RESTORATION PRACTICE

Erosion and Restoration of Two Headwater Wetlands Following a Severe Wildfire

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ABSTRACT

Wildfire can damage headwater wetlands, yet the value of post-fire restoration treatments in channels has been contested. Staff from the White Mountain Apache Tribe, students from the local Cibecue Community School, and researchers from the U.S. Forest Service collaboratively recorded channel responses over 13 years at two headwater wetlands lying within watersheds that were severely burned by the Rodeo-Chediski wildfire (Arizona, U.S.) in 2002. One site, Turkey Spring, was left largely untreated for 11 years following the fire, while the second site, Swamp Spring, was treated in 2005 by placing large rock riffle formations and vegetation transplants to prevent further incision and stimulate wetland development. The treatment was soon followed by cessation of channel incision and reestablishment of native wetland vegetation, while headcutting caused extensive erosion at the untreated site for eight years. Radio-carbon dating indicated that the eroding soils at Turkey Spring were over 8,000 years old. This study demonstrates that headwater wetlands in this region are vulnerable to extreme incision events following high severity wildfires, but that such impacts can be partially and gradually reversed. Targeted treatments of incising channels may be warranted to conserve wetlands, soils and associated values that have established over thousands of years.

Keywords: geomorphology, in-channel treatments, Native Americans, participatory research, radio-carbon dating, stream evolution, stream restoration

Restoration Recap

- Two headwater watersheds burned at high severity in an erosion-prone landscape experienced extreme channel incision that continued at an untreated site for at least eight years due to nickpoint migration.
- Soils being eroded at one of the sites were dated to be over eight thousand years old, representing loss of a valuable resource.
- Placement of rock riffle formations began to reverse the degradation process by facilitating sediment deposition and native wetland vegetation growth.
- Researchers worked with local community members to use relatively simple monitoring techniques such as photo points, geomorphic surveys, and vegetation transects to evaluate degradation and recovery over a long period based upon key indicators, including channel area and cover of grass-like vegetation.

Headwater wetlands are important to conserve because they perform valuable functions such as attenuating floods and supporting biological diversity (Meyer et al. 2007). Such wetlands are relatively rare in semi-arid regions such as the mountains of the Southwestern U.S., but the Mogollon Rim region has one of the highest concentrations of springs in Arizona (Stevens and Nabhan 2002). Wet meadows in this region can harbor endemic and other locally rare plants (Ramstead et al. 2012). Furthermore, in traditional Apache culture, wet meadows are valued as repositories of vitality, utility, and personal identity (Basso 1996, Long et al. 2003a).

The Rodeo-Chediski wildfire in June 2002, Arizona, U.S., (Figure 1) induced erosion at many of these wetlands in this rugged landscape. Understanding the effects of unusually large and severe fires of watersheds in semi-arid regions has become a critical focus for research and policy as such events have become more common in recent years (Neary 2009). However, the effects of wildfires on streams and wetlands have not received much study (Shakesby and Doerr 2006). In particular, site trajectories over long periods have rarely been documented and compared across sites with and

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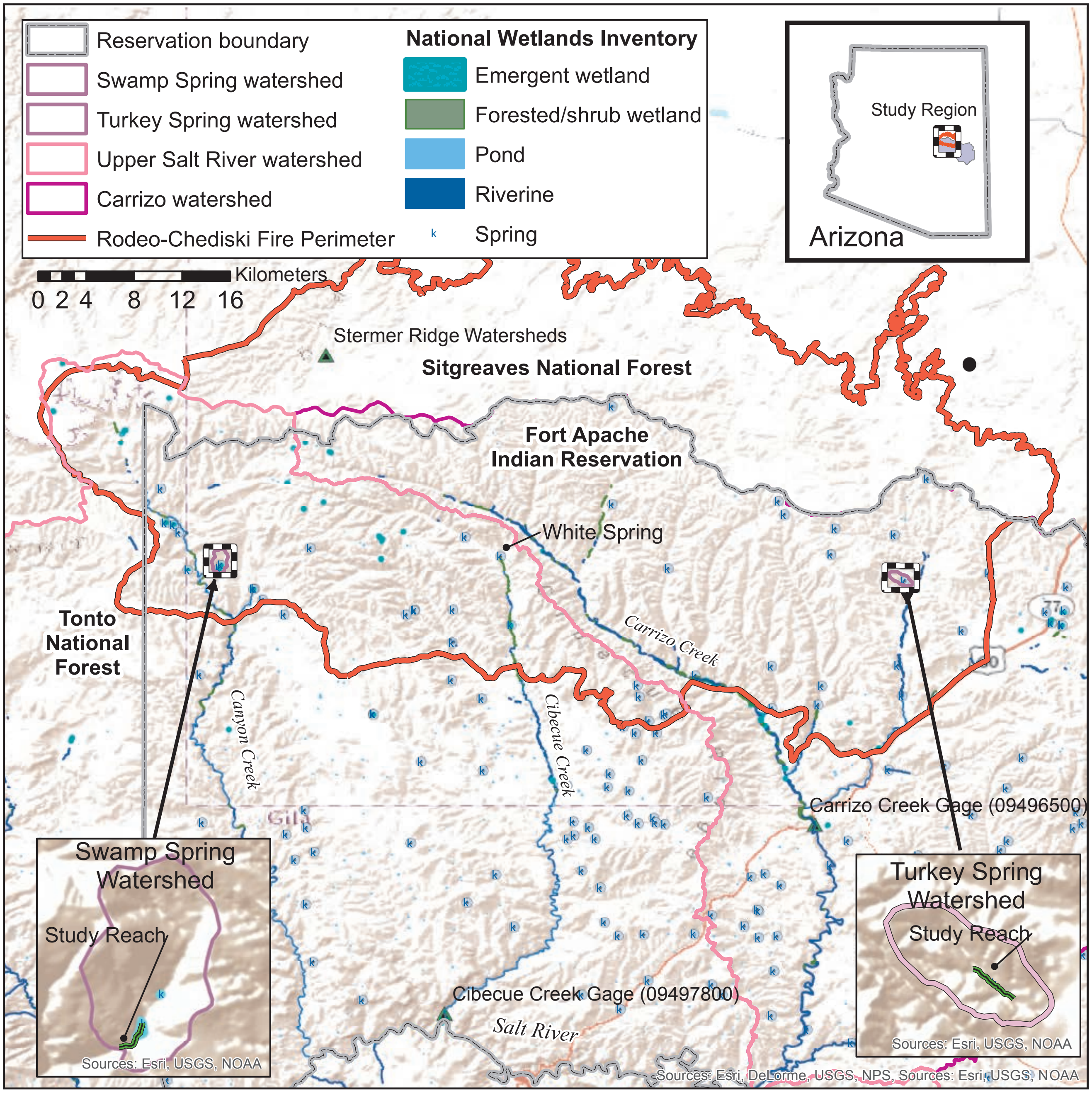

Figure 1. Map of the west side of the Fort Apache Indian Reservation (Arizona, U.S.) and the Rodeo-Chediski wildfire, featuring streams and wetlands in the National Wetlands Inventory (USFWS 2014) and USGS stream gages. The two inset maps highlight the study watersheds.

without treatment. However, researchers have noted that high severity fires can induce progressive incision of headwater channels as nickpoints, or abrupt drops in the longitudinal profile, develop and migrate upstream (Moody and Kinner 2006). Channel incision, especially in wet meadows, is a syndrome that triggers a cascade of geomorphic, hydrologic, and biological effects, including bank erosion, loss of fine substrates, lowered water tables, shifts in vegetative communities, and entrenched channels, which in turn can degrade habitat and water quality (Shields et al. 2010).

