Recovering the lost potential of meadows to help mitigate challenges facing California’s forests and water supply

April 12, 2023

FULL RESEARCH ARTICLE

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Published 12 April 2023 • www.doi.org/10.51492/cfwj.109.3

Abstract

Groundwater systems in snow-dominated drainage areas supply cool baseflows that support instream and downstream users late into the dry season. Yet, these catchments are becoming rarer with climate change and anthropogenic pressures that threaten groundwater systems. Restoration of low-gradient meadows and streams can recover a catchment’s natural storage potential, especially in Mediterranean biomes such as the Sierra Nevada of California where summer groundwater recharge is scarce. The degradation of meadows due to intense human modification has decreased groundwater elevations and shifted wet meadow plant communities toward more xeric forest and shrub communities. We applied machine learning tools to find potential “lost meadows” that may no longer support high groundwater elevations or meadow vegetation but do exhibit basic geomorphic and climatic characteristics similar to existing meadows. The model reveals potential meadow habitat in the Sierra Nevada of nearly three times its current extent. We offer two conceptual applications of the model for incorporating meadows in watershed restoration planning. The first application focuses on strategically expanding wet meadows already associated with fuel breaks for increasing wildfire resistance. The second shows how meadow restoration in post-wildfire landscapes could increase capture of sediment from burned hillslopes where increased sediment storage would benefit water storage. Meadows are important habitats that have become degraded due to long-term overuse. Re-envisioning their potential extent shows that, with restoration, meadows could also serve as components of California’s multi-tiered efforts to manage pressing threats to its forests and water supply.

Key words: climate change, Creek Fire, floodplain connectivity, potential operational delineation, process-based restoration, reservoir sedimentation, Sierra Nevada

Citation: Pope, K. L., and A. K. Cummings. 2023. Recovering the lost potential of meadows to help mitigate challenges facing California’s forests and water supply. California Fish and Wildlife Journal 109:e3.

Editor: Katrina Smith, Wildlife Branch

Submitted: 17 August 2022; **Accepted:** 23 September 2022

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Funding: Support for model development was provided by the U.S. Forest Service, Pacific Southwest Research Station.

Competing Interests: The authors have not declared any competing interests.

Introduction

Groundwater storage associated with headwater streams can maintain ecologically important summer low flows in mountain ecosystems (Tague et al. 2007; Godsey et al. 2014). Snow-dominated catchments (drainage areas from which water collects) that support groundwater-connected meadows tend to retain and slowly release cool water to sustain downstream fisheries, support recreational and water infrastructure needs, and provide valuable refugia for amphibians and aquatic macroinvertebrates (Price 2011; Snyder et al. 2015; Johnson et al. 2017). Climate is the primary control of streamflow dynamics: precipitation as winter snow delays peak runoff and extends groundwater recharge and summer flows, while precipitation as rain translates more directly to discharge with less water retained for groundwater recharge and dry season flows (Li et al. 2017; Jenicek et al. 2018). In addition to climate, catchment geomorphology, soils, and vegetation mediate storage potential by modifying evapotranspiration, infiltration, water release, and storage properties (Poff et al. 1997; Price 2011; Dralle et al. 2020).

Climate change and anthropogenic alterations to flow paths tend to increase the rate at which water flows through headwater catchments. Increases in air temperature will decrease snow and increase rain during winter (Li et al. 2017; Marty et al. 2017), causing earlier peak flows and reductions in summer low flows (Hunsaker et al. 2012; Jenicek et al. 2018). As the ratio of snow to rain decreases, catchment characteristics become more important in determining summer low flow (Merio et al. 2019). Unfortunately, many headwater catchments have been modified resulting in consistently enhanced hillslope-to-channel connectivity and run-off routing, thereby reducing catchment storage and summer low flows (Jones and Grant 1996; Jones 2000; Brown et al. 2018). Infrastructure such as roads, ditches, and diversions intercept diffuse surface and subsurface flow paths and constrict flows through confined, single-thread channels, which quickly transport water to the primary stream channel (Dymond et al. 2014; Pechenick et al. 2014; Wemple et al. 2018; Surfleet and Marks 2021). In addition, post-wildfire landscapes typically have bare, hydrophobic soils that enhance the transport of water off hillslopes into stream channels (Doerr et al. 2006; Malkinson and Wittenberg 2011; Shakesby et al. 2016).

These modifications to run-off in headwater catchments increase the importance of protecting and restoring low-gradient meadow zones where water can slow, spread, and infiltrate into spongy, organic soils thereby delaying run-off. This is especially important in Mediterranean biomes where summer groundwater recharge is scarce, summer wildfires are common, and mountain water resources support multiple water needs (Klausmeyer and Shaw 2009). The Sierra Nevada in California supports the freshwater needs of millions of people (Liu et al. 2021), while also providing habitat for a unique and valuable biota (Green et al. 2022). The Sierra Nevada is experiencing rapid alterations to its hydroclimatic conditions with droughts becoming more common (Maina et al. 2022; Patterson et al. 2022; Wang et al. 2022), and has extensive freshwater habitat degradation (Light and Marchetti 2007; Vernon et al. 2022), yet still serves as an important biodiversity hotspot (Davis et al. 2008; Forister et al. 2010; Abeli et al. 2018).

Meadows are clearly promising restoration targets for the Sierra Nevada because they retain groundwater and sustain summer baseflows (Loheide et al. 2009; Hill and Mitchell-Bruker 2010). Meadows in the Sierra Nevada tend to occur along low gradient benches where surface water slows and groundwater exchange occurs so that a high groundwater table can persist late into the dry season (Wood 1975). These conditions support wetland vegetation, predominantly herbaceous plants, including sedges, other graminoids, and forbs, but also woody plants such as willows that can tolerate low-oxygen soils (Weixelman et al. 2011). In the absence of degradation, wet meadows can improve a catchment's water quality and predictability by attenuating and dispersing flood flows, filtering water through hyporheic exchange, and retaining sediment (Gosselink and Turner 1978; Loheide and Gorelick 2006; Hammersmark et al. 2009; Loheide et al. 2009; Hunt et al. 2018). Meadows also support diverse wildlife communities including pollinators (Ziaje et al. 2018; Jones et al. 2019) and nesting birds (Campos et al. 2020). Great grey owls rely on wet meadows in the Sierra Nevada for vole prey (van Riper and Wagtendonk 2006; Kalinowski et al. 2014). Meadows also store carbon (Norton et al. 2011; Reed et al. 2021), create natural fire breaks (Fairfax and Whittle 2020), and support cultural and recreational activities (Long et al. 2003, Long and Pope 2014).

