Carbon Storage in Southwestern Riparian Ecosystems: Impacts of Climate Change, Human Modifications, and Restoration Strategies for Climate Mitigation

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ABSTRACT

Riparian ecosystems in the American Southwest store disproportionate amounts of carbon relative to their limited extent, yet their capacity is poorly quantified and threatened by climate and land-use change. We synthesize current knowledge of riparian carbon dynamics in Arizona and New Mexico and combine this with spatial datasets to estimate potential and current carbon storage. We review how climate, hydrology, geomorphic setting, and biota interact to control carbon stored in biomass, large wood, and floodplain soils. Using the national riparian basemap and hydroclimatic data, we map more than 3.5 million hectares of riparian area across Arizona and New Mexico and classify them into "warm & dry" and "cool & dry" climate classes. Applying carbon stock values from a global meta-analysis, we estimate that intact riparian ecosystems could store nearly 400 million Mg C, with National Forest System lands accounting for roughly 10% of this potential. We then use existing vegetation maps to show that only about 56% of mapped riparian extent currently supports riparian vegetation, and that riparian areas on National Forests and Grasslands store about 57% of their potential capacity, with substantial variation among forests. Finally, we report how climate change, water management, land use, livestock grazing, biological invasions, and fire jointly influence carbon pools, and we highlight restoration strategies that could increase or maintain carbon storage in southwestern riparian ecosystems. Together, our synthesis and spatial analysis demonstrate that restoring and conserving riparian ecosystems represents a high-leverage, yet underutilized, opportunity for climate mitigation and adaptation in the American Southwest.

Index terms: Arizona; ecosystem services; National Forests & Grasslands; New Mexico; streams & rivers

INTRODUCTION

Riparian ecosystems are critical components of the terrestrial carbon cycle (Battin et al. 2007; Aufdenkampe et al. 2011; Ruffing et al. 2016; Sutfin et al. 2016; Wohl et al. 2017). While streams and rivers tend to transport carbon, associated riparian areas can store large amounts for long periods of time (Sutfin et al. 2016; Wohl et al. 2017; Dybala et al. 2019). On a per-area basis, riparian corridors store more carbon than temperate and boreal forests, wetlands, savannas, grasslands, tundra, croplands, or deserts (Dybala et al. 2019). Although riparian ecosystems are recognized carbon sinks, most studies focus on temperate regions, with limited information available for arid climates like the southwestern United States (Sutfin et al. 2016; Dybala et al. 2019).

This paper focuses on the American Southwest, defined here primarily as Arizona and New Mexico (Figure 1). This region is characterized by arid to semi-arid climate, monsoon precipitation, and topography ranging from low desert basins to high-elevation mountain ranges. We synthesize research on riparian organic carbon dynamics, summarizing primary drivers, estimating carbon storage, and evaluating how climate change and other alterations influence sequestration. We also assess restoration potential for maintaining or increasing riparian carbon storage under shifting environmental conditions and identify key research needs.

Drivers of Riparian Carbon Dynamics

Riparian carbon is stored in three major pools: (1) above- and belowground biomass, (2) large woody debris, and (3) sediment, litter, and detritus in floodplain soils and on the forest floor (Wohl et al. 2012; Sutfin et al. 2016; Dybala et al. 2019). The dynamics of these pools are controlled by complex interactions between water availability, the geomorphic template, and biota.

Water availability is the primary constraint on riparian carbon storage in the Southwest, driven by interactions between climate, hydrology, and vegetation. Riparian carbon storage is generally positively correlated to moisture and negatively correlated with maximum temperature (Woodall and Liknes 2008; Sutfin et al. 2016; Dybala et al. 2019). Although riparian areas maintain higher soil moisture and denser vegetation than uplands (Friedman and Lee 2002; Sutfin et al. 2016), productivity and decomposition remain limited when potential evapotranspiration exceeds precipitation (Sutfin et al. 2016).

Summer monsoons contribute to the region's strong seasonal precipitation pattern and influence productivity, decomposition, and transport (Merritt and Wohl 2003; Harms and Grimm 2008; Stromberg et al. 2010; Sutfin et al. 2016). Along Arizona's San Pedro River, these summer storms raise groundwater levels and increase soil moisture, which alleviates water stress and increases carbon fixation in cottonwood (*Populus fremontii*) and mesquite (*Prosopis velutina*) forests (Scott et al. 2004; Gazal et al. 2006). Overbank flooding from these storms mobilizes labile