Authors of a recent stream evolution model have theorized that intermittent mountain meadows may have anastomosing or single-thread channels that have high habitat and ecosystem benefits (Cluer and Thorne 2014). They explain that those values diminish as the channels first degrade and then widen, but that those values can gradually recover as the channel aggrades, reestablishes a floodplain, and resumes a sinuous pathway. Alternative conditions include a channelized form and an arrested degradation form in which channels are constrained by artificially or naturally erosion-resistant beds and banks;

these were characterized as "dead-end" stages with low productivity and value. Key indicators that accompany the normal progression of stages include net losses of cross-sectional area and narrowing and deepening of the channel during the degradation stage, followed by widening (Olson-Rutz and Marlow 1992). At the next stage the channel begins to aggrade, with vegetative growth trapping fine sediments to accelerate that evolution. However, recovery of instream aquatic wildlife is generally slower and less complete than hydrogeomorphic recovery (Cluer and Thorne 2014). In particular, reduced shade, increased temperatures, and lack of instream features such as riffles can impede reestablishment of those aquatic communities (Dunham et al. 2007).

Both pre-fire prevention and post-fire intervention may be important for avoiding the pernicious effects of incision in valuable headwater wetlands. However, researchers and managers have provided little evidence to justify post-fire channel treatments for implementation under the Burned Area Emergency Rehabilitation (BAER, the federal program to stabilize areas following wildfires) except where threats to downstream values are great (Robichaud et al. 2000). In-channel treatments commonly applied in post-fire settings included placement of checkdams or larger structures made from logs, straw, rock, or rock placed within gabion baskets to provide grade control or to armor streambanks (Robichaud et al. 2000). However, post-fire reviews have criticized placement of instream-structures following wildfires, based upon the cost of such treatments and the principle that localized erosion generated ecological benefits in the form of freshly deposited sediments further downsteam (Beschta et al. 2004). A catalog of post-fire treatments suggests considering checkdams primarily for watersheds less than 2 ha (Napper 2006). Use of larger log or rock grade stabilizers has also been discouraged based upon lack of evidence that they were effective (Robichaud et al. 2000). Reviews have found that structural treatments of degraded wet meadows even in non-wildfire contexts have often appeared ineffective (Pope et al. 2015). On the other hand, studies have reported benefits from structural treatments that raised water tables in wet meadows (Ramstead et al. 2012) and marshes (Norman et al. 2014) Indeed, both Heede (1977) and more recently Zeedyk and Jansens (2009) have argued that without structural intervention, reattainment of dynamic equilibrium in rapidly incising channels would be very slow and costly. The variation in perspectives regarding structural interventions suggests that long-term evaluations are needed to determine the contexts in which such treatments may be beneficial.

In the 1990s, the White Mountain Apache Tribe in Arizona worked with USDA Forest Service researchers to test a technique to arrest erosion and restart formative processes in incising, low-to-moderate gradient channels in wet meadows on the wetter, higher-elevation eastern side of the Reservation. This "riffle formation" technique involved placement of heterogeneous mixtures of gravels and cobbles, reinforced with *Carex* (sedge) transplants (Medina and Long 2004). These formations are comparable to typical loose rock check dams; however, the formations are longer than typical checkdams and rely on the incorporation of the vegetation transplants to bind the materials (Medina and Long 2004). Because they do not include metal posts or gabion baskets, the formations are deformable during high flows. Both sites in this study were proposed for a scaled-up version of the riffle treatment using larger rock materials, even though their watersheds were considerably smaller than those where the technique had been piloted, because the channels were steeper and were moving larger rocks following the fire (Figure 2).

The objectives of this study were to record and quantify changes in channel morphology and streamside vegetation at two riparian wetland sites following the Rodeo-Chediski wildfire. The two sites are both located on the Fort Apache Indian Reservation (Figure 1), which is the homeland of the White Mountain Apache Tribe. One site, Turkey Spring, was largely untreated until 2014, while a second wet meadow site, Swamp Spring, was treated in 2005 through placement of rock riffle formations to provide grade control and reestablish favorable conditions for vegetation growth. An important element of the study was to train and engage staff and students from the Tribe to implement and monitor restoration efforts. Engaging community members in monitoring the conditions of local waterbodies was a strategy to develop community capacity and encourage long-term monitoring and recovery after the devastating fire (Burnette and DeHose 2009). Researchers have suggested that community engagement in monitoring may enhance resilience of local socioecological systems by helping communities better understand complex dynamics, adapt to changing conditions, and develop locally workable and effective stewardship practices (Fernandez-Gimenez et al. 2008).

Methods

Study Site Characteristics

Turkey Spring and Swamp Spring are both located in headwaters of the Mogollon Highlands of east-central Arizona and they share a number of similar attributes including watershed area, elevation, and soil texture (Figure 1, Table 1). However, the sites have different parent materials and topography. In particular, the soil erosion hazard at Swamp Spring was rated as much more severe owing to steep slopes of Swamp Creek Mountain (Mitchell 1981), and the channel gradient was steeper (Table 1). However, the wet meadow east of the reach at Swamp Spring was much larger and wetter than the relatively narrow wet meadow at Turkey Spring.

Another important difference was that the Swamp Spring site had experienced channel incision years before

Figure 2. Repeated photo points at Turkey Spring, Arizona, U.S. The top three rows of photopoints depict headcutting at three major nickpoints after the fire in 2002. The photo from November 2002 shows that channel incision was not yet continuous, but flows were moving very large rocks. Photos from 2003 to 2010 show that the channel deepened by over 4 m. Subsequent channel widening combined with placement of riffle formations in 2004 facilitated regrowth of vegetation by June 2015. The bottom row of photos shows a narrow, unincised channel next to a livestock watering drinker installed in 1959 (photo courtesy of Bureau of Indian Affairs, Branch of Land Operations). By September 2003 (photo taken from a slightly different angle), the channel had incised to the point that it was longer visible from this location.

the fire, as demonstrated by the presence of mature *Acer negundo* (boxelder) trees along the banks of the incised stream. Road construction to access a nearby iron mine in the 1930's may have been a cause of this incision. An aerial photograph of the Turkey Spring site from 1993 (not shown) suggested that a road crossing the channel may also have contributed to some localized incision before the fire. Furthermore, a photograph of Turkey Spring in 1959 (Figure 2) reveals a narrow (< 1 m) stream of water flowing on the surface of a narrow valley bordered by *Pinus ponderosa* (ponderosa pine) trees, with no indications of channel incision.

