with key hydrologic consequences (Brown and Wilby, 2012; Verbist *et al*., 2020).

In this study, we designed a stakeholder engagement and modeling process to evaluate the impacts of climate and LULC changes on the future hydrology of the Colorado River Basin. We simulated changes under alternative GCM forcings (a “top-down” structure) with scenarios of incremental forest disturbances (a “bottom-up” assessment). We used the Variable Infiltration Capacity (VIC) model with selected GCM products that represent ‘warm and wet’ and ‘hot and dry’ futures as bookends to drive our framework. We then modified land cover composition using a LULC model and applied cases of more drastic forest disturbances. In this process, we consulted with and incorporated feedback from basin water management stakeholders to ensure that a wide range of views were captured in the modeled cases and secure the production of decision-relevant analyses. Our integrated approach enabled us to identify forest disturbance cases that augment or neutralize the impacts of climate change to water resources in the CRB.

2. Methods

2.1 *Study Domain and Analysis Subbasins*

The CRB encompasses about 630,000 km^2, with headwaters originating in the Green River in Wyoming that flow through the main channel for about 2,253 km to northern México (Fig. 1a). Elevation ranges from 35 to 4391 m, with most high elevations contained in the Upper Basin (source area above Lees Ferry, AZ; Fig. 1a) where approximately 90% of streamflow originates as snowmelt. Land cover maps reveal that most of land areas are characterized by shrub or scrub ecosystems (~59%), followed by various forest types (~23%), and grassland or herbaceous cover (11%, Sleeter *et al*., 2012; INEGI, 2013). In consultation with basin water managers, we performed a model subbasin delineation for the source area above Imperial Dam and the Gila River subbasin in Arizona that yielded eight analysis subbasins (Upper Colorado, Green, Glen Canyon, San Juan, Grand Canyon, Little Colorado, Lower Colorado, Gila, Fig. 1b).

2.2 Stakeholder Engagement Process

Water resource decision making is complicated by a range of uncertainties that require linking knowledge production with the needs of decision makers (e.g., Smith *et al*., 2022; Brown *et al*., 2015; Mayer *et al*., 2017). To meet this goal, we held a series of meetings with water managers and other basin stakeholders across the CRB to gather and incorporate feedback during each stage of our model scenario development and appraisal process (Fig. 2). Each step of this process is detailed subsequently, but briefly these included: (1) comparing GCMs to identify climate bookends to force the model framework, (2) modifying land cover composition of model parameters using regional projections of a LULC model, (3) applying additional disturbances to forest cover, and (4) presenting scenarios to stakeholders to solicit their feedback.

2.3 Modeling Framework

Our modeling framework was centered on VIC, version 5.0 (Hamman *et al*., 2018), at 1/16º (~6 km) resolution. VIC is a regional model that solves the full water and energy balance on a regular grid, where each cell is divided into land cover tiles atop a three-layer soil column (Liang *et al*., 1994). The number of tiles in a cell depends on the land cover fraction (C_v). Tiles are modeled independently for snow water equivalent (SWE) and evapotranspiration (ET) components: snow sublimation (E_s), canopy evaporation (E_c), transpiration (T_v), and soil

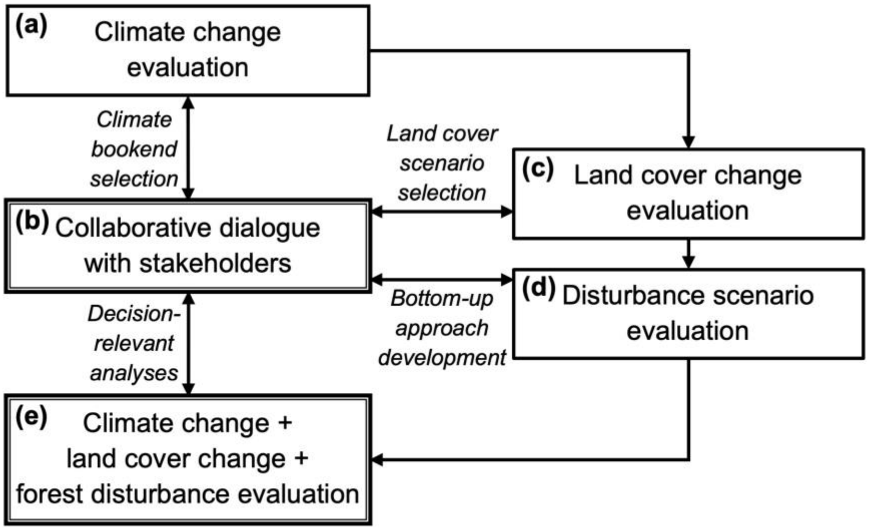

Fig. 2. Model scenario development and appraisal process, with each stage informed by iterative feedback from basin stakeholders (see section 3.4 for list of participating agencies). These included evaluations of the climate model futures (Table 2) to select bookends, the VIC simulated outcomes under the climate bookends when parameters were updated with FORE-SCE products, the VIC simulated outcomes under the climate bookends with alternative forest disturbances, and the decision-relevant analyses from the model framework.

evaporation (E_{soil}; Andreadis *et al*., 2009; Cherkauer and Lettenmaier, 2003). VIC accounts for heterogeneity in infiltration capacities and runoff (*R*) in a grid cell (Liang *et al*., 1994). Soil moisture (*SM*) moves vertically through the top two soil layers and is factored into baseflow (*BF*) within the third layer using a non-linear recession curve (Liang *et al*., 1994). Total fluxes for each cell are computed as the area-weighted sum across all component tiles. *R* and *BF* were then routed as streamflow (*Q*) using the R-VIC channel routing model (Lohmann *et al*., 1996).

2.4 Climate Forcings

Climate model forcings from GCMs in the Climate Model Intercomparison Project 5 were available for the stakeholder engagement process, including a subset of eight GCMs that best reproduced historical conditions in the CRB (Gautam and Mascaro, 2018). These GCM products were statistically downscaled to 1/16º resolution via the Locally Constructed Analogs technique (Pierce *et al*., 2014) for Representative Concentration Pathways 4.5 (R45) and 8.5 (R85; Taylor *et al*., 2012). Stakeholders preferred selecting two bookend climate cases to drive the modeling framework. To obtain these, we compared mean annual precipitation (*P*) and air temperature (*T*) changes in the 2066-2099 period (Far-Future) relative to the 1976-2005 period (Baseline; Table 2) and selected: (1) CanESM2 under historic and R45 emissions for the Warm/Wet scenario, and (2) IPSL-CM5A-MR under historic and R85 emissions for the Hot/Dry scenario. We used the downscaled climate forcings of these products from 1976 to 2099.

2.5 LULC Product

We used future projections of land cover compositions from the FOREcasting SCEnario (FORE-SCE; Sleeter *et al*., 2012) products based on the review of Sohl *et al*. (2016). These datasets include yearly historical (1992-2006) and future projected (2007-2100) LULC consistent

Table 2. GCM values of mean annual precipitation (*P*) and air temperature (*T*) in the indicated basins for the Baseline (top) and Far-Future period under R45 (middle) and R85 (bottom). Changes relative to baseline ([% for *P*] and [ºC for *T*]) in parentheses. Bolded values indicate the GCMs for the Warm/Wet (***italic***) and Hot/Dry (**non-italic**) cases.

