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Natural infrastructure in dryland streams (NIDS) can establish regenerative wetland sinks that reverse desertification and strengthen climate resilience

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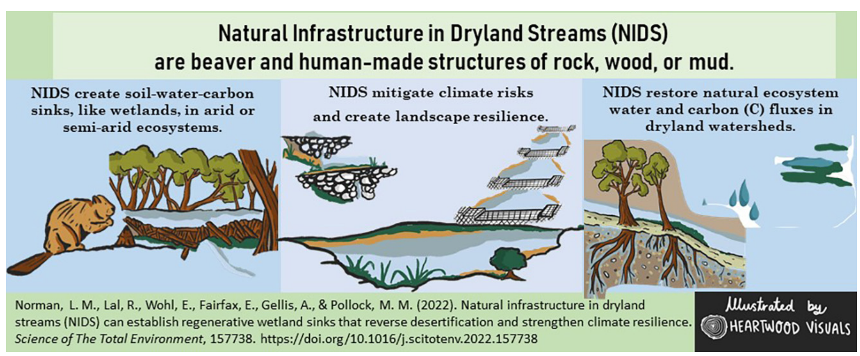
HIGHLIGHTS

- Natural infrastructure in dryland streams (NIDS) store water, sediment, and carbon
- NIDS can be installed by both beaver *or* humans, using rock, wood, and mud.
- NIDS can create *or* restore riparian wetlands in degraded, incised watersheds.
- NIDS sustain processes and functions that boost fluvial ecosystem resilience.
- NIDS initiate positive feedback loops that mitigate climate change.

GRAPHICAL ABSTRACT



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ABSTRACT

In this article we describe the natural hydrogeomorphological and biogeochemical cycles of dryland fluvial ecosystems that make them unique, yet vulnerable to land use activities and climate change. We introduce Natural Infrastructure in Dryland Streams (NIDS), which are structures naturally or anthropogenically created from earth, wood, debris, or rock that can restore implicit function of these systems. This manuscript further discusses the capability of and functional similarities between beaver dams and anthropogenic NIDS, documented by decades of scientific study. In addition, we present the novel, evidence-based finding that NIDS can create wetlands in water-scarce riparian zones, with soil organic carbon stock as much as 200 to 1400 Mg C/ha in the top meter of soil. We identify the key restorative action of NIDS, which is to slow the drainage of water from the landscape such that more of it can infiltrate and be used to facilitate natural physical, chemical, and biological processes in fluvial environments. Specifically, we assert that the rapid drainage of water from such environments can be reversed through the restoration of natural infrastructure that once existed. We then explore how NIDS can be used to restore the natural biogeochemical feedback loops in these systems. We provide examples of how NIDS have been used to restore such feedback loops, the lessons learned from installation of NIDS in the dryland streams of the southwestern United States, how such efforts might be scaled up, and what the implications are for mitigating climate change effects. Our synthesis portrays how restoration using NIDS can support adaptation to and protection from climate-related disturbances and stressors such as drought, water shortages, flooding, heatwaves, dust storms, wildfire, biodiversity losses, and food insecurity.

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1. Introduction

The study of ecohydrology in arid and semi-arid environments (collectively, 'drylands') can offer solutions to vast areas of the planet where aridification is occurring or expected to occur. Arid lands constitute the largest terrestrial biome on Earth and are home to >20 % of the world's population (Tchakerian and Pease, 2015). In the United States, approximately 25 % of the land is considered arid or semi-arid (areas that annually average < 25 cm and 25–50 cm of rain, respectively) (AghaKouchak et al., 2013). Desertification occurs when water availability declines and causes degradation of soil and vegetation (Lal, 2010; Lal et al., 2003). Land use changes and increased greenhouse gas emissions (GHGe) over the last century have increased aridification in vast drylands of the southwestern United States and elsewhere (Overpeck and Udall, 2020; Fig. 4). Highly variable precipitation and extended hot, dry conditions can result in drought, unpredictable floods and fires, surface and groundwater depletion, soil degradation, and vegetative change (Allen et al., 2010; Breshears et al., 2005; East and Sankey, 2020; Goodrich et al., 2004; Uhlman et al., 2020). The severity and frequency of such events are largely controlled by water and carbon (C) fluxes (Sahani et al., 2019).

As temperatures rise and humidity increases, clouds form in the top of the atmosphere (Dessler, 2010). Changes to the water cycle, and in particular the evapotranspiration and water vapor feedback loops may cause increased frequency and intensity of extreme storm events, floods, and droughts (Huntington, 2006). Water vapor also traps a portion of outgoing infrared radiation from Earth and reradiates it back, increasing warming effects. Water vapor is Earth's primary GHG (Graham et al., 2010) but atmospheric carbon dioxide (CO_2) is the most important GHGe related to anthropogenic impacts (Riebeek, 2011). Accounting for and minimizing anthropogenic CO_2while maximizing the biosphere carbon sink can reduce global warming (United Nations Framework Convention on Climate Change—UNFCCC, 2015). Carbon emissions currently outpace sequestration, but many ecosystems have feedbacks that can limit atmospheric CO_2 by sequestering more carbon than they emit (Lal, 2019a).

The 26th United Nations Climate Change Conference of the Parties (COP26) highlighted the potential for "nature-based solutions" to address the inter-related crises of climate change and impacts to biodiversity (U.S. Department of Interior, 2021). Because of this international political momentum surrounding nature-based solutions, there is a need for case studies that further describe climate adaptation and mitigation services they provide (Tye et al., 2022). Natural infrastructure are nature-based solutions that use or mimic natural processes and can contribute to conserving, rehabilitating, or creating important ecosystems and mitigating GHGe (Nesshöver et al., 2017; WWAP, 2018). Nature-based infrastructure costs less than built infrastructure, is cheaper to maintain, and more resilient to climate change (International Institute for Sustainable Development (IISD), 2021).

Naturally-occurring infrastructure such as beaver dams, log jams and geologic features, and human-made infrastructure such as rock check dams, beaver dam analogs (BDAs), gabions and weirs, all affect streamflow hydraulics and sedimentation and can enhance riparian plant establishment (DeBano and Heede, 1987; Gurnell, 1998). We refer to such natural and anthropogenic structures as natural infrastructure in dryland streams (NIDS) and describe how they can restore hydrogeomorphological and biogeochemical processes in watersheds (Fig. 1). We introduce this novel word, "NIDS" to reference both human and beaver-engineered infrastructure installed in arid and semi-arid riparian areas and wetlands as restoration tools. Specifically, our objectives are to (i) describe the different types of NIDS and explain the hydrologic, geomorphic, pedogenic, and biological feedback loops they initiate, (ii) describe how NIDS can be used to perennialize ephemeral streams, and (iii) describe how NIDS can be used to sequester carbon.

1.1. Overview of dryland meadows, wetlands (Ciénegas) and stream corridor carbon storage and hydrology

Understanding dryland ecosystem features is essential to understanding how NIDS impact their hydrogeomorphological and biogeochemical processes and functions. Below we discuss biogeochemical cycling of three historically common types of fluvial environments in arid ecosystems, mountain or wet meadows, *ciénegas* and stream corridors or *arroyos*.

Mountain meadows often exist near stream headwaters as flat, broad and historically well-vegetated landscape patches that provide the time and space for water to infiltrate. Unfortunately, many mountain meadows are degraded and streams that run through them are incised, resulting in loss of function (Hammersmark et al., 2008). *Ciénegas* are a type of wetland found in arid environments, often spring-fed and seasonally or permanently saturated with water, that occur in low relief rolling grasslands or alluvial plains bounded by vegetated mountain fronts, and they too are rapidly declining (Hendrickson and Minckley, 1985; Minckley et al., 2013). Stream corridors are areas where sediment is eroded (bed and banks) and deposited (bed, bars, floodplain) by flowing water and can include much of a valley floor. Stream channels in arid and semi-arid regions are often called *arroyos*, particularly when they are dry and/or incised into valley alluvium.

Prior to European settlement, other North American streams were similarly described as existing within extensive vegetated wetlands with high water tables that accumulated little sediment but stored substantial organic C (Walter and Merritts, 2008). Wetlands within a riparian area are connected to the river network through lateral movement of water between the channel and riparian area, via overbank flooding of subsurface flow (U.S. EPA, 2015). Wetlands play a crucial role in climate change mitigation and adaptation and are a NBS to reduce CO_2 emissions and reverse existing climate change trends (Erwin, 2009). However, they are vulnerable to alteration and loss and have been widely degraded by human activities (Davis, 1993; Jones et al., 2017). Research conducted by Heffernan (2008) reveal mechanisms underlying wetland development in desert ecosystems that depict dryland streams as an alternative stable state of *ciénegas*. And following, Minckley et al. (2013) describe the current degraded state of many *ciénegas* as dryland arroyos with minimal surface water and encroaching woody vegetation.

Wetland restoration has been suggested as a method to store C, and provide multiple other social, economic and cultural ecosystem services (De Groot et al., 2013). The importance of restoring and protecting coastal or marine wetlands, "blue carbon" ecosystems, for global C sequestration has been recently highlighted (Moritsch et al., 2021). However, inland freshwater wetlands, such as *ciénegas*, are "teal carbon" ecosystems that can store more carbon than estuaries (Krauss et al., 2018; Nahlik and Fennessy, 2016). The enhancement and management of soil organic C (SOC) in *ciénegas* and mountain meadows can ensure that soil is used, managed, and restored sustainably (Lal et al., 2021). Part of the C cycle includes the rate of exchange of CO_2 through biomass, via photosynthesis, which depends on plant life and growing seasons. Vegetation in riparian zones, floodplains, and wetlands can increase surface roughness, which decreases flow velocities and increases infiltration rates (Lane et al., 2018).

Stream corridors are areas where sediment is eroded (bed and banks) and deposited (bed, bars, floodplain) by flowing water and can include much of a valley floor. Surface water flows regulate ecological processes in river ecosystems (Poff et al., 1997). Subsurface lateral flow (a.k.a. throughflow, subsurface storm flow, subsurface runoff, and interflow) occurs when water infiltrates the soil, and moves preferentially laterally through the upper soil horizons toward the stream as ephemeral, shallow, or perched groundwater, above the main groundwater level (Hardie, 2011; Lehman and Ahuja, 1985). This mixing and storage region of sediment and porous space beneath and alongside streams is called the hyporheic zone, where residence time is increased, exchanges between surface and groundwater occur, and nutrient and C processing can take place (Grimm and Fisher, 1984).