Table 1. Characteristics of study site watersheds

Characteristic	Turkey Spring	Swamp Spring
Strahler stream order	1st–2nd	2nd
Watershed area (ha)	112	169
Initial BAER soil burn severity	83% high, 17% medium-low	98.8% high, 1.2% medium-low)
Vegetative burn severity based upon RdNBR one year post-fire	24% high, 61% moderate, 11% low	60% high, 32% moderate, 6% low
Elevation (m)	1850	1830
Aspect	East-facing	South-facing
Parent materials	Coconino formation	Troy Quartzite formation
Soil map unit (Mitchell 1981)	Elledge sandy loam, eroded, 8 to 15 percent slopes in the valley bottom, below Telephone-Rock outcrop complex, 30 to 50 percent slopes	Elledge-Overgaard-Rock outcrop complex, 30 to 50 percent slopes
Soil erosion hazard rating (Mitchell 1981)	Moderate for both map units	Severe
Channel gradient	6.8% measured between the 0 m and 205 m markers	9.3% measured between the 0 m and 284 m markers
Dominant streamside vegetation	*Eleocharis* (spikerushes), *Schoenoplectus pungens* (three-square bulrush), *Juncus saximontanus* (Rocky Mountain rush), *Juncus balticus* (Baltic rush), *Carex pellita* (woolly sedge), and *Equisetum arvense* (field horsetail)	*Eleocharis*, *Schoenoplectus pungens*, *Schoenoplectus acutus* (hardstem bulrush), *Scirpus microcarpus*, *Juncus saximontanus*, *Juncus balticus*, *Carex pellita*, and *Equisetum arvense*

Burn Severity and Post-fire Stormflows

Most of the watersheds above each of the two sites were mapped as having burned during 2002 at high severity in the initial BAER assessment (Table 1), which used post-fire satellite imagery but focused on soil indicators to identify areas with potential for accelerated post-fire erosion or flooding (see Safford et al. 2008). Although there was widespread mortality of trees in both watersheds, the vegetation burn severity mapped using relative differenced Normalized Burn Ratio (RdNBR) (MTBS 2009) one year after the fire indicated a much more moderate severity burn across much of the Turkey Spring watershed (Table 1), likely owing to rapid growth of shrubs. Precipitation and stormflows were not measured directly at the sites, but measurements from nearby locations may provide reasonable proxies of events that likely triggered the erosion. Notably, Ffolliott et al. (2011) reported measuring the largest known post-fire increase in peak stormflows in southwestern *P. ponderosa* forests from the small (24 ha) Stermer Ridge experimental watershed that the Rodeo-Chediski Fire also burned at high severity (Figure 1). The closest stream gage downstream from Turkey Spring, on Carrizo Creek (USGS gage 09496500) (Figure 1), recorded a total of eight floods that exceeded 34 m^3/s between July 16 and September 10, 2002, and 10 more such floods occurred the following year (McCormack et al. 2003). Those events were the largest floods in the watershed since the large winter floods of 1993 and 1995. Ffolliott et al. (2011) characterized the flood event on August 5 as a 100-year stormflow resulting from a 10-year precipitation event.

Post-fire Treatments

Throughout the wildfire, hillslopes that burned at high severity were aerially seeded using a mix of native grasses and forbs along with non-native sterile *Triticum aestivum* (common wheat) (Shive et al. 2013) and many were also replanted with tree seedlings. Dead *P. ponderosa* trees were felled and removed at the Turkey Spring site, in part to deter erosion from cantilever bank failures. In-channel treatments were not implemented at Turkey Spring until 2014 when crews placed gravel and cobble riffle formations along the study reach (Figure 3). Treatments at Swamp Spring began in 2005 with the placement of 10 rock riffle formations (Figure 4), which included very large rocks between 400–900 mm wide and were subsequently planted with wildlings of *Carex pellita* (woolly sedge) and *Scirpus microcarpus* (smallfruit bulrush). In addition, the failed culvert above the meadow was replaced with a rock-reinforced low-water crossing, and the very large scour hole below the steepest nickpoint was filled with large rock.

Monitoring

Combinations of tribal staff and students from the tribal community of Cibecue visited Swamp Spring nearly every year from 2004 through 2015. Tribal staff monitored conditions at Turkey Spring initially in the winter of 2003–2004, and they resumed monitoring in 2009 after roads that had provided access to the site were rendered passable following a period of widespread erosion. To evaluate physical changes at the site, we relied on repeat photography and repeated measurements of channel geomorphology. To simplify presentation of the longitudinal