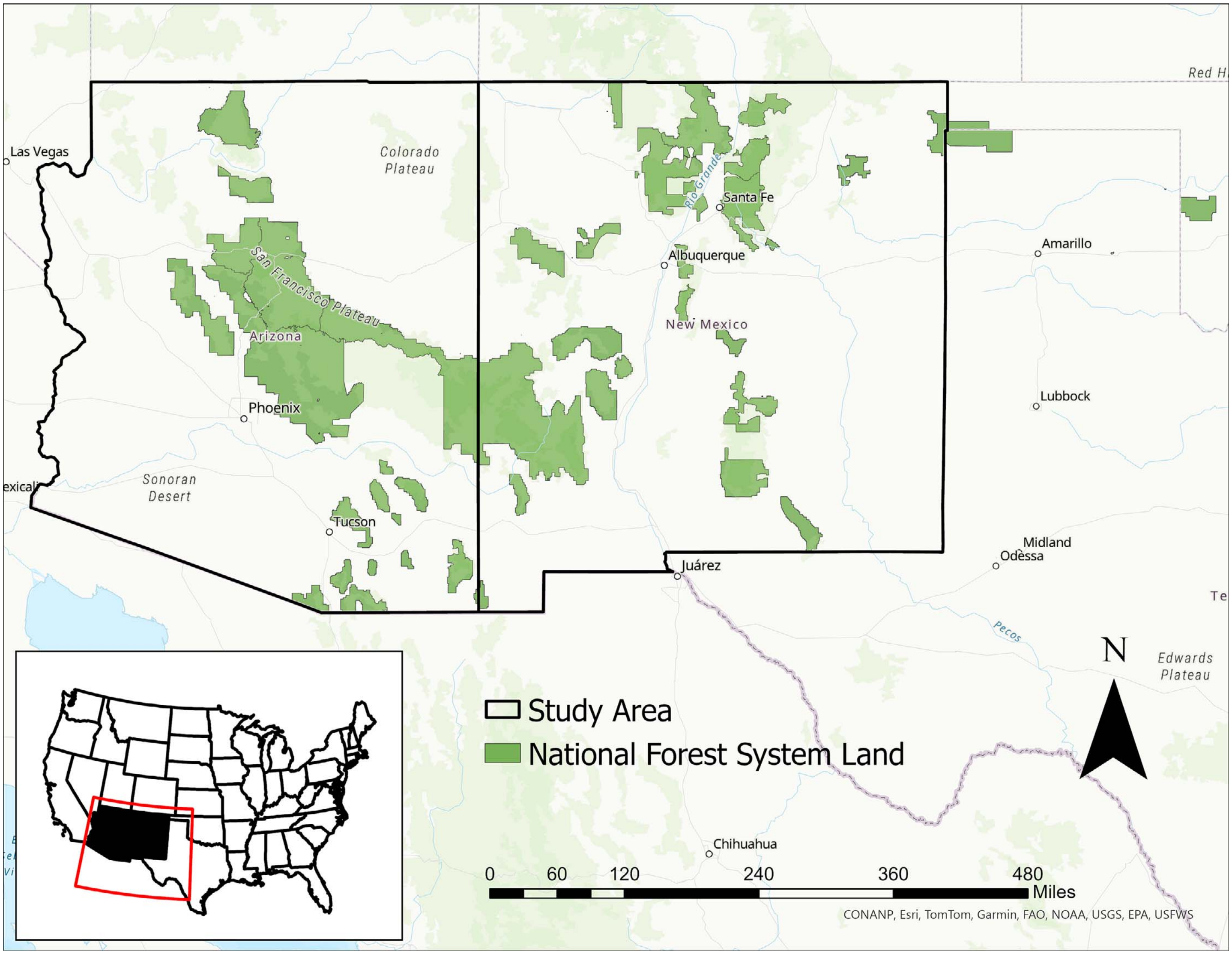

Figure 1.—This paper primarily focuses on riparian carbon dynamics within Arizona and New Mexico, but also includes analysis of riparian areas on National Forest System land that extends into Texas and Oklahoma.

organic matter that supports peak annual microbial biomass (Harms and Grimm 2008). Monsoonal moisture thus creates pulses of productivity and microbial activity that influence the size and turnover of all three major carbon pools.

Surface and subsurface hydrology regulate vegetation productivity throughout the year. Growth rates of native vegetation are tied to water availability and groundwater fluctuations, with annual cottonwood (*Populus deltoides*) diameter growth varying from 2 cm in dry habitats to 7 cm in wet habitats and radial growth rate increasing linearly with volume of surface flow (Stromberg 1993). Likewise, Arizona sycamore (*Platanus wrightii*) maintains highest productivity when groundwater depth is <2 m and fluctuations are <1 m (Stromberg 2001). These species-level patterns emerge at ecosystem scales, where water availability drives overall riparian productivity (Nguyen et al. 2015; Mendez-Estrella et al. 2017). Along the San Pedro River, surface flow permanence was the most important factor explaining variation in stand density and abundance of cottonwoods and willows, with native species remaining dominant and more productive when reaches experienced surface flow >76% of the time (Lite and Stromberg 2005).

Flow regimes control not only productivity but also carbon transport, decomposition, and distribution. Along the Rio Grande, regular overbank flooding reduces accumulation of litterfall and woody debris while promoting microbial activity and decomposition through increased soil saturation and inputs of labile organic carbon, with forest floor respiration increasing by three orders of magnitude following inundation (Molles et al. 1995; Ellis et al. 1999; Valett et al. 2005). High flows also redistribute carbon-laden sediment, with deposition patterns determined by valley form (Merritt and Wohl 2003). Conversely, low flows and channel drying depress productivity and decomposition, reducing carbon inputs while slowing microbial processing (Lite and Stromberg 2005; Stromberg et al. 2005; Nguyen et al. 2015).

Geology and topography establish the physical template that determines sediment supply, routing, and storage (Wohl et al. 2012; Beckman and Wohl 2014; Ruffing et al. 2016; Sutfin et al. 2016). Steep watersheds, actively uplifting formations, and erodible substrates generate large inputs of sediment and organic material through erosion and mass wasting (Clapp et al. 2001; Sutfin et al. 2016). These inputs are then transported downstream and deposited within riparian corridors.

Valley form determines where this material accumulates. Along a stream's longitudinal profile, confined valleys alternate with wide, low-gradient reaches (Stanford et al. 1996; Wohl et al. 2018). The concentrated flow of confined reaches scours the channel during high flows, which removes accumulated sediment and organic matter (Merritt and Wohl 2003). This export along with limited floodplain development translates to most carbon in confined reaches being stored as large wood (Wohl et al. 2012, 2017; Sutfin et al. 2016). In contrast, unconfined valleys allow water to spread laterally, depositing carbon-rich sediment across broad floodplains (Merritt and Wohl 2003). As a result, these reaches store substantial carbon in soils and aboveground biomass, especially where channels are obstructed by logs or beaver dams (Wohl et al. 2012, 2017). In headwater systems, such unconfined valleys occupy a small proportion of total channel length, yet contain as much as three-quarters of the stream network's total carbon (Wohl et al. 2012). In large, low-elevation rivers, unconfined floodplains can extend for hundreds of kilometers (Wohl et al. 2018). Overbank flooding and channel avulsion in these wide river valleys develop complex mosaics of multiple channels, flow obstructions, shifting gradients, and diverse aquatic habitats (Stanford et al. 2005). This complexity enhances carbon sequestration, as heterogeneous floodplains retain more organic material than simplified floodplains (Sutfin et al. 2016).

Finally, biota modify the physical environment in ways that enhance carbon storage beyond what would occur from abiotic processes alone (Sutfin et al. 2016). Vegetation provides carbon inputs through litter and large wood while simultaneously modifying the environment to retain those inputs (Wohl et al. 2012; Sutfin et al. 2016). Plant characteristics influence the size and turnover rates of carbon reservoirs, with species determining production and decomposition rates. Riparian plants also increase floodplain roughness, slow water, and increase sediment and organic matter deposition (Simon et al. 2004; Camporeale et al. 2013; Sutfin et al. 2016). Native riparian vegetation tolerates high shear stress during flooding (Simon et al. 2004; Sutfin et al. 2016), with roots increasing soil cohesion, reducing bank collapse and erosion, slowing shoreline water velocities, and facilitating aggradation.

