Section 5: Project Description

1. **<u>Project Objectives:</u>**

The primary goal of this project is to restore the carbon-storing ecosystem that dominated Tuolumne Meadows in the late 1800s. Direct benefits of the restoration will include increased soil water-holding capacity created by increased soil organic matter content and improved wildlife habitat from an increase in perennial plant cover. The types of impacts that affected Tuolumne have also degraded many meadows throughout the Sierra Nevada, and this research with provide protocols for restoration and measurement of the benefits of restoration that other programs can utilize. The restored vegetation will have dense tall aboveground stems and leaves that will slow overland flow and trap sediment reducing sediment flux to the Tuolumne River. The key benefit of restoring a sedge-dominated community however will be in the soil, where greatly increased production of roots and rhizomes will increase the long-term storage of partially decayed organic matter. Soil carbon will accumulate, remaining sequestered from the atmosphere, and improve the water holding capacity and nutrient exchange capacity of the soil, providing critical positive feedback by making meadow soils wetter and supporting wetland plant growth. Key secondary beneficiaries could include two species of rare amphibians, Sierra Nevada Yellow-legged Frog (*Rana sierra*) and Yosemite Toad (*Bufo canorus)*, which occur in the region, but are not known from Tuolumne Meadows.

2. ***<u>Background and Conceptual Models</u>:***

Meadows cover less than 3% of the Sierra Nevada land area (Fryjoff-Hung & Viers 2012), but they are disproportionately important for bird (Van Riper & Van Wagtendonk 2006), insect (Simonson *et al.* 2001; Hatfield & LeBuhn 2007), amphibian (Morton & Pereyra 2010; Liang & Stohlgren 2011), mammal (Grenfell & Brody 1986) and plant biodiversity and habitat (Jones 2011). In addition to their biotic and ecological significance, mountain meadows can attenuate flood peaks (Hammersmark 2008), store and transform carbon and nitrogen (Norton *et al.* 2011), and retain shallow groundwater and soil water (Loheide *et al.* 2008). For millennia, mountain meadows throughout the Sierra Nevada have accumulated mineral sediment and organic carbon (Wood 1975) from which prehistoric climate and vegetation have been reconstructed (Anderson & Smith 1994). This preserved record of accumulated carbon and sediment is evidence of the relatively stable meadow hydrologic and biogeomorphic processes over the past several thousand years (Benedict 1982; Ratliff

1985a). Frequent and/or large soil disturbance events would have destroyed the integrity of this layered history.

The abundant natural resources found in mountain meadows have made them focal areas for human use and impact. The two most widespread and severe direct impacts to mountain meadows have been intentional hydrologic modification (usually ditching and draining or unintentional effects from road building and logging) and livestock grazing. Ditching and draining of meadows fundamentally alters the basic hydrologic processes that maintain wetland ecosystem function. Hydrologic modification generally results in an increase in greenhouse gas emissions due to drying of the meadow and oxidation of soil carbon (Altor & Mitsch 2008). A number of restoration projects have focused on removing hydrologic impacts to mountain wetlands and monitoring the resultant effect on carbon fluxes (Chimner & Cooper 2003a,b; Schimelpfenig *et al.* 2013). Most hydrologic restoration projects have not quantified the resulting GHG fluxes.

In addition to intentional hydrologic impacts, intense grazing in Sierra Nevada meadows triggered soil erosion, gully formation, and significant and widespread unintentional hydrologic impacts (Sumner 1947). After livestock was removed from these meadows, the erosion gullies remained and continued to expand, causing greater drainage and drying of the meadow. Gully impacts to Sierra meadows are well known and documented. While gully formation is the most dramatic impact of prior land uses, it is not the most prevalent.

Starting in the 1850's and lasting into the 20th century, large flocks of sheep were summered in Sierra Nevada meadows. For example, in 1870 LeConte reported, "the Tuolumne Meadows are celebrated for their fine pasturage. Some 12,000 to 15,000 sheep are now pastured here. They are divided into flocks of about 2,500 to 3,000" (LeConte 1870). John Muir in his first summer in the Sierra, 1869 tended a flock similar to those described by LeConte (Muir 1911). Intense unregulated grazing persisted for many decades, even following the formation of Yosemite National Park (YNP) and other federal jurisdictions. The YNP Superintendent's report of 1898 documented that he ejected from parklands 214,050 head of sheep and hundreds of cattle and horses (Ernst 1949). The cessation of sheep and cattle grazing did not occur until 1905. The grazing impacted the vegetation and soils as sheep ate the most palatable plants, decreasing or destroying populations of sedges, rushes and other long-lived clonal plants with high root to shoot ratios (DeBenedetti 1980).