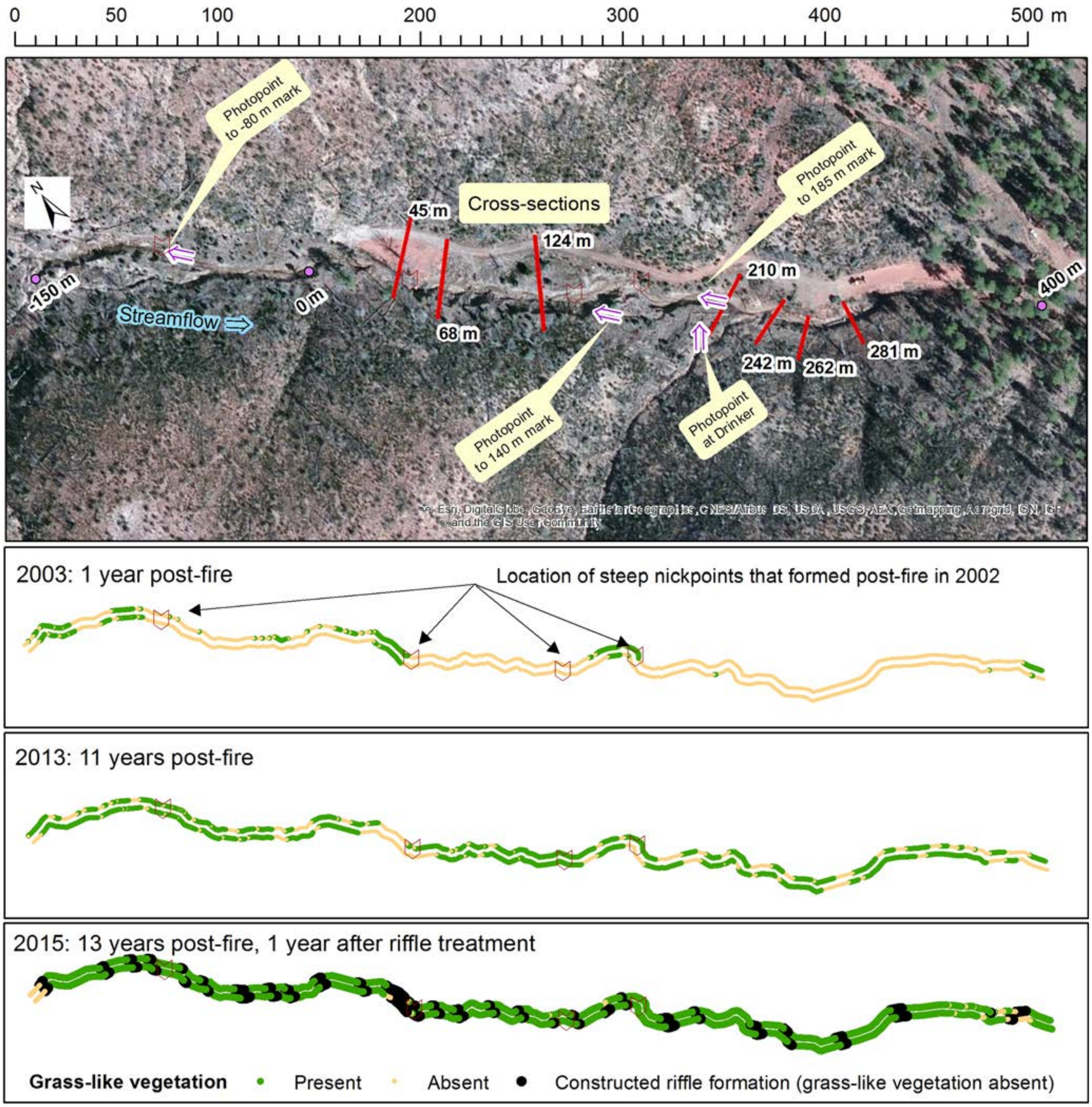

Figure 3. Planform view of the Turkey Spring site overlaid on an aerial photograph (post-fire, 2012) showing the reference points for monitoring, including locations of cross-sections, steep nickpoints and photopoints. Surveys along the 550 m reach recorded changes in the presence of grass-like vegetation and the location of riffle formations that were placed in 2014.

data, we compared conditions at Turkey Spring for the time periods between 2004 and 2010 (the period of most active erosion at Turkey Spring), 2010–2014 (when the site was relatively stable), and 2014–2015 (after the site was treated with riffle formations). For Swamp Spring, we compared changes in morphology between 2004 and 2009/2010 to evaluate initial effects of treatment, with some additional surveys in 2014–2015 to evaluate longer term conditions.

Post-fire Channel Geomorphic Surveys

The study reach at Turkey Spring was 550 m long (Figure 3), while the study reach at Swamp Spring was 400 m long (Figure 4). The reaches began upstream of the active nickpoints and ended where the valleys became very constricted. Despite extensive erosion at the sites, teams were able to relocate control points to calculate rates of erosion over time through repeated surveys of channel dimensions,

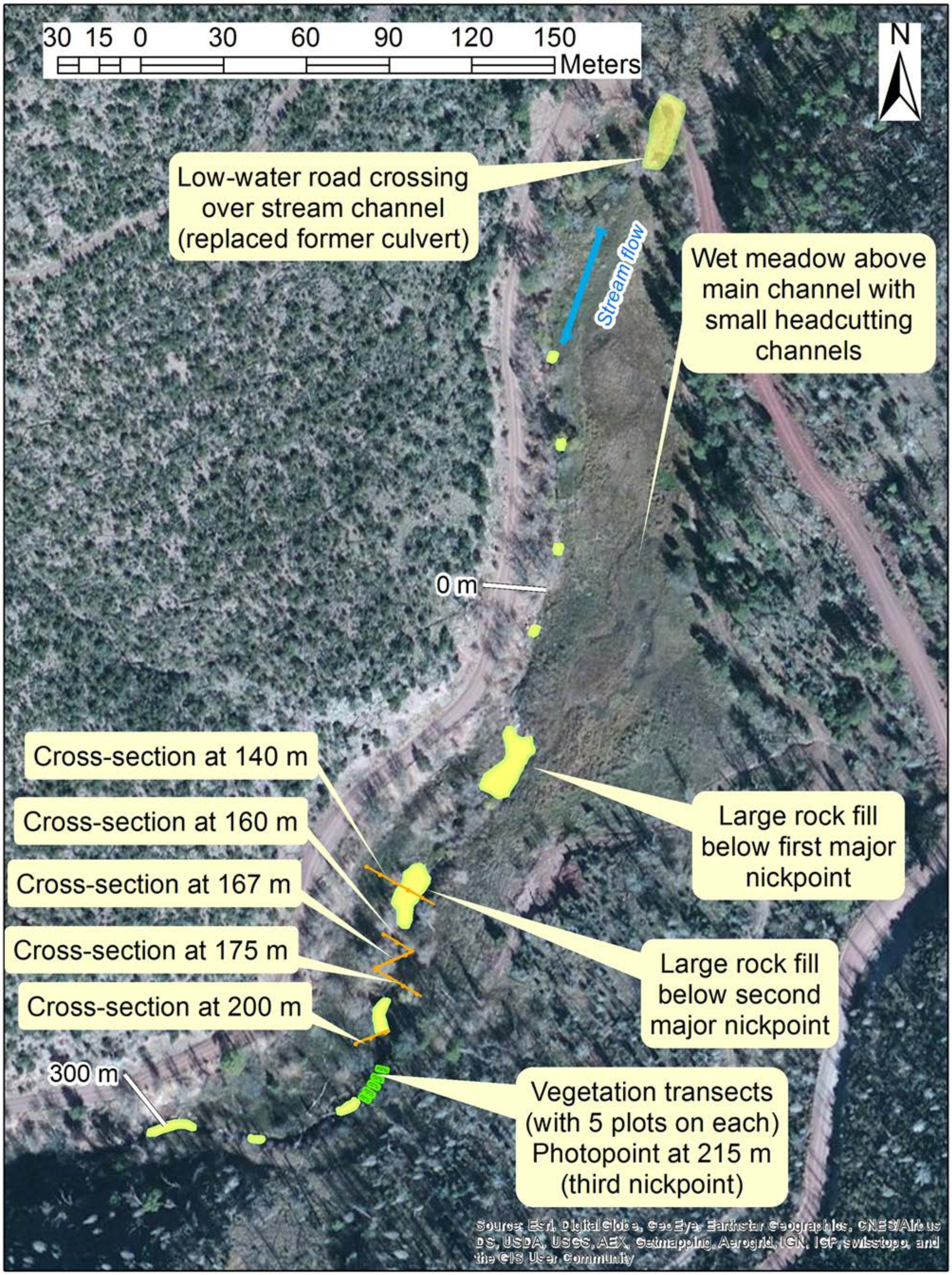

Figure 4. Map of the Swamp Spring site (Arizona, U.S.) showing the reference points for monitoring, including locations of cross-sections, riffle formations, vegetation plots, and a photopoint, overlaid on an aerial photograph (post-fire, 2012).

including channel cross-sections and longitudinal profiles using self-leveling level or total stations (Harrelson et al. 1994). We calculated changes in cross-sectional area (Olson-Rutz and Marlow 1992) since the previous measurement at 7 cross-sections at Turkey Spring and 5 at Swamp Spring using WINXSPRO software (version 2.0, USDA Forest Service, Fort Collins, CO). We also estimated the volume of soil lost at Turkey Spring between 2004 and 2010 through repeated measures of the cross-sectional area of the channel below the flat meadow surface at 5-m intervals along the study reach. We were unable to estimate change in volume reliably at Swamp Spring because there the break between the valley floor and the channel (the "top") was too complex and uneven to consistently measure, but the changes in area at the monument cross-sections can be compared to those at Turkey Spring.

