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Can Meadows Rescue the Planet from CO2?

An unusual research project is determining whether restoring California's meadows can reduce atmospheric carbon dioxide

By Jane Braxton Little on May 11, 2017

The record piles of snow across California's Sierra Nevada are melting away, exposing once again its breathtaking alpine meadows. As temperatures warm the moist soil, the meadows quicken, cycling carbon from the ground into the atmosphere and back again in a pattern essential to the planet's health. Scientists and land managers are heading into the mountains to measure the greenhouse gas activity at 16 hand-picked meadows—some recently restored, others degraded from a century of grazing and logging.

The four-year study is part of California's pioneering effort to reduce carbon emissions. The project is designed to determine whether restored meadows hold more carbon than those that have been degraded. The outcome could prove pivotal for California and the planet. Worldwide, soils store three times more carbon than vegetation and the atmosphere combined. If the research shows restored meadows improve carbon storage, it could stimulate meadow restoration around the world.

The $4.8-million project has an unusual twist, too. It is funded by the California Air Resources Board, which wants to know if restored meadows can hold enough tonnage of carbon dioxide equivalents, per acre per year, to qualify as carbon credits in California's cap-and-trade market. "It's kind of geeky but we're poised to do something that's never been done with alpine meadows," says Mark Drew, Sierra Headwaters director at California Trout, who is coordinating the work.

Meadows are new to soil carbon research. Carbon enters the soil as plants use solar energy to draw carbon dioxide from the atmosphere and make their own food. More enters the ground when plants die and are decomposed by microbes. And yet living plant roots expel carbon dioxide, and so do microbes as they decompose the dead plant matter, creating a cycle of carbon uptake and emission by soil. It is common for agricultural land to lose a fair portion of its original carbon stock as it is relentlessly farmed—as much as 50 to 70 percent, according to several estimates. Scientists suspect meadows may lose carbon as well, especially when they are degraded by logging and grazing activities that compact soils, erode streams and deplete native plants and animals.

Sky Parlor Meadow in Tulare, California. *Credit: Miguel Vieira Flickr (CC BY 2.0)*

Some scientists also think global warming itself is changing soil carbon stocks. A December study published in Nature, led by Thomas Crowther at Netherlands Institute of Ecology, found rising temperatures are stimulating a net loss of soil carbon to the atmosphere. Warmer soils accelerate the flux, sending more carbon into the ground and more carbon dioxide back out into the atmosphere. As warmth increases microbial activity, decomposition and respiration outpace photosynthesis, particularly in the world's colder places. "That's when the losses start to happen," Crowther says. The changes could drive a carbon–climate feedback loop that could accelerate climate change.

Drew was already starting to collaborate with several meadow restoration groups in 2014, when the Air Resources Board announced funding to study carbon flux in Sierra meadows. Rather than compete for small pots of money, the various stakeholders decided to work together—PhD scientists side by side with ranchers and landowners. Together they could build a database far larger than any one project could, Drew says.

The group already knew meadow restoration—usually done with heavy equipment to fill braided channels and re-create functioning floodplains—has well-documented ecosystem benefits. Returning streams to their natural meanders and raising the water table rejuvenates habitat for golden trout, willow flycatchers and other endangered species. Restoring

Morning clouds over the Sierra Mountains in Bishop, California. *Credit: David H. Carriere Getty Images*

meadows also improves their capacity to store and release water, a boon to a state that depends on the Sierra region for more than 60 percent of its water supply. Spurred by Air Board funding, the meadow partners set out to see what restoration could do for carbon storage as well.

The research covers meadows from the base of Lassen Peak in the north to areas nearer to Los Angeles. The meadows range in elevation from 3,045 to nearly 8,700 feet; they include granitic, volcanic and metamorphic soils. A critical facet of the partnership is developing precise procedures for when and how to measure and analyze meadow greenhouse gases. Although scientists have established protocols for monitoring carbon flux in forests and wetlands, none exist for alpine meadows. “We’re the guinea pigs,” Drew says.

Work has just begun and will continue until winter closes access. The data collection begins with pushing an eight-inch segment of PVC pipe into the ground vertically to seal off a small segment of meadow, then capping the cylindrical chamber. A monitor pokes a syringe into a tiny hole in the cap, drawing a sample of whatever meadow gases are captured inside. By taking three samples 15 minutes apart repeatedly over several months scientists can compare the ambient air with gases coming directly out of the meadow. The rate of change in the concentration of gases determines the soil’s CO2 emission rate. The researchers are also monitoring soil carbon by extracting core samples. Comparing the data from restored meadows with geographically similar degraded sites will show the effects of restoration.