	Air temperature (*T* in ºC)			Precipitation (*P* in mm yr^{-1})		
	Basin-wide	Upper Basin	Lower Basin	Basin-wide	Upper Basin	Lower Basin
Baseline						
ACCESS1-0	10.7	6.2	14.7	357.3	397.3	322.8
CanESM2	***10.8***	***6.3***	***14.7***	***365.1***	***407.3***	***328.8***
EC-EARTH	11.0	6.5	14.9	345.9	397.2	301.8
HadGEM2-ES	10.8	6.3	14.8	340.3	388.0	299.2
IPSL-CM5A-MR	**10.9**	**6.3**	**14.8**	**359.3**	**403.2**	**321.5**
MIROC5	10.7	6.1	14.6	347.8	389.7	311.7
MPI-ESM-LR	10.9	6.4	14.9	346.2	388.3	309.9
NorESM1-M	10.8	6.2	14.7	354.0	404.3	310.7
Far-Future (R45)						
ACCESS1-0	14.1 (+3.4)	10.0 (+3.8)	17.7 (+3.1)	349.9 (-2.1)	388.1 (-2.3)	317.0 (-1.8)
CanESM2	***14.2 (+3.4)***	***9.8 (+3.5)***	***17.9 (+3.2)***	***419.1 (+14.8)***	***472.3 (+16.0)***	***373.2 (+13.5)***
EC-EARTH	13.2 (+2.2)	8.7 (+2.3)	17.1 (+2.2)	391.6 (+13.2)	459.7 (+15.8)	332.9 (+10.3)
HadGEM2-ES	14.4 (+3.5)	10.0 (+3.7)	18.1 (+3.4)	353.5 (+3.9)	399.4 (+2.9)	313.9 (+4.9)
IPSL-CM5A-MR	14.1 (+3.2)	9.6 (+3.3)	18.0 (+3.2)	324.6 (-9.7)	377.1 (-6.5)	279.4 (-13.1)
MIROC5	14.0 (+3.3)	9.8 (+3.6)	17.7 (+3.1)	337.1 (-3.1)	406.6 (+4.3)	277.2 (-11.1)
MPI-ESM-LR	13.1 (+2.2)	8.6 (+2.2)	17.0 (+2.2)	353.5 (+2.1)	406.3 (+4.6)	307.9 (-0.6)
NorESM1-M	13.5 (+2.7)	9.1 (+2.9)	17.3 (+2.6)	362.1 (+2.3)	427.2 (+5.7)	306.1 (-1.5)
Far-Future (R85)						
ACCESS1-0	16.0 (+5.3)	11.9 (+5.8)	19.5 (+4.8)	304.6 (-14.7)	350.7 (-11.7)	265.0 (-17.9)
CanESM2	16.3 (+5.5)	11.9 (+5.7)	20.0 (+5.3)	480.4 (+31.6)	524.6 (+28.8)	442.3 (+34.5)
EC-EARTH	15.7 (+4.7)	11.3 (+4.8)	19.5 (+4.6)	344.2 (-0.5)	416.8 (+4.9)	281.7 (-6.6)
HadGEM2-ES	16.6 (+5.8)	12.4 (+6.1)	20.3 (+5.6)	325.9 (-4.2)	374.5 (-3.5)	284.0 (-5.1)
IPSL-CM5A-MR	**16.8 (+5.9)**	**12.3 (+6.0)**	**20.6 (+5.8)**	**277.7 (-22.7)**	**340.3 (-15.6)**	**223.8 (-30.4)**
MIROC5	15.6 (+4.9)	11.6 (+5.5)	19.0 (+4.4)	337.1 (-3.1)	414.0 (+6.2)	270.9 (-13.1)
MPI-ESM-LR	15.5 (+4.6)	11.0 (+4.6)	19.4 (+4.5)	320.4 (-7.5)	399.9 (+3.0)	251.9 (-18.7)
NorESM1-M	15.2 (+4.4)	10.9 (+4.7)	18.9 (+4.2)	362.7 (+2.4)	438.8 (+8.5)	297.1 (-4.4)

with IPCC (2000) at regionally-relevant scales. The FORE-SCE gridded resolution (250 m) was readily incorporated to our modeling framework through 17 different LULC classes that accounted for changes in cropland, pasture, forest, range, and urban landscapes. When presented with various LULC products, stakeholders agreed FORE-SCE products were a good candidate for the modeling scenarios. We used FORE-SCE maps under historic conditions in year 2005 (Fig. 1c) to parameterize the Baseline period, and under the SRES A2 scenario from year 2099 for the Far-Future period. The A2 scenario has an economic-development focus with rapid population growth that aligned with stakeholder interests in a wide breadth of LULC changes.

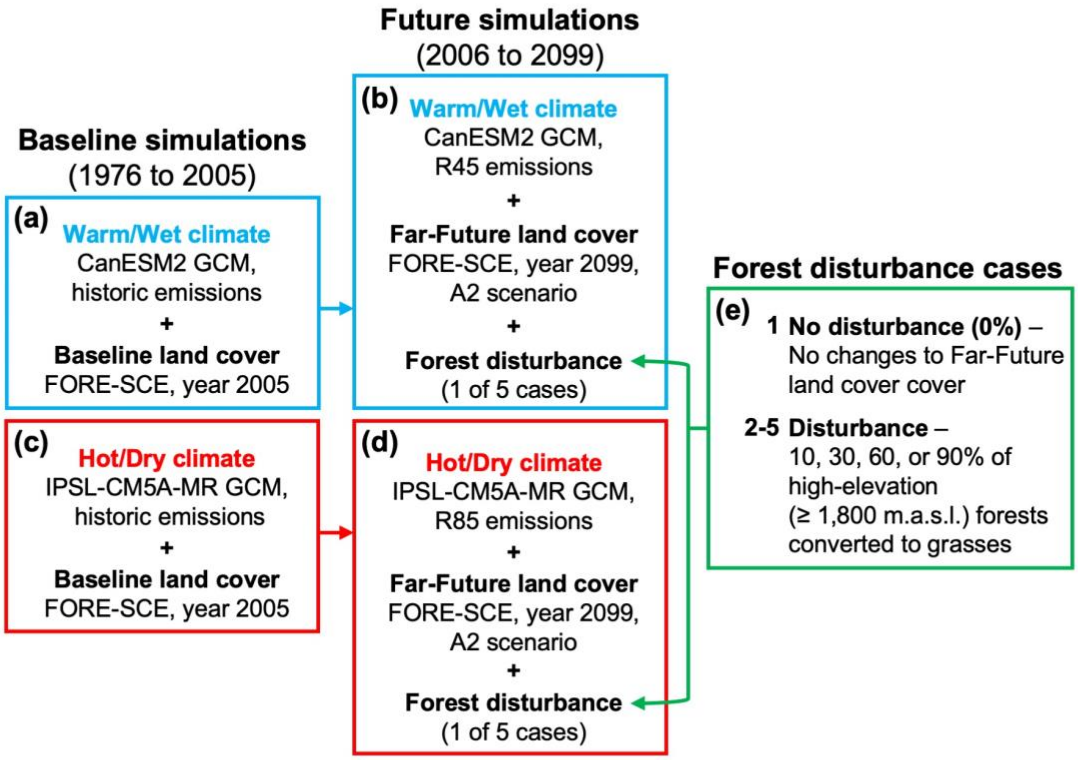

Fig. 3. Model scenario framework using downscaled GCMs and two emissions scenarios and FORE-SCE land cover map for the Baseline (left) and Future (middle) simulations based on the Warm/Wet (a, b) and Hot/Dry climates (c, d). (e) Forest disturbance cases (0, 10, 30, 60, or 90%) applied to the (b, d) Far-Future land cover conditions.

2.6 Forest Disturbances

We found a small amount of forest cover changes (affecting <1% of the CRB) in the FORE-SCE products. Most of our stakeholders requested a general approach with simple forest disturbances of a higher magnitude. Prior research indicates that hydrological responses to forest change are related to three key factors besides the hydroclimate regime: (1) the affected forest types, (2) the regenerated vegetation species, and (3) the elevation of forest disturbance (Zhang *et al*., 2017). In preliminary simulations, we found nearly identical hydrologic impacts when converting any of the forest types to grasses or shrubs, and higher impacts when changing forests at elevations ≥1,800 m. We then developed disturbance scenarios for all forest types at high elevations across the CRB which were converted to grasses (Rother *et al*., 2015; Haffey *et al*., 2018; Hurteau *et al*., 2014) at differing percent reductions (e.g., 10, 30, 60, or 90%). We chose the 30% conversion based on historic wildfire extents (Litschert *et al*., 2012) and the 90% amount based on empirical estimates of forest mortality rates due temperature warming by year 2100 (McDowell *et al*., 2016). Stakeholders were interested this bottom-up approach to enable identifying unexpected results and cases of a more vulnerable or robust water system.

2.7 Modeling Scenarios and Disturbance Parameters

Figure 3 presents the modeling scenarios. Climate change and forest disturbance impacts were assessed in terms of: (1) the changes in the Far-Future period (2066-2095 average) relative

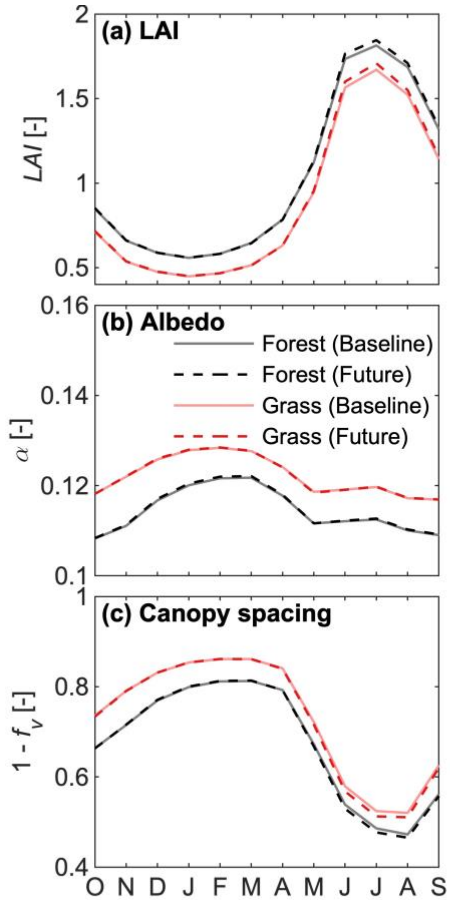

Fig. 4. Monthly average values of leaf area index (LAI), albedo (α), and canopy spacing (1- f_v) for forests and grasses under the Baseline and Far-Future conditions without forest disturbance. Forest values show the average across all forest types weighted by the cover fractions (C_v).