In dryland regions, little or no lateral or channel inflow occurs outside of flood periods, and runoff volumes are lost to channel transmission (infiltration or percolation, and evapotranspiration) in many waterways. Groundwater recharge in hot arid and semiarid areas occurs only where water is concentrated and focused, such as in channels, depressions, or areas of high infiltration (Coes and Pool, 2005). The development of perched water tables and subsurface lateral flow is unlikely to occur in dry

Fig. 1. Informative graphic portraying natural infrastructure in dryland streams (NIDS) in a watershed and descriptions of their documented climate-smart practices, illustrated by Heartwood Visuals (see Supplemental for 2-minute video animated by Hans J. Huth).

conditions (Brouwer and Fitzpatrick, 2002; Hardie et al., 2012; Smettem et al., 1991). Slower, deeper, and longer hyporheic flow paths can occur in streams of unconfined valleys, with moderate hydraulic gradients and extensive alluvial volumes. River exploitation has caused ecological degradation, biological diversity losses, and reduced streamflow (Poff et al., 1997). The degradation of riparian ecosystems of arid and semi-arid landscapes is also intrinsically linked to the lowering of alluvial groundwater tables and reduced floodplain connectivity (Hall et al., 2015). This can occur through channel incision, where the channel incises through alluvium, causing a drop in the shallow groundwater table and reduces the connectivity of flows to go over overbank onto the floodplain, reducing the flood hydroperiod and leading to a reduction in riparian vegetation. Degraded streams have limited ecological function (Pollock et al., 2014). River flow regime and successful restoration are dependent on geographic variations in climate, geology, topography, and vegetative cover (Poff et al., 1997). In streams impacted by human activities, restoration of hyporheic zones is essential for the recovery of stream functions and ecosystem services (Hester and Gooseff, 2010; U.S. EPA, 2015).

Rainfall and associated runoff response is the highest in mountainous regions of the desert, where small, ephemeral streams are most abundant creating the potential for an inordinate amount of dryland ground-water recharge (Glenn et al., 2015; Goodrich et al., 2004). These streams typically have more water available for infiltration; coarser sediment (more permeable); higher antecedent moisture; and closer proximity to shallow groundwater (U.S. EPA, 2015). Floodplain sediments in mountain streams have higher organic C content than other regions, particularly in large rivers (Sutfin and Wohl, 2017). Permeable soils, when pressurized with repeated infiltrating water, increase storage and build up water volume until it eventually reaches the water table (Coes and Pool, 2005). However, mountainous watersheds contain many steep channels and limited alluvial volumes, which reduces the hydrologic residence time and limits hyporheic exchange (Buffington and Tonina, 2009).

Steep hillslopes and channels induce erosion and sediment transport given heavy rainfall-runoff response. Ephemeral stream channels in arid and semi-arid regions are called *arroyos*, often incised into valley alluvium (Bull, 1997; Elliott et al., 1999; Vyverberg, 2010). Arroyo incision has occurred both in the modern and geologic record, with a period of widespread erosion and arroyo incision affecting many watersheds in the American Southwest in the late nineteenth and early twentieth centuries (Cooke and Reeves, 1976; Webb et al., 2014). Erosion breaks down soil structural aggregates, selectively removing and redistributing sediment and displaced C on the landscape (Lal, 2021). Reversing losses and restoring functionality in mountainous dryland *cienegas*, *arroyos,* and mountain meadows supports groundwater recharge, reduces downstream flooding, and enhances biogeochemical processes (U.S. EPA, 2015).

2. Natural infrastructure in dryland streams (NIDS)

Landscape restoration has been suggested as a cost-effective strategy for mitigating and adapting to climate change (Bustamante et al., 2019). Lal (2001) identified the link between desertification of the drylands and emission of CO_2 from soil and vegetation to the atmosphere, suggesting improvements to soil quality via land management such as establishing vegetative cover and water harvesting. He explored this idea in arid range and farmlands with composting, agrobiodiversity, winter cover crops, and establishing vegetation on contours and hillslopes to support pedogenesis (Lal, 2003). Channel restoration is often based on the theory that channels should be in equilibrium with flow, sediment, and gradient, and adjusting channel form can lead to this dynamic equilibrium state (Belnap et al., 2005; Gellis et al., 1995). Over the past decade many river restoration scientists have promoted the shift in focus from specific structural approaches to striving to restore stream processes (Beechie et al., 2010; Bernhardt and Palmer, 2011). Restoration should reverse declines in water quality, ecosystem services, and freshwater habitat (Briggs and Osterkamp, 2021).

Natural infrastructure can restore hydrologic, geomorphic, pedogenic, and biological processes in dryland streams by restoring historic wetlands or creating new wetland-like environments (Norman, 2021a). Examples of NIDS are beaver dams and their analogs, check dams, gabions, leaky weirs, one-rock dams, and *trincheras* (Table 1; Fig. 2). NIDS are known to exist on this planet for millennia and their impacts are globally recognized, both as human-made detention structures (Norman, 2022) and beaver dams (Wohl, 2021). However, the literature review using NIDS as a river restoration tool is limited (Bernhardt and Palmer, 2011; Pfaeffle et al., 2022). We attribute this to a disconnect associated with engineer, size, nomenclature, intention for use, place, and construction materials.

We have organized the abundance of conclusive scientific evidence describing the similar impacts of each of these types of structures in various dryland streams of the American Southwest to compare consistent, corresponding influences on watershed processes and function. An important facet of NIDS is that, despite some of them having the word "dam" associated with their nomenclature, they are neither damming water or forming water bodies, nor preventing downstream transmission, e.g., for hydropower (Norman, 2022). They are designed to retain sediment and organic matter and detain water, allowing it to slowly pass through. As such, they are more analogous to a semipermeable membrane than a dam.

2.1. NIDS create soil-water-carbon sinks

There are many similarities between the soil-water-carbon sinks resulting from different types of NIDS. Studies of the impacts of beaver dams, beaver dam analogs (BDAs), and rock detention structures allude to these likenesses (Norman et al., 2019; Pollock et al., 2003; Silverman et al., 2019; Wheaton et al., 2019). NIDS store water and this attenuates floods, provides soil-moisture reservoirs that can be used by plants, and increases nutrient availability. The role of beaver dams and rock detention structures in creating SWC sinks has been recognized for more than a thousand years by cultures who preferentially grazed or farmed in former beaver meadows or flats upstream of such structures (Buckley and Nabhan, 2016; Fish et al., 2013; Howard and Griffiths, 1966; Leopold, 1937; Norman, 2020; Wohl et al., 2019). There is a well-documented history of the use of NIDS to enhance water storage, increase downstream baseflows, enhance overbank flow, reduce peak flows, retain sediment, increase downstream water quality, increase SOC concentration, and bolster climate resilience (Callegary et al., 2021; Norman, 2020; Norman et al., 2021b; Wohl, 2021). The installation of a wide variety and large number of detention structures have also been suggested to restore *ciénegas* by slowing flows, increasing seepage and raising water tables (Minckley, 2013).

Table 1
Types of human- or beaver-made NIDS and their descriptions in the context of this review.

NIDS	Composition/description
Beaver Dams	Structures constructed by beaver (*Castor* spp.), perpendicularly in channel, made of branches, logs, stick, bark, rocks, mud, grass, leaves, etc. Beavers often build clusters or complexes of multiple dams in sequence along a channel (Fairfax and Whittle, 2020; Wohl, 2021).
Beaver Dam Analogs (BDAs)	Human-made structures, situated perpendicularly in the channel made of large wood and other materials and constructed in a manner that deliberately mimics form and function of a naturally occurring beaver dam; also known by many other terms, including 'Beaver Mimicry' and 'Simulated Beaver Structures' (Pollock et al., 2018; Silverman et al., 2019; Vanderhoof and Burt, 2018).
Check dams	Human-made structures, situated perpendicularly in the channel, constructed by stacking loose rocks approximately 1 m high, but varying in height and length, depending on channel dimensions (Norman et al., 2016).
Gabions	Human-made structures, situated perpendicularly in the channel, constructed using 'chicken wire' fence material to construct cages, filled with rocks and usually keyed into bedrock or larger channels, and sometimes stacked vertically upon each other, but varying in height and length, depending on channel dimensions (Norman et al., 2010b).
Leaky weirs	Human-made structures, situated perpendicularly in the channel, constructed by a loosely cemented wall of rocks, or masonry dam, keyed into bedrock, and varying in height and length, depending on channel dimensions (Coy et al., 2021).
One-Rock Dams	Human-made structures, situated perpendicularly in the channel, constructed with layer of rock on the bed and exactly 'one-rock" high but varying in length, depending on channel dimensions (Zeedyk, 2009).
Trincheras	Human-made structures, situated on hillslopes perpendicular to downslope flow, constructed by one or two layers of rock (Fish et al., 2013).

The hypothesis that *ciénegas* constitute an alternative stable state in desert streams was put forward by Heffernan (2008), where he found that vegetation establishment itself could retain sediment and provide a biogeomorphic structure that transformed ephemeral channels to perennial *ciénegas*. Likewise, research conducted on rock detention structures installed in ephemeral riparian areas of dryland mountain streams has documented a transformation in vegetation, sediment, and water to create wetlands or wet meadows that mimic the biogeochemical functions of *ciénegas* (Norman, 2022, Norman, 2021a). Similarly, beaver dams and BDAs slow and spread the flow of water, which helps recharge alluvial aquifers and benefits riparian and wetland plants (Pollock et al., 2014; Scamardo and Wohl, 2020; Wheaton et al., 2019). Photographs of a beaver dam construction depicts the similarities of installing human and beaver-made NIDS, as beavers often begin their dams as a short one-rock or check dam installed perpendicularly across a channel (Fig. 3a and b). As the dam becomes constructed toward completion, the materials shift to a larger component of woody debris (Fig. 3c and d) (Fairfax and Whittle, 2020).

Hydrogeomorphic structure and function determines the extent to which dryland streams are stabilized and what state their *ciénegas* exist (Heffernan, 2008). NIDS-enhanced soil-water-carbon sinks have hydrology, hydrophytic vegetation, and hydric soils that categorize them as wetlands (U.S. EPA, 2015). We compare the similarities of research on NIDS, where findings depict the development of a soil-water-carbon sink, or wetland - *cienega*, with all the associated benefits.

Fig. 2. Examples of human- and beaver-made NIDS, including a) leaky weirs (photo by Josiah Austin), b.) gabion (Photo by Andrea Prichard (Norman et al., 2010b), c.) check dams (photo by Jeremiah Liebowitz), d) one-rock dams (Photo by Deborah Tosline (Tosline et al., 2020)); e.) trincheras (Photo by Valer Clark), and f.) a beaver dam, where blue arrows portray direction of flow.