The researchers have a hint of what they might find from a limited study conducted by the University of Nevada, Reno (U.N.R.). Scientists collected soil samples at seven meadows in the northern Sierra restored between 2001 and 2016, pairing restored sites with similar, adjacent unrestored sites. The preliminary results found an average of 20 percent more soil carbon in restored meadows, with one site recording an increase of over 80 percent. Meadows immediately begin storing carbon following restoration, with significant increases over 15 years, says Cody Reed, a research assistant working with Ben Sullivan, a U.N.R. soil scientist and assistant professor. The investigation seems to show restored meadows add soil carbon and also slow losses to the atmosphere.

Another limited study looked at the effects of water in meadow soils. Steve Hart, an ecology professor at University of California, Merced, and Joseph Blankinship, assistant professor of microbial biogeochemistry at the University of Arizona, researched a Sierra meadow to understand how water affects the fluxes of carbon dioxide, methane and nitrous oxide. What they found surprised them: Carbon dioxide emissions were unaffected by soil moisture content, and methane sequestration was prevalent, particularly on the dry side of wet meadow. The 2014 study also found plant species richness and soil carbon concentration appeared more important than soil moisture in explaining carbon fluxes.

It is too soon to know if these results will be replicated on the larger Sierra-wide scale. With a full year of research already logged, Drew and his partners are digging in to a new season of fieldwork. A finding of dramatically increased soil carbon in restored meadows would have a limited effect globally because such large forces are at work. But the gain could be an important, added payoff for restoring these landscapes. The Sierra Meadows Partnership could also serve as a model to others working in very different landscapes that hold the potential to have a much greater effect on the carbon equation, Hart says. And if restored meadows do indeed hold significantly more carbon, then they could play a role in California's carbon market. The Sierra partners have until 2019 to present their results. “We’re poised to do something really unique,” Drew says. “Let's see where it takes us.”

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Geomorphic changes upstream of beaver dams in Bridge Creek, an incised stream channel in the interior Columbia River basin, eastern Oregon

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Abstract

Channel incision is a widespread phenomenon throughout the dry interior Columbia River basin and other semi-arid regions of the world, which degrades stream habitat by fundamentally altering natural ecological, geomorphological and hydrological processes. We examined the extent of localized aggradation behind beaver dams on an incised stream in the interior Columbia River basin to assess the potential for using beaver, *Castor canadensis*, dams to restore such channels, and the effect of the aggradation on riparian habitat. We estimated aggradation rates behind 13 beaver dams between 1 and 6 years old on Bridge Creek, a tributary to the John Day River in eastern Oregon. Vertical aggradation rates are initially rapid, as high as $0{\cdot}47$ m yr^{-1}, as the entrenched channel fills, then level off to $0{\cdot}075$ m yr^{-1} by year six, as the sediment begins accumulating on adjacent terraces. We found that a $0{\cdot}5$ m elevation contour above the stream channel approximately coincided with the extent of new riparian vegetation establishment. Therefore, we compared the area surrounding reaches upstream of beaver dams that were within $0{\cdot}5$ m elevation of the stream channel with adjacent reaches where no dams existed. We found that there was five times more area within $0{\cdot}5$ m elevation of the channel upstream of beaver dams, presumably because sediment accumulation had aggraded the channel. Our results suggest that restoration strategies that encourage the recolonization of streams by beaver can rapidly expand riparian habitat along incised streams.

Keywords: **incision; aggradation; *Castor canadensis*; riparian; Oregon**

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Introduction

Channel incision is a common occurrence in stream channels throughout the semi-arid regions of the interior Columbia River basin, where a fragile balance between climate, vegetation and geology makes the vertical stability of channels highly vulnerable to changes in hillslope erosion, stream discharge and loss of instream retention elements (Cooke and Reeves, 1976; Welcher, 1993; Peacock, 1994). We define incision as a rapid downcutting and lowering of the stream bed such that it reduces the frequency and duration of flooding onto the adjacent floodplain (*sensu* Leopold *et al.*, 1964). Incision is a common response of streams to land use changes throughout much of the semi-arid regions of the American West and in other regions of North America, Africa, Australia, Europe, Asia, the Middle East and South America (Cooke and Reeves, 1976; Schumm *et al.*, 1984; Nagle, 1993; Prosser *et al.*, 1994; Simon *et al.*, 1995; Vandekerckhove *et al.*, 2000).