While partial recovery has occurred in some meadows, many meadows have altered vegetation composition (Ratliff 1985; Bartolome, Erman & Schwarz 1990; Dull 1999; Allen-Diaz 2004; Cooper, Chimner & Wolf 2005), unvegetated patches, and reduced plant production. A study in the southern Sierra Nevada (Odion, Dudley & D'Antonio 1988) found that 50-80% of grazed meadows now dominated by dry meadow plants were formerly wet meadows, and were in need of restoration. These meadows have highly organic soils, but the vegetation of annual plants as well as weak rooted forbs could never have formed these soils.

Hydrologic impacts to mountain meadows have been relatively well studied and many restoration projects have been implemented to reverse that damage. However, little is known about the long-term effects of legacy grazing on the long-term vegetation production and organic matter storage function of meadows where erosion gullies and other hydrologic changes did not occur. The decimation of sedge-plant communities in mountain meadows reduced organic inputs and changed the soil carbon budget from storing carbon to losing carbon. Soil organic matter plays a key role in retaining soil water (Hudson 1994; Saxton & Rawls 2006, Ankenbauer and Loheide 2014). A change in plant community composition that causes a shift to an annual net-loss of soil carbon will result in a concurrent loss in soil water holding capacity. This sets up a feedback of degradation with the loss of soil water limiting vegetation growth and ground cover, exposing soil organic matter to the atmosphere resulting in greater decomposition. Tuolumne Meadows could remain stuck in an unrestorable herb state if it loses so much soil organic matter and water-holding capacity, that it is too dry to restore the sedge state.

Sierra meadows have populations of native ground squirrels and voles and these meadow-burrowing species through their consumption of above and below ground biomass and soil disturbances appear to maintain meadows with legacy grazing effects in the disturbed condition. This herbivory limits or prevents the spread or invasion of sedges and other clonal plants with high below ground production. The vegetation in this degraded state continues to have higher soil carbon losses than is being replaced by plant production. Restoration of the sedge-dominated plant community, and its soil-building function, is essential to restore meadow soil carbon storage processes.

Over the past four years we have performed field experiments and made empirical measurements to document carbon fluxes in Tuolumne Meadows, one of the largest subalpine meadows in the Sierra Nevada, as well as nearby meadows. We have identified the ecological restoration treatments required to restore the meadow vegetation composition and C storage function, and reverse the processes of C loss that has occurred since the period of heavy grazing.

Our conceptual model is that Tuolumne Meadows is in an alternative stable state. Decades of very heavy unregulated grazing destroyed the sedge-dominated community that formed the organic rich soils of the meadow. It was replaced by a forb-dominated carbon-losing state that dominates the western 1/2 of the meadow. Recovery to the sedge state has been prevented over the past 100 years largely by small mammal herbivory preventing clonal species from expanding from their few remaining patches, thus maintaining the alternative forb state. While the small mammal herbivores are native and herbivory is a natural process, the vegetation and soil state created by decades of heavy grazing reorganized the ecosystem so significantly that small mammals can now limit the vegetation production and maintain large areas of bare soil between plant tufts. Annual plants and forbs do not produce sufficient belowground biomass to match annual soil organic matter decomposition rates. We hypothesize that by reassembling the food webs, including introducing tens of thousands of clonal plants and reducing small mammal herbivory in Tuolumne by fencing, our project will restore the biotic composition, production and critical ecological functions that formed Tuolumne Meadow and its carbon rich soils.

We tested this conceptual model during 2012-2014 using a factorial field experiment designed to evaluate whether we could recreate the sedge state in Tuolumne Meadows. We achieved this by temporarily reducing small mammal herbivory using hardware cloth fencing and planting the sedge species that dominate partially recovered subalpine meadows in the central Sierra Nevada. This experiment explicitly tested whether we could assist ecosystem recovery, have the planted species survive, even during the most significant drought of the past century, and move the meadow toward carbon storage. Our experimental results clearly show that control plots (unplanted and unfenced) in Tuolumne Meadows are, and likely have been for 100+ years, a net source of carbon to the atmosphere (Figure 1, left panel). Plots protected from small mammal browsing by a fenced treatment lost significantly less carbon even without vegetation restoration efforts. Reference meadows, with intact sedge dominated vegetation are carbon storing, even without the fenced treatment.