Unfortunately, most meadows in the Sierra Nevada have been degraded so that they no longer provide the ecological values that they did prior to Euro-American colonization (Kattlemann 1996; Hunsaker et al. 2015). Intensive grazing and associated human manipulation of drainage patterns concentrated flow paths while also causing erosion (Ratliff 1985; Kattlemann 1996; Vernon et al. 2022). People drained meadows to increase the grazable area and allow for road and trail construction: sinuous, multi-threaded, sedge-lined flow paths were concentrated into single, often linear channels. Thus, mountain meadows that had been providing groundwater storage for centuries transitioned to incised channels that concentrated and rapidly transported water flow (Loheide and Booth 2011). Also, water tables dropped dramatically because incised channels drain surface and ground water to the elevation of the new channel bed (Loheide and Gorelick 2005). With the lowered groundwater elevation, forest and scrub vegetation replaced typical meadow vegetation (Halpern et al. 2010; Celis et al. 2017; Lubetkin et al. 2017; Stockdale et al. 2019; Hagedorn and Flower 2021).

Because meadows have been degraded and "lost" to forest encroachment, it is important to identify and quantify these changes to understand the full potential for recovery. We have recently attained the technological capacity to identify potential lost meadows at landscape scales. Given the current rarity (about 2% of the Sierra Nevada) but known value of meadows in the Sierra Nevada, it is important to apply advances in computing power and satellite imagery to gain a complete picture of the potential extent of meadow habitats. To help envision this extent, we trained a machine learning model to predict locations in the Sierra Nevada that may have historically supported meadows prior to human disturbance. We do not claim that all the model-predicted habitats were historically meadows; however, they do represent areas with similar geomorphic and climatic characteristics of extant riparian meadows, so they could be considered when planning restoration activities to maximize groundwater connectivity.

Details about the computational development of the model are described in a separate paper (Cummings et al. In review) and model code and output are available upon request. Here, we summarize model results and explore two example applications to highlight how the resulting maps can be integrated into wildfire management planning and post-wildfire restoration efforts. We discuss how these watershed-scale meadow restoration efforts can be partnered with process-based restoration techniques that address source problems, capitalize on locally sourced natural materials, and use fluvial and biological energy to assist with restoration efforts.

Methods

Overview of Model Development

We used the most complete known dataset of over 18,000 hand-digitized meadows in the Sierra Nevada (Sierra Nevada MultiSource Meadow Polygons Compilation Version 2, SNMMP) obtainable through the UC Davis Sierra Nevada Meadows Data Clearinghouse (**http://meadows.ucdavis.edu**) to create the positive training data for the Lost Meadow Model. The dataset was compiled and reviewed by experts at UC Davis Center for Watershed Science, USDA Forest Service Pacific Southwest Region, and others. The minimum meadow size was 0.1 ha and many small meadows in proximity were grouped into one larger meadow polygon.

We selected 60 Hydrologic Unit Code 10 (HUC-10) watersheds in the Sierra Nevada covering 25,300 km^2 as our study area (**Fig. 1**). We clipped the SNMMP dataset to the study area and further subset it to include only meadows with primary hydrogeomorphic types designated as “riparian” (Weixelman et al. 2011). We focused on riparian meadows because they are fed by both surface water and subsurface groundwater so are greatly affected by channel incision that alters run-off patterns and can be observed in LiDAR-derived imagery. The resulting 11,127 meadows from the SNMMP dataset were used to train a random forest model (Breiman 2001), to locate potential stream-associated historical meadows in the study area (Cummings et al. In review). Random forest models have been found to be highly accurate for land cover classification in heterogeneous landscapes (Rodriguez-Galiano et al. 2012).

Figure 1. Overview of the study area for which the Lost Meadows Model was applied (green

polygon). The model applied a Random Forest approach to identify areas with similar geomorphic and climatic characteristics to existing riparian meadow habitats.

We created the positive training data by randomly sampling 10,00 points across the 60 HUC-10 watersheds from within the SNMMP meadow polygons, and we created the negative training data by randomly sampling 9,000 points across the watersheds that occurred outside of the known meadow polygons. We included fewer positive training points to better mirror the relative rareness of meadows compared to other habitat types while maintaining a large number of training points in each category (Cummings et al. In review). For each point, we derived a suite of geomorphic values from 10 m^2 pixel digital elevation models (DEMs) to predict locations on the landscape that have similar physical characteristics to the extant meadows. The predictors used included local relative elevation, slope, distance to nearest stream channel (3 variables), and topographic wetness index (Cummings et al. In review). We also included median April snowpack for 2010–2020 because snow accumulation has been found to be an important predictor of meadow occurrence (Albano et al. 2019). We did not include vegetation-based predictors because we were specifically looking for locations that may have transitioned to non-meadow vegetation but otherwise have similar characteristics as existing meadows.

We used the randomForest R package (Svetnik et al. 2003) to assess the probability of each pixel in the study area to support potential meadow conditions. High probability meadow pixels that grouped to form at least 0.1 ha were delineated into polygons so we could compare areas of potential meadows to the areas of existing meadows. We did not aggregate multiple small polygons in proximity like was done for the SNMMP dataset. We assessed the model's performance by holding back 20% of the training data and using it to calculate the predictive accuracy for each of the 60 HUC-10 watersheds in the study area. In addition, we used a LiDAR-derived DEM with 1-m accuracy within the Creek Fire boundary to test our hypothesis that model-predicted meadow polygons occurred on similar geomorphic floodplains as the SNMMP meadows and that the predicted meadows had more channel incision (greater width and depth) than the SNMMP meadows (**Fig. 2**). We randomly selected 32 stream segments from SNMMP meadows, model-predicted meadows, and non-meadows and created four 40-m long cross-sections per stream segment. We measured channel slope from 20m above to 20m below each cross-section. For SNMMP and model-predicted cross-sections, we measured depth and width of visible channels through the floodplain. When no channel was apparent, depth and width were recorded as zero. We compared differences in slope across the three categories and channel area between the SNMMP and model-predicted cross-sections. For cross-sections outside of the polygons, channel differentiation from floodplain was more difficult to observe and we did not have any *a priori* hypotheses about expected channel size (**Fig. 2**), so we did not include the category in the channel comparison.