2.2. Climate adaptation and mitigation services

Climate risk management practices for riparian areas, wetlands, and groundwater-dependent ecosystems include increasing floodplain and channel water storage by managing for beaver populations (Bouwes et al., 2016; Hood and Bayley, 2008; Westbrook et al., 2020), specifically in dryland streams (Gibson and Olden, 2014). Contemporary restoration practitioners have qualitatively noted many effects of rock detention structures as cause for installation, including their potential as simple, nature-based stream restoration solutions (Zeedyk and Clothier, 2009). Urban and agricultural management has historically incorporated stormwater infrastructure and catchment BMPS to restore natural flow regimes, reduce pollution and restore chemical fluxes in degraded streams, yet not acknowledged this as river restoration (Bernhardt and Palmer, 2011). Research scientists recently noted the potential for riverscapes installed with beaver dams and BDAs as natural infrastructure to improve resilience to climate change and restore ecosystem health (Skidmore and Wheaton, 2022). Social scientists reviewed rock detention structure research at four locations to describe their potential as NBSs (Gooden and Pritzlaff, 2021). This idea was expanded upon spatially and temporally, to include more of the original research studies of rock detention structures, provide a cost-benefit example, and portray how using these structures can alleviate climate change

Fig. 3. Photographs of beaver dam a. and b.) in early stages of construction, and c. and d.) fully constructed (by Emily Fairfax).

impacts in socio-environmentally vulnerable regions (Norman, 2022). In Mexico, the National Forestry Commission (CONAFOR) promotes using detention structures to recover degraded lands, for soil and water conservation, erosion control, and rainwater harvesting as well as climate adaptation and mitigation (Gerencia de Restauración Forestal, 2018).

The rest of this paper describes an NBS to rehydrate arid lands and mitigate hydro-meteorological risk by using various NIDS, human-made or beaver-engineered, that instigate sustainable hydrogeomorphological and biogeochemical processes of wetlands with high soil, water, and carbon storage capacity. We present the climate adaptation and mitigation services of NIDS, including: (i.) increasing water availability, (ii.) reducing erosion and promoting soil formation and productivity, (iii.) storing C and N in wetland-like sinks, (iv.) controlling stormwater runoff and filtering water, (v.) increasing vegetation viability, and (vi.) decreasing temperatures and climate variability (Table 2). These are discussed in relationship to NIDS in Mediterranean California, North American Deserts, Northwestern Forested Mountains and Southern Semiarid Highlands ecoregions in the western United States (Fig. 4) and the hydrologic, geomorphic, pedogenic, and biological processes that improve resilience to natural hazards faced by drylands.

2.2.1. Increases water availability

Water is a limited resource in dryland environments and the changing climate in the American Southwest, where increased temperatures and reduced rainfall are expected to occur, threatening current supplies. Overland and shallow subsurface flows culminate in a river's discharge response to storm events, where groundwater pathways supply baseflow (Poff et al., 1997). The Colorado River faces a potential decline in baseflow by up to 33 % with predicted changes in climate (Miller et al., 2021). Results highlight that climate changes in high elevation hydrology impacts watershed water availability. The percentage of baseflow lost during in-stream transport is projected to decrease by 1–5 % relative to historical conditions (Miller et al., 2021). During drought periods, little water is available to recharge aquifers and other soil-water sinks, exacerbated by the effect of warming temperatures on evapotranspiration (Uhlman et al., 2020). Groundwater pumping adds to the depleted aquifer supplies impacted by climate change, and prolonged drought periods groundwater may simply not recharge (Schreiner-McGraw and Ajami, 2021).

Puttock et al. (2017) hypothesized that beaver-constructed features increase water storage within the landscape, with their creation of a stepped profile channel. Dams created by beavers result in ponds along the stream channel that raise the water table in the adjacent riparian zone (Bouwes et al., 2016; Macfarlane et al., 2017; Naiman et al., 1988; Pollock et al., 2003, 2014). Vanderhoof and Burt (2018) quantified increases in reach-scale stream surface area upstream of multiple BDAs in the Upper Missouri River Headwaters Basin, as well as decreases in stream surface area for reaches just downstream (through 500 m). In the restoration projects using BDAs and one-rock dams, Silverman et al. (2019) suggests that water stored behind restoration structures helps to reconnect floodplains at Gunnison, Colorado, and Bridge Creek, Oregon (Fig. 4). These structures

Table 2
List of climate adaptation and mitigation services and relevant scientific research for each natural infrastructure in dryland streams (NIDS).

Climate adaptation & mitigation services	Leaky weirs	Gabions	Trincheras and check dams	One-rock dams	Beaver dams and analogues
2.2.1. Increases Water Availability	Coy et al., 2019, 2021; Norman, 2021a	Fandel, 2016; Fandel et al., 2016; Norman, 2020, 2021a; Norman et al., 2014, 2019; Uhlman et al., 2020; Wilson and Norman, 2018;	Gerencia de Restauración Forestal, 2018; Heede and DeBano, 1984; Norman, 2020, 2021a; Norman et al., 2016; Norman and Niraula, 2016; Ponce and Lindquist, 1990	Norman, 2020, 2021a; Norman et al., 2021a, 2021b; Silverman et al., 2019; Tosline et al., 2020	Bouwes et al., 2016; Fairfax and Small, 2018; Fairfax and Whittle, 2020; Gibson and Olden, 2014; Gurnell, 1998; Macfarlane et al., 2017; Naiman et al., 1988; Pilliod et al., 2018; Pollock et al., 2003, 2014; Puttock et al., 2017; Silverman et al., 2019; Vanderhoof and Burt, 2018; Westbrook et al., 2006; White, 1990; Wohl, 2021
2.2.2. Sediment Storage, Formation, and Productivity	Coy et al., 2019, 2021; Norman, 2021a	Gerencia de Restauración Forestal, 2018; Norman, 2020, 2021a; Norman et al., 2010a, 2010b, 2017; Norman and Niraula, 2016	DeBano and Heede, 1987; Gerencia de Restauración Forestal, 2018; Geyik, 1986; Norman, 2020, 2021a; Norman et al., 2017; Norman and Niraula, 2016; Smith and Wischmeier, 1962	Gellis et al., 1995; Gerencia de Restauración Forestal, 2018; Norman, 2021a; Norman et al., 2021b; Silverman et al., 2019; Tosline et al., 2020;	Bouwes et al., 2016; Butler and Malanson, 1995; Gibson and Olden, 2014; Gurnell, 1998; Pollock et al., 2003, 2014, 2018; Puttock et al., 2018; Scarmando and Wohl, 2020; Silverman et al., 2019; Westbrook et al., 2006; Wheaton et al., 2019; Wohl, 2021
2.2.3. Carbon Sequestration and Storage		Callegary et al., 2021; Gerencia de Restauración Forestal, 2018; Norman, 2020, 2021a	Callegary et al., 2021; Gerencia de Restauración Forestal, 2018; Norman, 2020, 2021a; Norman et al., 2017; Norman and Niraula, 2016	Callegary et al., 2021; Gerencia de Restauración Forestal, 2018; Norman, 2020, 2021a; Silverman et al., 2019	Gibson and Olden, 2014; Lazar et al., 2015; Pollock et al., 2014; Johnston, 2014; Laurel and Wohl, 2019; Silverman et al., 2019; Sutfin and Wohl, 2017; Wohl, 2013, 2020, 2021
2.2.4. Flood Attenuation and Water Quality Protection	Coy et al., 2019, 2021; Norman, 2021a	Callegary et al., 2021; Fandel, 2016; Fandel et al., 2016; Fandel, 2016; Gerencia de Restauración Forestal, 2018; Norman, 2020, 2021a; Norman et al., 2010a, 2010b	Callegary et al., 2021; DeBano and Heede, 1987; Gerencia de Restauración Forestal, 2018; Geyik, 1986; Norman et al., 2017; Norman and Niraula, 2016	Gerencia de Restauración Forestal, 2018; Norman, 2021a, 2021b; Tosline et al., 2020;	Fairfax and Whittle, 2020; Gibson and Olden, 2014; Gurnell, 1998; Pollock et al., 2014; Westbrook et al., 2006; Wohl, 2021
2.2.5. Increases Vegetation Viability	Norman, 2021a; Wilson and Norman, 2019	Gerencia de Restauración Forestal, 2018; Norman, 2020, 2021a; Norman et al., 2014; Wilson and Norman, 2018; Wilson and Norman, 2019; Wilson et al., 2021	DeBano and Heede, 1987; Gerencia de Restauración Forestal, 2018; Norman, 2020, 2021a; Norman et al., 2014; Norman, 2020; Wilson and Norman, 2018; Wilson and Norman, 2019; Wilson et al., 2021	Gerencia de Restauración Forestal, 2018; Huryna and Pokorný, 2016; Norman, 2020, 2021a; Silverman et al., 2019; Wilson and Norman, 2019; Wilson et al., 2021	Fairfax and Small, 2018; Fairfax and Whittle, 2020; Macfarlane et al., 2017; Pilliod et al., 2018; Gibson and Olden, 2014; Gurnell, 1998; Pollock et al., 2003, 2014; Silverman et al., 2019; The Nature Conservancy and Gunnison Climate Working Group, 2017; Vanderhoof and Burt, 2018; Wohl, 2021
2.2.6. Decreases Temperatures and Climate Variability				Huryna and Pokorný, 2016; Norman, 2021b; Norman et al., 2021b; Tosline et al., 2020; Norman, 2021a; Norman et al., 2021a, 2021b; Tosline et al., 2020; Zeedyk and Clothier, 2009	Silverman et al., 2019; Weber et al., 2017

increase lateral connectivity, forcing water sideways and creating diverse wetland environments (Macfarlane et al., 2017). Bouwes et al. (2016) found increases in base flows, channel widening rates, and sinuosity after BDAs installation at Bridge Creek, OR. Beaver dams impact lateral and longitudinal connectivity by introducing roughness and heterogeneity elements that fundamentally change the timing, delivery, and storage of water, sediment, nutrients, and organic matter (Macfarlane et al., 2017). Studies portray flow patterns beneath beaver dams, where underflow carries stream water beneath the structures and impact lateral riparian groundwater levels (Gurnell, 1998; Westbrook et al., 2006; White, 1990). Beaver dams and BDAs can create depressions that are well positioned for enhancing hyporheic zones, increased infiltration, and hydrologic connectivity (Nash et al., 2021). Beaver dams have been shown to attenuate the rate of drawdown by providing the riparian area with water availability via surface and subsurface flow paths (Westbrook et al., 2006).

Other types of NIDS can have similar effects. For example, perennial flows were reinstated at Alkali Creek, CO (Fig. 4), 7 years after 132 small check dams were installed in ephemeral, gullied streams (Heede and DeBano, 1984). Likewise, in Sheep Creek, Utah, perennial flow was identified resulting from a small (5-m) dam built to retain sediment (Ponce and Lindquist, 1990). In Pearce, Arizona, a watershed treated with >2000 check dams experienced a 28 % increase in flow volume, with extended duration summer base-flows and the persistence of perennial pools, compared to an adjacent watershed which has none (Norman et al., 2016). Perched aquifers were suggested as being developed to store the water and slowly release it over time in stepwise pools (Norman et al., 2016). Field measurements at gabions installed in Elgin, Arizona, demonstrated increased soil moisture by an average of 10 % following gabion installation (Fandel et al., 2016; Fandel, 2016). At this location, the Soil and Water Assessment Tool (SWAT (Arnold et al., 2012)) watershed model depicted the potential of watershed-wide gabion installation to increase potential total aquifer recharge by a minimum of 4 % [from baseline conditions], with noted increases in subsurface connectivity and accentuated lateral flow contributions, similar to the results identified from beaver dams (Norman et al., 2019). In Arivaca, Arizona, the installation of gabions enhanced recharge isotope signatures, not occurring in areas without gabions, demonstrating the potential for enhancing groundwater recharge (Uhlman et al., 2020).