Table 3. Forest parameter values of root depths and fractions for each soil layer, minimum stomatal resistance, and architectural resistance (grass values in parentheses). Forest values show the average across evergreen, deciduous, and mixed types, weighted by the cover fractions (C_v).

Parameter [unit]	Forest (grass) values
Root depth [m]	
Soil layer 1	0.10 (0.10)
Soil layer 2	1.00 (1.00)
Soil layer 3	4.79 (0.50)
Root fraction [-]	
Soil layer 1	0.05 (0.05)
Soil layer 2	0.46 (0.70)
Soil layer 3	0.49 (0.25)
Minimum stomatal resistance [s m^{-1}]	149.54 (50.00)
Architectural resistance [s m^{-1}]	60.00 (25.00)

to the Baseline period (1976-2005 average) for cases with and without forest disturbances, and (2) Far-Future period conditions with forest disturbances relative to no disturbance in that same period. Due to the focus placed on the forest disturbances, we illustrate the differences between vegetation parameters of grass and forest cover in Figure 4 and Table 3. With increasing forest disturbances, the average vegetation parameter values across high elevation forest cells shifted towards the grass conditions, with implications on the hydrologic response, as discussed next.

3. Results and Discussion

3.1 Climate Change Impacts

We first compared the climate change impacts on annual hydrologic conditions without the forest disturbances. Figure 5 shows basin-wide mean annual values in the Baseline period and the Far-Future Warm/Wet or Hot/Dry climates. The Climate-only case using Baseline land cover and 0% disturbance case had nearly identical results, indicating that LULC changes from FORE-SCE had a negligible impact. Climate change reduced snow water equivalent, with larger declines in the Hot/Dry (-7.9 mm) than Warm/Wet (-4.6 mm) case relative to Baseline. This was

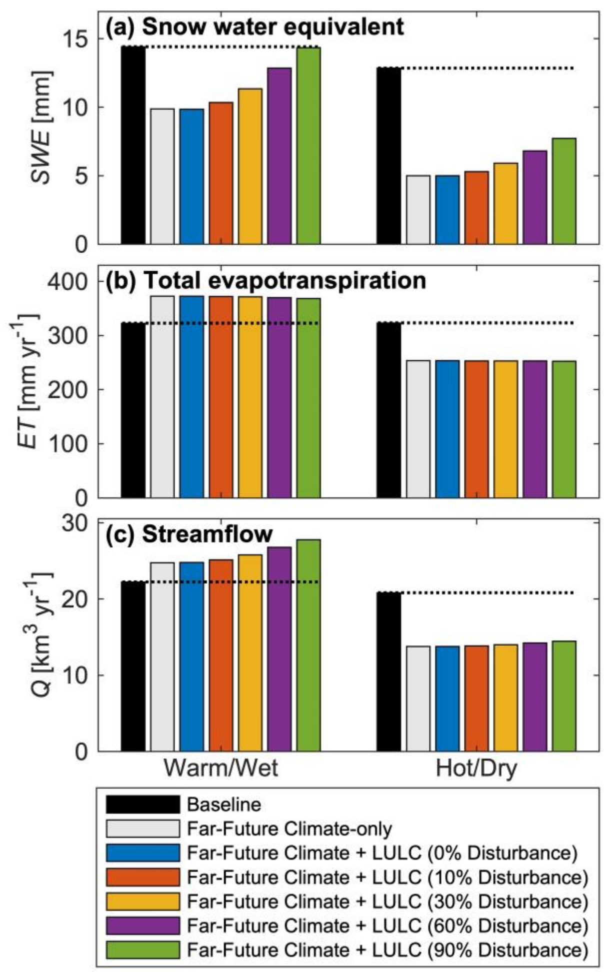

Fig. 5. Basin-wide mean annual (a) snow water equivalent (*SWE*), (b) evapotranspiration (*ET*), and (c) streamflow (*Q*) in the Baseline (1976-2005) and Far-Future (2066-2095) periods for different LULC scenarios under Warm/Wet (left) and Hot/Dry (right) climates. Dotted horizontal lines show Baseline values as a reference.

due to opposite precipitation trends and different levels of climate warming (Table 2), which led to greater snowfall (P_s) declines in the Hot/Dry case (-46.2% P_s in the Hot/Dry; -20.0% P_s in the Warm/Wet). Evapotranspiration and streamflow trends followed P, with increases in the Warm/Wet (+15.5% ET, +11.4% Q) and declines in the Hot/Dry (-21.7% ET, -33.4% Q) cases.

Figure 6 shows gridded Far-Future changes relative to Baseline that reveal spatial gradients underlying the noted contrasts in the two climate cases. Trends in ET followed spatial variations in P given the water-limited conditions in the CRB (Vivoni *et al.*, 2008). Warm/Wet conditions included widespread P and ET increases with larger changes towards the northwest (e.g., +84 mm yr^{-1} P, +71 mm yr^{-1} ET in Green vs. +33 mm yr^{-1} P, +35 mm yr^{-1} ET in Gila). Hot/Dry conditions led to P and ET declines in most regions except in high elevations of the north, with larger declines towards the southeast (e.g., -14 and -143 mm yr^{-1} ET in Green and Gila, respectively). Warm/Wet conditions increased soil moisture (SM) and runoff and baseflow (RBF) over high-elevations in the northwest (+283 mm SM, +330.2 mm yr^{-1} RBF), despite declines in SWE. The Hot/Dry case led to large RBF declines in northern high-elevation regions due to greater ET increases, and declines in SWE and SM. The Hot/Dry climate case amplified water-limited ET conditions and led to large declines in RBF efficiency ($RBFE$, or the amount of R and BF per P; by as low as -0.3), while the Warm/Wet case led to a transition to more energy-limited conditions with increased $RBFE$ (by as much as +0.1) across key headwater regions. These two climate futures modulated the forest disturbance impacts, discussed next.

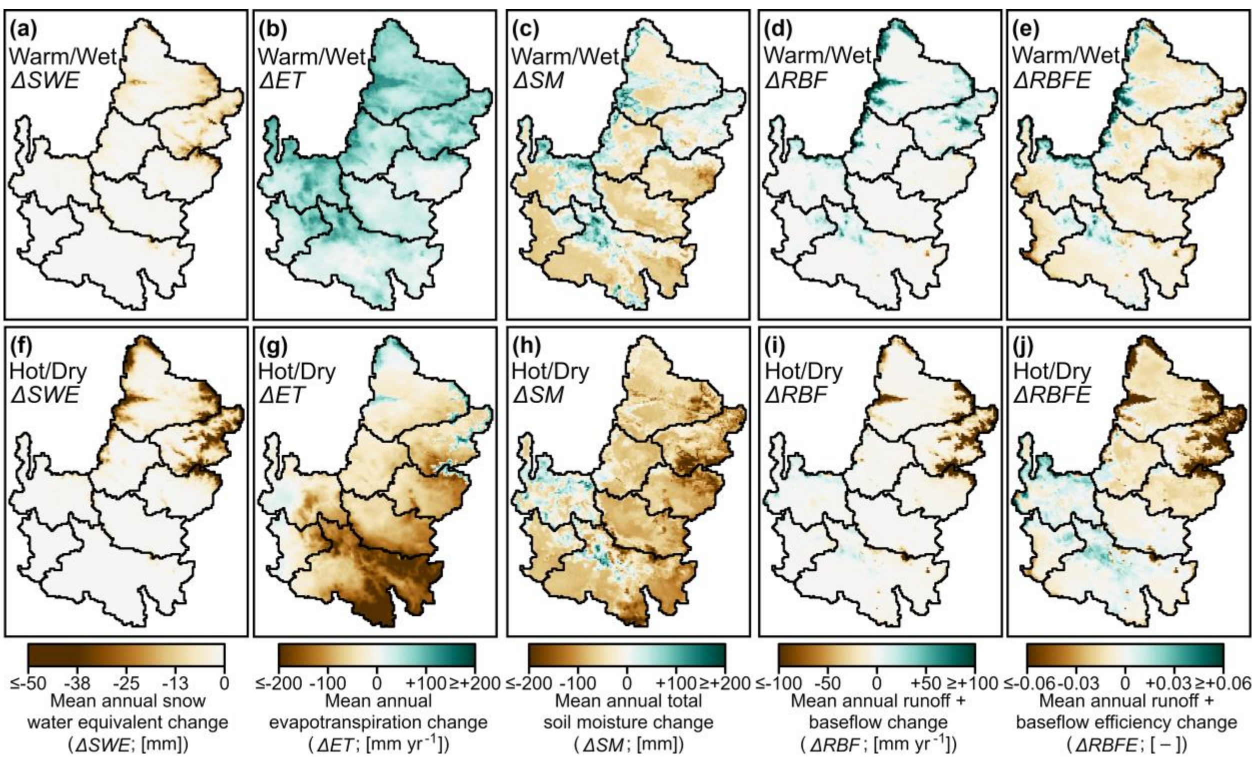

Fig. 6. Spatial distributions of mean annual changes in (a, f) snow water equivalent (*SWE*), (b, g) evapotranspiration (*ET*), (c, h) soil moisture (*SM*), (d, i) runoff and baseflow (*RBF*), and (e, k) runoff and baseflow efficiency (*RBFE*) in the Far-Future period relative to Baseline under Warm/Wet (top) and Hot/Dry (bottom) climates without forest disturbances.