Beaver create particularly strong geomorphic effects through dam construction that supports riparian plant communities, obstructs flow, and accumulates large amounts of fine sediment and carbon that can be retained for thousands of years (Persico and Meyer 2009, 2013; Wohl 2013b; Sutfin et al. 2016). These structures alter valley-scale hydrology and sediment dynamics, raising water tables, expanding wetland area, and creating deposition zones. Abundant beaver populations were historically active throughout the Southwest, with their past activity responsible for many remaining wetlands that continue storing carbon throughout Arizona and New Mexico (Fouty 2018). Although trapping severely reduced beaver abundance, relict meadows likely retain significant amounts of carbon, with substantially more stored in basins with active beaver populations (Wohl 2013b; Fouty 2018).

Estimating Potential Carbon Storage in Southwestern Riparian Ecosystems

Southwestern riparian ecosystems offer valuable but potentially underutilized carbon sequestration opportunities. Quantifying carbon storage in these systems is complicated by variations in hydrology, vegetation, and management practices. However, Dybala et al.'s (2019) global meta-analysis estimated carbon stocks for natural riparian forests based on regional climate, classifying areas as "cool" or "warm" and "wet" or "dry" depending on whether mean annual temperature exceeded 12.5°C and average annual precipitation surpassed 1400 mm.

Using the national riparian basemap (Abood et al. 2022) and HydroATLAS database (Linke et al. 2019), we quantified riparian extent across Arizona and New Mexico, classifying each area as either "warm & dry" or "cool & dry" per Dybala et al.'s (2019) thresholds (Figure 2). The basemap identifies riparian areas using National Hydrography Dataset (NHD) flowlines and 50-year flood heights plus geospatial data representing soils and wetlands. This map reflects areas with suitable conditions to support riparian ecosystems but does not incorporate human modifications, meaning the basemap reflects potential rather than current extent. We found over 3.5 million hectares of riparian ecosystems mapped across both states (Table 1). About 60% were warm & dry, and 40% were cool & dry. Arizona contained slightly more riparian area than New Mexico, with most falling into the warm & dry category. New Mexico's riparian corridors were primarily cool & dry. Applying Dybala et al.'s (2019) carbon storage estimates (warm & dry: 89 Mg C ha^{-1} in biomass and 35 Mg C ha^{-1} in soils; cool & dry: 65 Mg C ha^{-1} in biomass and 28 Mg C ha^{-1} in soils), we estimated that Southwestern riparian ecosystems could store nearly 400 million Mg C—more than 210 million Mg C in Arizona and over 181 million Mg C in New Mexico (Table 2).

The USDA Forest Service monitors carbon across National Forests and Grasslands, focusing on how land management and land cover change affect carbon stocks and CO_2 emissions (Heath et al. 2011). This monitoring relies on Forest Inventory and Analysis data, which exclude riparian areas. According to the national riparian basemap, more than 300,000 ha of riparian ecosystems fall within National Forest System lands in the Forest Service's Southwestern Region, including riparian areas in National Forests and Grasslands across Arizona, New Mexico, Texas, and Oklahoma (Table 3). The Cibola, Tonto, and Gila National Forests managed the most mapped riparian areas, with roughly three-quarters classified as cool & dry. Only the