2.2.2. Sediment storage, formation and productivity

In arid land environments, soils are often highly erodible, with high runoff potential, and poor water-holding capacity (Khresat et al., 2004). The North American monsoon extends over much of the southwestern United States from northwestern Mexico providing short-duration, intense, localized, convective thunderstorms from July through September (Adams and Comrie, 1997). As global warming increases water vapor in the

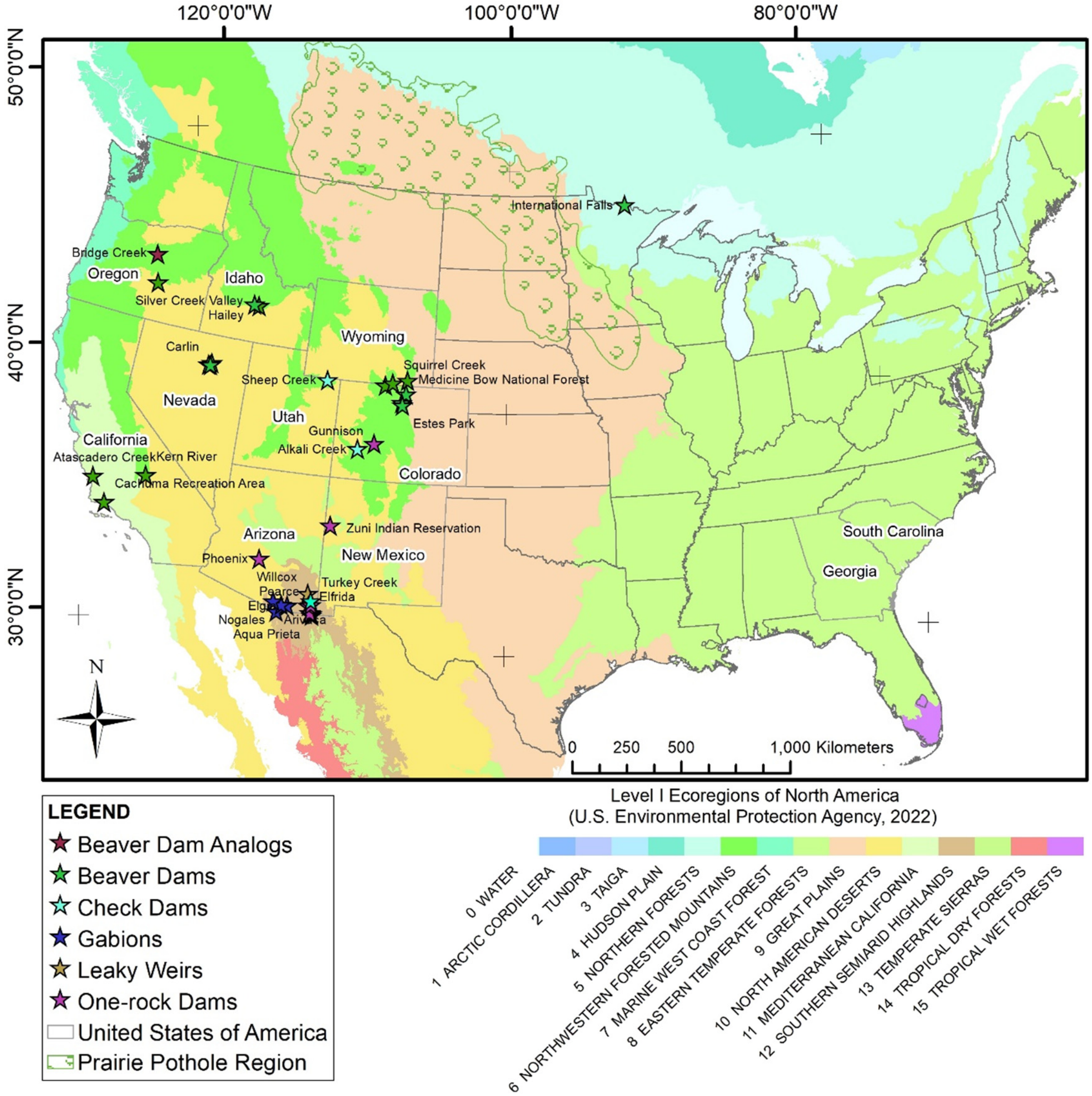

Fig. 4. Location map of the United States and the natural infrastructure in dryland streams, States, Ecoregions, and Regions discussed in this review (Table 2).

atmosphere, high intensity rainfall events are predicted to increase in southwestern North America (Seager et al., 2007), which when combined in semiarid areas with drought cycles, instigates huge erosional problems (Smith and Wischmeier, 1962). While steady overland and channel flows help regulate dispersion of soils, microbes, seeds and plant litter, excessive disturbance and precipitation pulses can cause erosional losses that exceed the natural range of variability (Belnap et al., 2005). Soil erosion has severe adverse impacts on soil quality and functionality, and increases emission of greenhouse gases such as CO_2, methane (CH_4), and nitrous oxide (N_2O)(Lal, 2002). Soil health is directly related to the health of plants, animals, people, ecosystem and the planet (Lal, 2020). Soil biomass is comprised of living organisms that maintain soil structure through aggregate formation, is dependent on organic matter derived from plants and animals for energy (from photosynthesis) and plays an important part in the food web. Total soil biomass and density in beaver ponds may be >2–5 times greater than sites with quicker moving streams (Naiman et al., 1988). Biogeochemical cycling, GHG fluxes, soil fertility, and primary production are all impacted by decomposition and pedogenic processes, and dependent on environmental conditions such as temperature and moisture (Belnap et al., 2005). Biologic soil crusts (communities of lichens, mosses, cyanobacteria) naturally form on desert soils and influence sediment transport, water storage, runoff, and C sequestration, but when disturbed, are especially vulnerable (Belnap et al., 2005; Caster et al., 2021). Dominant pedogenic or soil-formation processes in drylands are calcification in well-drained soils and salinization in poorly drained sites (Lal, 2001). Soils develop slowly in arid environments, but climates, rainfall-runoff response, and moisture can influence the speed of reactions and weathering (Lal, 2019b; Stavi et al., 2021).

Rock-based and other types of NIDS have often been installed primarily to conserve soil, prevent erosion, and increase soil stability. Erosion control and sediment capture have been documented at gabions (Norman et al., 2010a, 2010b, 2017), check dams (Norman et al., 2017; Norman and Niraula, 2016; Smith and Wischmeier, 1962), one-rock dams (Gellis et al., 1995; Norman et al., 2021b; Tosline et al., 2020), leaky weirs (Coy et al., 2019, 2021), beaver dams (Butler and Malanson, 1995; Naiman et al., 1988; Puttock et al., 2018) and BDAs (Scamardo and Wohl, 2020). In such NIDS, flow is slowed, leading to sediment deposition (Silverman et al., 2019). Hydrologic processes driven by beaver dams play a key role in soil development by maintaining waterlogged soil conditions for extended periods (Naiman et al., 1988; Westbrook et al., 2006). NIDS control sediment upstream, reduce turbidity and improve downstream water quality via increased water residence times and filtering. The increased water, vegetation, and sediment resulting from installing detention structures, increases bioproductivity and resilience of soil structural characteristics (Callegary et al., 2021; Lal, 2001; Wohl, 2013).

2.2.3. Carbon sequestration and storage

Low albedo, patchiness of plant cover, changes in geomorphology, biological crusting, and ratios of microbial biomass C to total organic C were suggested as the most pronounced edaphic changes resulting from climate change in western North America (West et al., 1994). Soil inorganic carbon (SIC), is derived from the C extracted from ores and minerals and parent rock, and is called lithogenic C (Lal, 2019b). Dryland restoration can help sequester C as secondary carbonates by means of SIC returned to the soil through formation of secondary carbonates and via increases in biomass (Lal, 2019b, Lal, 2008). Plants and living things are the source of organic C. Global soils contain 3 times the C in the atmosphere (880 Pg) and 4 times that in the vegetation (620 Pg), estimated to 1-m depth for SOC (1550 Pg) and SIC (950 Pg) (Lal, 2018). Soil organic matter (SOM) is a mixture that can include fine plant roots, particulate organics, charcoal, and living microbial biomass and can contain 50–60 % SOC (Lal, 2008; Stockmann et al., 2013). Erosion and sediment transport can break down soil structural aggregates, selectively removing and redistributing sediment and displaced C on the landscape (Lal, 2021). Lal et al. (2003) argues that the adoption of conservation-effective measures on eroded landscapes would reverse the degradation trends and increase soil and ecosystem C pools. SIC can make up a significant portion of arid and semi-arid soils, because of calcification and caliche, but exposure and loss of important arid land SIC has increased with wind and water erosion (Lal, 2019b, Lal, 2004a, Lal, 2001).

Organic carbon can be stored at riparian areas and freshwater wetlands in standing riparian plant biomass; large, downed trees; organic matter, litter and humus and sediments; and instream plant biomass (Wohl, 2013). Dryland wetlands help mitigate climate change by sequestering C through plant photosynthesis and accumulating organic matter (Limpert et al., 2020). This is sometimes negated when high rainfall events cause large CO_2 emissions (Ouyang et al., 2021) or if other biogeomorphic feedback loops are disrupted (Temmink et al., 2022).

Hydrologic saturation of wetland soils accelerates plant growth, limits oxidation that slows anaerobic microbial decomposition processes, and increases C sequestration through vegetation CO_2 uptake (Limpert et al., 2020). Perennial vegetation stores atmospheric C in both living and senesced biomass, often over decadal or longer time periods via root biomass and exudates (Lal, 2008, Lal, 2004b). Plants, working with soil microorganisms, remove atmospheric C and store it in the soil (Ohlson, 2014). Floodplains are important C sinks that trap and bury C-rich sediment and woody debris entrained in flood flows (Sutfin and Wohl, 2017; Wohl, 2020). At Voyageurs National Park, Minnesota, Naiman et al. (1988) identified the impact the beaver dams were having on the C cycle. Since then, the tremendous potential for C storage has been documented at various beaver sites around the country (Johnston, 2014; Laurel and Wohl, 2019; Wohl, 2013).

A watershed model was validated with high-resolution terrain measurements to quantify the amount of sediment stored behind check dams (Norman et al., 2017) and also used to extend estimates of erosion and sediment deposition therein (Norman and Niraula, 2016). Using sediment yield estimates derived from the watershed model and taking into account size of the watershed and number of structures (769 ha and 2000 check dams), Callegary et al. (2021) calculated a conservative estimate of total potential C capture at ~200–250 Mg/ha, equivalent to levels stored in wetlands (see Table 3).