We transplanted into Tuolumne Meadows two species of *Carex* that now are minor components of the vegetation, but which are abundant in partially recovered meadows and were planted into the research plots. When protected from herbivory, significantly more seedlings survived (Figure 1, right panel). It should be noted that this experiment was conducted during extreme drought conditions and with more average soil moisture conditions we anticipate much higher plant survival and greater carbon storage across all plot types. In our other meadow restoration projects in the Sierra Nevada we have documented nearly 100% transplanted seedling survival.

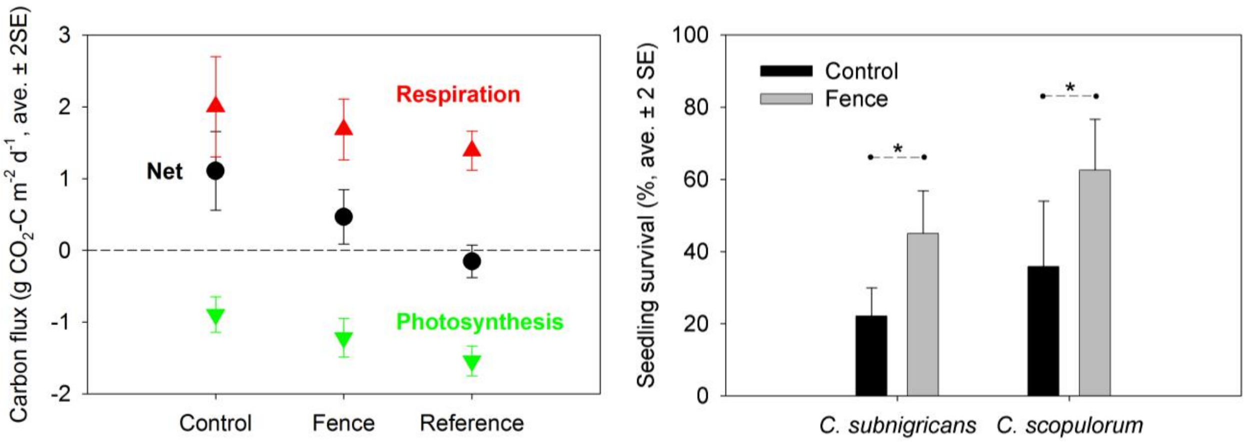


Figure 1. Left panel shows mean daily growing season carbon flux rates for *control* plots in Tuolumne Meadows, *fenced* treatment plots in Tuolumne Meadows that exclude mammal herbivory, and *reference* meadows that have clonal sedges. Net ecosystem exchange (Net) shows that reference meadows have C storage, while the *control* plots in Tuolumne Meadows continue to lose carbon, and the *fenced* treatments in Tuolumne Meadows are in balance. **Right** panel illustrates the one-year survival for seedlings of *Carex subnigricans* and *C. scopulorum* planted in Tuolumne Meadows in *control* and *fenced* plots. The fenced plots had significantly higher survival.

Scientific Concepts for Measurement and Modeling

Soil organic matter is produced by plant photosynthesis that fixes atmospheric CO_2 and uses this energy to grow above and belowground plant tissue. Aboveground plant tissue is influenced by herbivory, fire, solar heating, desiccation and wind transport or rapid decomposition after senescence. Most aboveground plant production has rapid turnover rates and contributes little to the soil carbon pool. Belowground production, including roots and rhizomes, delivers atmospheric carbon directly into the soil where the cool, low oxygen environment slows decomposition and allows greater inputs to the long-term soil carbon pool. Sedge-dominated plant communities are essential in forming and maintaining the soil organic matter and carbon storing capacity of mountain meadows.

Creating a Carbon Budget

To create an annualized model of carbon flux in Tuolumne Meadows we will measure and model the two primary CO_2 pathways into and out of the ecosystem: photosynthesis and respiration. The model for photosynthesis will be a function of incoming solar photosynthetically active radiation (PAR), air temperature, and plant phenology (the seasonal cycle of growth and senescence). The model for respiration will be a function of soil temperature, soil moisture, and plant phenology. The models will be calibrated using continuous field measurements of solar radiation made using a Campbell Scientific CR1000 data logger (Logan, UT) equipped with a REBS, Inc. Q*7.1 net radiometer (REBS Inc., Bellevue, WA), and biweekly field measures of photosynthesis and respiration made using a clear plastic chamber equipped with an infrared gas analyzer (IRGA, PP Systems EGM-4) at control, fenced, and the reference site plots from 2011-2014. We will also collect data on the environmental parameters for the models (temperature, water level, etc.), measured hourly using continuously logging water level pressure transducers (Onset Computer Corp model

U20L-04) and soil temperature sensors (Onset Computer Corp, model UA-001-08). We have approximately 50 ground water monitoring wells, many of which have logging pressure transducers that were installed in the study area in 2005. We will use these water level data in modeling and may create several models in different portions of the meadow, if water level differences warrant it. Soil moisture will be measured by hand (Campbell Hydrosense) just outside each gas flux plot (so not to disturb the soil within the plot) while readings or samples are being collected.