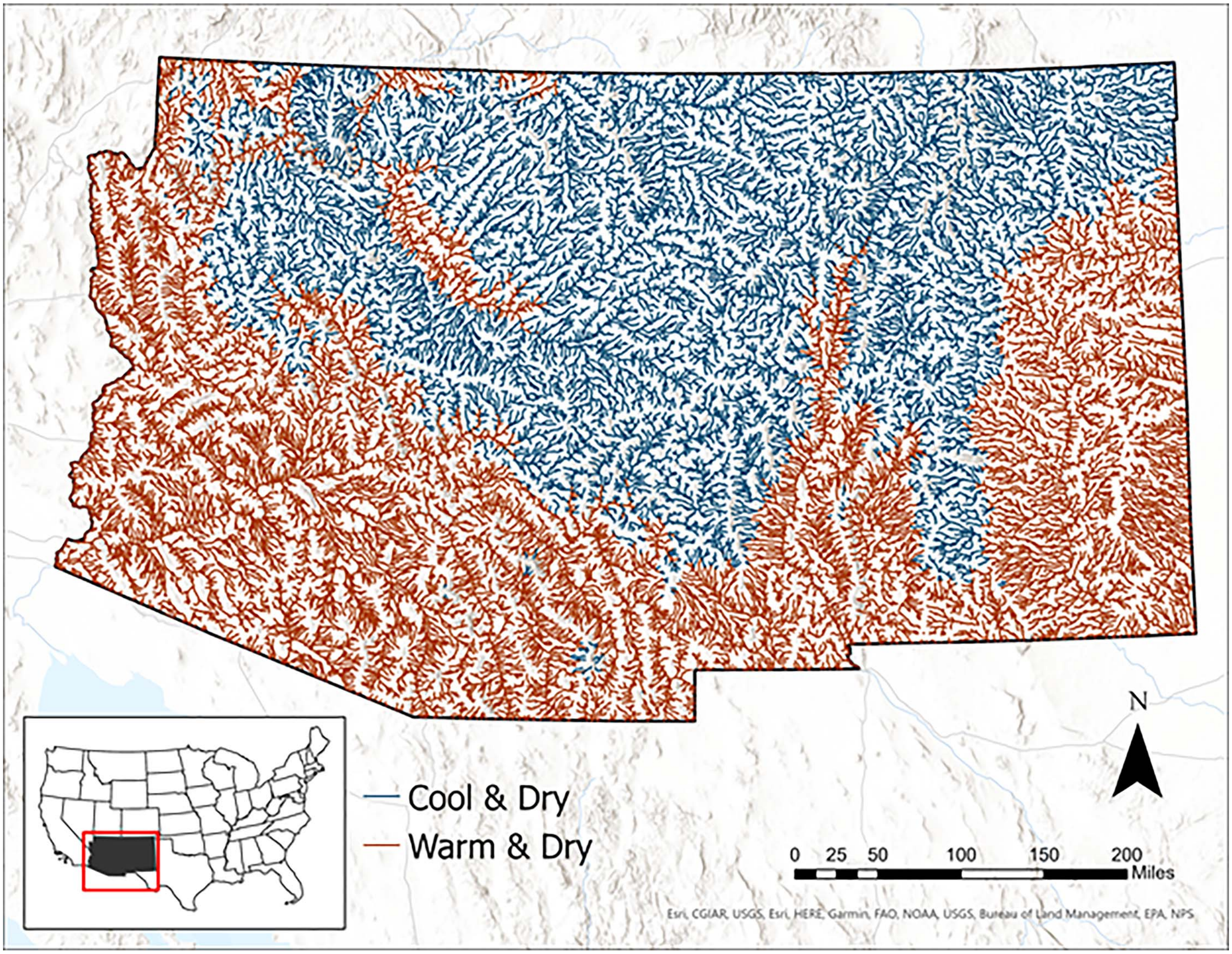

Figure 2.—Climate classifications for southwestern riparian ecosystems based on Dybala et al. (2019). Data for annual precipitation and annual temperature for each stream reach from Linke et al. (2019).

Coronado, Prescott, and Tonto National Forests had more warm & dry than cool & dry riparian areas. The Carson and Santa Fe National Forests in northern New Mexico contained only cool & dry riparian areas.

Based on Dybala et al.'s (2019) carbon stock values and the riparian basemap, we estimated that functional riparian ecosystems occupying their full extent on National Forest System land in the Southwestern Region could store over 33 million Mg C in biomass and soils (Table 3). The Tonto National Forest had the highest estimated storage potential, followed by the Cibola and Gila, due to their extensive riparian coverage. While the Cibola managed the most riparian acreage, the Tonto's riparian zones sequestered more carbon per hectare, with 87% classified as warm & dry. The Coronado National Forest had the highest average carbon density (121 Mg C ha^{-1}), followed by the Tonto (120 Mg C ha^{-1}), Prescott (112 Mg C ha^{-1}), and Lincoln (103 Mg C ha^{-1}), driven by high proportions of warm & dry areas. Forests with only cool and dry riparian areas (Santa Fe, Carson) or limited warm & dry areas (Kaibab) showed lower storage potential: 93 Mg C ha^{-1}, 93 Mg C ha^{-1}, and 94 Mg C ha^{-1}, respectively.

Climate Change Impacts on Carbon Storage

Southwestern riparian carbon dynamics are increasingly shaped by rising atmospheric CO_2 and climate change (Table 4; Serrat-Capdevila et al. 2007; Perry et al. 2012; Stromberg et al. 2013; Wohl et al. 2017). The three major carbon pools—biomass, large woody debris, and soil organic matter—respond directly to warming, altered precipitation, drought, and elevated CO_2, which influence rates of respiration, primary production, growth, and decomposition (Perry et al. 2012; Stromberg et al. 2013). Climate change also affects carbon storage indirectly by altering hydrologic and geomorphic processes (Perry et al. 2012; Smith and Finch 2016). As aridity increases throughout the

Table 1.—Hectares of riparian areas mapped in Arizona and New Mexico based on the national riparian basemap (Abood et al. 2022).

Climate	Arizona	New mexico	Total
Warm & Dry	1,330,843	771,220	2,102,063
Cool & Dry	494,118	918,999	1,413,118
Total	1,824,961	1,690,219	3,515,181

Table 2.—Estimated amount of carbon stored in riparian ecosystems of the American Southwest based on the national riparian basemap and carbon stock values from Dybala et al. (2019).

Climate	C Stock (Mg C/ha)	Arizona	New mexico	Total
Warm & Dry	Biomass (89)	118,445,027	68,638,614	187,083,641
	Soils (35)	46,579,505	26,992,713	73,572,218
	Total (124)	165,024,532	95,631,327	260,655,859
Cool & Dry	Biomass (65)	32,117,696	59,734,949	91,852,645
	Soils (28)	13,835,315	25,731,978	39,567,293
	Total (93)	45,953,011	85,466,927	131,419,938
	Total	210,977,543	181,098,254	392,075,797

Southwest, streams and riparian zones are projected to experience deeper groundwater tables, altered flood regimes, and increased flow intermittency (Stromberg et al. 2013; Smith and Finch 2016).

In dryland ecosystems, elevated CO_2 typically enhances photosynthesis, water use efficiency, and growth of C3 vegetation (Ainsworth and Long 2005; de Graaff et al. 2006; Perry et al. 2012). However, CO_2–induced increases in productivity may be offset by higher temperatures and drought. Many key riparian species, including cottonwood, mesquite, and sycamore, reduce photosynthesis and growth in response to heat stress (Perry et al. 2012). In the San Pedro River, modeled climate change impacts predict that by 2100, recharge and baseflows will decrease (Serrat-Capdevila et al. 2007). These changes are expected to increase flow intermittency, which in this system is associated with reduced pre-monsoon productivity (Nguyen et al. 2015).

Changes in hydrology and moisture availability are expected to shift riparian plant community composition. Increasing drought, combined with reduced snowpacks, earlier runoff, and altered precipitation, will likely favor drought-tolerant species that differ in productivity and biomass accumulation (Perry et al. 2012; Stromberg et al. 2013). Along the San Pedro River, increasingly intermittent flows are predicted to shift vegetation from hydric pioneers like cottonwood and willow to xeroriparian species such as tamarisk (*Tamarix* sp. L; Stromberg et al. 2010). This transition, along with shifts to younger, denser stands with lower basal area in response to more frequent extreme flooding, will reduce carbon stored in biomass and large wood (Stromberg et al. 2010).

Changes in plant productivity and composition will directly influence biomass, large woody debris, and soil organic matter by altering both inputs and turnover rates. Under warmer and drier conditions, vegetation stress reduces litter production and quality, diminishing inputs to soil carbon reservoirs (Perry et al. 2012). Shifts in community composition, including replacement of native species by nonnative or drought-adapted vegetation, further compound these effects. For example, cottonwood-dominated stands in the Rio Grande bosque produce substantially more litter than tamarisk-dominated sites (Ellis et al. 1998). Drought-induced water stress, particularly in native drought-intolerant trees, also accelerates branch and crown dieback, increasing short-term large wood inputs (Perry et al. 2012; Stromberg et al. 2013; Smith and Finch 2016). Over time, however, greater disturbance frequency, reduced productivity, and a shift toward younger, more homogeneous forests are expected to lower total biomass and decrease the recruitment of large wood from mature riparian and upland stands, thereby reducing long-term carbon storage across both living and dead woody pools (Turner 2010; Wohl 2013a; Sutfin et al. 2016).