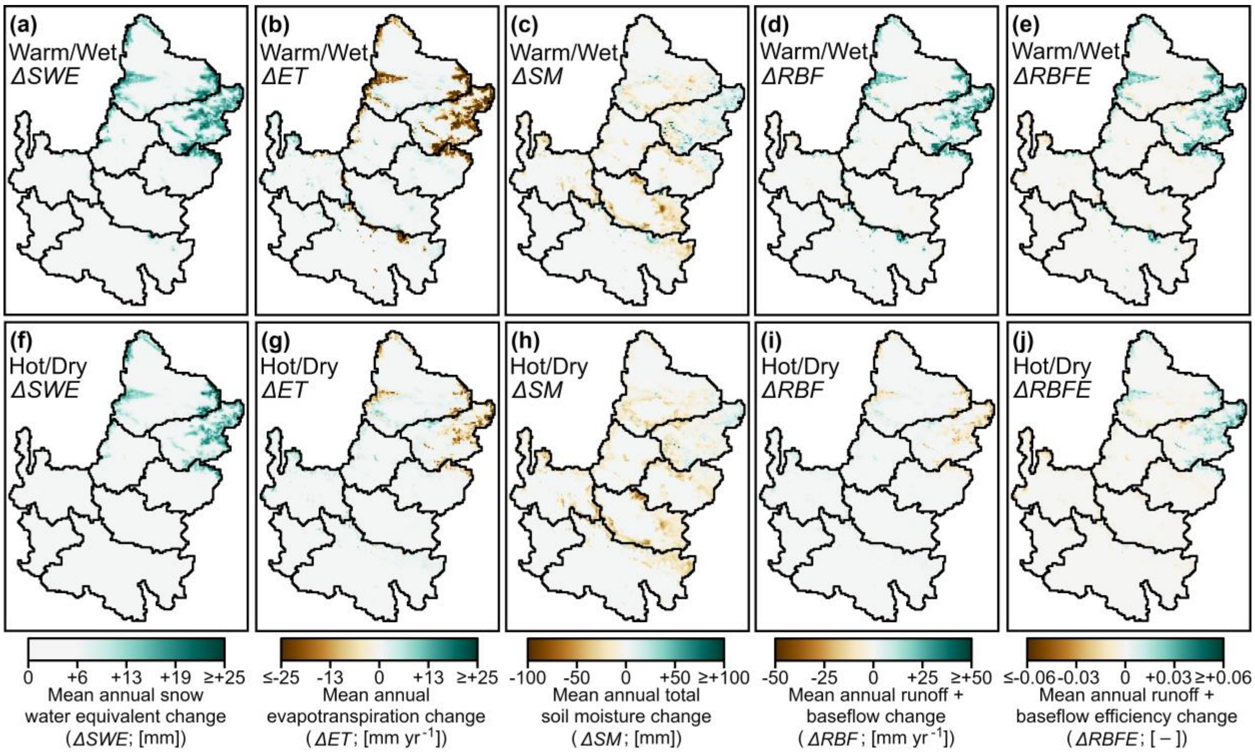

Fig. 7. Spatial distributions of mean annual changes in (a, f) snow water equivalent (*SWE*), (b, g) evapotranspiration (*ET*), (c, h) soil moisture (*SM*), (d, i) runoff and baseflow (*RBF*), and (e, k) runoff and baseflow efficiency (*RBFE*) under the 30% forest disturbance case relative to no disturbance in the Far-Future period under Warm/Wet (top) and Hot/Dry (bottom) climates.

3.2 Forest Disturbances Impacts under Climate Change

Figure 5 shows that forest disturbances minimized *SWE* declines under climate change due to canopy reductions (e.g., smaller *LAI* and greater canopy spacing, 1 - f_v, when grasses replace forests; Fig. 4) and increased ground snowpack accumulation. This effect was more pronounced in the Warm/Wet case and led to a near-recovery of Baseline *SWE* for the 90% forest disturbance case. Overall, forest disturbance slightly reduced *ET* relative to no disturbance, but differed in their magnitude based on the amount of *P* in each climate case. We attributed these simulated *ET* reductions to canopy evaporation from reduced *LAI* and larger canopy spaces when converting forests to grasses. Disturbance effects to *SWE* and *ET* increased *Q* relative to the case without disturbance, with larger changes in the Warm/Wet case than the Hot/Dry case (up to 12% and 5% larger than no disturbance, respectively). Although disturbances neutralized mean annual *Q* losses under the Hot/Dry climate, the effects were not enough to fully offset warming and *P* declines even under the 90% forest disturbance case.

Figure 7 shows the hydrologic effect of forest disturbances (30% compared to 0%) for the Far-Future period under the two climate bookends. Impacts were larger under the Warm/Wet case, including more substantial *SWE* increases and *ET* declines, and in turn larger *RBFE* increases in the northeast (+39.2 mm *SWE*, -66.8 mm yr^{-1} *ET*, +0.08 *RBFE* in Warm/Wet vs. +30.5 mm *SWE*, -34.1 mm yr^{-1} *ET*, +0.05 *RBFE* in Hot/Dry). Disturbances also slightly increased *ET* over some mid-elevation regions and especially in the Hot/Dry case due to larger E_{soil} increases that overshadowed *T* and E_c declines. Overall, the two climate bookends led to opposite impacts to *RBF* in key headwater regions, including increases in the Warm/Wet (up to

+70.7 mm yr^{-1}) and declines in the Hot/Dry (as low as -34.1 mm yr^{-1}) cases. This indicated that forest disturbance impacts were smaller in the more water-limited conditions of the Hot/Dry case under which the majority of *P* was lost to *ET* regardless of vegetation status. The Upper Basin exhibited the largest forest disturbance impacts due to *P* trends and the larger area of disturbed forests at high elevations (≥ 1,800 m, Table 4). We next characterized streamflow trends at finer temporal and spatial scales to further diagnose the forest disturbance impacts.

3.3 Streamflow Variability under Combined Climate-Forest Disturbances

We evaluated the impacts to streamflow in terms of the average monthly *Q* for the two climate bookends and the forest disturbance cases in Figure 8. Climate change alone shifted the timing of peak *Q* to one month earlier in both climate cases (June in the Baseline vs. May in the Far-Future under 0% disturbance). While the Warm/Wet case increased *Q* (by +0.04 to +1.5 km^3 mon^{-1} in Dec. to June), the Hot/Dry case decreased *Q* (by -0.07 to -2.28 km^3 mon^{-1} in May to Jan.). Forest disturbances increased *Q* relative to the case without disturbance in late spring to early winter, but decreased *Q* in the early spring. This difference was due to higher ground snowpacks under forest removal and the accompanied shift in peak snowmelt to later spring months. In the Warm/Wet case, snowmelt increase was sufficient to reverse the climate change effects on *Q* in key months for all forest disturbance cases and on a mean annual basis. However, the forest disturbances in the Hot/Dry case were only enough to offset warming effects to *Q* in some months (e.g., +0.29 km^3 mon^{-1} in May with 10% Disturbance), but not on an annual basis.

Figure 9 presents the spatial distributions of changes in the runoff and baseflow efficiency (*RBFE*) in the cool- (Oct. through Mar.) and warm- (Apr. through Sep.) seasons for the 30% disturbance case. Forest disturbances caused substantial *RBFE* increases in the warm-season (+0.24 in Warm/Wet and +0.25 *RBFE* in Hot/Dry) and small *RBFE* decreases in the cool-season (-0.07 in Warm/Wet and -0.06 in Hot/Dry). This seasonal difference was largely related to the shift in peak snowmelt to later spring months. Impacts to *RBFE* were more moderate and more variable across the domain in the cool-season and included small *RBFE* increases in the northeast due to larger *ET* declines in both climate cases. Increases in *RBFE* in both seasons were more widespread in the Warm/Wet case due to more energy-limited conditions. Overall, forest disturbance impacts to annual streamflow efficiency (Fig. 7e,k) reflected the warm-season behavior, with the largest changes occurring in the Upper Colorado, Green, and San Juan subbasins due to a greater forested area (Table 4) and less water-limited conditions.