Incision has degraded instream and riparian habitat throughout the Columbia River basin, suggesting that restoration of such streams would benefit numerous species. Of particular interest is improving habitat for salmonids, because many of the Columbia River stocks are listed under the United States Endangered Species Act. Many streams in the Columbia River basin that historically supported salmon no longer do so, and habitat conditions are severely degraded in these incised streams (Nehlsen *et al.*, 1991; Elmore *et al.*, 1994; Wissmar, 1994). Incision can dramatically affect stream habitat for salmon and other fishes by the lowering of stream-adjacent water tables and the subsequent loss of riparian vegetation. The loss of above-ground vegetation reduces shading and organic inputs to the stream (Brown and Krygiier, 1970; Kiffney *et al.*, 2000), while the loss of below-ground roots increases the erodibility of stream banks (Smith, 1976). The lowered water tables also directly impact the stream by reducing groundwater inputs to the stream. This is a significant concern in semi-arid regions such as in our study area because many streams have incised to bedrock and therefore the water table is at or near the bedrock and there is little opportunity for water to be stored in the alluvium. As a result, many incised streams cease flowing or have substantially reduced flows in the summer because there is no baseflow provided by the alluvial aquifer (Elmore and Beschta, 1987). The loss of cool groundwater inputs also leads to increased summer stream temperatures (Poole and Berman, 2001). Further, incised streams rarely access their floodplains, high flows are concentrated within the incised channel, and fish have no access to slow-water refugia during floods (Harvey and Watson, 1986; Elmore and Beschta, 1987; Shields *et al.*, 1995). In contrast, numerous studies suggest that when local water tables of incised streams are raised, usually through the construction of beaver dams or small human-made dams, flows increase and intermittent streams become perennial (reviewed by Ponce and Lindquist, 1990; Pollock *et al.*, 2003).

The historical record suggests that numerous streams in the semi-arid region of the interior Columbia River basin once contained narrow, deep and gently meandering channels lined with dense riparian forests of cottonwoods, *Populus*, willows, *Salix*, and/or sedges, *Carex*, numerous beaver, *Castor Canadensis*, dams (which are generally constructed out of numerous pieces of small diameter (1–4 cm) wood and mud), abundant and easily accessible off-channel habitat on the floodplain and good flow and cool temperatures throughout most of the year (Buckley, 1992; Wissmar *et al.*, 1994). Today many of these same streams are incised and contain little or no riparian vegetation or beaver dams. Stream temperatures are high and flow is ephemeral (Elmore and Beschta, 1987; Buckley, 1992; Peacock, 1994; CBMRC, 2005).

Land use change, climate change or localized high intensity rainfall can cause channel incision, either by increasing the tractive force of water or by decreasing the resistance of the stream bed (Cooke and Reeves, 1976). Within the Columbia River basin, the exact mechanism that caused widespread channel incision remains uncertain, although its timing almost invariably followed the widespread trapping of beaver and the onset of intensive sheep and cattle grazing in the mid 19th and early 20th centuries (Russell, 1905; Buckley, 1992; Peacock, 1994). In other semi-arid regions, aggradation (recovery from incision) has been observed when grazing practices and riparian land uses are altered to allow the re-establishment of riparian vegetation (Zierholz *et al.*, 2001). Aggradation has also been observed to occur where beavers are able to build dams on streams (Scheffer, 1938; Butler and Malanson, 1995; McCullough *et al.*, 2005). This suggests that recovery will occur when natural processes are allowed to operate. However, the time frames for recovery may range from decades to centuries. Recovery rates are related to both the quantity of sediment entering a channel and the ability of the channel to retain this sediment.