Decomposition rates are controlled by microbial and fungal activity, which are sensitive to temperature, moisture, and anoxic conditions. Warming generally increases decomposition by accelerating microbial activity and biochemical reactions (Briones et al. 2007; Perry et al. 2012), but also enhances evaporative loss and reduces soil moisture (Rustad et al. 2001; Perry et al. 2012). Declining baseflows and streamflow permanence further limit moisture availability (Kaplan and Muñoz-Carpena 2011; Pirastru and Niedda 2013; Schilling et al. 2021). Because microbial processing is influenced by flooding regimes, climate-driven changes in flood timing, duration, and magnitude may suppress decomposition (Perry et al. 2012; Yin et al. 2019; Annala et al. 2022). On the Rio Grande, early summer snowmelt floods increased litter breakdown and nutrient release during peak growing season, while sites that did not flood retained nutrients in dry litter, which only began decomposing after late-summer monsoons (Ellis et al. 1999).

Litter breakdown rates can also be influenced by plant species and characteristics of the river system. In the Rio Grande bosque, cottonwood and tamarisk leaves decayed at similar rates, while Russian olive (*Elaeagnus angustifolia* L.) decomposed significantly faster (Ellis et al. 1998; Harner et al. 2009). On the regulated Colorado River, cottonwood leaves broke down faster than tamarisk, which decomposed faster than willow (Pomeroy et al. 2000). Overall, decomposition rates were lower in the Colorado than in other systems, likely due to low microbial metabolic rates and scarce shredder macroinvertebrates (Pomeroy et al. 2000).

Climate-driven changes in disturbance regimes, particularly flooding, may significantly alter riparian carbon storage. Overbank flows transport organic matter downstream and deposit carbon-rich sediments across valley bottoms (Jones and Smock 1991; Tockner et al. 1999; Kaase and Kupfer 2016), potentially burying surface litter. This burial can either slow or accelerate decay depending on oxygen availability (Sutfin et al. 2016). Flooding and channel avulsion can undercut trees and contribute large wood to riparian corridors (Wohl 2013a). Large wood recruitment, transport, and decay are influenced by peak flow magnitude and duration, which are expected to shift with climate change (Wohl 2013a; Sutfin et al. 2016). Additionally, the structure and longevity of large wood inputs will be increasingly

Table 3.—Potential riparian area and estimated carbon storage on National Forest System lands in the USDA Forest Service Southwestern Region. Values are based on the national riparian basemap (Abood et al. 2022), which identifies areas with suitable conditions to support riparian ecosystems but may not reflect current extent due to degradation or other modifications. Carbon stock estimates are from Dybala et al. (2019).

National Forest	Total riparian area (ha) – national riparian basemap	Area of cool & dry riparian (ha) – national riparian basemap	Area of warm & dry riparian (ha) – national riparian basemap	Estimated carbon stored in riparian biomass (Mg C)	Estimated carbon stored in riparian soils (Mg C)	Total potential carbon (Mg C) – national riparian basemap
Apache-Sitgreaves	35,126	33,577	1549	2,320,384	994,377	3,314,762
Carson	23,624	23,624	0	1,535,551	661,468	2,197,019
Cibola	53,663	43,912	9750	3,722,099	1,570,814	5,292,914
Coconino	29,659	21,555	8105	2,122,352	887,187	3,009,539
Coronado	18,058	1589	16,469	1,569,014	620,902	2,189,916
Gila	38,353	35,805	2548	2,554,104	1,091,722	3,645,826
Kaibab	20,410	19,925	484	1,338,247	574,859	1,913,105
Lincoln	18,083	11,954	6129	1,322,463	549,215	1,871,678
Prescott	17,065	6359	10,706	1,366,182	552,768	1,918,950
Santa Fe	24,585	24,585	0	1,598,057	688,394	2,286,451
Tonto	48,307	6422	41,885	4,145,181	1,645,786	5,790,966
Total	326,933	229,307	97,626	23,593,635	9,837,492	33,431,127

shaped by climate-induced changes to wildfire, insects, and disease (Turner 2010; Wohl 2013a; Sutfin et al. 2016).

Climate change interactions with human modifications

Dramatic shifts in Southwestern riparian ecosystems driven by climate change are occurring within the context of widespread and long-standing human modifications (Table 5). Although riverine carbon dynamics are understudied in the American Southwest, centuries of human activity have clearly altered riparian carbon storage capacity. Human actions generally increase organic carbon inputs to rivers while reducing long-term storage in riparian zones (Wohl et al. 2017). Throughout Arizona and New Mexico, riparian carbon storage capacity has likely been affected by surface flow diversion and regulation, groundwater extraction, channelization, land use change, livestock grazing, and biological invasions (Patten 1998; Brinson and Malvárez 2002; Perry et al. 2012; Stromberg et al. 2013; Smith and Finch 2016). These stressors interact and shift over time, complicating their effects on riparian carbon storage and underscoring the need for further research.

Table 4.—Climate change impacts on riparian carbon storage in the southwestern United States.