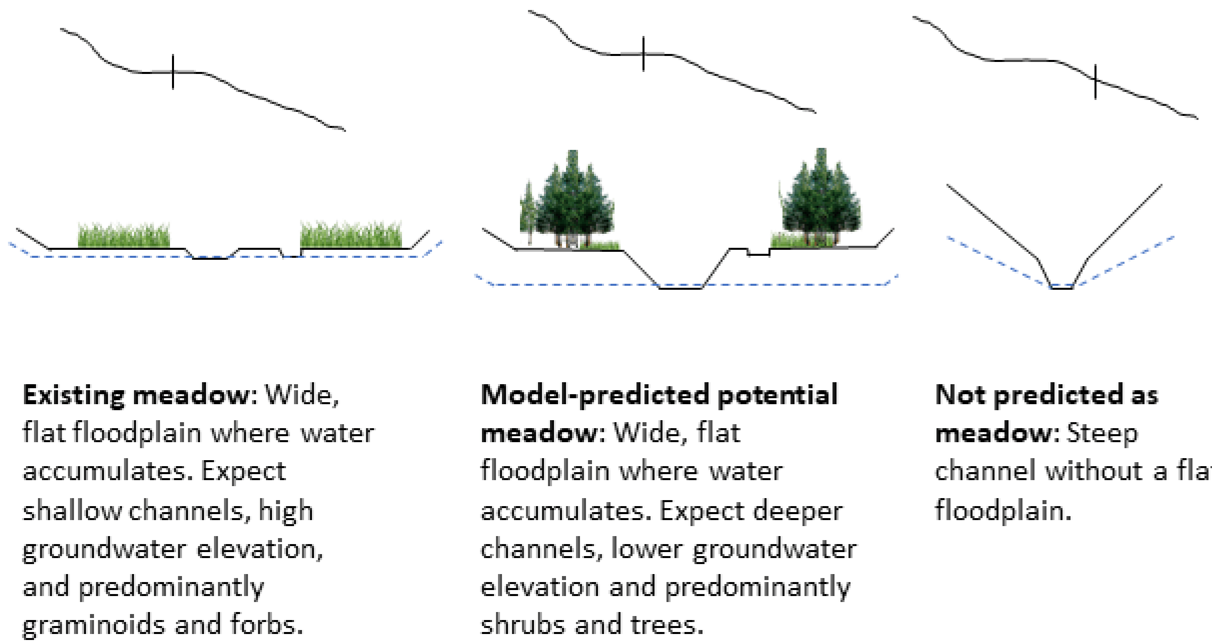

Figure 2. Conceptual cross-sections of an existing meadow stream channel, model-predicted potential meadow stream channel, and a stream segment not predicted as a potential meadow with our expectations described below each diagram. Solid black line represents the ground surface and dashed blue line represents the groundwater elevation. Positions of the cross-sections along a hypothetical long-profile of a stream reach are sketched above each diagram.

Model Application

We used the model output to focus on two watersheds to explore potential applications of the model for restoration planning. The first example focused on the Silver Creek Watershed in the Eldorado National Forest to show how the model output can integrate with wildfire response planning through targeted restoration in areas where potential wet meadows intersect with delineated potential fuel breaks that could serve as control points around fire management units (Wei et al. 2018, Dunn et al. 2020). The second example focused on the Jackass Creek Watershed, which burned in the 2020 Creek Fire, to show how the model output can also be integrated into post-wildfire restoration planning.

Silver Creek Watershed: Integration with Wildfire Response Planning.—Scientists studying wildfire risk have recently introduced potential operational delineations (PODs) as a means to integrate risk-based fire planning in fire-prone landscapes to account for local high value infrastructure and ecological resources while also considering the benefits of wildfire in some areas (Dunn et al. 2020). The POD planning units rely on boundaries defined by potential fuel breaks or fire control locations including ridgelines, roads, and aquatic features such as streams and meadows (Dunn et al. 2020). We overlaid POD boundaries developed for the Silver Creek watershed with existing SNMMP meadow polygons and the Lost Meadows Model output to identify areas where meadow restoration could also serve to improve fire management along POD boundaries (Fig. 3). Better control along these boundaries allows managers more flexibility when deciding whether to let some fires burn in areas where they are beneficial. We created a 50-m buffer around POD boundary lines and calculated the quantity and area of SNMMP and model-predicted polygons adjacent or overlapping with POD boundaries to estimate potential gains in fire resistance by increasing wet meadow habitat to the model-predicted meadow boundaries (Fig. 3).