2.2.4. Flood attenuation and water quality protection

Extreme precipitation events can cause large quantities of stormwater runoff to rapidly flow across the landscape (Norman et al., 2010a). The velocity of overland and surface flow can transport sediment and vegetation, scouring upland hillslopes; the rate of flow largely determines its fate in the water budget (Goodrich et al., 1994). Catastrophic flooding reduces vegetation and erodes desert streams, causing *cienega* degradation (Heffernan, 2008). Hot, dry climates have high evaporation, accelerated by increased water surface area. High velocity flows on the surface have more power to transport sediment or other obstacles it encounters than slow-moving flows (Lal, 2021). As water infiltrates the surface, it can contribute to subsurface or lateral flows, percolate to the groundwater or transpired by plants, supporting ecological and biogeochemical processes. Erratic and intense precipitation events, predicted to be increasing with changing climates, can overwhelm transport systems, causing flooding, which put livelihoods, public health, and human lives at risk (Norman, 2021b; Norman et al., 2010a).

Jia et al. (2020) described how extensive management of urban rainwater, called sponge measures, are improving soil-hydrological conditions in China's Loess Plateau. Likewise, NIDS and their soil-water-carbon sinks help regulate both high and low stream flows and improve downstream water quality via associated increases in water residence times. Water storage offered by beaver ponds reduce downstream flooding. Beaver ponds were instrumented prior to a huge storm event in Alberta, Canada, in 2013, finding that after quickly filling, levels were dynamic during the event (Westbrook et al., 2020). That same year, the rainfall-runoff response of a watershed treated with thousands of check dams was measured, portraying a reduction of peak flow events by half (Norman et al., 2016). Gabions installed in Nogales, Sonora, Mexico, were also modeled to identify their impacts on the storm-event hydrograph, with results depicting large reduction of flow events derived from smaller precipitation events (10-year/1 h), with little impact on flows induced by larger storms (100-year/6-h rain events; (Norman et al., 2010b)).

NIDS that retain sediment, can reduce nonpoint source pollution downstream and improve water quality (Norman et al., 2017, Norman et al., 2016, Norman et al., 2010b). Reduced rates of flow, when modeled, portray lower turbidity and clearer downstream water supplies (Norman and Niraula, 2016). Wang et al. (2020) found that wetlands can remove diffuse nitrogen loads via lateral flows. Organic matter in sediments (both C and N) trapped during post wildfire runoff events were 2 to 10 times greater behind NIDS than in off-channel soils (Callegary et al., 2021). A series of NIDS assisted rapid reburial of mobilized biomass, SOM, and charred OM (pyrogenic C) during runoff events following an occurrence of wildfire (Callegary et al., 2021). We conclude that NIDS are a climate adaptation strategy that can attenuate floods and improve water quality.

Table 3
Ascending Rates of soil C storage as reported in literature.

Reference	Description	Place	Soil Mg C/ha
Tangen and Bansal, 2020	Prairie Pothole Region wetland (inner area)	Upper Midwest, USA	66
Buringh, 1984	Dry grassland soils	Global	40–100
Bedard-Haughn et al., 2006	Prairie Pothole Region wetland	Upper Midwest, USA	175.1
Badiou et al., 2011	Prairie Pothole Region wetland	Upper Midwest, USA	205
Callegary et al., 2021	Rock detention structure soil-water-carbon sinks	Southeast Arizona, USA	200–250
Ouyang et al., 2020	Mangrove (tidal wetlands)	Global	283–361
Wohl, 2013	Relict beaver meadows, Rocky Mountain National Park	Estes Park, Colorado, USA	300–400
Krauss et al., 2018	Marsh Sites Along the Upper Tidal Estuaries of the Savannah River	Georgia, USA	455
Krauss et al., 2018	Marsh Sites Along the Upper Tidal Estuaries of the Waccamaw River	South Carolina, USA	1258
Wohl, 2013	Active beaver meadows, Rocky Mountain National Park	Estes Park, Colorado, USA	1150–1400

2.2.5. Increases vegetation viability

Effective NIDS treatments help improve off-site productivity, extending their benefits to a larger portion of the watershed and sustain the benefits for a longer time period. Beaver damming creates beaver ponds that act as buffers against the effects of drought on nearby riparian vegetation by retaining water during wetter parts of the year and gradually releasing it during drier parts of the year into soils where riparian vegetation can access the water (Fairfax and Small, 2018; Fairfax and Whittle, 2020; Gurnell, 1998; Pilliod et al., 2018). Fairfax and Small (2018) calculated the evapotranspiration and normalized difference vegetation index (NDVI) of riparian vegetation from 2013 to 2016 at creeks used as a control vs. treated by beavers. Evapotranspiration of riparian areas with beaver damming was 50–150 % higher and NDVI was 6–88 % higher than without beaver activity. Differences peaked when the landscape was at its hottest and driest state. Results indicate that dryland riparian areas with beaver dams are better able to maintain vegetation productivity than areas without, during both short and extended periods of drought (Fairfax and Small, 2018).

The installation of BDAs resulted in increases of riparian greenness along restoration reaches of the Missouri River Headwaters basin (Vanderhoof and Burt, 2018). Satellite imagery was also used to evaluate changes in "greenness" of one-rock dams near Gunnison, Colorado, and BDAs in Oregon's Bridge Creek (Silverman et al., 2019). Low-tech restoration (one-rock dams and BDAs) at riparian and wet meadow systems effectively increased productivity of vegetation in magnitude and duration, suggesting enhanced soil water storage and the potential for basin-wide improvements that are more resilient during drought (Silverman et al., 2019). This study found the growing season was extended to late summer and fall months with greenness increases up to 25 % after streams were restored compared to pre-damming with wetland plant cover increasing 160 % (ranging from 28 to 245 %) at four treated sites, compared to a 15 % increase at untreated sites (four years' post-treatment).

Likewise, on the border of Douglas, Arizona, United States, and Agua Prieta, Sonora, Mexico, large gabions were used to restore a historic *ciénega*. Using satellite imagery depicting the area over a 27-year time period, vegetation productivity was documented to be maintained and improved at gabion structures, despite drought conditions (Norman et al., 2014), and that this was evidenced extending up to 5 km downstream and 1 km upstream of each structure (Wilson and Norman, 2018a). The retention of sediment and reduction in peak discharge of flashy flow events support and propagate plant growth, which continues the cycle of retaining sediment and reducing flows (Norman, 2021b, Norman et al., 2021a; Norman et al., 2014; Wilson and Norman, 2018a). In addition to the increase in vegetation condition and cover created by NIDS, wetland obligates are appearing at study sites, associated with prolonged saturation or flooding in the created wetlands (Norman et al., 2014; Wilson and Norman, 2019, Wilson and Norman, 2018a).

2.2.6. Decreases temperatures and climate variability

Deserts and clouds have high albedos and reflect a large portion of short-wave solar radiation (some out to space). Depending on a cloud's temperature and composition, clouds will absorb longwave radiation emitted by Earth's surface and reemit some radiation back toward the surface. Longwave radiation emitted by the surface can also be absorbed by trace gases in the air, heating the air and reradiating energy back again toward Earth's surface causing air near surface to heat up more (Graham, 1999). This heating effect of air on the surface is the atmospheric greenhouse effect, due mainly to water vapor in the air, but enhanced by GHGe and decreased albedo. Well-vegetated soil absorbs and reradiates less heat to the atmosphere than non-vegetated bare earth. Reduction in albedo, as is observed in afforestation of arid lands affects the energy balance and evapotranspiration from new vegetation results in surface cooling and enhances moisture and precipitation (Yosef et al., 2018). Latent heat absorbed and released during evaporation and condensation, transfers energy from the warm surface to the cooler atmosphere, where infrared radiation is emitted back to space (Siler et al., 2019). In cooler temperatures, latent heat is released through condensation, forming cloud droplets and precipitate to transport water back to Earth's surface (Graham et al., 2010).

The role of water and plants in the reduction of temperature gradients is emphasized by Huryna and Pokorný (2016), with examples of restoration of dry landscapes having positive effects of rainwater retention and the recovery of permanent vegetation. The soil-water-carbon sinks and the plants that grow there, have water in them that uses energy during vaporization that cools the surface. Cloud microdroplets too small to fall out as rain, will form clouds that provide shade. In addition to the C sequestration that can help slow and reverse climate change (described in Section 2.2.3), the noted increase in water availability (described in Section 2.2.2.), within and beside NIDS-created soil-water-carbon sinks, vegetation viability is increased (described in Section 2.2.5.), which in turn shades, cools, and shelters more of Earth's surface from intense sun, wind, flooding, and other extremes (Donavan, 2020; Jehne, 2016, 2017).

Weber et al. (2017) studied stream temperature regimes at beaver dams and BDAs, finding reduced stream and air temperatures, specifically enhanced by increased water availability in the overall watershed; they suggest these NIDS could be used to create refugia to mitigate climate impacts that may threaten sensitive species. In Phoenix, Arizona, a micro-climate cooling effect was documented at newly installed one-rock dams. Even before sediment or vegetation impacts could develop, temperatures were reduced by 2-3 °C following rainfall (Norman et al., 2021b; Tosline et al., 2020). The clustering of rocks and detention of flow held the water's cooling properties for 2–3 days post-rainfall. While each structure can instigate micro-climate variability on site, the impacts of more and more structures will be greater, expanding to larger areas. As soil-water-carbon sinks develop, more water should be hosted therein, and cooling effects should multiply as vegetation takes root, providing shade; hydrology and heat dynamics cause transpiration to occur, which keeps cooler water available in the soil; and condensation may cause clouds to form over vegetated areas and perpetuate the cycle, bringing moisture back at a larger scale. This climate mitigation strategy, of installing NIDS, has cumulative cooling effects over time and space (Norman, 2021b; Norman et al., 2021b; Tosline et al., 2020).

2.3. Resilience to hydro-meteorological risk

Hazards related to climate change present global environmental challenges. In dryland regions of the western United States, climate change is increasing hazardous drought, water shortage, flooding, heatwave, dust storm, and wildfire disturbances (Overpeck, 2021). Healthy ecosystems are more resistant to and able to recover more quickly from to external disturbances (Pimm, 1984).

The development of new wetland-like environments, or soil-water-carbon sinks, reduces ecosystem sensitivity to climatic change, creating resilience that can be sustainable and help regulate climate via C sequestration and storage. Increased vegetation density, health, and area identified at beaver dams and BDAs help to slow the flow of water and ultimately reduce the intensity of floods, droughts, and wildfires within the riparian zone (Fairfax and Small, 2018; Fairfax and Whittle, 2020; Randall, 2021). Vegetation composition and abundance before disturbances, like fire, increase resiliency of wetlands to recover post-fire. Rock detention structures have been documented via a rigorous interdisciplinary study, to reduce vulnerability to drought and flooding, promote soil conservation, sequester carbon, increase water availability, and also promote cooling effects (Norman, 2020; Norman et al., 2021b). The effectiveness of NIDS-induced soil-water-carbon sinks in relation to hydro-meteorological risk reduction at landscape and watershed scales is portrayed via their potential to create climate adaptation and mitigation services, described in Section 2.2., and portrayed in summary in Table 4.