Recovery of incised streams has both a physical and a biological component, though the two are interdependent. Physical recovery includes both the geomorphic and hydrologic changes that occur as a channel aggrades, while biological recovery includes the changes in riparian vegetation and instream biota that can either initiate or result from physical recovery. Much of the literature examining incised streams has focused on the changing geomorphic characteristics of such streams as they cycle through stable, incising and aggrading states (Leopold *et al.*, 1964; Schumm *et al.*, 1984; Darby and Simon, 1999). A general conceptual model has emerged regarding the channel evolution of incising streams (Figure 1). The model has numerous variants, but most include (a) a sequence of relative stability followed by (b) rapid downcutting such that the stream is isolated from its floodplain, (c) an increased stream width-to-depth ratio, a decrease in stream sinuosity and extensive widening of the incised trench, which eventually leads to (d) a stream at a lower base level and a lower longitudinal slope, with a new inset floodplain that develops a more sinuous planform and lower width-to-depth ratio, then (e) slow, long-term aggradation of the streambed and inset floodplain that (f) may or may not reach the level and the longitudinal gradient of the former floodplain before a new cycle of incision begins. Because the incision phase is rapid and causes dramatic physical and ecological changes, research efforts have focused on understanding causes of incision, to what extent they are the result of land use practices versus a natural phenomenon and how future incision can be prevented (Schumm *et al.*, 1984; Darby and Simon, 1999). Less attention has been focused on factors influencing the post-incision phases and in particular the factors that might influence aggradation rates (but see Shields *et al.*, 1999). Generally, it has been assumed that aggradation of incised streams is a slow process that operates on a multi-century timeframe, and that extensive widening of the incision trench must occur prior to aggradation (Leopold *et al.*, 1964; Schumm *et al.*, 1984; Rosgen, 1996). However, such assumptions are based almost entirely on the physical principles of sediment transport in fluvial systems, and do not include the effects of large wood, beaver dams (i.e. small wood) or riparian vegetation on sediment transport and deposition and the modification of fluvial landforms. Nonetheless, the channel evolution model illustrated in Figure 1 provides a framework for understanding the sequence of geomorphic changes that might be expected to occur following incision and how aggradation rates might be altered by large wood, live vegetation or beaver dams.

Live vegetation, particularly dense, emergent graminoids such as sedges, has been shown to effectively remove suspended sediment from water columns, primarily by creating a low velocity zone near the stream bed, which allows