We will use modified published equations (Riutta *et al.* 2007) to model gross primary production (GPP) and ecosystem respiration (ER). GPP will be modeled as a function of PAR and a seasonality/phenology term based on a four-week running average (21 days before, 7 days after) of daily mean air temperature (RAV) [Equation 1]. A rectangular hyperbola function will be used to model ecosystem photosynthetic response to incoming PAR, and a Gaussian function will be used for the seasonality term, allowing modeled GPP to follow seasonal dynamics associated with plant phenology.

$$\boldsymbol{GPP_i = \frac{A_{max} * \alpha * PAR_i}{A_{max} + \alpha * PAR_i} * e^{\left[-0.5\left(\frac{RAV_i - RAV_{optGPP}}{RAV_{devGPP}}\right)^2\right]}} \qquad (1)$$

In Equation 1, A_{max} (g CO_2-C m^{-2} hr^{-1}) represents the asymptotic maximum potential rate of GPP, and α (g CO_2-C µmol PAR^{-1}) represents the light use efficiency, or initial slope of the light response function. The parameter RAV_{optGPP} (C°) represents the optimum value of RAV for GPP and RAV_{devGPP} (C°) represents the standard deviation of the Gaussian function, which controls the spread of the distribution.

Ecosystem respiration will be modeled as a function of air temperature (AT), water table position (WTP), and a seasonality term [Equation 2]. A modified van't Hoff equation will be used to model ER as increasing exponentially with air temperature. The response of ER to water table position will be modeled as a negative exponential equation, and a Gaussian function similar to that of the GPP model will be used to account for seasonal variation in ER.

$$\boldsymbol{ER_i = R_{10} * Q_{10}^{\left(\frac{AT_i - 10}{10}\right)} * e^{-b * WTP_i} * e^{\left[-0.5\left(\frac{RAV_i - RAV_{optER}}{RAV_{devER}}\right)^2\right]}} \qquad (2)$$

In Equation 2, R_{10} (g CO_2-C m^{-2} hr^{-1}) represents ER at 10°C when other model factors are not limiting, Q_{10} represents the rate of increase in ER per 10°C increase in air temperature, b (g m^{-2} cm^{-1}) represents the initial slope of the rate of increase in ER per decrease in water table position below the peat surface. RAV_{optER} (C°) and RAV_{devER} (C°) represent the optimum RAV value for ER and the standard deviation of the Gaussian function controlling seasonality in ER, respectively.

We have previously demonstrated the effect of hydrologic restoration on carbon fluxes in mountain meadows using these same approaches (Chimner & Cooper 2003a,b; Schimelpfenig *et al.* 2013). These efforts were for sites that were hydrologically modified by ditches and other dewatering processes and natural intact meadows in the Rocky Mountains. However, we have previously demonstrated that Tuolumne Meadows has not been hydrologically modified (Cooper *et al.* 2006). We know of no relevant studies in mountain wetlands that document the effect of vegetation restoration in areas that were not also hydrologically modified. Therefore, our restoration research will add a significant new body of information to science, and guide future mountain meadow restoration efforts in the Sierra Nevada where many meadows have degraded vegetation.

In mountain meadows where the water table drops below the ground surface for a significant portion of the year, like Tuolumne Meadows, methane production is likely to be very near zero because the soil oxidation reduction potential never drop to levels (lower than -250 mV) necessary for methanogenesis (Cooper *et al.* 1998; Dwire, Kauffman & Baham

2006). In a study at Delaney Meadow, (one of our references sites ~2 miles from Tuolumne Meadows), 68 of 72 plot measurements showed a small average net uptake of methane (Blankinship & Hart 2014). Similarly, the flux of nitrous oxide is expected to be negligible in Tuolumne Meadows due to a very small load of nitrogen in high elevation Sierra watersheds (Williams *et al.* 1995). Research at Delaney Meadow (Blankinship & Hart 2014) found a small net uptake of nitrous oxide across all plots. However, they note that they may have missed a significant nitrous oxide pulse emission during snowmelt (Christensen & Tiedje 1990). Therefore, our sample protocol will began as soon as soil is exposed by melting snow, and we will attempt gas flux measurements in winter when a snow pack is present.