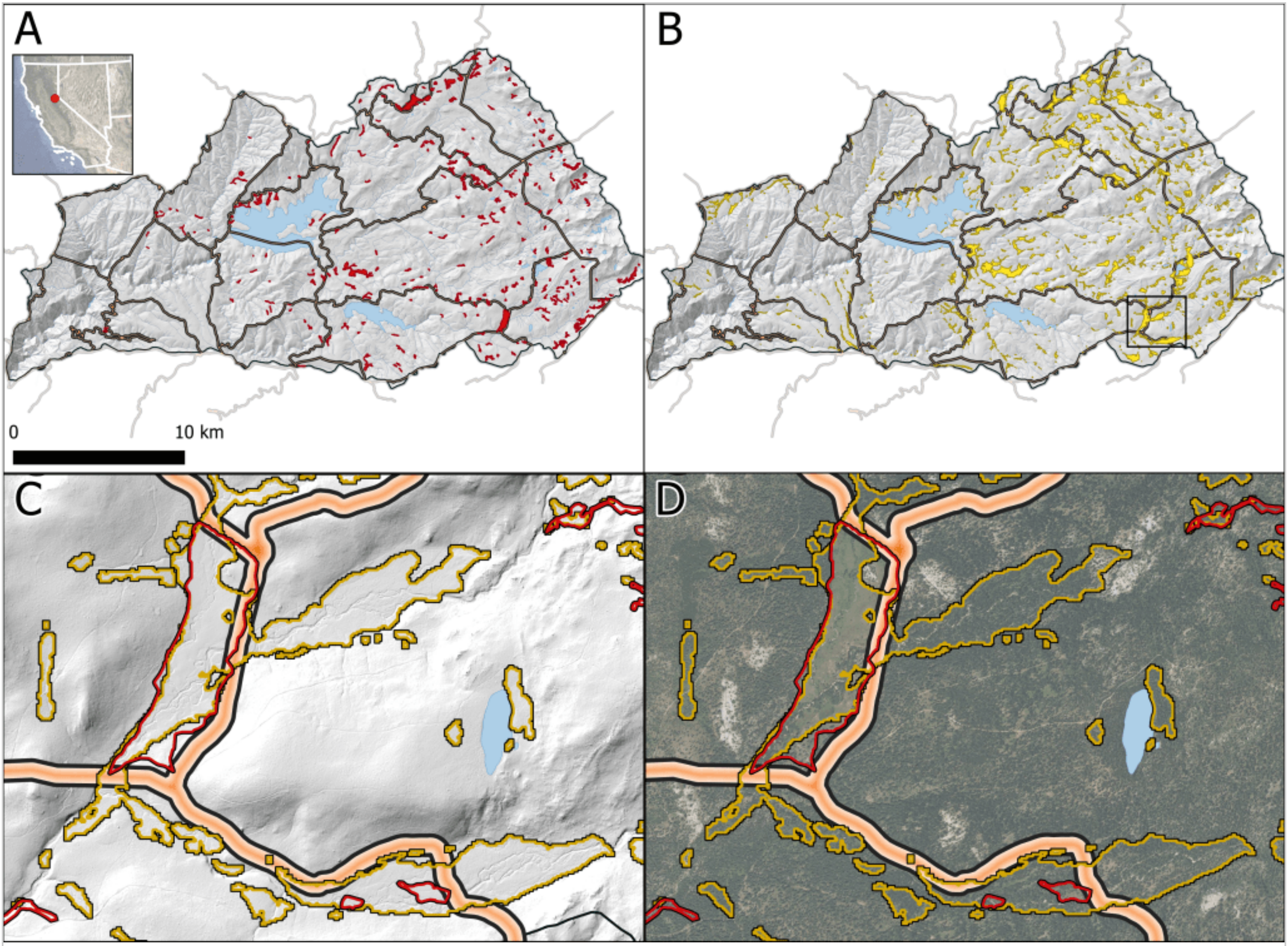

Figure 3. LiDAR-derived hillshade of the Silver Creek Watershed showing Potential Operational Delineation (POD) boundaries in orange and outlined in black, existing, hand-digitized, Sierra Nevada MultiSource Meadow Polygons in red (A), and model-predicted meadows in gold (B). The POD boundaries were delineated to make use of natural and human-made features where wildfire management efforts could be focused to affect fire behavior. The black box highlights an area showing correspondence between meadows and POD boundaries overlaid on LiDAR-derived hillshade (C) and aerial imagery (D). Note in C that much of the model-predicted meadow habitats (polygons outlined in gold) occur within the same flat floodplain as the existing meadow habitat (polygons outlined in red) but can be seen to support conifers instead of meadow vegetation in the aerial image (D). With aquatic restoration, this area may be converted to meadow to increase wildfire resistance near the POD boundaries.

Jackass Creek Watershed: Application to Groundwater Storage and Sediment Capture.—We overlayed model output with existing SNMMP meadow polygons for the Jackass Creek Watershed, a tributary to the San Juaquin River upstream of the Mammoth Pool Reservoir (Fig. 4). The watershed burned in the 2020 Creek Fire, a high severity fire covering 153,738 ha that destroyed over 800 structures and was fueled by a high density of dead and stressed trees caused by drought and bark beetles (Stephens et al. 2022). We estimated potential gains in meadow quantity and area as well as stream lengths within the habitat polygons. Stream lengths were calculated from the National Hydrography Dataset, High Resolution (NHD_HR) streamlines.