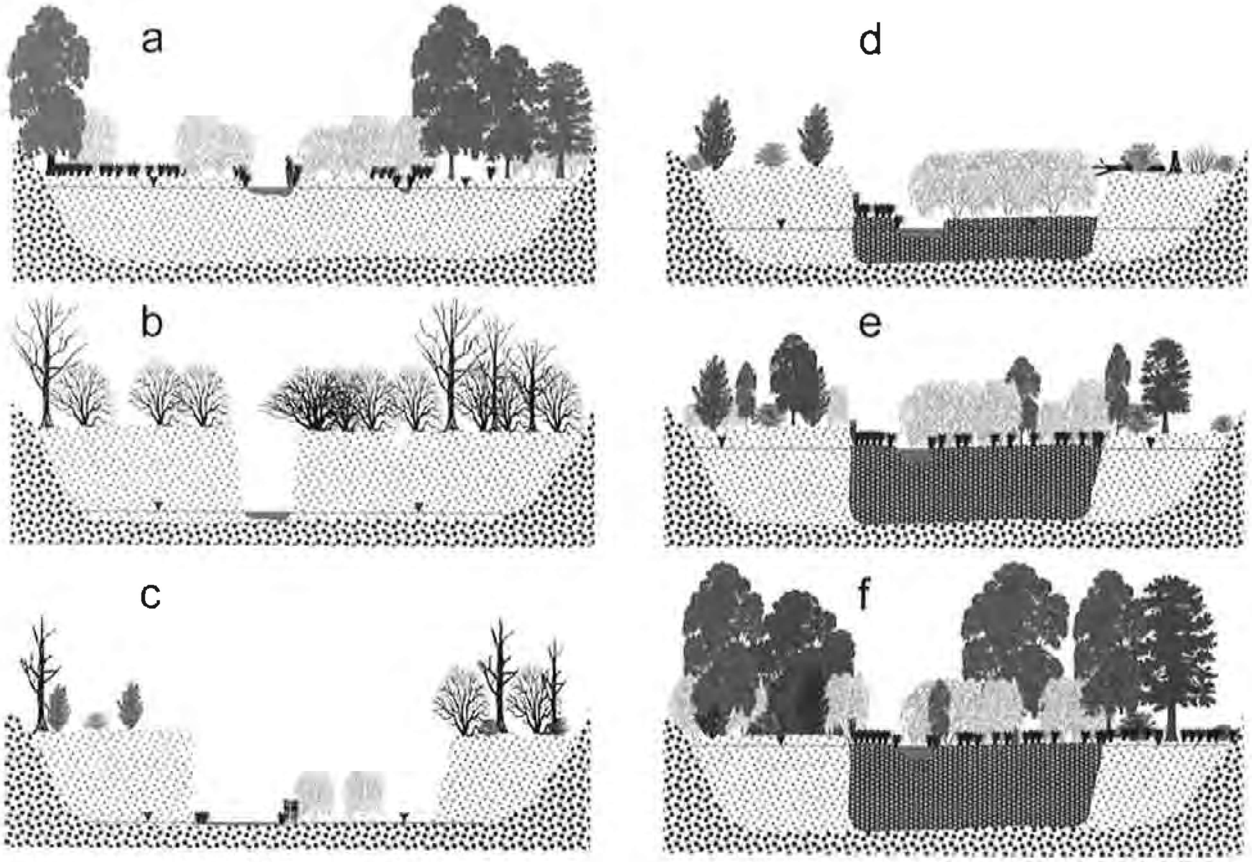

Figure 1. Conceptual diagram of incision and filling cycle in a semi-arid environment such as the interior Columbia River basin. (a) A fully aggraded stream connected to its floodplain and a water table near the floodplain surface. (b) Incision is triggered, usually by a change in land use practices that result in increased stream power. The water table lowers, resulting in the death of riparian vegetation. The channel is confined to a narrow trench. (c) Eventually, the incision trench widens as the channel develops meanders, and a narrow floodplain establishes with a greatly diminished riparian area. Xeric plant communities dominated by juniper and sagebrush develop on the former floodplain. (d) Floodplain vegetation such as sedges and willows trap sediment during high flows, and the developing meandering pattern of the stream lowers the stream gradient. Within the incised trench, aggradation begins to occur and the water table rises. (e) Over time, continued aggradation begins to reconnect the stream to its former floodplain, and the water tables continue to rise. During this period, plant diversity is high because both xeric and riparian species are present. (f) As conditions become more favorable to riparian species, the xeric species die out and riparian plant biomass continues to increase. The stream and riparian forest return to the pre-incision state.

fine-grained material to settle out of suspension (Elliot, 2000; Braskerud, 2001; Carollo *et al.*, 2002). Establishment of emergent vegetation following the cessation of cattle grazing has been implicated as an important prerequisite for aggradation of incised streams in the semi-arid regions of Australia (Zierholz *et al.*, 2001). Similarly, beavers affect sediment transport when they dam small streams by weaving together numerous small pieces of wood and packing the interstices with mud (Morgan, 1986). The dams create low velocity stream reaches where sediment can drop from suspension. Additionally, they often raise the water level such that it permanently floods the adjacent floodplain or low terrace, thus creating a large shallow littoral zone suitable for the establishment of emergent and other riparian vegetation (Pastor *et al.*, 1993). Thus beaver dams should affect sediment transport by directly influencing stream velocities, and indirectly by creating an environment conducive to the establishment of emergent vegetation that traps sediment. The geomorphic effects of beaver dams has been documented (reviewed by Gurnell, 1998; Pollock *et al.*, 2003), though few studies have examined aggradation rates and only one has done so in an incised stream (McCullough *et al.*, 2005). Butler and Malanson (1995) estimated sedimentation rates of 0·02–0·28 m yr^{-1} above four beaver dams in Glacier National Park, MT, while Meentemeyer and Butler (1999) observed average sediment depth of 0·28 m in five ponds 5 yrs old or less (i.e. a minimum aggradation rate of 0·06 m yr^{-1}), in Glacier National Park, MT, while Scheffer (1938) observed aggradation of 0·55 m over a two year period on a small tributary to the Columbia River in eastern Washington. Naiman *et al.*

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(1986) estimated that 3.2×10^6 m^3 of sediment were stored behind all the beaver dams in second-fourth order streams in their study area in Quebec. They calculated that if this sediment were distributed evenly across all the streambeds, it would raise them by 42 cm. McCullough *et al.* (2005) studied beaver colonization of an incised stream in Nebraska and found that in a reach where beaver had been established for 12 years stream bed aggradation averaged 0·65 m.