As stated above, we will measure CO_2 flux in-situ in real time using an infrared gas analyzer and portable plastic chamber. During each measurement period we will measure fluxes throughout a 24 hour period. Methane and nitrous oxide will be sampled from the chamber headspace using syringes, stored in glass exetainers under dark, refrigerated conditions, and transported to a lab for analysis on a gas chromatograph within one week of sampling. The methods for CO_2 and CH_4 will follow published methods (Chimner, Cooper & Parton 2002) and N_2O methods will follow Blankinship and Hart (2014). Sampling will begin as soon as soil is exposed by spring melt of the snow pack and will continue until the threat of snow in the fall. In-situ carbon dioxide flux will be measured twice per month and methane and nitrous oxide samples will be taken 4 times during the summer: 1) at the very first exposure of soil, 2) during vigorous spring growth of meadow plants, 3) at peak summer standing biomass, and 4) in late summer when plants are senescing. Each time these gasses are sampled, we will collect 4 gas samples, one from the chamber at the start of the measurement period, and one each at 15, 30 and 45 minutes. From these data a flux will be determined using regression techniques.

To determine whether the soils reach the oxidation-reduction potential (Eh) at which methanogenesis occurs, we will directly measure the oxidation state of soils. An Eh exceeding +350 mV indicates oxidized soil with sufficient free O_2 to supply respirative demand. An Eh between +250 mV and +225 mV indicates free O_2 is unavailable and nitrate (NO_3^-) is used as a terminal electron receptor in metabolic processes. Nitrate can be reduced to nitrous oxide (N_2O), nitrogen gas (N_2) or ammonium (NH_4^+). From +225 mV to -250 mV, manganese (Mn^{+4}), iron (Fe^{+3}) and sulfur (SO_4^{+2}) are used as terminal electron receptors. Below -250 mV, CO_2 is metabolized to methane (CH_4). Therefore, measurement of redox potential can give valuable insight whether the soil is in an oxidation state capable of producing either nitrous oxide or methane.

We will deploy three automated redox potential measuring systems and install two in the planted restoration treatments, and one in a control plot in Tuolumne Meadows. Each station will be powered by a solar panel with battery, and operated by a Campbell CR1000 data logger. Platinum tipped electrodes will be paired with a Beckman Calomel reference electrode, and eight pairs of electrodes will be installed at 10–20 cm depth at each site. The voltage difference between the platinum and reference electrodes will be measured and recorded hourly by the logger. The data will be corrected for the reference electrode by adding 244 mV to the measured value, and also corrected for soil pH. This system was designed, built and reported on previously (Cooper & Wagner 2013). We will relate soil redox potential to water table depth measured in our monitoring wells. Tuolumne Meadows has one of the best records of water table depth and dynamics of any meadow in the Sierra Nevada.

Uncertainty

A primary area of uncertainty in our current dataset of greenhouse gas flux in Tuolumne Meadows is for processes occurring at the meadow surface below the winter snowpack. This uncertainly exists for any study of gas fluxes in mountains where deep and long lasting snow packs form. We will attempt winter subnivean sampling collecting below-snow gas samples by pushing a rod with attached gas-sample hose down through a hole bored through the snowpack to the meadow surface following the methods of (Hubbard *et al.* 2005). Carbon dioxide concentration will be measured in-situ using the PP Systems EGM-4. The process of CO_2 sampling will pump air through the hose, purging the line, and all data and samples will be taken following the purge after CO_2 readings have stabilized. Immediately following CO_2 sampling, syringe samples will be extracted from the hose for CH_4 and N_2O analysis in the lab, as above.

We expect that our combined effect of planting sedges and protecting them from herbivory will result in a net CO_2 storage increase even greater than the difference we measured between Tuolumne control plots and reference plots: a reduction of emissions of at least -1.26 g CO_2-C g m^{-2} d^{-1}. Based on the cited studies, we expect to see very low fluxes of methane and nitrous oxide during the summer growing season, although significant unknown fluxes may occur very early during saturated snowmelt conditions. The restoration of sedges should have little effect on these two gasses, although the aerenchyma in sedge roots and shoots may serve as a conduit for the movement of methane and N_2O from deeper soil layers to the atmosphere, which would facilitate release of these gasses to the atmosphere.

