Creek Carbon

Mitigating Greenhouse Gas Emissions through Riparian Revegetation

University of California Cooperative Extension

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Cover Photo

Adobe Creek in 1977 (upper) and 2006 (lower) following riparian restoration by Casa Grande High School and United Anglers partnership.

Summary

Conservation practices related to stream restoration typically target woody vegetation establishment. As implemented practices and planted shrubs and trees mature over time, carbon and nitrogen may be sequestered in the soil profile and woody biomass, reducing their availability as greenhouse gases. This has been well documented for temperate forests by quantifying the carbon sequestered in living trees. In California's Mediterranean rangelands, stream and river corridors are hot spots for woody plant species because of available water in the soil profile to support growth. The primary objective of this study was to document carbon sequestration over time across a chronosequence of riparian revegetation projects in soil and plant biomass and to understand the recalcitrance of the sequestered carbon in soil. We also evaluated the capacity of these systems as nitrogen sinks.

We employed a retrospective, cross-sectional study of 42 stream reaches across Marin, Napa, and Sonoma Counties, in Northern California. Soil sampling and plant community measurements were conducted in three plots per site, stratified by three landforms: active channel, depositional floodplain, and upperbank terrace. Surveyed stream restoration project sites ranged in age from 0 to 45 years since restoration, with a mean project implementation age of 15 years. Mean project length was 716 m (2,296 ft), with a minimum length of 12 m (38.5 ft) and a maximum length of 4.3 km (13,794 ft). Mean project width was 24 m (77 ft), with a minimum and maximum of 10 m (32 ft) and 60 m (192 ft), respectively.

Mean carbon stocks in soils were 1.04 kg/m^2 (0.2 lbs/ft^2), 8.82 kg/m^2 (1.8 lbs/ft^2), and 16.8 kg/m^2 (3.36 lbs/ft^2) in the channel, floodplain, and upperbank positions, respectively. Similarly, woody vegetation carbon stocks for the same landscape positions were 19.2 kg/m^2 (3.84 lbs/ft^2), 37.5 kg/m^2 (7.5 lbs/ft^2), and 9.02 kg/m^2 (1.8 lbs/ft^2) in the channel, floodplain, and upperbank positions, respectively. Combined results across the three landscape positions indicate that there is an average of 267 kg/m (176 lbs/ft) of carbon and 22.8 kg/m (15.64 lbs/ft) of nitrogen in the soil and similarly, 311 kg/m (206 lbs/ft) of carbon and 2.1 kg/m (1.4 lbs/ft) of nitrogen in woody vegetation per linear unit at the study sites.

These values demonstrate the relative differences in soil and vegetation carbon stocks, with greater soil carbon in the upperbank and greater woody vegetation carbon in the channel and floodplain positions. These landscape patterns are consistent with general site conditions, including finer grained soils that are dominated by annual and in some cases perennial grasses in the upperbank, compared with the courser grained aggrading sediment and woody vegetation in the floodplain and channel positions where restoration practice activities are primarily focused.

Data driven linear mixed effects models identified statistically significant positive relationships between project age and carbon and nitrogen stocks in soil and woody vegetation, indicating that carbon and nitrogen are accruing over time in soil and vegetation at the studied sites. In the case of soil stocks, the annual increases of carbon and nitrogen per year are 0.2 kg/m^2 (0.04 lbs/ft^2) and 0.009 kg/m^2 (0.0002 lbs/ft^2), respectively. Similarly, annual increases of carbon and nitrogen per year in woody vegetation are 0.9 kg/m^2 (0.18 lbs/ft) and 0.007 kg/m^2 (0.0014 lbs/ft^2), respectively. Further confirmation of soil carbon accrual is provided by an observed increase in the soil carbon and nitrogen ratio with revegetation project age. Admittedly, the type of organic matter accruing in the soil can influence this ratio. Additionally, permanence of the soil carbon accrual over time is indicated by a documented decrease in the ratio of fulvic to humic acid extractable soil organic carbon with revegetation project age. This

ratio is used as an indicator of the resistance of soil organic matter to microbial oxidation to carbon dioxide (CO_2).