Climate driver	Primary mechanisms	Affected carbon pools	Resulting impacts on carbon storage	Representative references
Warming temperatures	Increases plant and microbial respiration; raises evapotranspiration; induces heat stress in vegetation	Biomass, Soil Organic Matter	Reduced productivity and litter inputs; enhanced decomposition and CO_2 release	Perry et al. 2012; Stromberg et al. 2013; Briones et al. 2007
Increased aridity & drought	Lowers groundwater tables; limits soil moisture; increases vegetation mortality	Biomass, Large Woody Debris, Soils	Declines in growth and recruitment; short-term pulse of large wood from dieback but long-term loss of woody biomass and soil C inputs	Perry et al. 2012; Smith and Finch 2016; Wohl 2013a
Altered precipitation & snowmelt timing	Reduces runoff and baseflow; shifts growing-season water availability, increased intermittency	Biomass, Soils	Decreased riparian productivity, especially pre-monsoon; altered litterfall and decomposition timing	Serrat-Capdevila et al. 2007; Nguyen et al. 2015; Ellis et al. 1999
Changes in flood frequency, duration, and magnitude	Alters overbank sediment deposition, litter burial, and wood recruitment	Large Woody Debris, Soils	Reduced sediment and carbon deposition on floodplains; fewer large wood inputs; variable decomposition depending on oxygen availability	Merrit and Wohl 2003; Sutfin et al. 2016; Wohl 2013a
Elevated atmospheric CO_2	Enhances photosynthesis and water-use efficiency in C3 plants under non-limiting water	Biomass	Potential short-term productivity gains offset by drought and heat stress	Ainsworth and Long 2005; de Graaff et al. 2006; Perry et al. 2012
Vegetation composition shifts	Replacement of native hydric species by drought-tolerant or nonnative taxa	Biomass, Soils	Lower litter quantity and quality; altered decomposition; reduced overall C storage	Ellis et al. 1998; Stromberg et al. 2010; Perry et al. 2012
Increased disturbance frequency (fire, flood, insects, disease)	Alters stand age, structure, and regeneration dynamics	Biomass, Large Woody Debris	Younger, more homogeneous forests with smaller trees, reduced long-term C storage; episodic pulses of coarse wood	Sutfin et al. 2016; Turner 2010; Wohl 2013a

Table 5.—Human modifications influencing riparian carbon storage in the southwestern United States.

Human stressor	Primary mechanisms	Affected carbon pools	Resulting impacts on carbon storage	Representative references
Dams, diversions, and channelization	Alter flow regimes, disconnect floodplains, reduce sediment deposition	Biomass, Large Woody Debris, Soils	Reduced overbank flooding and hydrologic connectivity; lower productivity and litter inputs; less carbon burial	Brinson and Malvárez 2002; Wohl et al. 2017; Graf 2006
Groundwater extraction	Lowers water tables and baseflows; increases drought stress	Biomass, Soils	Vegetation dieback; reduced litter production and soil C accumulation	Stromberg et al. 1996; Webb and Leake 2006
Urbanization & Infrastructure	Increases impervious surfaces; fragments corridors; alters runoff	Biomass, Soils	Reduced plant productivity, increased erosion and decomposition	Forman and Alexander 1998; Jones et al. 2000; Burton et al. 2009
Agricultural conversion	Replaces native riparian vegetation and organic-rich soils with cropland	Biomass, Soils	Loss of long-term soil carbon, altered hydrology and nutrient cycling	Mitra et al. 2005; Sutfin et al. 2016
Livestock grazing	Reduces plant cover, compacts soils, destabilizes banks	Biomass, Soils	Decreased inputs and retention; soil C loss; conversion from sinks to sources	Belsky et al. 1999; Trimble and Mendel 1995; Fesenmyer et al. 2018
Invasive plant species	Alter litter quality, rooting depth, and productivity	Biomass, Soils	Changes in decomposition rates and C accumulation; dominance by low-C species (e.g., tamarisk)	Ellis et al. 1998; Harner et al. 2009; Hu et al. 2022
Fire regime alteration (suppression or increased severity)	Changes fuel loads and post-fire recovery	Biomass, Large Woody Debris, Soils	Combustion losses of surface and woody C; potential sediment C deposition post-fire	Pettit and Naiman 2007; Webb et al. 2019; Wohl et al. 2017

Hydrologic Alterations and Channelization: Dams, diversions, groundwater pumping, channelization, and floodplain loss degrade hydrologic connectivity and alter carbon dynamics in riparian ecosystems (Patten 1998; Brinson and Malvárez 2002; Wohl et al. 2017). Nearly all major rivers across Arizona and New Mexico experience significant flow regulation, and large sections of the floodplains associated with the Rio Grande, Gila, and Colorado Rivers are disconnected from their rivers by levees (Graf 2006; Driscoll et al. *in review*). In the Santa Cruz and San Pedro watersheds, groundwater extraction has lowered water tables and reduced baseflows, stressing riparian vegetation (Stromberg et al. 1996; Webb and Leake 2006). These hydrologic changes have created drier floodplains, reduced flood frequency, and lessened channel migration, all impacting carbon cycling by altering plant composition and productivity, decomposition, large wood recruitment, and the fate of litter and sediment (Wohl et al. 2017). Warmer and drier conditions imposed by climate change will likely exacerbate these impacts by increasing consumptive water use, altering flow regimes, and intensifying disturbances like wildfire and flooding (Serrat-Capdevila et al. 2007; Palmer 2009; Mittal et al. 2016; Smith and Finch 2017).

Land Use Change: Land use change modifies hydrology, vegetation, and soil processes with significant implications for riparian carbon dynamics. Roads and impervious surfaces fragment riparian corridors, compact soils, and disrupt shallow groundwater flow, reducing hydrologic connectivity and plant productivity (Forman and Alexander 1998; Jones et al. 2000). Urbanization and agricultural development increase nutrient and sediment inputs, remove native vegetation, and alter streamflow regimes through water diversions and drainage infrastructure (NRC 2002; Groffman et al. 2003; Burton et al. 2009). In arid and semi-arid settings, these changes interact with climate stressors to accelerate soil drying, decomposition, and shift riparian zones from carbon sinks to carbon sources (Patten 1998; Perry et al. 2012; Kaushal et al. 2014; Wohl et al. 2017). Agricultural land use in floodplains often replaces carbon-rich wetland soils with lower-carbon cultivated soils, reducing long-term storage potential (Mitra et al. 2005; Sutfin et al. 2016). These drivers compromise riparian ecosystem resilience, limiting their role in carbon cycling and highlighting the need for integrated land and water management to support climate mitigation goals.

Livestock Grazing: Livestock grazing is widespread in the Southwest (Krueper 1995; Zaimes 2007) and significantly affects riparian carbon dynamics by degrading vegetation, compacting soils, and disrupting hydrology. Grazing reduces plant cover, root growth, and bank stability, diminishing carbon inputs and retention (Trimble and Mendel 1995; Belsky et al. 1999). Trampling and overgrazing reduce herbaceous and woody biomass, increase erosion and sedimentation, and deplete soil organic matter and nutrient cycling capacity (Clary and Webster 1989; Krueper 1995; Belsky et al. 1999). These impacts are especially acute in arid environments, where limited water constrains productivity and carbon sequestration (Krueper 1995). Under rising temperatures, increased aridity, and altered hydrologic regimes, grazed riparian zones may suffer further declines in vegetative recovery and soil moisture, compounding losses in carbon storage (Archer and Predick 2008; Fesenmyer et al. 2018). In degraded areas, grazing can convert riparian areas from carbon sinks to greenhouse gas sources due to increased decomposition and reduced organic inputs (Limpert et al. 2021). Addressing the cumulative impacts of livestock use and climate stress is critical for conserving riparian carbon and sustaining ecosystem services in Southwestern watersheds.