Field observations of small incised streams within the Columbia River basin suggest that incision depths typically range from 1 to 2 m, less frequently up to 5 m and in some extreme cases may incise as much as 20 m (see, e.g., Peacock, 1994). The aggradation rates behind beaver dams reported in the literature suggest that where beaver dams are present in incised streams aggradation may occur at a rate sufficient to reconnect a stream to its former floodplain on decadal timescales, thus increasing projected rates of recovery by an order of magnitude or greater over recovery estimates when it is assumed no beaver dams are present (see, e.g., Rosgen, 1994).

Because we know that historically beaver were abundant throughout the semi-arid regions of the Columbia River basin (Johnson and Chance, 1974; Buckley, 1992), we hypothesized that their reestablishment in incised streams could greatly increase aggradation rates and accelerate the recovery of stream and riparian habitat. The purpose of this study was to assess volumetric and vertical aggradation rates of beaver ponds in an incised stream and to estimate the projected time to accumulate the sediment necessary to reconnect the stream to abandoned floodplain terraces.

Site Description

The Bridge Creek watershed is a 710 km^2 watershed draining directly into the lower John Day River in eastern Oregon (Figure 2). Elevation ranges from 499 m at the mouth to 2078 m at the summit of Mt. Pisgah. The basin is dominated by sagebrush-steppe, *Artemisia*, and juniper-steppe, *Juniperous occidentalis*, in the lower elevations, with the vegetation changing progressively to forests dominated by Ponderosa pine, *Pinus ponderosa*, Douglas-fir, *Pseudotsuga menziesii*, and then spruce, *Picea englemannii*, with increasing elevation. Most of the mainstem and lower tributary reaches of Bridge Creek are incised and thus the riparian vegetation is limited to a very narrow band along the stream. Riparian vegetation is dominated by willows, but cottonwood is present in some areas, as are a variety of shrubs. High flows in Bridge Creek occur during the spring, when runoff from the melting snowpack raises water levels to near bankfull height for weeks at a time. Peak flows also occur during this time, typically when localized storm cells provide high amounts of precipitation that add to the existing high water levels. Maximum

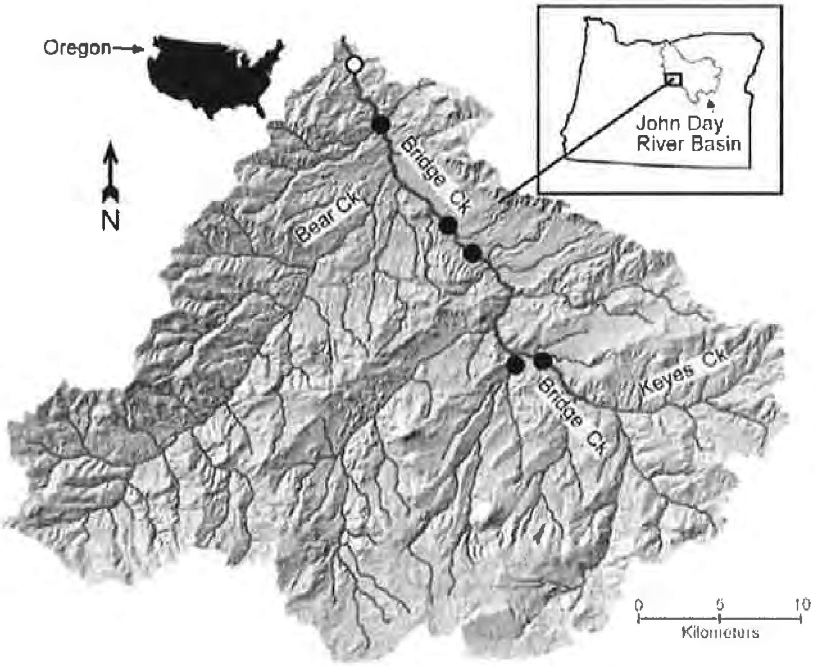

Figure 2. Bridge Creek drains a 710 km^2 basin into the lower John Day River in eastern Oregon. The John Day is a major tributary to the Columbia River. The black dots on the map of Bridge Creek are the general areas where beaver ponds are located. The white dot is the location of the gauging station.

estimated peak flow in Bridge Creek near the mouth is 28 $m^3 s^{-1}$, while late-summer low flows have been measured as low as 0·15 $m^3 s^{-1}$ (Anna Smith, BLM, Prineville, OR, personal communication).