A representative site 1 km (0.6 miles) long with a 45 year old revegetation project could contain as much as 748 tonnes (824 short tons) of soil carbon and 3,671 tonnes (4,046 short tons) of woody vegetation carbon above baseline conditions. Similarly, this same representative site could accumulate 54 tonnes (59.5 short tons) of soil nitrogen and 24 tonnes (26.5 short tons) of woody vegetation nitrogen. The carbon accrued at this site equals the energy used by 1,478 homes or emissions from 3,411 passenger cars in one year (US EPA, 2015). Regionally, within 41 kms (25 miles) of revegetated streams in Marin County (Lewis et al 2011), there is an estimated 25,262 tonnes (27,846 short tons) of soil carbon and 55,003 tonnes (60,630 short tons) tons of woody vegetation carbon and correspondingly 1,956 tonnes (2,156 short tons) of soil nitrogen and 439 tonnes (483 short tons) of woody vegetation nitrogen in projects with ages ranging from 6 to 45 years. The amount of carbon sequestered at these sites equals emission from 61,959 passenger cars or the energy used by 26,853 homes in one year.

Considering only the carbon accrued at the 1 km representative site, there is 4,419 tonnes equating to 16,217 tonnes of carbon dioxide equivalents (CO_2e). *Marin's Climate Action Plan 2015 Update* has the goal of reducing greenhouse gas emissions by an additional 84,160 tonnes CO_2e (ICF International, 2015). This amount could be offset with the implementation of 5.2 km (3.23 miles) of stream revegetation. Cost estimates for stream revegetation are $316 per linear meter ($96 per linear foot) or $19.75 per tonne CO_2e.

Study results add to the understanding of environmental services, including greenhouse gas mitigation, provided by stream and riparian areas and how restoration and revegetation facilitate those services. Confirming that stream restoration and the revegetation of riparian areas leads to the accrual and sequestration of carbon and nitrogen provides additional endorsement for implementation of these conservation practices in partnership with private and public landowners.

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1.0 Introduction

Land managers have restored river and stream corridors through revegetation for over four decades to meet multiple objectives. The number of river and stream restoration projects in the United States has steadily increased since the 1980s from 100 to over 4,000 projects per year (Bernhardt et al., 2005, Palmer et al., 2007). In California, over $2 billion has been spent on river restoration since 1980, with riparian vegetation management the most common project type (Kondolf et al., 2007). In Marin County, more than 25 miles of stream have been revegetated and 40 miles of stream have been fenced to manage livestock access (Lewis et al., 2011).

Despite this effort and funds expended, there has been limited systematic documentation of project effectiveness to provide quality habitat and watershed functions (Kondolf et al., 2007, Miller and Hobbs 2007, Palmer et al., 2007). Quantification of restoration trajectories for community and ecosystem attributes offer a method for conducting such documentation and evaluation. Such studies use the amount of time since project implementation to evaluate long-term project success and timelines for achieving specific objectives (Zedler and Callaway 1999, Gardali et al., 2006). Examples of project effectiveness assessment in the restoration ecology literature include investigations of riparian revegetation impacts on watershed functions and ecosystem services such as diversity (Hobbs 1993, Hupp and Osterkamp 1996), pollination (Kremen et al., 2004), sedimentation (Hupp and Osterkamp 1996, Corenblit et al., 2007), trophic dynamics (Baxter et al., 2005, Muotka and Syrjanen 2007), nutrient cycling (Kauffman et al., 2004, Sheibley et al., 2006, Bush 2008), water quality (Phillips 1989, Gregory and Moral 2001, Peterson et al., 2001, Houlahan and Findlay 2004), infiltration (Kauffman et al., 2004), flood retention (Hupp and Osterkamp 1996, Corenblit et al., 2007), and habitat (Dobkin et al., 1998, Opperman and Merenlender 2004, Gardali et al., 2006).