Biological Invasion: Invasive plant species can fundamentally alter riparian carbon dynamics by modifying vegetation structure, productivity, and decomposition rates (Martin et al. 2017; Hu et al. 2022). Tamarisk, Russian olive, and several other species have spread widely across Southwestern riparian corridors (Ringold et al. 2008; Nagler et al. 2011), replacing native vegetation with functionally distinct communities that differ in litter quality, rooting depth, and evapotranspiration rates (Ellis et al. 1998; Pomeroy et al. 2000; Harner et al. 2009; Hultine and Bush 2011). These changes alter carbon cycling, with invasive species producing more resistant litter that slows decomposition or reduces carbon inputs through lower productivity or altered phenology (Liao et al. 2008). Dense monocultures can suppress native plant and microbial diversity, disrupting belowground carbon storage and nutrient cycling (Ehrenfeld 2003). In the Southwest, invasions often interact with climate stressors, including drought, streamflow alteration, and rising temperatures (Zaimes 2007; Smith and Finch 2016). These environmental changes promote dominance by nonnatives while limiting recovery of native vegetation, reducing ecosystem resilience, and affecting potential for long-term carbon sequestration (Shafroth et al. 2005; Stromberg et al. 2007).

Fire: Fire reshapes riparian carbon pools through combustion, vegetation mortality, and post-fire hydrogeomorphic processes (Ffolliott et al. 1996; Pettit and Naiman 2007; Meigs et al. 2009; Webb et al. 2019; Verma and Sati 2025). Effects vary based on burn severity and timing, vegetation type, hydrologic conditions, and whether fire occurs in the uplands or valley bottom. Upland fires can increase runoff, erosion, and debris flows, depositing carbon-rich sediment, woody debris, and organic matter in riparian floodplains (Ffolliott et al. 1996; Wohl et al. 2017). Riparian fires burn litter, duff, and standing biomass, leading to immediate carbon losses (Pettit and Naiman 2007). In Arizona and New Mexico, riparian fire severity often reflects prior hydrologic conditions (Webb et al. 2019). Along the Rio Grande, floodplain disconnection has led to accumulation of thick organic layers that fuel more severe fire and greater carbon loss than frequently flooded areas that burn less severely and retain more surface carbon (Ellis 2001). Impacts to aboveground biomass can be substantial. In southeastern Arizona, riparian woodlands saw 26% tree mortality following fire, with many cottonwoods and willows surviving only as resprouts, reducing mature biomass, but possibly maintaining belowground carbon stocks (Bock and Bock 2014).

Carbon Storage on Southwestern National Forests and Grasslands: To illustrate landscape-scale effects of human modification and riparian loss, we re-estimated current riparian carbon stocks on National Forests and Grasslands in the USDA Forest Service Southwestern Region using maps of existing vegetation (USDA Forest Service, Southwestern Region 2025). Unlike Table 3, which presents potential carbon storage based on the riparian basemap that identifies areas with suitable conditions for riparian ecosystems, Table 6 presents estimated current carbon storage based on mapped existing riparian vegetation. Only about 56% (183,862 ha) of the riparian areas shown on the basemap were mapped with existing riparian

Table 6.—Current riparian area and estimated carbon storage on National Forest System lands in the USDA Forest Service Southwestern Region. Values are based on existing vegetation maps (USDA Forest Service, Southwestern Region 2025), which reflect current riparian extent. The "Percent of Potential Carbon" column shows the ratio of current carbon storage to potential storage from Table 3. Carbon stock estimates are from Dybala et al. (2019).

National forest	Total riparian area (ha) – existing vegetation map	Area of cool & dry riparian (ha) – existing vegetation map	Area of warm & dry riparian (ha) – existing vegetation map	Estimated carbon stored in riparian biomass (Mg C)	Estimated carbon stored in riparian soils (Mg C)	Total carbon (Mg C) – existing vegetation	Total potential carbon (Mg C) – riparian basemap	Percent of potential carbon
Apache-Sitgreaves	23,940	23,207	733	1,573,690	675,451	2,249,141	3,314,762	68
Carson	22,665	22,665	0	1,473,223	634,619	2,107,841	2,197,019	96
Cibola	19,889	8345	11,544	1,569,832	637,696	2,207,528	5,292,914	42
Coconino	13,338	6824	6514	1,023,294	419,056	1,442,350	3,009,539	48
Coronado	4039	288	3751	352,570	139,354	491,924	2,189,916	22
Gila	26,862	23,250	3612	1,832,684	777,406	2,610,090	3,645,826	72
Kaibab	1909	1451	459	135,125	56,676	191,801	1,913,105	10
Lincoln	2491	1725	766	180,305	75,112	255,417	1,871,678	14
Prescott	16,235	5731	10,504	1,307,390	528,114	1,835,504	1,918,950	96
Santa Fe	17,967	17,967	0	1,167,860	503,078	1,670,938	2,286,451	73
Tonto	34,527	5119	29,408	2,950,020	1,172,601	4,122,621	5,790,966	71
Total	183,862	116,571	67,291	13,565,992	5,619,163	19,185,155	33,431,127	57

vegetation. The Tonto, Gila, and Apache-Sitgreaves National Forests managed the largest areas of existing riparian vegetation (Table 6). Approximately 63% of these mapped riparian areas occurred in cool & dry climates, the remainder in warm & dry zones.

Based on Dybala et al.'s (2019) carbon stock estimates and the existing vegetation map, riparian areas on National Forest System land in the Southwestern Region currently store an estimated 19+ million Mg C (Table 6), or about 57% of their potential storage estimated in Table 3. The Tonto, Gila, and Apache-Sitgreaves National Forests likely store the most carbon, and the Kaibab, Lincoln, and Coronado store the least. Existing riparian areas on the Carson and Prescott National Forests are estimated to store approximately 96% of potential carbon, while the Kaibab, Lincoln, Coronado, Cibola, and Coconino each store less than half of their potential. These latter forests offer opportunities for riparian restoration to enhance carbon storage.