Climate projections influence on this restoration effort

Projections for Sierra Nevada climate changes over the next 50-100 years predict a rise in snow line, an increase in annual precipitation variation, warmer temperatures, and drier late summer soil (Dettinger *et al.* 2004). These changes would result in a longer growing season in Tuolumne Meadows, but an earlier drying of the soil and onset of plant water stress and senescence. Therefore, the proposed restoration action of reestablishing a sedge-dominated community that will increase soil organic carbon, and soil water holding capacity, could buffer meadows from projected future climates. However, without restoration the longer summer season and drier late season soil will cause even more rapid degradation of the existing soil carbon pool, creating a greater source of greenhouse gas emissions and making future restoration efforts more difficult by decreasing the soil water holding capacity.

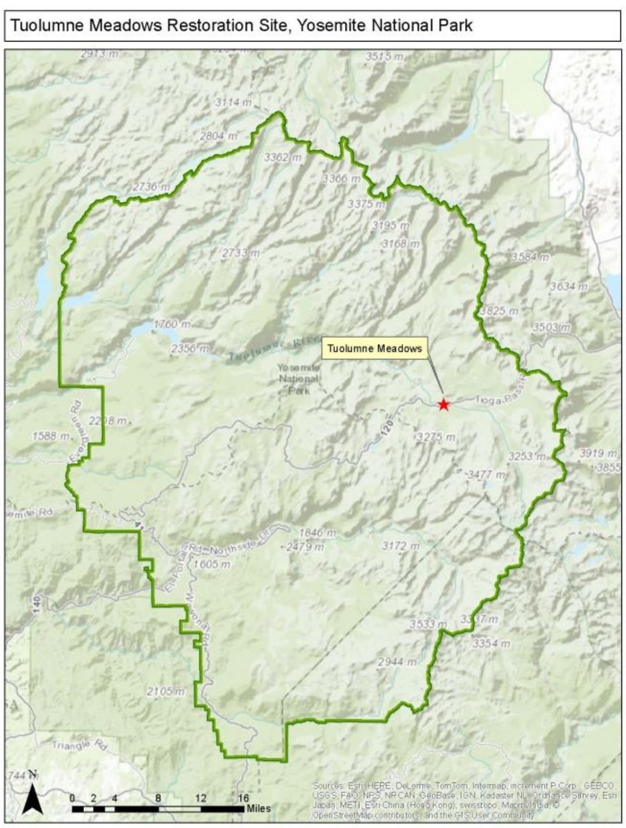
The project area is within a US National Park, and the land use will not change. Thus the restoration project area will not have a land use change.

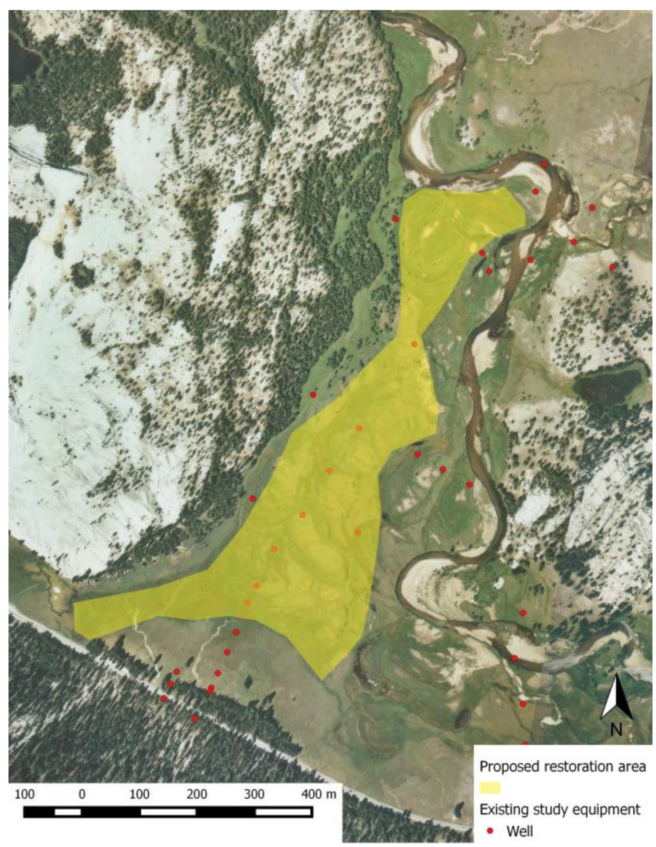
3. *<u>Detailed project description, including all tasks to be performed</u>:*