What is lacking in the current knowledge base is an understanding of the relationship between soil properties and riparian restoration (Richter et al., 1999). Studying tree encroachment on semi-arid grasslands, Throop and Archer (2008) documented increases in soil carbon and nitrogen as a function of tree size, a proxy for age. In a similar setting, Hughes et al. (2006) documented increases in above ground carbon and nitrogen storage and cycling as a result of woody plant species encroachment. Similar dynamics for the role of individual oak trees in above and below-ground carbon and nitrogen in Mediterranean ecosystems have also been identified (Dahlgren et al, 2003).

These contributions are useful for understanding carbon and nitrogen storage and cycling in the face of increasing woody plant species on the landscape. They do not however, explicitly document how stream and river restoration interact with these nutrient functions and other ecosystem services. One example of this type of study was conducted by Janis Bush (2007) along the San Antonio River, Texas. By sampling and re-sampling soils at 12 restoration project sites ranging from 5 to >150 years in age, Bush established a data-driven model for the rate and magnitude of nitrogen and carbon sequestered in revegetated riparian soils. A similar endeavor for restored riparian forests along the Sacramento River in California was conducted by the Matezak et al. (2015). By combining tree and shrub density measurements with soil carbon sampling and analysis from 19 sites grouped within four age classes to a maximum age of 20 years, rates of carbon accumulation on reclaimed orchards were determined.

Our earlier work documented response trajectories of plant community and stream morphology in relation to time since riparian restoration at 102 project sites (Lennox et al., 2009). We documented the outcomes from riparian restoration projects in terms of the

magnitude of change and the duration required to achieve a given change. This represents one of the few studies that assess long term recovery of watershed function and ecosystem services after restoration in California.

In riparian restoration projects, vegetation, geomorphology and soil undergo complex transformations over time, making it difficult to predict restoration outcomes.   The goal of this study was to evaluate the magnitude of carbon and nitrogen sequestration in response to riparian restoration over time. We returned to a subset of sites studied by Lennox and others (2009) to measure the extent of nitrogen and carbon sequestration in soil and woody vegetation. We also evaluated the trajectory of carbon and nitrogen accumulation in restoration projects spanning ages from 0 to 45 years.   Information from this study is useful and timely for policies and programs that offset greenhouse gas (GHG) emissions and develop market driven incentives for carbon sequestration. The information will also assist the restoration community in forming realistic expectations and objectives for projects.

2.0 Methods

2.1 Overview

Studied riparian revegetation sites were located in the mixed oak woodland and annual grassland of California's north coast. The region has a Mediterranean climate with cool wet winters and hot dry summers. It should be noted that this coastal region of California is cooler with more moderate rainfall than most hardwood rangelands. Streams and rivers in the region are dominated by varying degrees of channel incision (Darby & Simon 1999) and are located in watersheds with an average area of 23.5 km^2 (range = 0.2 − 133.1 km^2), elevation of 145.3 m asl (range = 3.7 − 656.4 m asl), and forest cover of 21.9% (range = 0 − 100%).

We employed a retrospective, cross-sectional study design to evaluate 42 stream reaches across Marin, Napa, and Sonoma Counties, in Northern California (Figure 1). Site selection focused on locations where comparable stream reaches of different project age (years since project implementation) were adjacent to each other with similar soil and stream morphology. Soil sampling and plant community measurements were conducted in three plots per site, stratified by three landforms: active channel, depositional floodplain, and upperbank terrace (Figure 2).

Revegetation design at surveyed projects ($n = 34$) was site-specific and focused on establishing *Salix* species to initiate establishment of riparian forests. Restoration practitioners use these species with the aim of controlling erosion and to enhance other watershed functions (Kauffman et al., 1997). In general a combination of practices was used to install projects, including tree or shrub planting with dormant willow posts or container plants (Johnson 2003), biotechnical bank stabilization (Johnson 2003; Flosi et al., 2004),

Figure 1: Project study sites across Marin, Napa, and Sonoma Counties in Northern California.