Restoration and Conservation as Climate Mitigation Strategies

Despite limited extent and widespread alteration, Southwest riparian corridors provide critical ecosystem services, including carbon sequestration (Stromberg et al. 2013). These ecosystems often represent the most productive portions of arid landscapes, and their capacity to accumulate and store carbon makes them high-leverage targets for reducing climate exposure (Dybala et al. 2019). Increasing carbon storage through conservation and stewardship has been identified as an important component of cost-effective climate solutions (Field and Mach 2017). Given their high sequestration potential, restoring and protecting Southwestern riparian ecosystems can meaningfully contribute to climate change mitigation (Lewis et al. 2015; Sutfin et al. 2016; Wohl et al. 2017, 2018; Matzek et al. 2018; Dybala et al. 2019).

Restoration approaches that focus on establishing complex and connected floodplains are valuable for maximizing carbon storage in riparian ecosystems because more carbon is sequestered in wide, complex floodplains with strong three-dimensional hydrologic connectivity (Sutfin et al. 2016; Wohl et al. 2018; Dybala et al. 2019). These unconfined, heterogeneous riparian systems allow for channel migration, which can trap sediment, bury carbon deep in subsurface floodplain soils (D'Elia et al. 2017), promote growth of complex vegetation, and slow decomposition (Dybala et al. 2019). For managers and communities aiming to use riparian restoration as a climate mitigation tool, recovering such dynamic floodplains with intact hydrology may be a priority.

Recent studies show that restoring riparian woodlands, especially in warm & dry or cool & dry climates like those in Arizona and New Mexico, can rapidly increase carbon accumulation. Dybala et al. (2019) found that planting riparian forests more than doubles initial growth rates compared to naturally regenerating riparian forests, leading to substantial gains in carbon storage within a decade. A Colorado study indicates that unconfined valleys with a history of only natural disturbance have higher coarse particulate organic matter storage than comparable valleys with logging history (Livers et al. 2018). The authors suggest that conserving riparian forests would be valuable for increasing wood loads in streams, leading to multithread channels that recruit more wood and form heterogeneous stream reaches that retain more carbon (Livers et al. 2018).

These findings emphasize that restoration efforts must go beyond replanting vegetation to also restore geomorphic and hydrologic processes. In the Southwest, this means prioritizing recovery of low-gradient, unconfined valley bottoms with potential for multithread channel development and floodplain reconnection. In such settings restoration efforts can yield large carbon storage gains while simultaneously enhancing biodiversity, water retention, and resilience to disturbance (Livers et al. 2018; Dybala et al. 2019).

Another promising strategy is beaver reintroduction or installation of beaver dam analogs (BDAs), which mimic natural beaver activity's geomorphic and hydrologic effects (Pollock et al. 2014). BDAs and other low-tech process-based restoration methods are increasingly used in Arizona and New Mexico (e.g., USDA Forest Service restoration projects in the Gila, Apache-Sitgreaves, Santa Fe, and Coconino National Forests). They aim to raise water tables, promote sediment deposition, and expand riparian vegetation—contributing to both ecosystem recovery and carbon sequestration (Pollock et al. 2014).

Ultimately, a diverse suite of riparian restoration and conservation options are available across the region. When designed with carbon storage in mind, these actions offer opportunities to address both local watershed objectives and global climate goals. Restoring even a small fraction of degraded riparian areas could yield meaningful carbon benefits while supporting a broader set of ecological, hydrological, and social values.

Conclusions and Future Research Needs

Riparian ecosystems in the arid and semiarid American Southwest store disproportionately large amounts of carbon relative to their limited extent. Our review highlights how riparian carbon storage is shaped by complex interactions between climate, hydrology, and land use. Climate change threatens to destabilize floodplain carbon pools through rising temperatures, increased aridity, declining snowpack, and reduced streamflow permanence (USGCRP 2023). These changes interact with land use legacies such as overgrazing, channelization, fire suppression, and water diversions, to reduce riparian productivity and carbon accumulation while degrading habitat and ecosystem function.

Despite these challenges, restoration can improve vegetation cover, raise water tables, reestablish hydrogeomorphic processes, and enhance carbon storage (Schultz 2023; Bosworth et al. 2025; Driscoll et al. 2025). Using published carbon values for riparian soils and vegetation, we estimated that riparian ecosystems across Arizona and New Mexico could store hundreds of millions of metric tons of carbon, with National Forest lands potentially contributing up to 10% of the total. Our results also indicate that there is substantial opportunity for restoration to increase carbon storage in riparian areas based on comparisons of current and potential riparian extent. These estimates should be interpreted cautiously as the datasets do not capture local variability in hydrology, vegetation, disturbance history, or stressors such as fire, invasive species, or groundwater depletion. Furthermore, the values from Dybala et al. (2019) may not fully reflect arid Southwest conditions.

These limitations highlight key research needs:

- **Collect regionally representative field data** to quantify carbon stocks across Southwestern riparian ecosystems, including understudied ephemeral and intermittent streams, and to refine estimates of carbon stored in biomass, soils, and large wood.
- **Improve understanding of spatial and temporal carbon storage variability** by integrating vegetation structure, geomorphic setting, groundwater dynamics, and hydrologic conditions.
- **Evaluate climate change, disturbance, and restoration effects** through empirical and longitudinal studies that track carbon responses to management actions, water availability, and vegetation change.
- **Clarify how climate change and other stressors interact** to influence carbon stability, turnover, and sequestration potential, especially under scenarios of groundwater depletion, fire, and invasive species.
- **Incorporate riparian carbon storage into broader climate strategies** by assessing its socioecological benefits, including biodiversity conservation, water quality enhancement, and cultural resource protection, while supporting its inclusion in national inventories and mitigation frameworks.

Despite their importance, riparian ecosystems remain underrepresented in national carbon accounting. Integrating them into climate policy offers a cost-effective opportunity to enhance sequestration while delivering co-benefits for biodiversity, water, and cultural resources. As climate change intensifies, fully recognizing the multifunctional role of riparian ecosystems will be essential for advancing ecosystem resilience and meeting climate goals at regional and national scales.

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