Radiocarbon Dating

To estimate the age of soils underlying the meadow at Turkey Spring, we examined the stratigraphy of the cut bank and obtained radiocarbon dates for three samples of charcoal buried in exposed debris flows at depths of 0.9, 1.4, and 4.1 m. Three samples were sent to the University of Arizona, Accelerator Mass Spectrometry (AMS) lab for 14C analysis then calibrated to actual dates using OxCal 4.2 (Bronk Ramsey 2009). Although the first author observed similar charcoal in layers at Swamp Spring, the channel treatments buried those exposed layers before we planned to collect samples.

Vegetation

Monitoring riparian vegetation in ways that are precise, accurate, and feasible for summer field crews is challenging, although many methods can be effective in quantifying large changes in vegetation cover (Coles-Ritchie et al. 2004). Due to constraints on time and to explore the feasibility of different approaches, crews used different methods for monitoring vegetation changes at each site. At Turkey Spring, we evaluated the extent of vegetative recovery in 2003 (shortly after the fire), 2013 (11 years post-fire, but before treatment), and 2015 (after the riffle treatment). Crews established line transects along each edge of the stream (the low-water mark on each side of the stream) along the entire 550 m study reach using fixed starting points. Crews recorded the presence/absence of grass-like vegetation (specifically plants in the genera *Carex, Eleocharis, Schoenoplectus, Scirpus*, *Juncus,* and *Equisetum*) along the transects, with gaps longer than 0.1 m recorded as absences. The crews also recorded the presence of constructed riffle features placed in 2014–2015. We prepared a graphical representation of these data in ArcMap (version 10.1, ESRI, Redlands, CA) to show changes over time throughout the study reach (Figure 3).

At Swamp Spring, crews measured ground cover along five transects each containing five quadrats (each 80 × 20 cm) placed across the low-water channel above one of the riffle features (Figure 4). They estimated ground cover using classes suggested by Bailey and Poulton (1968) for the following categories: exposed soil (< 2 mm unconsolidated particles), hardpan (compacted clay); gravel (2–64 mm); cobble (64–256 mm); boulder/bedrock (rock > 256 mm); litter; and canopy cover of live plants (Long et al. 2003b). For analysis, we summed live plant cover for the following categories: grass-like plants (same taxa as above); aquatic forbs including *Nasturtium officinale* (watercress); *Veronica* sp. (speedwell) and *Mimulus guttatus* (monkeyflower); other forbs; and grasses (non-aquatic species). We applied a permutation test of mean difference for paired data in R (version 3.1.0, R Core Team, Vienna, Austria) to evaluate the likelihood that the changes between the two periods were due to chance alone.

Differences between the two methods prevent direct comparisons of vegetative cover between the two sites. The line transects at Turkey Spring provided a relatively rapid method for students and staff to collect information throughout the entire reach, while the quadrats at Swamp Spring detailed changes within a shorter reach, and yet took more time and required more training in estimating cover. The line transect method yielded higher cover estimates than did the quadrats, because observers ignored small gaps in the canopy. Although not directly comparable, the results from both methods help to quantify the changes over time that are evident in repeat photographs.

Photo Sequences

Photographs were taken at various locations at Turkey Spring beginning in November 2002 (6 months post-fire) (Figure 2) and Swamp Spring beginning in September 2002 (3 months post-fire) (Figure 5). The extensive erosion complicated photo retakes, but the use of a GPS-enabled camera in more recent years facilitated repositioning. The photos complemented the quantitative survey data by illustrating how vegetation and nickpoints changed. The use of photos taken over time at the same location has been recommended for documenting changes and communicating effects that might easily be missed through in-stream measures of water quality and habitat (MacDonald and Smart 1993). We found only one oblique photo of the channel Turkey Spring prior to the fire, taken in 1959 (Figure 2), and none for Swamp Spring.

Results

Initial Signs of Degradation

Both sites experienced channel incision and lateral bank erosion following stormflows in the first year after the fire. The channel incision exposed extensive layers of finely-textured organic hardpans at each site. Initial surveys (Figures 2 and 3) revealed the presence of steep nickpoints,

Figure 5. Swamp Spring photo point at 215 m on the surveyed reach, note that the hanging, broken branch at center for reference. In September 2002, there was a 1.5 m high channel nickpoint. In the following two years, the nickpoint migrated upstream, and large chunks of the meadow on the upright were sloughing into the channel. In June 2005, students and volunteers planted *Carex* and *Scirpus* transplants on top of the newly placed riffle formation, which contributed to rapid growth of dense vegetative cover that has persisted.

Table 2. Channel volume along the 550 m reach at the Turkey Spring site during the initial survey (February 2004) and a repeat survey in June 2010. The difference represents net soil loss from the site.

Attribute	2004	2010	Change 2004–2010	Average change per year
Channel volume (m^3)	997.3	9716.0	8718.8	1377.4
Channel volume (m^3) / distance (m) = Channel area (m^2)	1.8	17.7	15.9	2.5
Channel volume / surface area = average depth (m)	0.6	1.8	1.3	0.2
Channel volume (m^3) / area of study watershed (ha)	8.9	86.4	77.6	12.3

which indicate high potential for meadow incision (Chambers and Miller 2011). We included photo sequences that reveal the changes at three such nickpoints at Turkey Spring (Figure 2) and one at Swamp Spring (Figure 5). Channel incision at Turkey Spring was initially discontinuous, with intervening reaches that initially resisted incision due to armoring by gravels and cobbles, tree roots, and the cohesive organic horizons (Figure 2). At Swamp Spring, erosion not only formed steep nickpoints along the main channel but also caused mass wasting of soils from the large wet meadow on the east side of the channel (Figure 5).