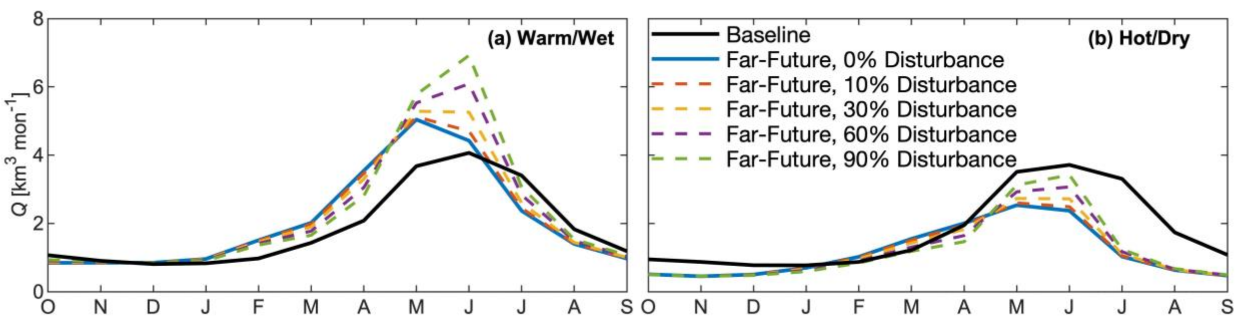

Fig. 8. Basin-wide mean monthly streamflow in the Baseline and Far-Future periods for each disturbance case (0, 10, 30, 60, or 90%) under Warm/Wet (left) and Hot/Dry (right) climates.

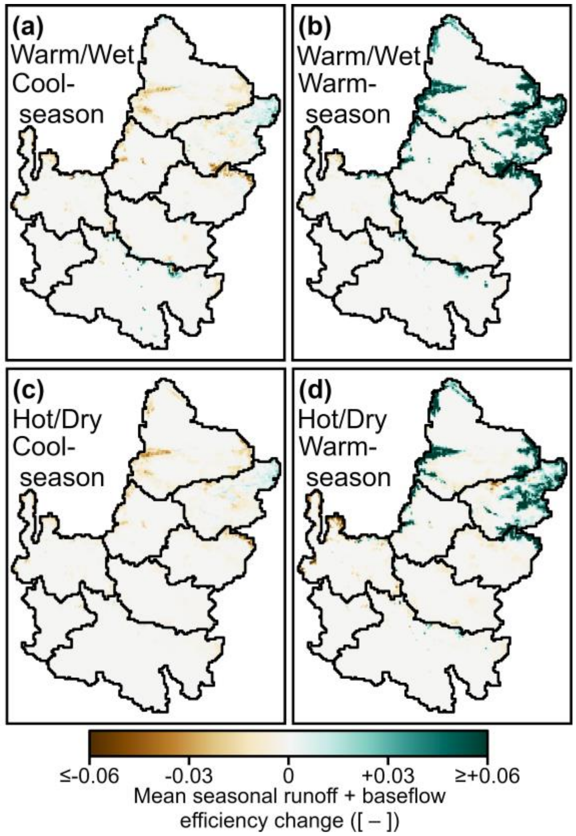

Fig. 9. Spatial distribution of changes in mean cool-season (left), and warm-season (right) efficiencies of runoff and baseflow (*RBFE*) for the Far-Future period under Warm/Wet (top) and Hot/Dry (bottom) climates for the 30% forest disturbance case relative to no disturbance.

Finally, we evaluated the impacts of forest disturbances in the Far-Future period in terms of changes to mean annual efficiency and streamflow relative to the Baseline period. Fig. 10 compares *RBFE* and *Q* for the Upper Colorado, Green, and San Juan subbasins as representative cases of the headwater regions. Although *RBFE* declined for all subbasins due to climate change alone (0% disturbance case), *Q* increased due to *P* increases in the Warm/Wet case (+7.6% *Q* and +12.9% *P* in Upper Colorado and +17.7% *Q* and +20.3% *P* in Green). Forest disturbances increased *RBFE* in the Warm/Wet case for all subbasins (by +0.003 to +0.028 with 90% forest disturbance) and in the Hot/Dry case for most subbasins. Forest disturbances of 30% or more were sufficient to reverse the impacts of climate change on streamflow only in the Warm/Wet case for the San Juan subbasin, as indicated by the cross-over point on the horizontal line at 0% change at about 45% forest disturbance. A similar cross-over was found for *RBFE* in the Upper Colorado and Green subbasins at 30% forest disturbance for the Warm/Wet case. In contrast, there were more limited impacts of forest disturbances on *RBFE* and *Q* in the Hot/Dry climate in all subbasins, such that positive values (e.g., increases relative to Baseline) were not found. This was attributed to the water-limited conditions of the Hot/Dry case where forest changes have a more limited impact. As discussed next, stakeholders responded to the contrasting outcomes of the climate bookends with respect to forest disturbances as a means to reduce warming effects.

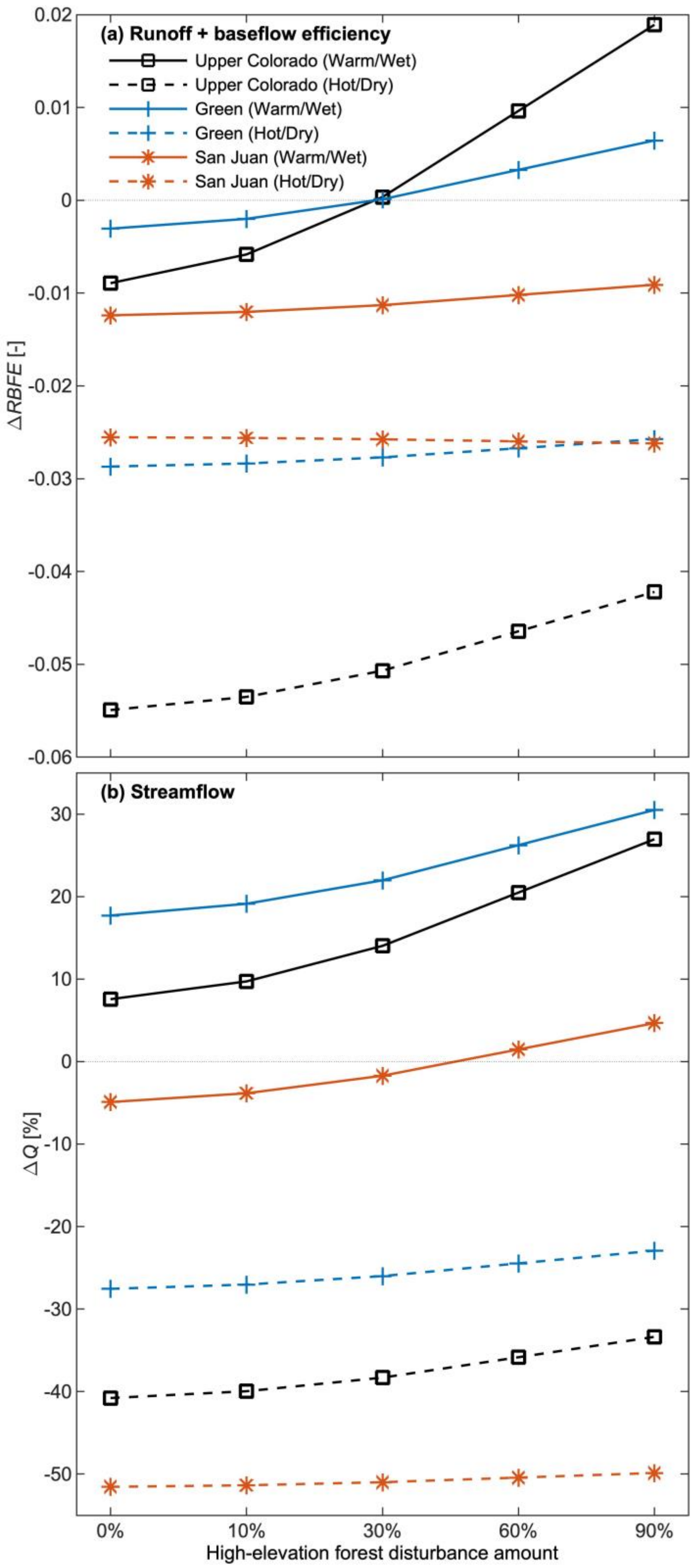

Fig. 10. Changes in mean annual (a) runoff and baseflow efficiency (*RBFE*) and (b) streamflow (*Q*) for the Upper Colorado, Green, and San Juan subbasins for each forest disturbance case under the Warm/Wet and Hot/Dry climates, relative to the Baseline period.