The surficial geology of Bridge Creek is dominated by thick layers of basalt and andesite that originated from numerous lava flows of the Eocene and Oligocene period. There are also substantial areas of highly erosive volcanic ash known as the John Day Formation that also originated from a series of volcanic eruptions in the Oligocene and Miocene. The lower main valley of Bridge Creek is surrounded by cohesive, fine-grained quaternary alluvium, much of which is derived from the ashes of the John Day formation.

Bridge Creek and its tributaries are utilized by an anadromous run of Middle Columbia steelhead, *Oncorhynchus mykiss*, that are part of the ecologically distinct Lower John Day population, which occupies the lower, drier Columbia Plateau ecoregion within the John Day Subbasin, and are listed under the Endangered Species Act (CBMRC, 2005). Bridge Creek is a priority watershed for restoration because its salmonid production and abundance potential is high (CBMRC, 2005). Chinook salmon have also been recently documented in Bridge Creek (M. Pollock, personal observation, June 2007). Habitat quantity, temperature, sediment load, habitat diversity and flow have been identified as limiting factors in Bridge Creek. Summer stream temperatures in Bridge Creek frequently exceed 27 °C when stream flows are at a minimum. Not surprisingly, Bridge Creek is on the 303(d) list of temperature impaired streams (CBMRC, 2005). Due to the erosive nature of some of the geologies, and in particular the large number of incised, failing stream banks, sediment loads are high in Bridge Creek, especially during peak flow events.

Methods

Sediment accumulation behind 13 beaver dams was estimated by establishing a grid of points upstream of the dam. Transects were spaced every 10 m upstream and sediment depth measurements were made every 5 m along each transect. Sediment depth was estimated by pushing a sediment corer through the surface layer of fine-grained unconsolidated sediment until a more compact layer was reached, which often contained larger clasts such as gravels. A clear boundary between loose, fine-grained surface material underlain by more compact, coarser-grained material existed at almost every point. The aggradation of unconsolidated fine-grained material was assumed to be recently deposited and to result from the construction of the beaver dam downstream. This was a reasonable assumption because sites that had no beaver dam downstream had no layer of fine-grained unconsolidated sediment, while all sites we examined upstream of beaver dams contained such a layer.

The age of the 13 beaver dams was determined from a database provided by the Bureau of Land Management, Prineville office. The BLM has been surveying for beaver dams along the mainstem of Bridge Creek for over a decade and has a GIS layer identifying the location of each beaver dam and each year that it has been present.

Digital orthophotographs for the mainstem of Bridge Creek were obtained from a three-band color imagery and light detection and ranging (LIDAR) survey of Bridge Creek from the mouth to approximately 28 km upstream to the town of Mitchell that was flown in September 2005 by Watershed Sciences, Portland, OR. The area within 0·5 vertical elevation of the stream channel was estimated by using the LIDAR coverage to develop 0·5 m contour bands above the existing stream, which were then verified in the field. Field observations and analysis of the orthophotos indicated that most recently established riparian vegetation was found within 0·5 m of the current stream bed. Thus the 0·5 m elevation contour above the streambed is a reasonable approximation of where riparian vegetation is at present or might be expected to establish in the near future.

The bed slope above 18 beaver dams (another 5 in addition to the 13 where sediment accumulations were measured) and reaches above and below the area of aggradation above the dam were estimated using a DEM grid generated from the LIDAR coverage. The vertical accuracy of the LIDAR is 4–7 cm, and the DEM grid cells are 0·5 m^2. Slope measurements were also made in the field to verify the accuracy of the remote sensing measurements.

Results

The aggradation rate decreased with age and was described by the power equation

$$AR = 0{\cdot}3835\ Age^{-0{\cdot}9093} \qquad (1)$$

where AR is the aggradation rate, measured in m yr^{-1}, and Age is the dam age, measured in years ($r^2 = 0{\cdot}72$, $n = 13$; Figure 3). The data indicate initially high rates of aggradation, as much as 0·45 m in the first year, followed by a rapid decline and leveling off towards 0·075 m yr^{-1} by year six (Figure 3). Volumetric sediment accumulation rates among the 13 sites were variable, averaging 171 $m^3 yr^{-1}$, with a minimum of 17 $m^3 yr^{-1}$ and a maximum of 522 $m^3 yr^{-1}$. A