Rate and Extent of Channel Erosion

Turkey Spring. Cross-sections reveal extensive erosion due to headcutting that continued until 2010, eight years after the fire (Figure 6). Within the surveyed reach of Turkey Spring, over nine times more erosion occurred in the 6.3 years from February 2004 to June 2010 than the amount eroded from an assumed pre-entrenched condition to February 2004 (1.7 years post-fire) (Table 2). The deepest incision occurred below the nickpoint at 57 m to about 200 m, as shown in the photos (Figure 2) and cross-section results (Figure 6). Erosion was less extreme below the 200 m point where the valley narrows considerably. Cross-sections between 210 m and 262 m revealed predominantly channel widening after 2004, although further downstream at 281 m, the channel both widened and incised due to headcut retreat. The cross-sections show reductions in cross-sectional area at five of the cross-sections since 2010, with the placement of riffle formations contributing to that aggradation. However, the two deepest cross-sections (68 m and 124 m) showed a small net soil loss as the steep banks continued to slough (Figure 6).

Swamp Spring. The placement of rock formations along the channel (Figure 5) in 2015 reduced the channel area at the cross-sections (Figure 7), particularly in the upper part of the reach where one of the largest rock formations was placed. Since the treatments, the channel cross-sections have shown minor changes, indicating that they have remained stable.

Radiocarbon Dates of Exposed Debris Flows at Turkey Spring

The stratigraphy of the exposed channel wall in the middle of the Turkey Spring site revealed cobble-rich sandy loam to sandy loam soils with spatially distinct charcoal layers interbedded with or below angular to sub-rounded gravel to boulder-sized clasts. We interpreted these features as debris flow flood deposits following prehistoric wildfires. The three samples yielded calendar age dates of AD 722 ± 56 at 0.9 m, AD 623 ± 48 at 1.4 m, and BCE 6,235 ± 140 at 4.1 m.

Indicators of Recovery

Vegetation transects and photo points at the two sites document the recovery of wetland graminoids (e.g., *Eleocharis, C. pellita, Juncus, Schoenoplectus pungens*, and *Scirpus microcarpus*) following the fire. The graphical representations in Figure 3 depict the colonization of the stream channel by native wetland graminoids throughout the treated area of Turkey Spring. That recovery is also evident in the repeat photographs following placement of riffle formations (Figure 2). Native wetland plants had not yet covered the riffle formations themselves as of 2015, although we observed *C. pellita* and *Salix* (willows) beginning to grow through the gravels.

Repeat photographs of the Swamp Spring site (Figure 5) revealed rapid recolonization of the stream channel following treatment in 2005. The most significant changes were growth of wetland and aquatic vegetation, including grass-like plants, aquatic forbs, and algae, as well as associated litter. Meanwhile, the very high amount of exposed hardpan present prior to treatment was replaced by other cover types in the 2009 survey (Table 3).

Discussion

In the aftermath of wildfires, attention is often directed to large rivers where life and property are vulnerable to flooding. The rapid and extensive erosion was a surprising outcome for participants in the long-term monitoring of these two headwater wetlands. Community members and tribal staff learned more about the channel dynamics of headcutting and the potential for recovery, and it led them to implement treatments at Turkey Spring, consistent with an adaptive management approach. Consequently, this

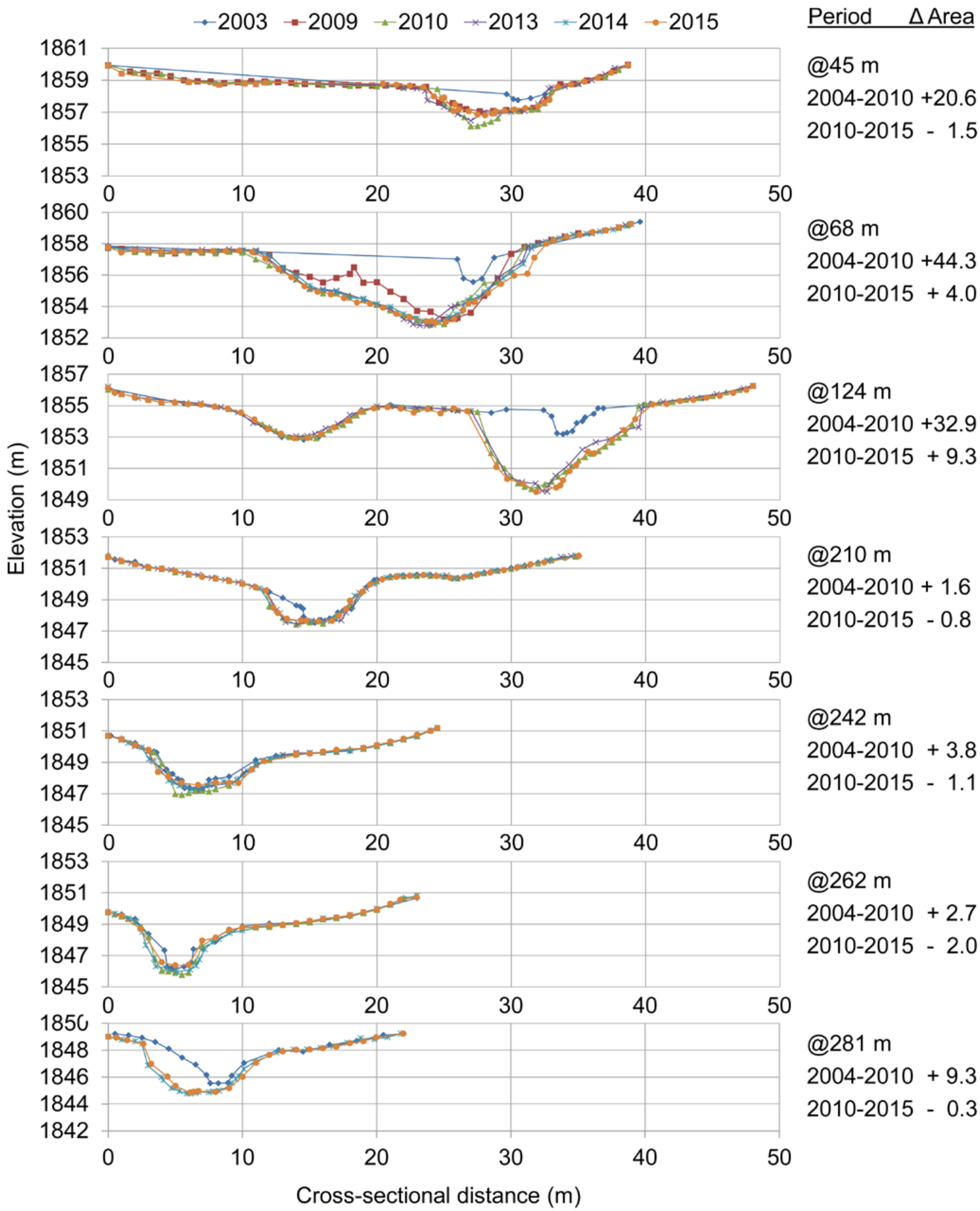

Figure 6. Repeated cross-sections at Turkey Spring site, downstream view, with changes in cross-sectional area (m^2) between sampling periods (positive values signifying erosion, negative values signifying filling).