3.4 Reflections on the Stakeholder Engagement Process

Our project began in collaboration with water resource analysts and managers at the Central Arizona Project (CAP), the agency that operates, maintains, and plans the aqueduct system that delivers CRB water to Arizona. This partnership enabled us to recruit a larger group of stakeholders from across the CRB, including a total of 20 individuals from 12 different agencies: CAP, Arizona Department of Water Resources, Colorado Department of Natural Resources, Colorado River Board of California, Colorado River District, Colorado Water Conservation Board, Denver Water, Metropolitan Water District of Southern California, New Mexico Interstate Stream Commission, Southern Nevada Water Authority, Upper Colorado River Commission, U.S. Bureau of Reclamation, and Wyoming State Engineer's Office. We consulted with these stakeholders over four meeting stages to guide our research (Fig. 2).

We found that their questions and suggestions became more targeted as they learned more about the modeling process and results throughout these meetings. For instance, during our project kick-off meeting that introduced our improved VIC framework, stakeholders were initially interested in seeing results under the full subset of eight GCMs. They noted that these can provide valid sources of climate information given that we selected products those that best reproduced historical conditions in the CRB (Gautam and Mascaro, 2018). When we later provided this full ensemble of results under climate-change alone, stakeholders proposed we use products from two climate models (including those with 'worst or best case' futures) when we adding the additional complexity of land cover changes.

We then completed the climate bookend selection process (Fig. 2a) and our land cover evaluation (Fig. 2c) according to this feedback and presented the outcomes. Stakeholders liked the idea of applying additional forest cover changes given the lack of hydrologic impacts from FORE-SCE changes alone (Fig. 5), noting a need and interest across the larger resource management community for forest cover change impact research. Discussions mainly revolved around the topic of whether to explore the impacts of individual narratives (e.g., planned thinning, wildfire, beetle-infestation) or to use a more general approach of forest disturbances not tied to anyone cause. We reached a consensus to use the latter method, since the likelihood of any individual disturbance type varies across the basin (Seidl *et al*., 2011). Stakeholders proposed the use of a bottom-up approach but emphasized a need to establish bookend scenarios that are relevant to prior observed outcomes of specific narratives. When we described the computational costs required to run multiple scenarios, they suggested we run a series of small-scale sensitivity tests to determine the forest changes that would have the highest impact (Fig. 2d) and to then apply those changes uniformly across the entire domain. Stakeholders indicated that our analyses should identify any thresholds within the bottom-up results that lead to large (beneficial or negative) water resource consequences, as this would be most relevant for their needs (Fig. 2e). These fruitful interactions formed the basis of the methods, analyses and results presented above and helped ensure targeted outcomes that improve decision-making capacities, summarized next.

4. Conclusions

We developed a stakeholder engagement and modeling process to conduct a basin-wide assessment of forest disturbance impacts to Colorado River hydrology under climate changes. We used the Variable Infiltration Capacity model forced with two climate model products that represent Warm/Wet and Hot/Dry conditions, and adjusted land cover parameters with differing forest reduction levels according to stakeholder preferences. Forest reductions minimized snowpack declines and evapotranspiration increases under climate change, leading to increased streamflow relative to the case without disturbance. Snowmelt increases in winter months were the primary cause for the annual streamflow increase, which is supported by findings of prior work (Buma and Livneh, 2015; Livneh *et al*., 2015; Moreno *et al*., 2016). The increases in water yield scaled with the forest disturbance amounts, confirming similar conclusions of prior regression-based estimates (Williams *et al*., 2022). While forest reductions applied at historic rates (i.e., 30% reductions) or more were sufficient to reverse the impacts of climate warming in the Warm/Wet case, the effects were not enough to offset the high rates of evapotranspiration in the water-limited conditions of the Hot/Dry future. These results are analogous to observations of negligible wildfire impacts to streamflow in warmer conditions (Biederman *et al*., 2022). These findings also confirm prior modeled results in northeastern regions under similar Hot/Dry cases (Bennett *et al*., 2018; Yates *et al*., 2015) and reveal that the water-limited conditions inhibited a recovery of historic streamflow amounts for the entire CRB water budget.

The latest National Climate Assessment indicates drastic actions must be taken collectively across society to achieve the lower emission pathway underlying the more favorable Warm/Wet case, and so the Hot/Dry future appears the more likely outcome if such interventions do not occur (DeAngelo *et al*., 2017). While more intense forest management options (e.g., forest thinning or prescribed burns) could partially offset the impacts of this Hot/Dry future, such actions are financially expensive and can result in substantial decline in the provisioning of other ecosystem services including flood hazard mitigation, erosion control, water quality maintenance, recreational benefits, amongst others (Bennett et al., 2009). As such, plans should include a diverse set of forest management and other preventative water management actions that explicitly consider associated trade-offs (Howe *et al*., 2014). Our findings indicate forest management can be incorporated in these plans to achieve greater water security. We acknowledge too that there are certain limitations of our methods, mainly: (1) the application of uniform disturbances over the same elevation range across the domain, (2) imposed forest disturbances at the same time occurring right after the historical period, and (3) a lack of plant succession and forest regeneration. However, our integrated modeling approach explained the variable hydrological responses to forest disturbance across the domain as found in prior work and quantified changes in these behaviors under future climate conditions. Basin-managers at CAP also indicated their intent to consider these results when revisiting the guidelines that dictate water supply and reservoir operations during drought conditions in the CRB, which further illustrates the success of our approach to meet decision-maker needs. As a result, this stakeholder engagement and model framework can also be tailored for future investigations of resource management tradeoffs and other water security inquiries in the Colorado River Basin and basins elsewhere.

References

Anderegg, W. R. L., J. M. Kane, and L. D. L. Anderegg. 2013. "Consequences of widespread tree mortality triggered by drought and temperature stress." *Nat. Clim. Change*. 3: 30–36. https://doi.org/10.1038/nclimate1635.

Andreadis, K. M., P. Storck, and D. P. Lettenmaier. 2009. "Modeling snow accumulation and ablation processes in forested environments." *Water Resour. Res.* 45: W05429. https://doi.org/10.1029/2008WR007042.

Bart, R. R. 2016. "A regional estimate of postfire streamflow change in California." *Water Resour. Res.* 52 (3): 1465–1478. https://doi.org/10.1002/2014WR016553.

Bennett, A. R., J. J. Hamman, and B. Nijssen. 2020. "MetSim: A Python package for estimation and disaggregation of meteorological data." *J. Open Source Softw.* 5 (47): 2042. https://doi.org/10.21105/joss.02042.

Bennett, K. E., T. J. Bohn, K. Solander, N. G. McDowell, C. Xu, E. R. Vivoni, and R. S. Middleton. 2018. "Climate-driven disturbances in the San Juan River sub-basin of the Colorado River." *Hydrol. Earth Syst. Sci.* 22: 709–725. https://doi.org/10.5194/hess-22-709-2018.

Bennett, E. M., G. D. Peterson, and L. J. Gordon. 2009. "Understanding relationships among multiple ecosystem services." *Ecol.* 12 (12): 1394–1404. https://doi.org/10.1111/j.1461-0248.2009.01387.x.

Bhave, A. G., A. Mishra, and N. S. Raghuwanshi. 2014. "A combined bottom-up and top-down approach for assessment of climate change adaptation options." *J. Hydrol.* 518: 150–161. https://doi.org/10.1016/j.jhydrol.2013.08.039.

Biederman, J. A., P. D. Brooks, A. A. Harpold, D. J. Gochis, E. Gutmann, D. E. Reed, E. Pendall, and B. E. Ewers. 2014a. "Multiscale observations of snow accumulation and peak snowpack following widespread, insect-induced lodgepole pine mortality." *Ecohydrol.* 7 (1): 150–162. https://doi.org/10.1002/eco.1342.

Biederman, J. A., A. A. Harpold, D. J. Gochis, B. E. Ewers, D. E. Reed, S. A. Papuga, and P. D. Brooks. 2014b. "Increased evaporation following widespread tree mortality limits streamflow response." *Water Resour. Res.* 50 (7): 5395–5409. https://doi.org/10.1002/2013WR014994.

Biederman, J. A., M. D. Robles, R. L. Scott, and J. F. Knowles. 2022. "Streamflow responses to wildfire differs with season and elevation in adjacent headwaters of the Lower Colorado River Basin." *Water Resour. Res.* 58: e2021WR030687. https://doi.org/10.1029/2021WR030687.