2.3.1. Increases biodiversity

Plants, animals, and microorganisms occurring both above and below ground comprise the biotic community. NIDS increase ecohydrological integrity by supporting variability that enables biotic communities to thrive. Diverse composition and structure of plant communities' aids in water harvesting to resist drought and helps plants recover from drought. Native

Table 4
Hydro-meteorological risks that can be addressed by natural infrastructure in dryland streams (NIDS) as Nature-Based Solutions based on their Climate Adaptation or Mitigation effects, with references.

Risk	Nature-Based Solution	Climate mitigation or adaptation strategy	References
Drought	NIDS reduce ecosystem sensitivity to drought by enhancing soil-water capture, storage, and safe release, and by promoting vegetation productivity and diversity in soil-water-carbon sinks, this supports overall ecosystem function using less precipitation.	2.2.1. Increases Water Availability; 2.2.2. Sediment Storage, Formation, and Productivity; & 2.2.5. Increases Vegetation Viability.	Gurnell, 1998; Huryna and Pokorný, 2016; Norman et al., 2014; Robinne et al., 2021; Silverman et al., 2019; The Nature Conservancy and Gunnison Climate Working Group, 2017; Uhlman et al., 2020; Vanderhoof and Burt, 2018; Wilson and Norman, 2018.
Water Shortage	NIDS promote surface-water availability, subsurface, hyporheic flows, and recharge via capture, storage, and safe release. They increase overall hydrologic function of channels, which helps them resist reductions in water availability and helps them recover when a reduction does occur.	2.2.1. Increases Water Availability	Fairfax and Small, 2018; Fairfax and Whittle, 2020; C. Fandel et al., 2016; C. A. Fandel, 2016; Gibson and Olden, 2014; Gurnell, 1998; Norman, 2020, 2021b; Robinne et al., 2021; Silverman et al., 2019; The Nature Conservancy and Gunnison Climate Working Group, 2017; Uhlman et al., 2020; Vanderhoof and Burt, 2018; Wilson and Norman, 2018.
Flooding	NIDS help regulate small to medium sized flood events and retain NPS pollutants.	2.2.4. Flood Attenuation and Water Quality Protection.	Norman, 2020, 2021b; Norman et al., 2010a; Gurnell, 1998; Norman et al., 2010b; Robinne et al., 2021.
Heatwaves	NIDS help reduce impacts of heatwaves via increased vegetative biomass, and water content in vegetation and at rock structures, that provide cooling effects.	2.2.3. Carbon Sequestration and Storage; & 2.2.6. Decreases Temperatures and Climate Variability.	Norman et al., 2014; Wilson and Norman, 2019; Callegary et al., 2021; Norman et al., 2021a, 2021b; Silverman et al., 2019; Tosline et al., 2020; Weber et al., 2017.
Dust Storms	NIDS increase site and soil stability and can control a landscape's susceptibility to erosion by wind or water.	2.2.2. Sediment Storage, Formation, and Productivity.	Gurnell, 1998; Norman and Niraula, 2016; Norman et al., 2017; Smith and Wischmeier, 1962.
Wildfire	NIDS promote fire resilient soil-water-carbon sinks; they create greener/wetter riparian areas with saturated soils that are harder to ignite (firebreaks), provide refugia for wildlife, and their increased biodiversity aids in quicker recovery post-fire.	2.2.1. Increases Water Availability; & 2.2.5. Increases Vegetation Viability.	Fairfax and Whittle, 2020; Goldfarb, 2018; Norman, 2021a; Robinne et al., 2021; Silverman et al., 2019; Stockdale et al., 2019; Tensegrity, 2018; Wheaton et al., 2019.
Biodiversity losses	NIDS support slow-moving and clear wetland environments that provide nurseries for multiple organisms, including rare and unique plants and aquatic life. Increases in vegetation further provides opportunity of more species' habitat provisioning and forage.	2.2.5. Increases Vegetation Viability; 2.3.1. Increases Biodiversity.	Davee et al., 2019; Geist and Hawkins, 2016; Gibbs, 2000; Gurnell, 1998; Naiman et al., 1988; Norman et al., 2014; Pollock et al., 2003; Sabo et al., 2005; The Nature Conservancy and Gunnison Climate Working Group, 2017; Vanderhoof and Burt, 2018; Wilson et al., 2016; Wilson et al., 2021; Wilson and Norman, 2019.
Food insecurity	NIDS have been used for improving food security (farming and rangeland) for over a thousand years.	2.2.1. Increases Water Availability; 2.2.2. Sediment Storage, Formation, and Productivity; & 2.2.5. Increases Vegetation Viability.	Buckley and Nabhan, 2016; Fish and Fish, 1984, 2007; Fish et al., 2013; Gilbert, 2021; Howard and Griffiths, 1966; Leopold, 1937; Norman, 2020; Wohl et al., 2019.

diversity fills niches that might otherwise be open for invasive species. In addition to the increase in vegetation condition and cover at NIDS, increases in diversity occurs in soil-water-carbon sinks, documented by the appearance of wetland vegetation (water obligates) occurring at study sites, associated with prolonged saturation or flooding caused by rock detention structures (Norman et al., 2014; Wilson and Norman, 2019, Wilson and Norman, 2018a) and by beaver dams (Naiman et al., 1988; Silverman et al., 2019). By increasing vegetation viability and longevity, and promoting flow regimes and maintenance of upland perennial pools in dryland ecosystems, critical ecological processes can be maintained for many species (Bogan and Lytle, 2011). Even minor rehabilitation of degraded ecosystems can restore some biodiversity and key services (Geist and Hawkins, 2016). And larger efforts can have huge impacts on a species. For example, 385 one-rock dams were installed in Colorado to restore 20 ha over 13.7 stream km, which improved approximately 160 ha of sagebrush habitat that Gunnison sage-grouse depend on throughout the year (The Nature Conservancy and Gunnison Climate Working Group, 2017).

Freshwater biodiversity is threatened by impacts of climate change. The presence of beaver dams can increase vegetation density and create fish habitat with higher productivity or diversity (Pollock et al., 2003). Research has found that BDAs improved habitat for steelhead trout (*Oncorhynchus mykiss*), a fish listed under the Endangered Species Act (Bouwes et al., 2016; Pollock et al., 2014; Weber et al., 2017), greater sage grouse (*Centrocercus urophasianus*), and Columbia spotted frogs (*Rana luteiventris*) (Davee et al., 2019). In Montana, macroinvertebrate density was found to be higher in sections of a stream treated with beaver and BDAs than control sites (Reinert et al., 2022).

3. Feedback cycle

The direction and magnitude of feedback cycles in the environment can either hinder or facilitate water storage and carbon sequestration. When a trigger process starts and begins to build upon itself, a series of reactionary processes can respond that can be either detrimental, causing degradation, or beneficial, leading to restoration. Temmink et al. (2022) reviewed recent research on the role of reciprocal feedbacks between geomorphology and landscape-building vegetation of peatlands or coastal wetland environments and documented the potential to either disrupt or restore these critical processes. We describe the similarities of freshwater wetlands and riparian zones that can be left (to degrade) or treated with NIDS (to restore), with some examples of what that looks like on the landscape.

3.1. Riparian and channel degradation

Historically, drainages of the American southwest supported productive *ciénegas*, but these were dramatically reduced during the late 19th and early 20th century ode to land use and climate changes (Heffernan, 2008; Hendrickson and Minckley, 1985; Minckley, 2013; Minckley et al., 2013).

Concurrently, beaver populations have declined drastically in the United States and elsewhere, eliminating their cumulative and substantial hydrologic, geomorphic, and biological wetland development (Naiman et al., 1988; Pollock et al., 2003; Wohl, 2021). Degradation of *ciénegas* causes a conversion into grasslands and shrub-lands (Minckley et al., 2013), as obligate wetland species can no longer survive when groundwater levels decrease >25 cm below the surface (Stromberg et al., 1996). When beaver are removed from wet beaver meadows, the landscape also often reverts to relatively dry grasslands, reducing C storage to 40–100 Mg C/ha (Buringh, 1984; Wohl, 2013). Dry grasslands are more receptive to large-scale wildfires, whose increasing frequency impacts the severity and scale of riparian disturbance, commonly shifting affected streams to a degraded state (and emitting CO_2). In dryland ecosystems, sparse vegetation results in poorly developed soil horizons that are overly exposed to rainfall. Such conditions favor overland flow rather than infiltration, increasing the amplitude of floods (Villarreal et al., 2022). Since water availability is a key driver of microbial processes in arid ecosystems, decreased soil moisture inhibits the microbially-mediated nutrient cycling which help to build soils (Belnap et al., 2005). Established reservoirs of organic carbon in dryland riparian ecosystems are influenced by the amount, timing and intensity of precipitation and flooding (Wohl, 2013). Heavy rainfall on degraded landscapes influences erosional processes, delivery ratios, and transport mechanisms. Increased soil loss associated with high-intensity precipitation events suggests that a few infrequent but high-energy storms could determine the overall impact of erosional events on terrestrial C cycling (Lal, 2004b). Erosional events can cause incision, with the concomitant lowering of the stream bed and alluvial aquifer (Gellis et al., 1991; Pollock et al., 2014). Combined with groundwater overdrafts, this results in a loss of connectivity between the water table and root zone (Minckley et al., 2013).

Channel incision is generally caused by extrinsic factors, such as land use (i.e. overgrazing, dam removal) and climate (higher precipitation and intensity), and intrinsic factors (i.e. steepening of valley slope) (Balling and Wells, 1990; Cooke and Reeves, 1976; Gellis et al., 1991; Leopold, 1951). Studies examining the stratigraphic record in alluvial valleys cut by arroyos indicated that the nineteenth-century arroyo-formation episode was one of several periods of valley incision during the Holocene (Elliott et al., 1999; Haynes, 1968; Karlstrom and Karlstrom, 1986). When channels incise to form arroyos, a complex series of changes termed "the arroyo cycle", occur progressing from channel incision, to widening, to aggradation, and eventually, filling of the channel and proceeds upgradient through the watershed (Patton and Schumm, 1981). Much of the degradation to fluvial ecosystems results from disconnecting vertical, lateral, and longitudinal processes (Ciotti et al., 2021).

Warming temperatures create more aridity, which increases the risk of hot drought (Overpeck and Udall, 2020). Climate changes affect atmospheric water vapor concentrations, clouds, precipitation patterns, and runoff and stream flow patterns (Graham et al., 2010). Drought conditions reduce soils' water availability, which can cause large scale vegetation die-off (Breshears et al., 2005). As soils dry out, there is less water to evaporate, so solar radiation heats the ground further (Borunda, 2021). Drier and warmer climates promote the development of surface-layer macroporosity, along with its disproportionate effects on saturated hydraulic conductivity, which may further alter the distribution of soil moisture and affect related hydrological processes, such as evapotranspiration (Hirmas et al., 2018).