Table 3. Groundcover (mean ± SD) along transects across the channel at Swamp Spring in June 2004 and June 2009.

Cover component	June–04	June–09	*p*-value (two-sided test)
Soil (< 2 mm, loose)	14.8 ± 12.6	28.4 ± 10.4	0.124
Hardpan (clay)	44.4 ± 31.1	0.0 ± 0.0	< **0.001**
Gravel (2–63 mm)	21.1 ± 13.6	3.0 ± 3.0	0.063
Cobble (64–255 mm)	9.9 ± 11.8	11.7 ± 8.3	0.813
Boulder/Bedrock(≥ 256 mm)	2.1 ± 3.4	3.3 ± 2.7	0.563
Litter	1.2 ± 1.9	4.3 ± 2.9	< **0.001**
Grass-like plants	0.1 ± 0.1	17.4 ± 9.9	< **0.001**
Aquatic forbs	0.4 ± 0.6	10.8 ± 4.5	< **0.001**
Non-aquatic grasses	0.6 ± 1.4	1.8 ± 1.3	0.188
Non-aquatic forbs	0.9 ± 0.9	7.8 ± 7.1	0.062
Algae	0.0 ± 0.0	9.1 ± 9.4	< **0.001**

study demonstrated many of the benefits of local community participation in monitoring that have been postulated by researchers (Fernandez-Gimenez et al. 2008).

Post-fire Erosion

Post-fire erosion typically peaks within the first three years following a fire, although elevated erosion rates have been reported for over a decade following a severe fire in Arizona (Neary et al. 2005). The formation of large gullies in forested areas has been rarely featured in post-fire literature (Shakesby and Doerr 2006). Consequently, the extensive channel erosion observed at both sites is unusual, and the amount at Turkey Spring is particularly remarkable when compared to previous studies of gully erosion. For example, the 2.5 m^3/m/year of erosion observed at Turkey Spring between 2004 and 2010 was much higher than the 0.16 m^3/m/year for gullies that were not structurally treated in a study in Colorado by Heede (1977); however, erosion at that site was the result of long-term grazing impacts rather than post-fire flooding.

Recovery Rates and Extent

Cessation of downcutting, stabilization of nickpoints, widening of the channel, and regrowth of vegetation indicate progression toward a more productive condition, according to the criteria by Cluer and Thorne (2014). These indicators were present soon after treatment at Swamp Spring in 2005; however, such stabilization appeared to take another 5–7 years at Turkey Spring without intervention. Treatments at Turkey Spring starting in 2014 induced aggradation and may have accelerated vegetative growth. Wetland conditions, including luxuriant obligate plants such as *Eleocharis* (spikerush), *Juncus* (rushes), and *Carex* (sedges), have reestablished in the channels, but the channels are confined in relatively narrow floodplains. The lowering of the water table, combined with losses of organic matter and fine-textured soils, likely constitute a persistent decline in productivity and wildlife habitat quality, particularly at the formerly unincised meadow of Turkey Spring.

Applicability to Other Sites

This study cannot separate the relative contributions of the unusually severe wildfire from the pre-existing instability associated with roads and past incision associated with failed stream crossings. However, most sites along the Mogollon Rim, except those in wilderness areas, have similar histories of land use and potential for high-severity fires. The primary treatment was not randomly assigned nor strictly replicated, although managers chose to treat Swamp Spring first based on their fears that erosion would be actually be worse there, and important watershed attributes including erosion hazard and burn severity were consistent with those concerns. The striking outcomes at the two sites offer compelling demonstrations of the potential benefits of interventions where headwater meadows are threatened by rapid headcutting following fires.

A Long-term View on Fire Impacts

An important question is whether the kind of post-fire erosion observed at these sites might be considered natural or even beneficial from a long-term perspective. Post-fire debris flows from headwater reaches are an important geomorphic process because they can rejuvenate downstream habitats (Dunham et al. 2007). The radiocarbon dates for the two debris flows sampled at Turkey Spring appear to coincide with major droughts and fire-related sedimentation reported for the Southwestern U.S. by Frechette and Meyer (2009) and Waters and Haynes (2001). This evidence suggests that high-severity fire and flood events may have occurred several times in the past few thousand years. However, those events resulted in filling of the valley, or pyrocolluviation as described by Buckman et al. (2009). In this study, however, post-fire erosion shifted the Turkey Spring site from a relatively unincised wet meadow with deep organic soil layers to a deeply entrenched channel with relatively depauperate habitat for over 8 years. Meanwhile, the erosion constituted a huge export of sediment from headwater channels, where they supported important habitat values, toward the downstream reservoir of Roosevelt Lake where sedimentation has had costly impacts.