Our goal is to change the vegetation of Tuolumne Meadows from the current dominance of annual and tap-rooted short-lived forbs to dominance by long-lived clonal sedges. The species to be planted are the vegetation dominants of wet meadows in the Tuolumne region, and are excellent restoration candidates. This vegetation change will produce a directional long-term change in vegetation height, culm density, leaf area, composition, above ground biomass production and standing crop, below ground biomass production, and increased soil carbon storage. Our proposed tasks include: (1) late summer seed collection of target species (*Carex scopulorum, C. subnigricans*) for propagation in commercial nurseries (we luckily collected sufficient seed in 2014 for use in 2015), (2) seed germination and seedling propagation in winter and spring months in a commercial greenhouse, (3) planting seedlings in Tuolumne Meadows as soon as the snow melts each year, (4) building small mammal exclusion fencing (20-30 cm tall) around planting sites (fences will be erect during the summer, and laid flat in winter, and where small mammals are present in the treatment areas, we will live trap them and move them to other parts of Tuolumne Meadow) (5) establish research study plots.

Our research would quantify vegetation change over time and quantify site carbon dynamics, focusing on spatial and temporal carbon storage processes. The study site would quantify: (a) planted seedling survival, (b) seedling biomass production above and below ground, (c) seedling tillering rates (formation of new shoots from rhizomes), (d) changes in shoot density, plant canopy cover, bare soil and litter cover, (e) vegetation composition and canopy cover for all species in 100 randomly established plots within our planted treatments, (f) photosynthesis rates for planted *Carex* individuals and communities (rates of carbon fixation), (g) rates of carbon emissions, (h) net ecosystem exchange (the net of C fixation minus respiration). In addition, there will be the measures of soil redox potential, water table, soil water content and temperature, and mineral sediment deposition.

Within the western ½ of Tuolumne Meadows, the study area for this project, a 1 acre site will be chosen for the first year's planting in May 2015. The 1 acre site will be representative of the meadow and have a relatively homogenous depth to water table. *Carex* seedlings (4 month old) would be planted at a density of 4 plants per square yard, or approximately 20,000 plants per acre. We will use our existing research plots where vegetation composition and cover by species has been monitored for the past 10 years as controls for the research component of this work. The planted 1 acre site will have a 30 cm tall wire mesh fence to exclude ground squirrels and voles. The wire will be stapled to the ground to limit entry. We anticipate that some animals will have ranges within the study plot or invade over time. These animals will be live trapped and move outside of the plot. The plot will be maintained relatively small mammal free for the 5 year study period. This same procedure would be used for the 3 and 5 acre study plots in 2016 and 2017. Within each treated area we will randomly choose approximately 10 plots per acre for quantification of the variables described in a-h above.





Map 1 (left): Map showing the location of Tuolumne Meadows in Yosemite National Park.
Map 2 (right): Map showing the location of the proposed restoration area and the existing well network on the west side of Tuolumne Meadows.

A spatially stratified random sample of 20 seedlings will be exhumed at the end of each growing to assess above and belowground biomass. Collected plants will be cleaned, dried, and weighed. We have existing above and belowground biomass from control plots for comparison with treatments. Below- and aboveground production in all plots will also be quantified using clipping and in-growth root bags (respectively) following the methods of (Chimner & Cooper 2003b).

Laura Jones, ecologist, will be writing the Minimum Requirement Analysis for the project which occurs in designated wilderness, submitting the Army Corp permits and performing logistics. The volunteer coordinator, Molly Downer, will be recruiting volunteers to collect seed and planting in the plots. The NPS work leader will lead the volunteer crews in collecting seed and planting. The NPS Archeologist will be providing archeological clearance for the work to be done in the meadow. David Cooper and Evan Wolf, with field assistance, will complete the rest of the proposed work.

Co-benefit Monitoring

All open water bodies will be surveyed for tadpoles to document habitat use by the rare amphibians, Sierra Nevada Yellow-legged Frog (*Rana sierra*) and Yosemite Toad (*Bufo canorus),* in Tuolumne Meadows. In addition, all sightings of amphibians in the meadow will be documented with GPS locations, and the individuals photographed. We will attempt to determine if amphibian use increases in our restoration areas. We will install 100 sediment disks in transects across the meadow to quantify sediment deposition each year to determine if there is greater sediment retention due to the restoration.