Terrestrial evapotranspiration can affect precipitation and the associated latent heat flux helps to control surface temperatures, with important implications for regional climate characteristics such as the intensity and duration of heat waves (Jia et al., 2018). Hotter air also means the precipitation that arrives is more likely to fall as rain than snow or melt the snowfall that does occur, eliminating the critical snowpack in the high mountains' that stores winter precipitation and extends its seasonality (Huning and AghaKouchak, 2020; Martin et al., 2020). As NIDS are installed, vegetation structure and function can be degraded by beaver (Naiman et al., 1988) and by restoration practitioners (Wilson and Norman, 2018). Anaerobic wetlands have the potential to increase CH_4 emissions (Moritsch et al., 2021) and boreal beaver ponds have high rates of CH_4 and CO_2 fluxes (Johnston, 2014). These landscape processes promote emissions of C.

3.2. Riparian and channel restoration

Aridifying degradation trends can be reversed to restore regenerative natural processes and feedback loops by installing NIDS back into the landscape (Ciotti et al., 2021; Lal, 2015; Norman, 2020; Pollock et al., 2014; Silverman et al., 2019; Wheaton et al., 2019; Wohl et al., 2005). Installation of NIDS in dryland riparian ecosystems can restore wetlands, or create soil-water-carbon sinks, and nurtures a hydrating cycle and self-sustaining ecosystem. Channel evolution can be curbed and gullies can be controlled using NIDS (Gellis, 1998; Schumm, 1985). NIDS capture and detain sediments and create wetland-like environments that help balance emissions and draw down legacy C back into the soil by collecting organic debris, burying soil organic carbon and securing it in these wetland-like pools (Naiman et al., 1988).

NIDS increase flow resistance, trap sediment, cause aggradation that restores fluvial systems and facilitates vegetative growth and longevity, which further increases flow resistance (Norman et al., 2014; Ponce and Lindquist, 1990). Soil conservation, erosion control, and restoration of eroded soils are climate-smart practices (Lal, 2014).

NIDS detain water, storing some beneath the streambed, enhance these near-surface exchanges where groundwater and surface water meet (lateral flows in the hyporheic zone), and result in bank storage that releases water during dry periods in arid lands (Westbrook et al., 2006). Water storage and redistribution are a function of soil pore space and size distribution, for which macro-porosity development is further influenced by climate (Kutílek, 2004). Increased water availability triggers C and N fixation, resulting in increases of plant biomass, soil aggregates, soil surface roughness, and soil stability, all of which stimulate feedback linkages (Belnap et al., 2005). Increased water availability and soil productivity associated with NIDS contributes to the establishment of vegetation (Gerencia de Restauración Forestal, 2018).

Increased vegetation at NIDS further protects against erosion and promotes soil formation and health. Plants help accelerate soil development by accumulating OM at the surface, modifying soil surrounding plant roots, and facilitating the presence of soil microorganisms, as well as taking C out of the atmosphere and storing it in the soil (Jacoby et al., 2017). Diverse native plant communities hold water in place, allowing it to soak in and percolate the groundwater. Vegetation growth is supported by NIDS on top of the soil and by the deep rooting occurring below the soil surface that interact with fungal colonies composed of mycelium, and store C.

Silverman et al. (2019) found that as restoration projects using NIDS matured, resulting increases in productivity were apparent for longer durations in the annual cycle, suggesting a successional pattern to recovery. As productivity of soils increases, so does their capacity to regulate water via percolation, filtration, storage, and redistribution, that can cool microclimates and enhances soils' C sink capacity (Lal, 2004b). Organic C is likely to be retained in cases where soils remain saturated and have low oxygen concentrations; conditions similar to wetland soils (Pollock et al., 2014). Biological activity in the soil is determined by a complex combination of factors, including environmental conditions such as temperature and moisture and proximity to live vegetation (Rango et al., 2006). More atmospheric moisture creates atmospheric pressure that is alleviated via precipitation (Trenberth, 2011). In water-limited environments, NIDS support plant productivity and soil moisture by making water available over longer growing seasons (Norman et al., 2016, Norman et al., 2014; Silverman et al., 2019). More water for longer time rehabilitates a wetland's water table, which has the potential to store and sequester C in soil (Limpert et al., 2020). Rock structures were used to treat degraded grasslands, finding potential to increase soil moisture and nutrient-cycling (Martyn et al., 2022). Because of the increased moisture, NIDS can lower wildfire risks to the landscape (Fairfax and Small, 2018; Stockdale et al., 2019). These landscape processes all promote drawdown of atmospheric C.

3.3. Example of degradation cycling and restoration cycling in neighboring watersheds

Photographs at a paired watershed study (Norman et al., 2016; Norman and Niraula, 2016) depict the natural hydrogeomorphological and biogeochemical processes and how NIDS impacts them (Fig. 5). The control watershed portrays bare ground and bedrock, large cobble, deep gullying, and exposed roots; this system is losing water and C (Fig. 5a and b). The adjacent watershed, treated with >2000 NIDS 30 years ago, depicts a lusher, greener channel, with no exposed bedrock or roots, but instead, soil-water-carbon sinks support vegetation in the channel, their root systems, and their seasonality; this system is sequestering C and storing water for extended use (Fig. 5c and d). Deep, rich sediment loads fill the channel in stepped pools, that promote productivity of riparian vegetation and longevity of growth that simply would not be there otherwise. The NIDS creates a succession of these wetland-like environments, up and down the channel, with evidence of increased spatial and temporal extent of saturation. Installing NIDS can reverse degradation and desertification of landscapes by restoring hydrogeomorphic and biogeochemical processes.

4. Discussion

Modern permaculture farmers, water harvesters, and restoration practitioners take their cues from indigenous agriculture and have identified benefits of slowing flows, composting soil, and recycling water in greenhouses, to increase native biodiversity, food production, and cooling. Journalists, filmmakers, artists, and authors are developing materials to communicate and share these ideas and practices. And organizations and businesses are growing and poised to implement restorative stewardship practices based on this burgeoning community of practice. However, there is still some confusion about types of practices, impacts, and applications in arid and semi-arid ecosystems, causing rock or wood detention structure installations and beaver relocation efforts to be highly regulated, sometimes contended, and often rejected due to lack of consensus in the scientific community regarding documented impacts (Pfaeffle et al., 2022).

We synthesize decades of our own research here, together for the first time, with many other notable scientific references, to provide an authoritative scientific foundation that can promote learning, increase restoration stewardship, and catalyze a paradigm shifts that acknowledges NIDS as NBS to so many hydro-meteorological risks confronting the world today. We present mounting factual and technical evidence, as well as quantitative data that we have collected, to highlight the ease, benefits, replicability, and precautions of NIDS. This review summarizes decades of research that tests traditional knowledge, intuition, logic, and experience on the ground, using scientific methods that can and have been transparently reproduced, and have been demonstrated to be consistent. We share our common findings that NIDS create soil-water-carbon sinks, or wetland ecosystems, and promote them as best management practices in dryland riparian ecosystems, to reverse land and watershed degradation and promote sustainable, regenerative, natural processes as an actionable way to fight climate change.

4.1. Caveats

Societal and political expectations for restoration are often not well matched with reality (Geist and Hawkins, 2016; Pfaeffle et al., 2022).

Fig. 5. Photographs of paired watersheds, one with no natural infrastructure for dryland streams (NIDS): a.) looking downstream; b.) and looking upstream; and c.) looking upstream and at the adjacent watershed with over 2000 NIDS and d.) looking downstream (all photos by Jeremiah Liebowitz, Nov. 29,2021).

This article takes a broad look at the potential of NIDS to create wetland-like environments that have substantial positive impacts on developing C sinks and storing water, but there are many conditions for considering implementation. There is no one-size-fits-all panacea for dryland river restoration. The benefits being tallied in this manuscript are site- and time-dependent, and definitely not guaranteed, but if we can shift the focus to understanding processes that can be nurtured by installing NIDS, combined with some intuitive limitations, it can help to ensure their success. It is important to consider the initial disturbance associated with the installation of NIDS, which is site and size dependent. For example, large gabions may require the use of machines to move materials, which will have short-term negative impacts as landscapes take time to recover (Gerencia de Restauración Forestal, 2018; Wilson and Norman, 2018). Also, when structures are extremely dry, the runoff response will be delayed as they re-wet, and in the case of very light rains, they may not reach saturation and receive all the associated benefits (Norman et al., 2016). It is also important to consider: (i.) location and scale of the project being considered; (ii.) practice-based knowledge being employed, planning and guidebooks; (iii.) maintenance and monitoring of restoration for adaptive management; and (iv.) allow for some natural variability.

4.1.1. Location and scale considerations

A process-based design has been proposed to address causes of degradation (Beechie et al., 2010), that should be based on fundamental parameters of space, energy, materials, and time (Ciotti et al., 2021). If NIDS are used or placed improperly, they can be destructive to existing riparian zones and sometimes, long-time spans can pass before the effects of management action become visible, so investigations must be of wide scope (DeBano and Heede, 1987). It is important to understand the geomorphology of pre-installation landscape before implementing or assessing affects (Johnston, 2014). And likewise, it's important to understand the extent of degradation where restoration is being considered (Reinert et al., 2022). For example, understanding the arroyo cycle and the stage (or state) of the channel and upland elements was an important first step for the placement of earthen dams or rock and brush structures at the Zuni Indian Reservation, New Mexico (Gellis, 1998; Gellis et al., 1995). In order to be sustainable and to initiate the successful natural processes, NIDS should mimic the natural setting as much as possible whether humans are constructing BDAs and one-rock dams or by partnering with beaver (Wheaton et al., 2019).

Most restoration projects are too small and isolated to address watershed-scale degradation (Bernhardt and Palmer, 2011). Beechie et al. (2010) recommends the scale of restoration match the scale of processes it seeks to address. Larger, landscape-scale stream-restoration strategies that incorporate collections and series of NIDS installations, in multiple tributaries, of a river system or mountain range have more potential to succeed. Naturally-occurring stepped beaver meadows are spatially extensive complexes of multiple dams and ponds in varying states of activity or abandonment (Wohl et al., 2019). Likewise, in areas where historic rock detention structures are most abundant, their effect on local run-off and hydrology is profound (Howard and Griffiths, 1966). Because of installation of beaver dams and BDAs in multitudes in the Pacific northwestern United States, the overall system resilience is bolstered and in the potential for failures (i.e., blowouts), impacts aren't considered catastrophic (Pollock et al., 2014). Although large-scale efforts are more radical to consider, they are doable, and the benefits can certainly outweigh the costs. For example, The Nature Conservancy installed >750 one-rock dams in their efforts for sage-grouse rehabilitation (The Nature Conservancy and Gunnison Climate Working Group, 2017). Borderlands Restoration Network members have installed over 1000 check dams in Patagonia, AZ. Cuenca los Ojos installed over 2000 check dams at the 769-ha Turkey Pen Watershed, southeast AZ (Callegary et al., 2021; Norman et al., 2016; Norman and Niraula, 2016).