Biederman, J. A., A. J. Somor, A. A. Harpold, E. D. Gutmann, D. D. Breshears, P. A. Troch, D. J. Gochis, R. L. Scott, A. J. H. Meddens, and P. D. Brooks. 2015. "Recent tree die-off has little effect on streamflow in contrast to expected increases from historical studies." *Water Resour. Res.* 51 (12): 9775–9789. https://doi.org/10.1002/2015WR017401.

Brown, C. M., J. R. Lund, X. Cai, P. M. Reed, E. A. Zagona, A. Ostfeld, J. Hall, G. W. Characklis, W. Yu, and L. Brekke. 2015. "The future of water resources systems analysis: Toward a scientific framework for sustainable water management." *Water Resour. Res.* 51 (8): 61106124. https://doi.org/10.1002/2015WR017114.

Brown, C., and R. L. Wilby. 2012. "An alternative approach to assessing climate risks." *EoS*. 93 (41): 401–402. https://doi.org/10.1029/2012EO410001.

Buma, B., and B. Livneh. 2015. "Potential effects of forest disturbances and management on water resources in a warmer climate." *For. Sci.* 61 (5): 895–903. https://doi.org/10.5849/forsci.14-164.

Cazares-Rodriguez, J. E., E. R. Vivoni, and G. Mascaro. 2017. "Comparison of two watershed models for addressing stakeholder flood mitigation strategies: Case study of Hurricane Alex in

Monterrey, México." *J. Hydrol. Eng*. 22 (9): 05017018. https://doi.org/10.1061/(ASCE)HE.1943-5584.0001560

Chen, F., G. Zhang, M. Barlage, Y. Zhang, J. A. Hicke, A. Meddens, G. Zhou, W. J. Massman, and J. Frank. 2015. "An Observational and Modeling Study of Impacts of Bark Beetle–Caused Tree Mortality on Surface Energy and Hydrological Cycles." *J. Hydrometeorol.* 16 (2): 744–761. https://doi.org/10.1175/JHM-D-14-0059.1.

Cherkauer, K. A., and D. P. Lettenmaier. 2003. "Simulation of spatial variability in snow and frozen soil." *J. Geophys. Res.* 108 (D22): 8858. https://doi.org/10.1029/2003JD003575.

DeAngelo, B., J. Edmonds, D. W. Fahey, and B. M. Sanderson. 2017. "Perspectives on climate change mitigation." In *Climate Science Special Report: Fourth National Climate Assessment, Volume I* [Wuebbles, D. J. et al. (eds.)], 393–410. Washington, DC, USA: U.S. Global Change Research Program. https://doi.org/10.7930/J0M32SZG.

Gautam, J., and G. Mascaro. 2018. "Evaluation of Coupled Model Intercomparison Project Phase 5 historical simulations in the Colorado River Basin." *International Journal of Climatology*. 38: 3861–3877. https://doi.org/10.1002/joc.5540.

Gergel, D. R., B. Nijssen, J. T. Abatzoglou, D. P. Lettenmaier, and M. R. Stumbaugh. 2017. "Effects of climate change on snowpack and fire potential in the western USA." *Clim. Change.* 141: 287–299. https://doi.org/10.1007/s10584-017-1899-y.

Goeking, S. A., and D. G. Tarboton. 2020. "Forests and water yield: A synthesis of disturbance effects on streamflow and snowpack in western coniferous forests." *J. For.* 118 (2): 172–192. https://doi.org/10.1093/jofore/fvz069.

Guardiola-Claramonte, M., P. A. Troch, D. D. Breshears, T. E. Huxman, M. B. Switanek, M. Durcik, and N. S. Cobb. 2011. "Decreased streamflow in semi-arid basins following drought-induced tree die-off: A counter-intuitive and indirect climate impact on hydrology." *J. Hydrol.* 406 (3–4): 225–233. https://doi.org/10.1016/j.jhydrol.2011.06.017.

Haffey, C., T. D. Sisk, C. D. Allen, A. E. Thode, and E. Q. Margolis. 2018. "Limits to ponderosa pine regeneration following large high-severity forest fires in the United States Southwest." *Fire Ecology*. 14 (1): 143–163. https://doi.org/10.4996/fireecology.140114316.

Hallema, D. W., F.-N. Robinne, and K. D. Bladon. 2018a. "Reframing the challenge of global wildfire threats to water supplies." *Earth's Future*. 6 (6): 772–776. https://doi.org/10.1029/2018EF000867.

Hallema, D. W., G. Sun, P. V. Caldwell, S. P. Norman, E. C. Cohen, Y. Liu, K. D. Bladon, and S. G. McNulty. 2018b. "Burned forests impact water supplies." *Nat. Commun.* 9: 1307. https://doi.org/10.1038/s41467-018-03735-6.

Hamman, J. J., B. Nijssen, T. J. Bohn, D. R. Gergel, and Y. Mao. 2018. "The Variable Infiltration Capacity Model, Version 5 (VIC-5): Infrastructure improvements for new applications and reproducibility." *Geosci. Model Dev.* 11: 3481–3496. https://doi.org/10.5194/gmd-11-3481-2018.

Hicke, J. A., M. C. Johnson, J. L. Hayes, and H. K. Preisler. 2012. "Effects of bark beetle-caused tree mortality on wildfire." *For. Ecol. Manag*. 271: 81–90. https://doi.org/10.1016/j.foreco.2012.02.005.

Howe, C., H. Suich, B. Vira, and G. M. Mace. 2014. "Creating win-wins from trade-offs? Ecosystem services for human well-being: A meta-analysis of ecosystem service trade-offs and synergies in the real world." *Glob. Environ. Change*. 28: 263–275. https://doi.org/10.1016/j.gloenvcha.2014.07.005.

Hurteau, M. D., J. B. Bradford, P. Z. Fulé, A. H. Taylor, K. L. Martin. 2014. "Climate change, fire management, and ecological services in the southwestern US." *For. Ecol. Manag*. 327: 280–289. http://dx.doi.org/10.1016/j.foreco.2013.08.007.

INEGI. 2013. "Conjunto de datos vectoriales de Uso del Suelo y Vegetación, Escala 1: 250 000, Serie V (Capa Unión)." Accessed January 1, 2016. https://www.inegi.org.mx/app/biblioteca/ficha.html?upc=702825007024

IPCC. 2000. *Land Use, Land-Use Change, and Forestry. Special Report of the Intergovernmental Panel on Climate Change* [Watson, R.T., I.R. Noble, B. Bolin, N. H. Ravindranath, D. J. Verardo, and D. J. Dokken (Eds.)], Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Li, Q., X. Wei, M. Zhang, W. Liu, H. Fan, G. Zhou, K. Giles-Hansen, S. Liu, and Y. Wang. 2017. "Forest cover change and water yield in large forested watersheds: A global synthetic assessment." *Ecohydrol.* 10: e1838. https://doi.org/10.1002/eco.1838.

Liang, X., D. P. Lettenmaier, E. F. Wood, and S. J. Burges. 1994. "A simple hydrologically based model of land surface water and energy fluxes for general circulation models." *J. Geophys. Res.* 99 (D7): 14415. https://doi.org/10.1029/94JD00483.

Litschert, S. E., T. C. Brown, and D. M. Theobald. 2012. "Historic and future extent of wildfires in the Southern Rockies Ecoregion, USA." *For. Ecol. Manag.* 269: 124–133. https://doi.org/10.1016/j.foreco.2011.12.024.

Livneh, B., J. S. Deems, B. Buma, J. J. Barsugli, D. Schneider, N. P. Molotoch, K. Wolter, and C. A. Wessman. 2015. "Catchment response to bark beetle outbreak and dust-on-snow in the Colorado Rocky Mountains." *J. Hydrol.* 523: 196–210. https://doi.org/10.1016/j.jhydrol.2015.01.039.

Lohmann, D. R., R. Nolte-Holube, and E. Raschke. 1996. "A large-scale horizontal routing model to be coupled to land surface parametrization schemes." *Tellus* 48 (5): 708–721. https://doi.org/10.3402/tellusa.v48i5.12200.

Lukas, J., and E. Payton. 2020. *Colorado River Basin Climate and Hydrology: State of the Science.* https://doi.org/10.25810/3hcv-w477. U. Colorado: Western Water Assessment.

Mayer, A. S., E.R. Vivoni, D. Kossak, K. E. Halvorsen, and A. Robles-Morua. 2017. "Participatory modeling workshops in a water-stressed basin result in gains in modeling capacity but reveal disparity in water resources management priorities." *Water Res. Manag*. 31(15): 4731–4744. https://doi.org/10.1007/s11269-017-1775-6

McDowell, N.G., A. P. Williams, C. Xu, W. T. Pockman, L. T. Dickman, S. Sevanto, R. Pangle, J. Limousin, J. Plaut, D. S. Mackay, J. Ogee, J. C. Domec, C. D. Allen, R. A. Fisher, X. Jiang, J. D. Muss, D. D. Breshears, S. A. Rauscher, and C. Koven. 2016. "Multi-scale predictions of massive conifer mortality due to chronic temperature rise." *Nat. Clim. Change* 6: 295–300. https://doi.org/10.1038/nclimate2873.