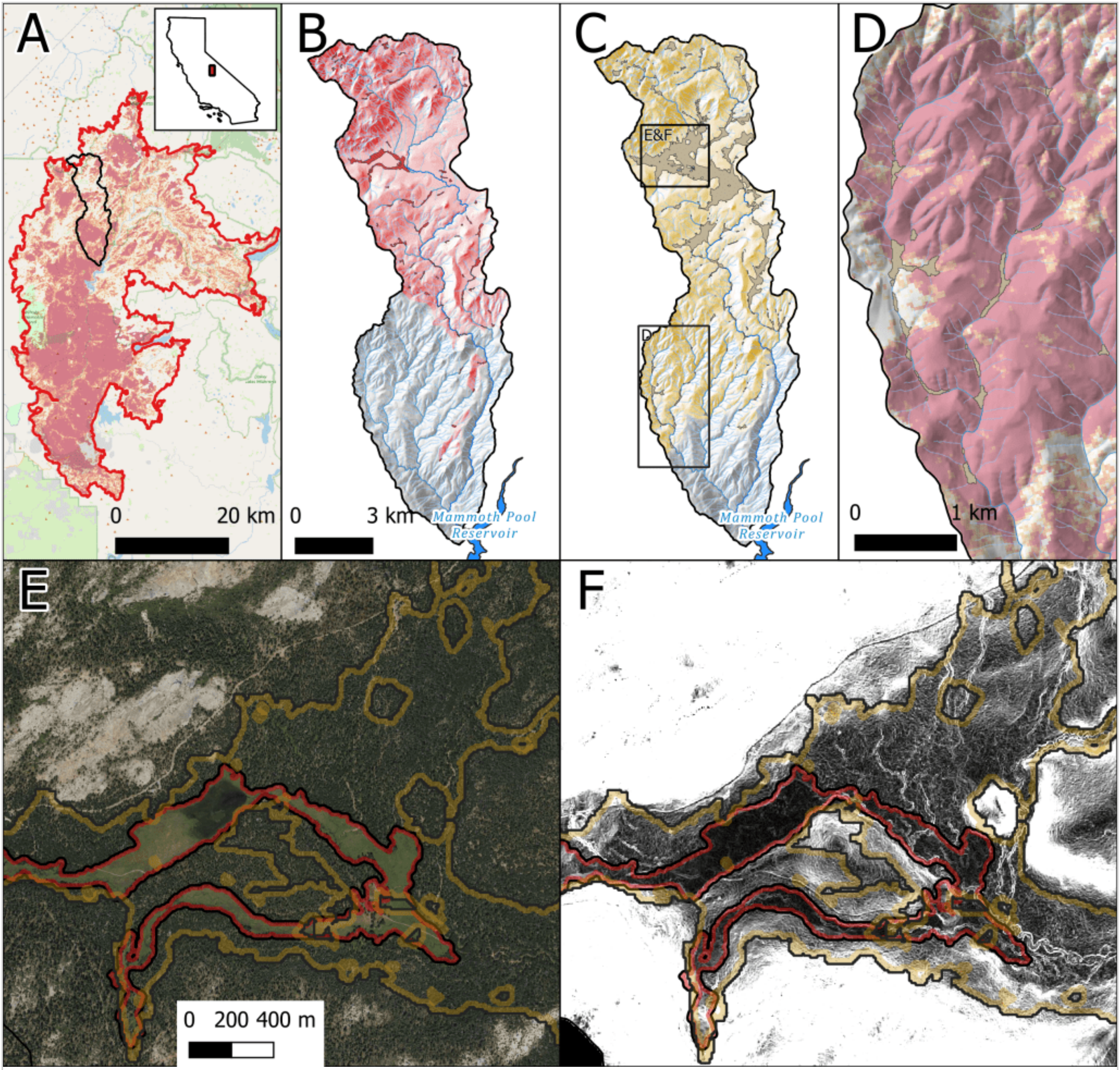

Figure 4. Location of the Jackass Creek Watershed (HUC-12) within the Creek Fire burn area with high severity zones in red (A). Distribution of existing, hand-digitized, Sierra Nevada MultiSource Meadow Polygons (SNMMP) within the watershed with red shading to indicate catchments upstream of existing meadows (B). Distribution of model-predicted meadow boundaries within the watershed with yellow shading to indicate catchments upstream of predicted meadows (C). Western region of the Jackass Creek Watershed that burned with high severity (red) where a series of model-predicted meadows were identified but no corresponding SNMMP meadows occur (D). Aerial view of Jackass Meadow area with SNMMP meadow boundaries in red and model-predicted boundaries in gold (E),

and a slopeshade raster of the same area highlighting many deeply incised flow paths crossing the low-gradient forested zone of the model-predicted meadow polygons (F).

We considered potential gains in water retention and sediment capture for the predicted meadow habitats compared to the existing SNMMP meadows. We used estimates of change based on existing literature summarizing field measured gains (Loheide and Gorelick 2007, Pollock et al. 2014, Hunt et al. 2018) or modelled gains (Loheide et al. 2009, Ohara et al. 2014). For water retention, we assumed that the habitats would be treated to increase temporal and spatial overbank flooding and groundwater recharge with an average groundwater elevation increase of 0.2 m. We assumed a drainable porosity of 20% for meadow soils (Nash et al. 2020). For sediment capture, we assumed that restoration would dramatically decrease flow velocities through the stream reaches within the potential meadow polygons, thereby reducing the sediment transport capacity and increasing sediment aggradation. We used the mean estimated channel depths and widths calculated for the model-predicted meadow stream cross-sections to estimate fillable channel space for sediment accumulation. We estimated the contributing area (catchment size) for the existing and the model-predicted meadow polygons and estimated the total potential gains in sediment capture for stream segments in model-predicted polygons. We did not have estimates of sediment production and transport for the watershed but assumed high availability, at least in the first few years following the fire, due to the high severity of the fire and high percentage of bare soils, factors that are known to increase rill erosion and sediment production (Benavides-Solorio and MacDonald 2005, Silins et al. 2009, Wagenbrenner et al. 2016, Cole et al. 2020). Sediment production typically decreases quickly following wildfire (Nyman et al. 2013), so post-fire timing will likely impact sediment capture potential and rate.

Results

The Lost Meadows Model identified large areas with similar geomorphic and climatic characteristics to extant meadows expanding the potential meadow area in the Sierra Nevada by nearly 3 times from 2.0% to 5.8%. The average predictive accuracy of the model was 0.95 (range 0.85-0.98). In addition, the LiDAR-derived stream cross-sections supported our hypotheses that the model-predicted meadows had similar floodplains and more incised channels than the SNMMP meadows (**Fig. 5**). We found that NHD_HR stream cross-sections within model-predicted meadows had similar slopes (mean = 3.9%, SD = 2.4, n = 87) to the slopes of streams flowing through existing meadows (mean = 3.4%, SD = 2.2, n = 47), while streams not falling within either polygon had steeper slopes (mean = 13%, SD = 8.2, n = 40). Furthermore, cross-sections within model-predicted polygons had larger channel areas (mean = 6.2 m^2, SD = 8.4 m^2, n = 82) than those within existing SNMMP meadow polygons (mean = 3.2 m^2, SD = 6.1 m^2, n = 45). Some model-predicted meadow polygons encompassed and enlarged existing meadow polygons while others encompassed areas without previously delineated meadows. Only about 20% of the model-predicted polygons were greater than 2 ha but these larger polygons made up about 88% of the model-predicted meadow area (**Fig. 6**). The model results provide an opportunity to rethink meadow restoration planning to maximize a watershed’s recovery potential beyond currently defined meadow footprints. We show how the modeled polygons can be integrated into wildfire response planning in the Silver Creek watershed and used to assess the potential for meadow habitat gains for water and sediment capture post-wildfire in the Jackass Creek watershed.