4.1.2. Practice-based knowledge, planning and guidebooks

Watershed restoration is most effective when experienced practitioners are installing on a needs-based strategy and defining target states and goals, rather than haphazardly adding structures to the landscape (Norman et al., 2022). The type of NIDS is dependent on the landowner preferences, the desired outcomes, the desired sustainability and maintenance regime, and the locational aspects. Restoration practitioners and scientists have developed guidebooks to help improve the success rate of installing NIDS. Specific treatment measures for installing gabions, leaky weirs, and brush, log and loose rock check dams are described for planning installations (Gerencia de Restauración Forestal, 2018; Geyik, 1986). Other structures that offer promise of these same wetland-like environments can be considered too, like the 'pond and plug' type methods (a.k.a. 'priority 1' approach) (Hammersmark et al., 2008; Rosgen, 1997). Restoration practitioners installing one-rock dams can follow guidelines (Zeedyk and Clothier, 2009). The Wood Jam Dynamics Database and Assessment Model (WooDDAM) is a tool for understanding and predicting wood jam change through time (Wohl et al., 2019). And the Low-Tech Process Based Restoration of Riverscapes (Low Tech PBR (Wheaton et al., 2019)) and other manuals provide guidelines for initiating process-based restoration (like BDAs) in structurally-starved riverscapes (Bureau of Reclamation and U.S. Army Engineer Research and Development Center, 2016; Pollock et al., 2018; Scott et al., 2019).

4.1.3. Maintenance, monitoring and adaptive management

The maintenance of structures and their lifetime is not elaborated on in this review article but is critical when thinking about NIDS. Some structures, such as beaver dams and beaver dam analogs, have natural lifetimes ranging from a single season to 100+ years depending on the physical environmental setting (Laurel and Wohl, 2019; Pilliod et al., 2018). Natural beaver dams and BDAs are installed as temporary features on the landscape, intended to invoke a process response, not to remain as permanent structures (Pollock et al., 2014). These structures are designed to be transient at the individual level, but at the landscape-scale are most effective when consistently cycling between active/inactive states over 100's to 1000's of years (Naiman et al., 1988). For example, the potential magnitude of C storage associated with individual or multiple structures in relation to local, regional, or global carbon stocks may help people to understand the effects of this type of restoration. Rock detention structures, on the other hand, are often built with longer intended functional lifetimes, to enact processes and ultimately get buried. Thousands of rock detention structures exist in North America and have persisted through centuries to millennium with very little, if any, maintenance (Norman, 2022). And fortunately, the majority of NIDS require very low-cost maintenance, providing great benefits when abundantly installed (Wheaton et al., 2019).

There are likely just as many NIDS that have collapsed and failed – although failure is a relative term. If NIDS are buried, they may not be actively functional (e.g., to capture new sediment), but could be part of the legacy of modern-day streams that store substantial organic C (Walter and Merritts, 2008). Naturally occurring large floods can and should be able to mobilize the rocks used to build some types of NIDS. In some cases, the collapsed NIDS can still maintain some function. For example, beaver ponds that breached during high flows, still delayed downstream floodwater transmission (Westbrook et al., 2020). While beaver are well-known for their creation and maintenance of wetlands, they should also be recognized for their ability to preserve them in times of drought (Fairfax and Small, 2018; Hood and Bayley, 2008). Both beaver and restoration practitioners can and will adapt management to repair or rebuild NIDS after damage (e.g., end-cutting, blowouts, or under scour) and employ progressive strategies to raise the height of a structure, typically by building new structures on top of the soil-water-carbon sinks created, upstream of the NIDS (Pollock et al., 2018, Pollock et al., 2014).

In addition, it is important to note the need for monitoring the impacts of various watershed and channel restoration (Palmer et al., 2007). Findings often can work hand-in-hand to identify where maintenance is needed or can portray unexpected, yet extremely valuable results. For example, surveys of beaver dams revealed them as locations of green 'safe havens', where on average, vegetation near dams burned three times less than in areas lacking dams (Fairfax and Whittle, 2020). Likewise, monitoring discharge over time at check dams revealed the soil-water storage capacity being developed at them (Norman et al., 2016). Careful planning, implementation and structure-appropriate maintenance and monitoring can increase the success and long-term climate resilience.

4.1.4. Variability

Natural variability increases uncertainty of magnitude and patterns of future warming, which when considered with scientific and/or scenario uncertainty can confound policymaking (Terando et al., 2020). However, stochasticity is inherent to ecological functionality and watershed restoration; there are always uncontrollable or uncertain outcomes (Ciotti et al., 2021; Nash et al., 2021; Sutfin and Wohl, 2017). With the recognition of the potential to help protect and restore natural systems using NBS, to help remove significant amounts of C from the atmosphere as CO_2 as plants grow, there is a movement to develop institutional mechanisms for addressing questions of uncertainty and timescale in funding projects (Conservation International, 2020). Although models and monitoring can provide some basic understanding of Earth processes, there remains a constant potential for error in predicting outcomes. Ideally implementation can afford some flexibility to adaptively manage NIDS installations and achieve NBS solutions with the most favorable outcomes (Nesshöver et al., 2017; Norman et al., 2022).

4.2. Future research

The potential to continue to translate restoration science into climate-smart practices, identifying economic and public policy, and international markets, and bringing NIDS into these arenas is critical for NIDS to be employed at large scales. Climate scientists within the international research community need to evaluate and improve management practices to inform decision-makers (Terando et al., 2020). Moreover, when governments measure the costs and benefits of making an investment decision, they need rigorous science to document impacts of their choices on societal (cultural and spiritual), economic, and environmental values (Tye et al., 2022). Conservation specialists, restoration practitioners, land managers, and educators can play an important role in bringing expertise about NIDS restoration innovations to landowners to promote floodplain connectivity and to enhance ecological resilience in degraded waterways (Fairfax and Whittle, 2020; Norman et al., 2022, Norman et al., 2021a; Pollock et al., 2018; Wheaton et al., 2019; Wohl, 2021).

Decision criteria are needed for conservation, harnessing natural recovery, restoring connectivity and habitat diversity as well as developing some geomorphological structural template to include hydrodynamic processes. Jones et al. (2017) developed a geospatial approach to target restoration and conservation efforts, based on the spatial distribution of wetland storage capacities at the watershed scale; this provides insights into patterns of historical drainage to inform restoration. Watershed models are used that can help strategically situate NIDS to generate selected ecosystem services, such flood detention (Norman et al., 2010a, 2010b), erosion control (Norman et al., 2017), climate resilience (Norman, 2021b) and groundwater recharge (Norman et al., 2019), though notably more research about the geohydrologic response to NIDS is warranted. Villarreal et al. (2022) identify locations where NIDS would be most beneficial based on a combination of fire and watershed model predictions. Likewise, beaver restoration can be targeted at suitable sites, more likely to sustain re-introduced beaver populations (Gurnell, 1998; Pollock et al., 2014; Macfarlane et al., 2017; Scamardo et al., 2022). Research to understand how to maximize the benefits from NIDS installations and plan the biggest and most effective chains of soil-water-carbon sinks, will save both financial and environmental resources in the future.

A challenge we face is in advancing this new understanding and theory across disciplines, to best communicate findings in ways that have meaning for people, culture and society to adopt and have impact on the larger global environment (Tye et al., 2022). One suggestion is using market exchange, mitigation banking and credits, incentives or offsets to compensate for carbon or water footprints via restoration or conservation easements using NIDS (Norman, 2020, 2021a). The accurate accounting of NIDS-related benefits is vital to allow their inclusion in carbon-offset programs (Nahlik and Fennessy, 2016). In dryland ecosystems, low soil moisture coupled with high soil alkalinity acts to decrease both soil N and P availability, which affects desert plant life forms and warrants further research related to NIDS (He et al., 2015). We recommend research to document the occurrence, structure, and impacts of biological soil crusts related to climate and disturbances at NIDS.

Modeling the fate and transport of sediment, combined with state and transition models, can portray different outcomes of C with and without NIDS. Research studying gaseous emissions from NIDS-treated riparian lands and those without, by measuring emissions of methane and nitrous oxide is important to document. We need to better understand the net gain of C by NIDS (net sink or net-primary productivity vs. gross) and to determine over time whether C is emitted (via methanogenesis) or re-sequestered in NIDS after erosion takes place. This investigation to understand C cycling, mitigating increases in atmospheric CO_2, and supporting critical biogeochemical transformations globally using NIDS will require documenting and then uncoupling water, nitrogen, phosphorus, sulfur, other processes. It is our hypothesis that coupled cycling between these, and the other processes that cause C to go back into the atmosphere would further strengthen NIDS contribution.

More research is needed to depict the potential of NIDS soil C stock over time, identifying upper limits and determinants, to define the SOC sink capacity at different scales—including estimates of SIC, and of the biomass C (above and below ground) to support inclusion in carbon-offset programs. Further investigation into the soil C budget and component studies is also warranted to compare impacts of NIDS with mass balance, soil C burial, and lateral fluxes in wetlands (Johnston, 2014; Krauss et al., 2018; Naiman et al., 1988). Total soil carbon stock in drylands comprises a larger amount of SIC than that in humid and subhumid regions. Therefore, assessment of the formation of secondary carbonates in the riparian zones is essential to determine the impact on total carbon stock and sequestration of SIC by both biotic and abiotic processes. The importance of formation of secondary carbonates and sequestration of SIC cannot be over-emphasized and additional research is needed.

5. Conclusions

Restoration of drylands requires revitalizing natural hydrogeomorphological and biogeochemical cycles and strengthening the positive feedback loops embedded therein. The critical first step for initiating successful restoration in dryland watersheds is slowing the rapid drainage of water from the landscape by restoring natural infrastructure in fluvial environments. Beaver and human-made structures of rock, wood, or mud are natural infrastructure in dryland streams (NIDS) that can transform drying riparian areas into step-pool channels of wetland-like soil-water-carbon sinks. This nature-based solution is not necessarily expensive and can be practiced with minimal technical engineering and design. Our research highlights the potential to reverse degradation and reestablish natural feedback cycles in large watershed-scale restoration efforts. Widespread implementation of NIDS could have significant effects on the global water and carbon cycles, help to mitigate additional climate change through sequestration of carbon, support sustainable development, and make dryland ecosystems more resilient to climate-related disturbances.

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Abbreviations

BDAs	Beaver Dam Analogs
C	Carbon
CH_4	Methane
cm	centimeter
CO_2	carbon dioxide
GHGe	greenhouse gas emissions

ha	Hectare
m	Meter
Mg	Megagram (10^6 g = 1 metric ton)
N	Nitrogen
N_2O	Nitrous oxide
NBS	Nature-based solutions
NIDS	Natural Infrastructure in Dryland Streams
NDVI	Normalized Difference Vegetation Index
O	Oxygen
OM	Organic Matter
Pg	Petagram
SIC	Soil Inorganic Carbon
SOC	Soil Organic Carbon
Tg	Teragram

CRediT authorship contribution statement

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