Milly, P. C. D., and K. A. Dunne. 2020. "Colorado River flow dwindles as warming-driven loss of reflective snow energizes evaporation." *Sci.* 367 (6483): 1252–1255. https://doi.org/10.1126/science.aay9187.

Moreno, H. A., H. V. Gupta, D. D. White, and D. A. Sampson. 2016. "Modeling the distributed effects of forest thinning on the long-term water balance and streamflow extremes for a semi-arid basin in the southwestern US." *Hydrol. Earth Syst. Sci.* 20: 1241–1267. https://doi.org/10.5194/hess-20-1241-2016.

Penn, C. A., L. A. Bearup, R. M. Maxwell, and D. W. Clow. 2016. “Numerical experiments to explain multiscale hydrological responses to mountain pine beetle tree mortality in a headwater watershed.” *Water Resour. Res.* 52 (4): 3143–3161. https://doi.org/10.1002/2015WR018300.

Pierce, D. W., D. R. Cayan, and B. L. Thrasher. 2014. “Statistical downscaling using localized constructed analogs (LOCA).” *J. Hydrometeorol.* 15: 2558–2585. https://doi.org/10.1175/JHM-D-14-0082.1.

Robles, M. D., R. M. Marshall, F. O’Donnell, E. B. Smith, J. A. Haney, and D. F. Gori. 2014. “Effects of climate variability and accelerated forest thinning on watershed-scale runoff in southwestern USA ponderosa pine forests.” *PLoS ONE*, 9 (10): e111092. https://doi.org/10.1371/journal.pone.0111092.

Rother, M. T., T. T. Veblen, and L. G Furman. 2015. “A field experiment informs expected patterns of conifer regeneration after disturbance under changing climate conditions.” *Can. J. For. Res.* 45 (11): 1607–1616. https://doi.org/10.1139/cjfr-2015-0033.

Seidl, R., P. M. Fernandes, T. F. Fonseca, F. Gillet, A. M. Jönsson, K. Merganičová, S. Netherer, A. Arpaci, J.-D. Bontemps, H. Bugmann, J. R. González-Olabarria, P. Lasch, C. Meredieu, F. Moreira, M.-J. Schelhaas, and F. Mohren. 2011. “Modelling natural disturbances in forest ecosystems: a review.” *Ecol. Modell.* 222 (4): 903–924. https://doi.org/10.1016/j.ecolmodel.2010.09.040.

Sleeter, B. M., T. L. Sohl, M. A. Bouchard, R. R. Reker, C. E. Soulard, W. Acevedo, G. E. Griffith, R. R. Sleeter, R. F. Auch, K. L. Sayler, S. Prisley, and Z. Zhu. 2012. “Scenarios of land use and land cover change in the conterminous United States: Utilizing the special report on emission scenarios at ecoregional scales.” *Glob. Environ. Change.* 22: 896–914. https://doi.org/10.1016/j.gloenvcha.2012.03.008.

Smith, R., E. Zagona, J. Kasprzyk, N. Bonham, E. Alexander, A. Butler, J. Prairie, and C. Jerla. 2022. “Decision science can help address the challenges of long-term planning in the Colorado River Basin.” *J. Am. Water Resour. Assoc.* https://doi.org/10.1111/1752-1688.12985.

Sohl, T. L., M. C. Wimberly, V. C. Radeloff, D. M. Theobald, and B. M. Sleeter. 2016. “Divergent projections of future land use in the United States arising from different models and scenarios.” *Ecol. Modell.* 337: 181–297. https://doi.org/10.1016/j.ecolmodel.2016.07.016.

Stavros, E. N., J. T. Abatzoglou, D. McKenzie, and N. K. Larkin. 2014. “Regional projections of the likelihood of very large wildland fires under a changing climate in the contiguous Western United States.” *Clim. Change.* 126 (3–4): 455–468. https://10.1007/S10584-014-1229-6.

Sun, G., D. Hallema, and H. Asbjornsen. 2017. Ecohydrological processes and ecosystem services in the Anthropocene: a review. *Ecol. 6*, 35. http://doi.org/10.1186/s13717-017-0104-6.

Taylor, K. E., R. J. Stouffer, and G. A. Meehl. 2012. “An overview of CMIP5 and the experiment design.” *BAMS.* 93: 485–498. https://doi.org/10.1175/BAMS-D-11-00094.1.

U.S. Geological Survey (USGS). 2016. “USGS National Elevation Dataset (NED) 1 arcsecond downloadable data collection.” U.S. Geological Survey. Accessed January 1, 2018. https://www.usgs.gov/core-science-systems/ngp/tnm-delivery.

van Mantgem, P. J., N. L. Stephenson, J. C. Byrne, L. D. Daniels, J. F. Franklin, P. Z. Fulé, M. E. Harmon, A. J. Larson, J. M. Smith, and A. H. Taylor. 2009. “Widespread increase of tree mortality rates in the western United States.” *Sci.* 323: 521–524. https://doi.org/10.1126/science.1165000.

Verbist, K. M. J., H. Maureira-Cortés, P. Rojas, and S. Vicuña. 2020. “A stress test for climate change impacts on water security: A CRIDA case study.” *Clim. Risk Manag.* 28: 100222. https://doi.org/10.1016/j.crm.2020.100222.

Vivoni, E. R., H. A. Moreno, G. Mascaro, J. C. Rodriguez, C. J. Watts, J. Garatuza-Payan, and R. L. Scott. 2008. “Observed relation between evapotranspiration and soil moisture in the North American monsoon region.” *Geophys. Res. Lett.* 35: L22403. https://doi.org/10.1029/2008GL036001

Wang, S., T. R. McVicar, Z. Zhang, T. Brunner, and P. Strauss. 2020. “Globally partitioning the simultaneous impacts of climate-induced and human-induce changes on catchment streamflow: A review and meta-analysis.” *J. Hydrol.* 590: 125387. https://doi.org/10.1016/j.jhydrol.2020.125387.

Whetton, P., K. Hennessy, J. Clarke, K. McInnes and D. Kent. 2012. “Use of Representative Climate Futures in impact and adaptation assessment.” *Clim. Change.* 115: 433–442. https://doi.org/10.1007/s10584-012-0471-z.

Williams, A. P., C. D. Allen, A. K. Macalady, D. Griffin, C. A. Woodhouse, D. M. Meko, T. W. Swetnam, S. A. Rauscher, R. Seager, H. D. Grissino-Mayer, J. S. Dean, E. R. Cook, C. Gangodagamage, M. Cai, and N. G. McDowell. 2013. “Temperature as a potential driver of regional forest drought stress and tree mortality.” *Nat. Clim. Change.* 3: 292–297. https://doi.org/10.1038/NCLIMATE1693.

Williams, A. P., B. Livneh, K. A. McKinnon, W. D. Hansen, J. S. Mankin, B. I. Cook, J. E. Smerdon, A. M. Varuolo-Clarke, N. R. Bjarke, C. S. Juang, and D. P. Lettenmaier. 2022. “Growing impact of wildfire on western US water supply.” *PNAS.* 119 (10): e2114069119. https://doi.org/10.1073/pnas.2114069119.

Wine, M. L., and D. Cadol. 2016. “Hydrologic effects of large southwestern USA wildfires significantly increase regional water supply: fact or fiction?” *Environ. Res. Lett.* 11: 085006. https://doi.org/10.1088/1748-9326/11/8/085006.

Yates, D. N., K. A. Miller, R. L. Wilby, and L. Kaatz. 2015. “Decision-centric adaptation appraisal for water management across Colorado's continental divide.” *Clim. Risk Manag.* 10: 35–50. https://doi.org/10.1016/j.crm.2015.06.001.

Zou, C. B., P. F. Ffolliott, and M. Wine. 2010. “Streamflow responses to vegetation manipulations along a gradient of precipitation in the Colorado River Basin.” *For. Ecol. Manag.* 259 (7): 1268–1276. https://doi.org/10.1016/j.foreco.2009.08.005.

Zhang, M., N. Liu, R. Harper, Q. Li, K. Liu, X. Wei, D. Ning, Y. Hou, and S. Liu. 2017. “A global review on hydrological responses to forest change across multiple scales: Importance of scale, climate, forest type, and hydrological regime.” *J. Hydrol.* 546: 44–59. https://doi.org/10.1016/j.jhydrol.2016.12.040.