Existing planning framework

Tuolumne Wild and Scenic River Comprehensive Management Plan (TRP) clearly lays out the ecological issues influencing Tuolumne Meadows and identifies approaches for future management, research and restoration (National Park Service 2014). A study conducted by park staff characterizing meadow vegetation and substrate across dozens of meadows in Yosemite informed this planning effort. That study documented that Tuolumne Meadows had higher bare ground as well as a much higher occurrence of plots with >50% bare ground than meadows of similar elevation and hydrologic regime. In addition, in Tuolumne Meadows, forbs dominated 4-8 times more plots than sedges and other clonal monocots (Ballenger & Acree 2008). The TRP identifies a range of restoration projects to be implemented and our proposed restoration program dovetails with all of them. These other projects, including restoration of banks along the Tuolumne River, and the removal of road and gully impacts is ongoing by Yosemite National Park staff.

4. ***Timeline:***

2015: We will contract with a commercial nursery in California to germinate and grow seedlings for planting in June 2015. Plants would be installed into a 1 acre restoration area as soon as the snow melts and road access is permitted into the study area. Crews of volunteers organized by YOSE will assist the researchers in installing all plants. Small mammal fences would be installed simultaneously with plantings. We will then install GHG monitoring plots, and plots to quantify plant survival, and growth. GHG measures, water table measures, and soil redox potential measures would be performed all summer. Seeds to be dried, cleaned, stratified and grown into seedlings for 2016 planting would be collected in September 2015.

2016: As above, germinate and grow seedlings. Plant seedlings. Add a new 3 acre restoration plot for the 2016 planting area. Monitor seedling survival from 2015 and 2016 cohorts. Continue to measure seedling growth. Continue to measure GHG and other

variables during 2016. Collect seed for 2017 plantings.
2017: As above, germinate and grow seedlings. Plant seedlings. Add a new 5 acre restoration plot for the 2017 planting area. Monitor seedling survival from 2015, 2016 and 2017 cohorts. Continue to measure seedling growth. Continue to measure GHG and other variables during 2017.
2018: Measure GHG and all other variables for all seedling cohorts.
2019: Measure GHG and all other variables for all seedling cohorts. Produce final report.

5. ***Deliverables:***

All collected data will be stored and analyzed by Colorado State University researchers for the duration of the project. Upon project completion a final report will be submitted to the California Department of Fish and Wildlife and made available to the public online. Raw data will be retained by the principle investigators and made available upon request.

6. ***Expected quantitative results (project summary):***

Our restoration target for Tuolumne Meadows is carbon flux similar to or exceeding reference sites. Our current and future GHG flux data will be annualized using a series of models to create an accurate accounting of the uptake and emission of CO_2, CH_4, and N_2O. Since those models have not yet been run, we used the CO_2 flux data from our control plots and reference sites, with an average day and growing season length, to estimate total annual potential CO_2 storage as a result of the proposed restoration (Table 1).

Table 1. Estimated carbon sequestration capacity of plant restoration in Tuolumne Meadows.

Existing long-term soil pool	26952	g CO_2-C m^{-2} yr^{-1}
Annual loss from unrestored meadow (control)	100	g CO_2-C m^{-2} yr^{-1}
Annual gain in reference meadows	14	g CO_2-C m^{-2} yr^{-1}
Total projected annual rentention+gain from restoration	114	g CO_2-C m^{-2} yr^{-1}
Multiplied by the 36422 m^2 restoration area	4135729	g CO_2-C yr^{-1}

Our experiment has demonstrated that we can assist in moving Tuolumne Meadows communities from the forb to the sedge state using a combination of sedge plantings and temporary fencing to limit small mammal herbivory. Our 4 years of carbon flux data from experimental control & treatment plots in Tuolumne Meadows, as well as reference meadows, form an excellent baseline data set to quantify changes in carbon storage from our restoration efforts over the 5 years proposed for this restoration and research effort. The planted species form high root-to-shoot biomass ratios, it is expected that a significant proportion of their annual productivity will be incorporated into the soil carbon pool, rather than being decomposed and respired quickly at the soil surface. This project will test the concept of mountain meadow carbon function restoration in Tuolumne and provide long term carbon storage in Tuolumne, while importantly establishing concepts and protocols for using these approaches in other Sierra Nevada meadows.

7. ***Protocols:***

The methods presented above draw from the best available science for restoring mountain meadows and measuring the greenhouse gas fluxes, and variables influencing these fluxes, as well as the effects of planting on the overall vegetation and soil of the study area. There are no established protocols for Sierra Nevada meadows other than these scientific methods. Our work will help advance the science of restoration and greenhouse gas monitoring in these mountain ecosystems and can inform future decisions regarding a standardized protocol.

8. ***Literature Cited:***

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