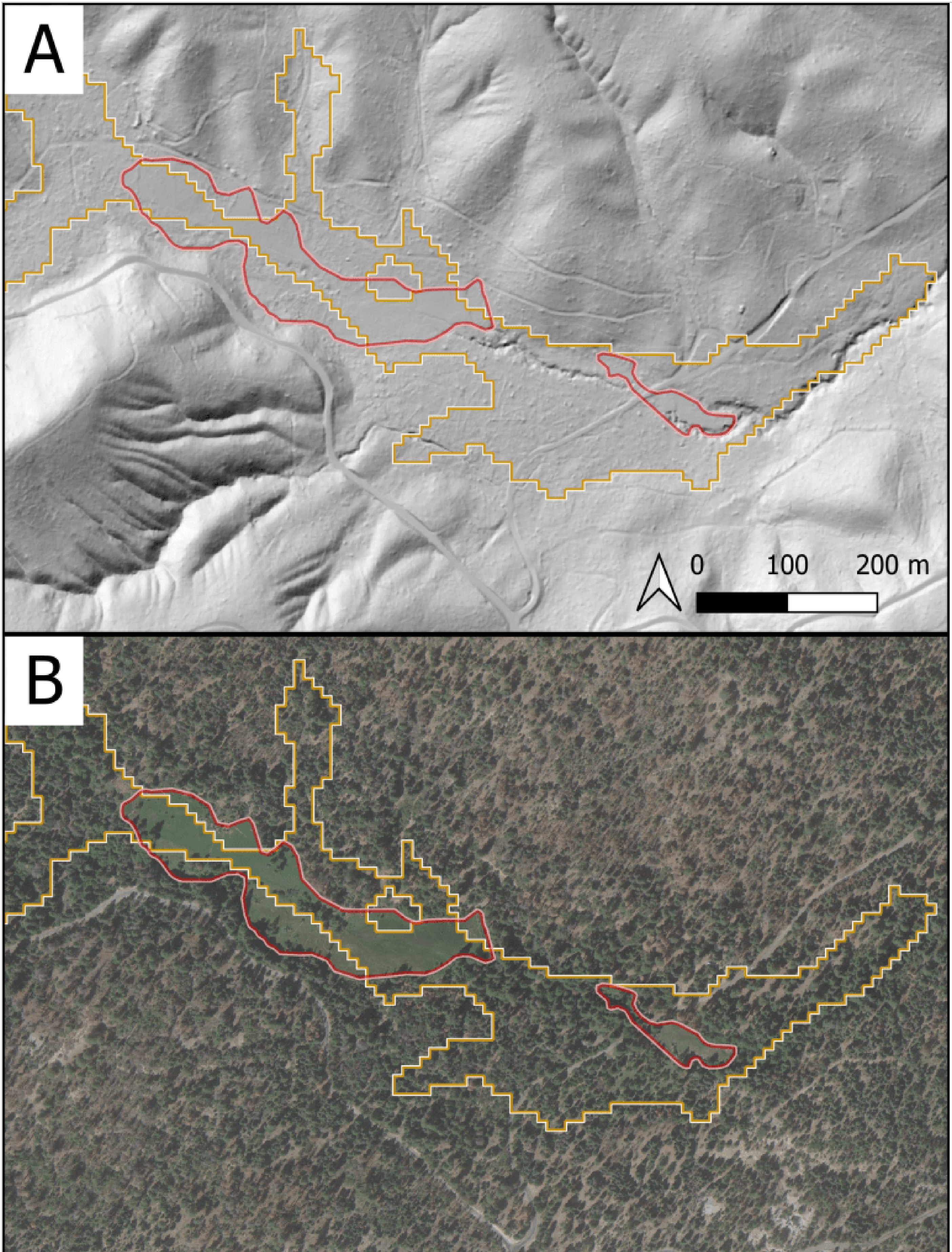
A
0
100
200 m
B

Figure 5. LiDAR-derived hillshade (A) of a long, flat floodplain on the Sierra National Forest with the Sierra Nevada MultiSource Meadow Polygons highlighted in red and the model-predicted polygon in gold. Note the clearly identifiable incised channel between the two SNMMP polygons and downstream of the rightmost SNMMP polygon where the Lost Meadow Model predicted potential meadow habitat. The aerial imagery (B) shows that the SNMMP polygons (outlined in red) support meadow vegetation while the areas with incision outside the SNMMP polygons but within the model-predicted areas (outlined in gold) support forest. The left SNMMP meadow is named Long Meadow and is 440 m long. The model-predicted potential meadow encompassing Long Meadow is 1,170 m long.