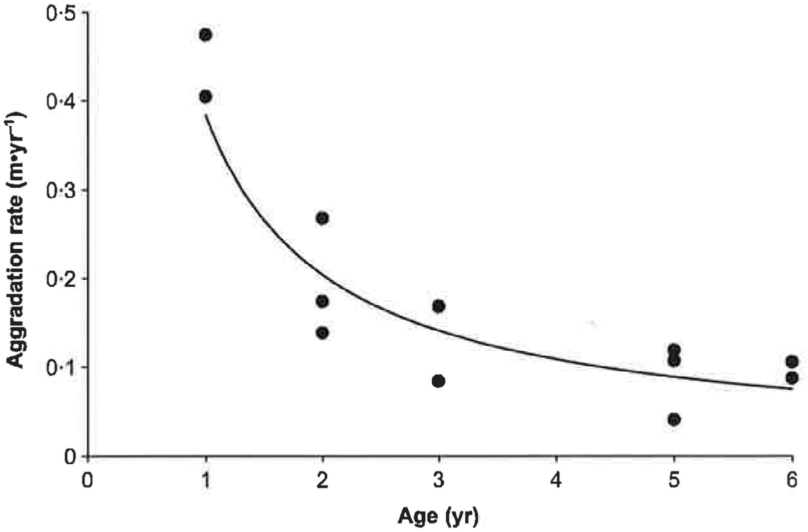

Figure 3. The relationship between beaver dam age and the aggradation rate (AR) upstream of the dam is described by the power equation Age $= 0{\cdot}3835\ \mathrm{AR}^{-0{\cdot}9093}$ ($r^2 = 0{\cdot}72$, $n = 13$, $p < 0{\cdot}001$).

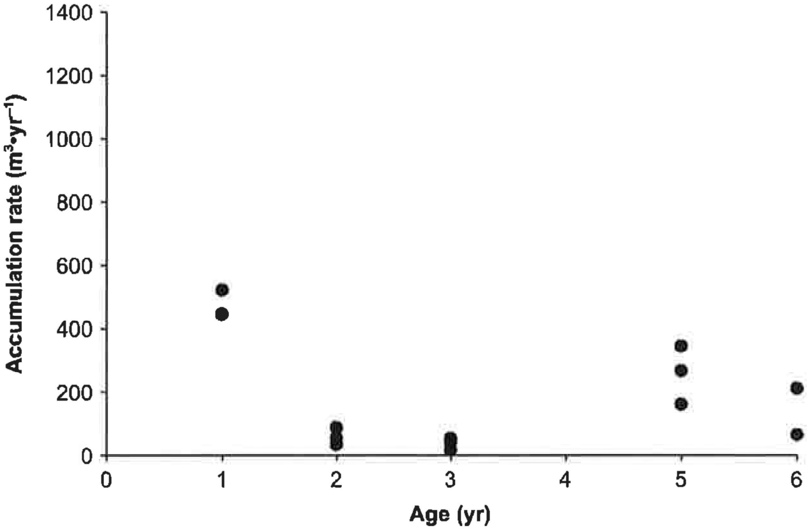

Figure 4. There was no significant overall trend between annual volumetric sediment accumulation rates and beaver dam age (linear regression: $p = 0{\cdot}6$, $r^2 = 0{\cdot}02$, $n = 13$), though both one-year-old dams did have the highest annual rate of volumetric sediment accumulation.

linear regression indicated no significant trend in the volumetric accumulation rate with age ($p = 0{\cdot}6$, $r^2 = 0{\cdot}02$, $n = 13$, Figure 4).

Sediment accumulations behind the beaver dams changed the bed slope. Upstream of beaver dams, bed slopes ranged between 0·001 and 0·014, averaging 0·004 (Figure 5). The underlying bed slopes ranged between 0·008 and 0·028, averaging 0·018. On average, the sediment accumulations reduced slopes by a factor of 4.5 or an average reduction in slope of 1.3%. In no instances did sediment accumulation behind beaver dams increase the slope of the stream.

Immediately upstream and downstream of the channel reaches where sediment accumulation occurred, the width of the area within 0·5 m elevation of the stream channel was remarkably consistent, averaging 8.6 m, with a range of 7.5–12.0 m. In contrast, where aggradation had occurred, the width of area within 0·5 m elevation increased and also became more variable, ranging from 16 m to 105 m, and averaging 44 m. The difference in widths between where aggradation had occurred and the average of the adjacent upstream and downstream reaches where aggradation had not occurred was significant (paired *t*-test, $p < 0{\cdot}001$, $n = 18$).