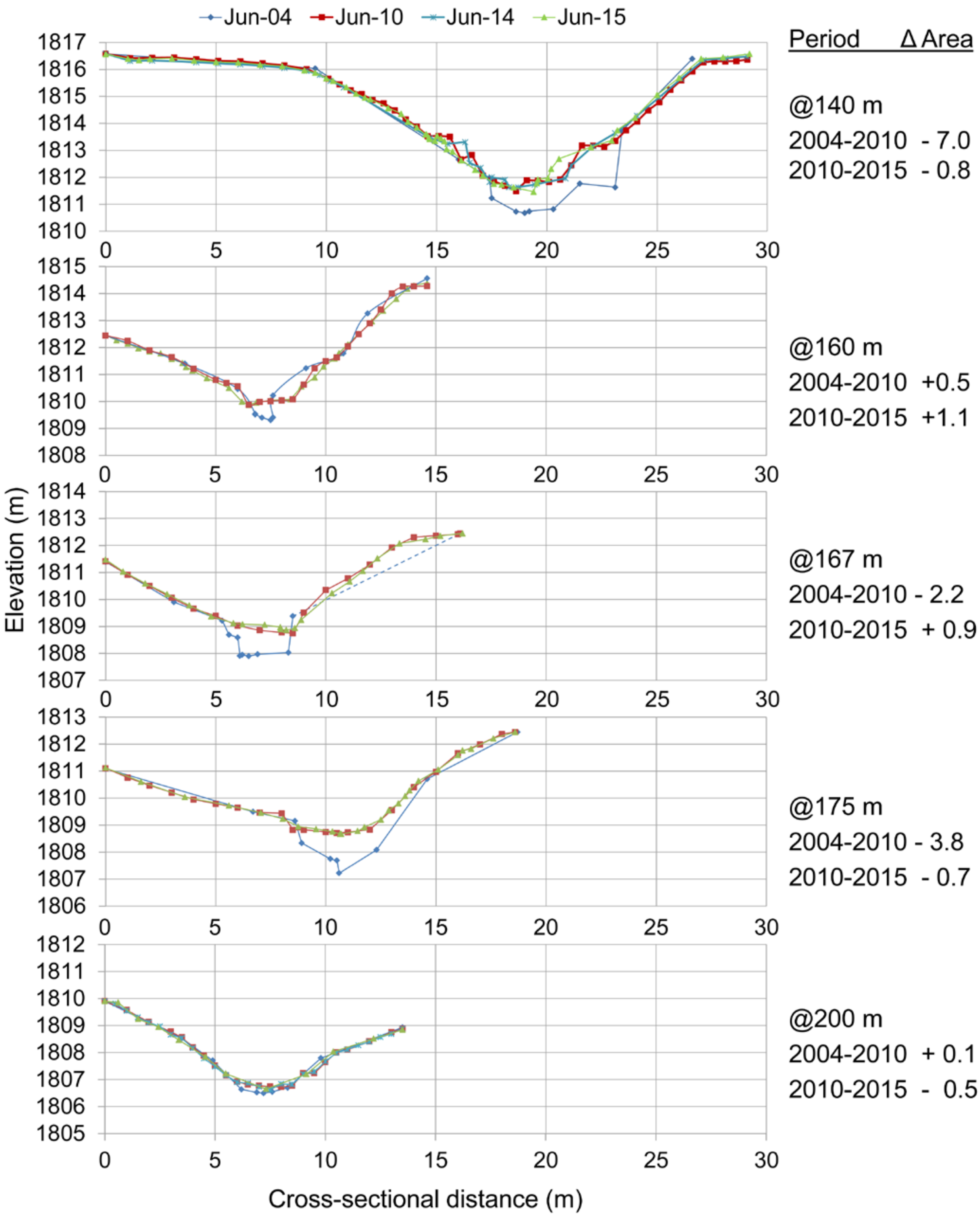

Figure 7. Repeated cross-sections at Swamp Spring site, downstream view, with changes in cross-sectional area (m^2) between sampling periods (positive values signifying erosion, negative values signifying filling).

This study is consistent with earlier research identifying this region as one of the highest risk areas in the U.S. for post-fire impacts to downstream reservoirs (Moody and Martin 2004). The findings also reinforce previous studies that noted that relatively small areas along stream channels can be a dominant source of eroded sediment following wildfires (Moody and Martin 2001).

Channel incision may eventually stop when the channel exposes naturally erosion-resistant layers, but such conditions represent a low productivity "dead end" state (Cluer and Thorne (2014). However, Cluer and Thorne (2014) have suggested that restoring rivers to aggradational, but still incised channels, is a relatively ineffective strategy unless the channel is deformable. Although the channels at the two study sites remain confined, the riffle formations do allow for lateral movement of the channel. The extensive growth of wetland vegetation may encourage continued aggradation. Zeedyk and Jansens (2009) proposed an alternative strategy of constructing dams with a single tier of large rocks that would be reinforced by incoming bedload and supplemented over time. However, it may take many years for coarse sediments to accumulate in upstream channels and for another major disturbance to deliver them to the treated reaches. Furthermore, a single treatment (ideally supported by long-term monitoring and maintenance), is likely to be far more practical than multiple treatments over a long period, especially if supported with post-fire recovery funds.

An important question is whether the treated channels will be resilient to future flooding, especially given that climate change is likely to intensify erosion associated with fires and storms (Nearing et al. 2004). The relatively long study at Swamp Spring suggests that minor floods are unlikely to unravel the formations; and the charcoal evidence from the Turkey Spring site suggests that major floods are often associated with infrequent wildfires. The extent, severity, and frequency of future fires may determine whether future floods result in reincision or instead stimulate further aggradation. The potential for such instability has been demonstrated at another spring-fed riparian wetland system, White Spring, which is located between the two study sites (Figure 1). The relatively small but severe White Springs fire of 1996 triggered headcutting at the site. Because the spring was very important for people from Cibecue, the reach below the spring was treated with large rock riffle formations in 1998 (Long et al. 2005). The watershed above that site was again burned severely by the Rodeo-Chediski Fire just a few years later, and the site experienced major floods and channel adjustments, including dislocation of rocks placed in the main channel below the spring. However, the rock riffle formations placed directly below the spring remained intact and likely helped to maintain lush wetland vegetation growth (Long et al. 2005). The dynamism of wetland systems in this fire-prone landscape demonstrates the need for long-term monitoring to evaluate the effects of interventions, as suggested by Ramstead et al. (2012).

Conclusion

Because wet meadows are rare and valuable, managers, community members, and researchers should anticipate severe erosion in similar landscapes following large and severe fires. While proactive treatments to reduce forest fuels and vulnerability of sensitive wetlands could reduce the need for post-fire interventions, the widespread legacy of roads, skid trails, and grazing impacts renders many sites vulnerable. The results of these case studies add to previous research in suggesting that targeted in-channel interventions can abate local erosion and facilitate channel aggradation and wetland development, even after severe wildfires. Many factors including watershed size, propensity for severe burns, structural design, and site geomorphic characteristics, are likely to influence where such interventions generate lasting benefits. Nevertheless, efforts to accelerate the recovery of rare and ancient wet meadows may be particularly warranted because they are highly valued by local communities.

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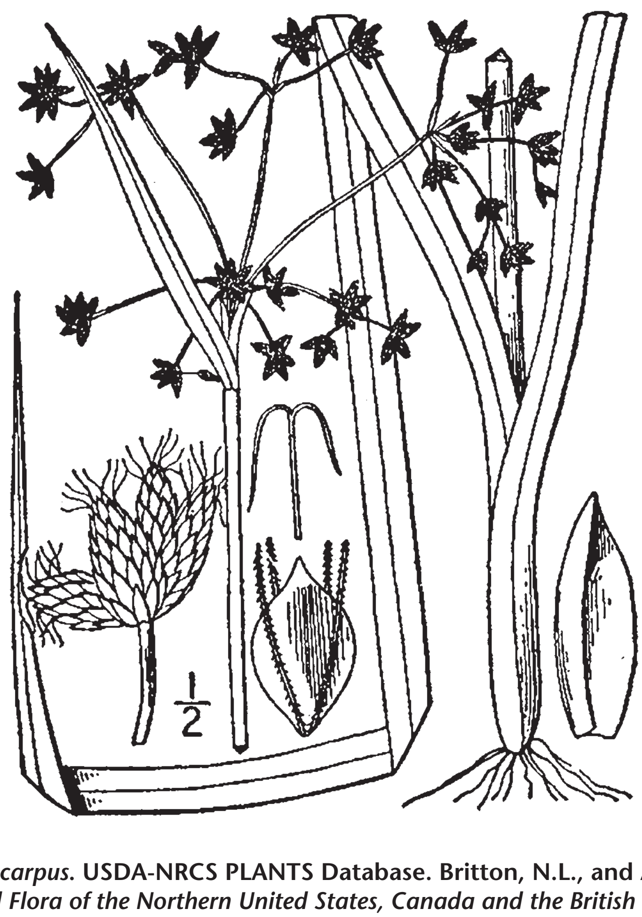

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