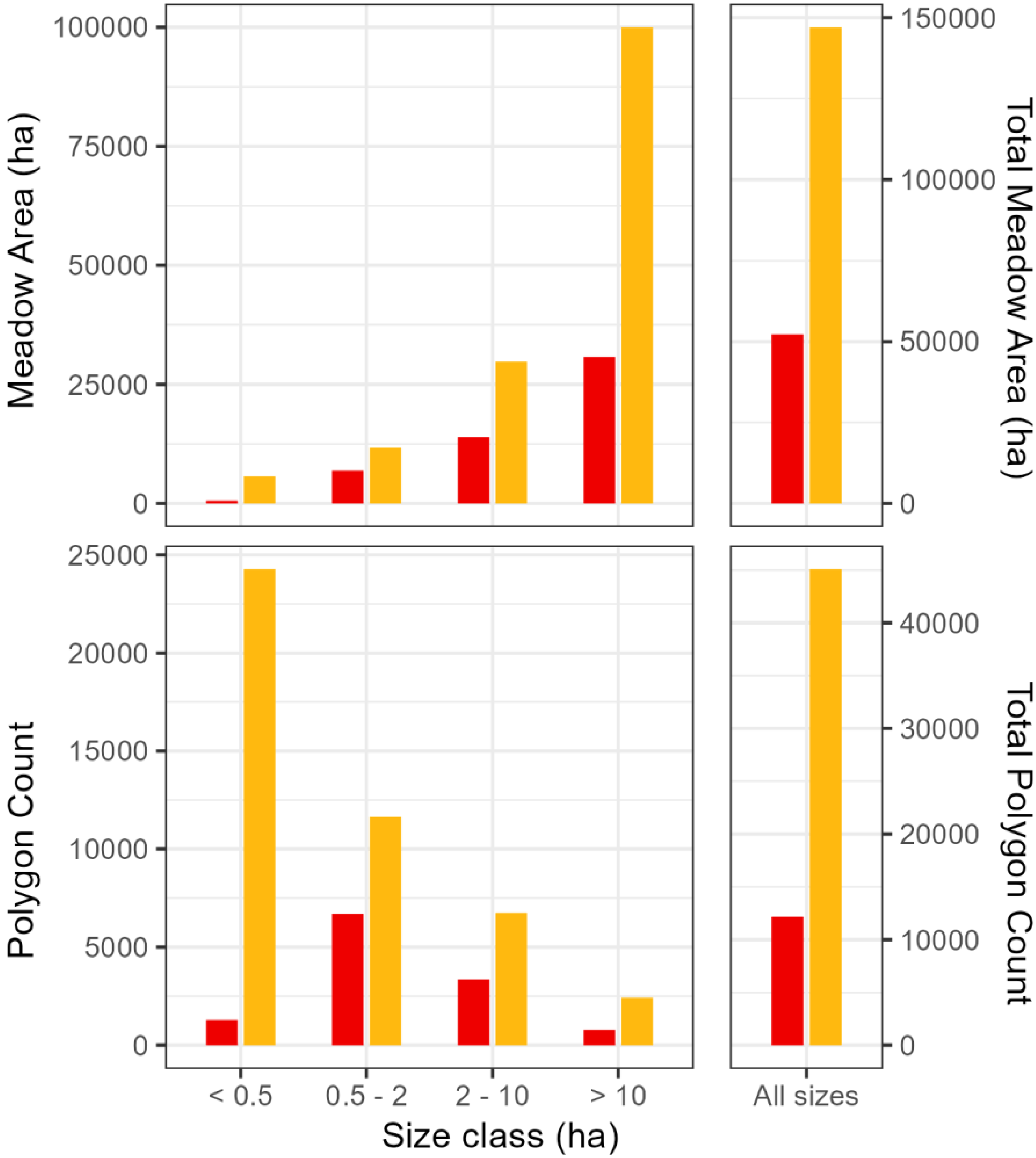

Figure 6. Comparison of Sierra Nevada MultiSource Meadow Polygons (red bars) and model-predicted polygons (gold bars) by polygon size class for (A) total meadow area and (B) number of meadow polygons.

Silver Creek Watershed

Model Results.—The Silver Creek watershed (45,934 ha) currently supports 271 meadows identified from the SNMMP database ranging in size from 0.2 ha to 43.8 ha (median = 1.2 ha) for a total meadow area of 613 ha (1.3% of the watershed, **Fig. 3A**). The model output predicted 909 potential meadows ranging in size from 0.1 ha to 109.5 ha (median = 0.5 ha) for a total potential meadow area of 1,984 ha (4.3% of the watershed, **Fig. 3B**), an increase of 3.2 times the existing area. The largest predicted meadow polygon overlaps three SNMMP meadow polygons totaling 37.5 ha. The watershed has 2,078 km of NHD_HR streamlines, of which 52.7 km occur within SNMMP polygons and 181.5 km occur within the model-predicted polygons.

Integration with Wildfire Response Planning.—The watershed supports approximately 16 designated PODs with 274 km of POD boundaries (**Fig. 3)**. A portion of 50 SNMMP meadow polygons (464 ha) and 126 model-predicted polygons (1,725 ha) overlap with the 50-m buffered POD boundaries. However, only a small portion of these meadow polygons (35 ha and 95 ha, respectively) occur within the 50 m-wide POD boundaries. Most of the boundaries were delineated along roads positioned at the edge of stream floodplains so miss or just clip the meadow polygons (**Fig. 3**). Although most of the POD and meadow boundaries do not overlap, several POD boundaries correspond with model-predicted meadow areas and, with restoration, could greatly improve the size and effectiveness of the fuel breaks and fire control points (**Fig. 3C&D**).

Jackass Creek Watershed

Model Output.—The HUC-12 Jackass Creek watershed (8,672 ha) supports 59 meadows identified from the SNMMP database ranging in size from 0.3 ha to 52.6 ha (median = 0.8 ha) for a total meadow area of 126.2 ha (1.5% of the watershed, **Fig. 4B**). The model output predicted 153 potential meadows ranging in size from 0.1 ha to 410.3 ha (median = 0.4 ha) for a total potential meadow area of 708.7 ha (8.2% of the watershed, **Fig. 4C**), an increase of 5.6 times the existing area. The largest predicted meadow polygon of 410 ha encompasses Jackass Meadow with a current size of 52.6 ha and 8 additional smaller SNMMP meadow polygons totaling 64 ha. The area outside of the existing meadow polygons and inside the model-predicted polygon occupies the same low, flat floodplain as the existing meadow but supports a similar forest structure to the surrounding upland forest (**Fig. 4E**). LiDAR imagery shows several visible incised channels and gullies throughout the basin that likely disconnected the channels from the floodplain and caused groundwater elevations to drop (**Fig. 4F**).

The watershed has 556 km of NHD-HR streamlines, of which 18.5 km occur within SNMMP polygons and 66.5 km occur within the predicted polygons. Catchments upstream of existing meadows cover 59% of the total watershed area and predicted meadow catchments cover 80%. Much of the additional catchment area occurs in a high severity burn area where a series of potential stringer meadows were predicted (**Fig. 4D**).

Application to Groundwater Storage and Sediment Capture.—If we assume a groundwater elevation increase of 0.2 m due to restoration, we could increase groundwater storage by 283,480 m^3 (230 acre-ft) by restoring the model-predicted meadows.

Assuming an average sediment storage potential of 3.2 m^2 per m of stream in existing meadows and 6.2 m^2 per m in model-predicted potential meadows, existing meadows could capture 59,000 m^3 (48 acre-ft) of sediment and model-predicted meadows could capture 412,000 m^3 (334 acre-ft) of sediment. The watershed is directly upstream of the Mammoth Pool Reservoir (**Fig. 4**). Meadow restoration at this scale might cost an estimated $3,000,000 based roughly on the cost of implementing four meadow restoration projects using low technology, process-based restoration methods on similar National Forest System Lands in California in 2022. Cost includes design, implementation, two years of follow-up treatments, and some monitoring (change in stream length, number of difluences and confluences, inundation area, and change in vegetation greenness (NDVI)), but not permitting or environmental review. Process-based restoration methods use the fluvial and biological energy in the system and take advantage of materials found onsite to create in-stream complexity and spread flows onto the meadow floodplain, making the technique potentially useful for expanding to larger areas (Pollock et al. 2014; Wheaton et al. 2019; Ciotti et al. 2021).

Discussion

The Lost Meadows Model applies machine learning tools to identify areas with similar geomorphic and climatic characteristics to existing stream-associated meadow habitats. We do not expect that all the model-predicted habitats historically were meadows but they represent areas that may have transitioned to forest as natural processes and human practices caused forest habitats to enclose meadows and other open spaces (Stockdale et al. 2019). As the importance of water storage and summer low flows increases with climate change and increased water demands, it may be valuable to consider these habitats for restoring headwater storage capacity and groundwater exchange. These actions would have the added benefit of capturing sediment (Pollock et al. 2014; Ciotti et al. 2021), improving wildlife habitat (Murphy et al. 2004; Bouwes et al. 2016; Campos et al. 2020), increasing carbon storage (Reed et al. 2021; Reed et al. 2022), and increasing the forest’s resistance to wildfire (Jordan and Fairfax 2022).

Meadows have long been considered important habitats but are treated as local and rare so are seldomly considered during watershed- and landscape-scale restoration planning. Indeed, the existing SNMMP meadow polygons encompass only 2% of the 25,300 km^2 modeled study area. The model-predicted output increases the potential area of meadow habitat by about three times, making possible gains from restoring meadows more relevant to landscape-scale climate and wildfire resilience planning. Relatively more of the model-predicted meadow polygons were under 2 ha compared to SNMMP polygons (**Fig. 6**). We are not surprised by this finding for a few reasons: (1) small meadows in close proximity were aggregated to create the SNMMP dataset but not the model-predicted polygons; (2) we would expect that small meadows were more susceptible to complete forest encroachment because they have a greater perimeter-to-area ratio than large meadows, and therefore, would not be considered as meadows in the SNMMP dataset but would be found by the Lost Meadow Model; and (3) small meadows were likely more easily missed during the hand-digitization process used to create the SNMMP dataset. Indeed, in our review of the model output, we incidentally found some small model-predicted polygons that clearly supported meadow vegetation. Regardless, the model did identify polygons of multiple sizes and the bigger ones represent most of the potential area gains.

To highlight how meadow restoration could aid watershed resilience planning, we considered two hypothetical applications of the Lost Meadow Model in the Silver Creek and Jackass Creek watersheds. The first example focused on strategically expanding meadow habitats already being used as control points for wildfire management, thereby widening natural fuel breaks that may also provide refugia for wildlife during wildfires. A recent study by Fairfax and Whittle (2020) showed how large, wet, floodplain complexes maintained by North American beavers (*Castor canadensis*) create natural fuel breaks that remain green even in high severity fires. The second example capitalized on the concept that meadows are natural depositional zones where water slows and sediment deposits. Applying this concept through post-wildfire landscapes could increase capture of expected sediment pulses from burned hillslopes in appropriate depositional zones where the sediment is beneficial for filling incised channels and raising water tables (**Fig. 7**). This may be especially important above reservoirs where sedimentation steadily depletes reservoir capacity and threatens the reliability of water supplies (Morris 2020). We estimated that incised channels within modeled potential meadow habitats in the Jackass Creek Watershed could capture approximately 412,000 m^3 (334 acre-ft) of sediment above Mammoth Pools Reservoir. Note that Jackass Creek Watershed is only 3.3% of the Mammoth Pool Reservoir's entire watershed, leaving open many more upstream restoration opportunities.

Figure 7. Post-fire sediment pulse in a burned meadow in the Plumas National Forest. Fire can present an opportunity to capture sediment, reconnect floodplains, and raise water tables by using instream wood structures like beaver dam analogs or post-assisted log structures.

We do not expect that all of the model-predicted areas could be converted to meadow habitats; however, restoration actions to reconnect floodplain connectivity in stream-adjacent areas with low slope and minimal topographic barriers have proven to have significant positive effects whether by humans or beavers (Bouwes et al. 2016; Fairfax and Whittle 2020; Ciotti et al. 2021; Jordan and Fairfax 2022). The application of low-tech, process-based restoration (PBR) approaches (Beechie et al. 2010; Pollock et al. 2014; Wheaton et al. 2019; Ciotti et al. 2021) in these systems may make meadow and stream restoration feasible and cost-effective at watershed-scales (Jordan and Fairfax 2022). These approaches are designed to work with nature to recover degraded stream catchments by removing impediments to physical and biological processes and harnessing the system's fluvial and biological energy to do most of the restoration "work." In our Jackass Creek example, we estimated $3,000,000 to restore 215 meadows encompassing 713 ha and 66.6 km of stream using these nature-based techniques. In contrast, many single-meadow restoration projects using engineering designs and construction-based approaches exceed $3,000,000 for under 75 ha. While a single meadow restoration project may have differing goals from process-based restoration approaches designed to slow and spread water and accumulate sediment over time, the cost comparison highlights the value of thinking about restoration opportunistically and incorporating natural processes to work at larger scales.

The Lost Meadows Model enables us to envision the potential for regaining meadows and low-gradient floodplain habitats in California's mountain landscapes. It can easily be incorporated into climate change and biodiversity conservation measures such as California Executive Order N-82-20 that commits California to conserve 30% of lands and coastal waters by 2030 (**https://www.californianature.ca.gov/pages/30×30**). However, we are just beginning to develop the restoration tools and workforce to meet the demand for the increased pace and scale needed. For example, the new California Process-based Restoration Network was launched in 2022 with a goal of increasing capacity to restore degraded stream and meadow ecosystems (**calpbr.org**). In addition to building the human capacity to implement restoration projects, research and monitoring remain important for understanding and identifying where and when meadow restoration can succeed and what techniques are best to maximize ecohydrological benefits.

In conclusion, we identified nearly three times more potential meadow habitats in the Sierra Nevada than are currently mapped. With this new dataset, we examined the potential for restoring these important groundwater-dependent habitats across watersheds to affect catchment characteristics and help mitigate some of the largest challenges facing California's forest landscapes, including managing wildfire and maintaining water supply. We encourage watershed restoration planners and restoration practitioners to think beyond the current meadow boundaries to see larger potential gains through re-envisioning what is possible.

Acknowledgments

We thank G. Mak for patiently running and rerunning the Lost Meadows Model and for obtaining necessary GIS layers. Members of the Sierra Meadows Partnership, Klamath Meadows Partnership, and Cal-PBR Network provided background and insight for model development. We thank all the people (D. Weixelman, R. Peek, C. Monohan, A. Merrill, and others) who developed the SNMMP dataset and made it accessible for use. We thank D. Ciotti, K. Swift, and P. Manley for helping to develop application ideas and to three anonymous reviewers, D. Dralle, P. Richardson, and B. Harvey for providing reviews of an earlier version of the manuscript. Finally, we thank L McLean, CDFW, for inviting us to participate in the 2022 Science Symposium. Support for model development was provided by the U.S. Forest Service, Pacific Southwest Research Station.

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