Figure 2: Riparian cross section identifying three studied landforms.

and passive restoration (Kauffman et al., 1997) using large herbivore management (e.g., removal, reduced stocking rate, or exclusionary fencing for livestock and/or deer). Non-restored sites were surveyed ($n = 8$) where local experts indicated that a particular stream reach had vegetation similar in structure to the project site before revegetation occurred.

2.2 Soil Sampling and Analysis

For the depositional floodplain and upperbank positions soil sampling was conducted from the

Figure 3: Depositional floodplain soil sampling pit.

surface to a depth of 50 cm and stratified by dominant soil horizons (Figure 3). An additional sample was collected from 50 cm to 100 cm using an auger. Soil samples for the channel landform were collected in the first 10 cm of gravel bed.

Soil samples were passed through a 2mm sieve to remove coarse fragments and macro-organic matter. Total carbon (TC) and total nitrogen (TN) were analyzed by a direct combustion analyzer. We verified that the samples contained no detectable carbonates, thus TC was considered a measure of organic carbon. In order to express soil organic carbon on a dry weight basis, separate subsamples were oven dried at 105°C for 24 h to determine gravimetric water content of air dried soil. Humic and fulvic acid extractions were conducted to assess the relative recalcitrance of soil organic matter, following the basic extraction procedure recommended by the International Humic Substance Society (Hayes, 1985; Swift 1996). Labile carbon extraction, a measure of the readily degradable organic residue, was done with a permanganate extraction (Culman et al., 2012). Bulk density was measured by 3-D Laser scanning of aggregates (Rossi et al., 2008). Soil bulk density was used to convert gravimetric measurements of materials (e.g. % TC) to volumetric pools (g/m^2).

2.3 Vegetation Sampling and Analysis

To make TC and TN calculations for woody vegetation at studied sites, we employed and combined: 1) field vegetation measurements at each study site with; 2) destructive sampling of selected riparian species; and 3) established allometric rating curves and values in the literature. This process provided biomass and percent carbon and nitrogen measurements and rating curves needed for final calculations.

Field measurements of restored riparian forest species composition and abundance were made using two-meter radius sampling plots placed in the center of a representative section of the upperbank and floodplain landform classes. For the active channel landform, we characterized the vegetation from bankfull to water's edge. We also documented the stand density of any additional woody species within the project area growing outside of our vegetation plot. We made diameter at breast height (DBH) measurements of trees and shrubs at

140 cm height and estimated tree height. We quantified ground cover and herbaceous species composition with a 20 x 20 cm quadrat within the vegetation plot.

Based upon extensive literature and the intensive meta-analysis of Thomas and Martin (2012a) and Jenkins et al. 2003, we focused our destructive sampling for percent carbon and nitrogen on common species in the studied riparian areas that were not well quantified by previous studies, specifically: *Alnus rubra; Bacharis pilularis; Rubus discolor; R. ursinus; Salix lasiolepis; and S. lucida*. These species were harvested for analysis of carbon and nitrogen content by similar types of wood tissue as explained by Thomas and Martin (2012b). Specifically, three individuals for each of these six species were sampled discretely at the bottom, middle, and top of the trunk or stem and at the branches. Samples were oven dried, ground to a fine powder, and analyzed for percent carbon and nitrogen at the UC Davis Stable Isotope Facility by combustion at 1000 ºC on a PDZ Europa ANCA-GSL elemental analyzer (Sercon Ltd., Cheshire, UK) (Bremner and Tabatabai 1971). Additionally, to determine tissue density, volumetric measurements were made by displacement (Hughes 2005, Chave 2005).

Woody biomass at studied sites was calculated by species using DBH-based equations (Jenkins et al., 2003). With the exception of *Rubus discolor* and *R. ursinus,* TC and TN was calculated using our field measurements of DBH multiplied by species-specific C and N percent values from our measurements or literature values from Thomas and Martin (2012b). For *Rubus discolor* and *R. ursinus* biomass was calculated using the following equation we derived from our destructive sampling:

Equation 1:   biomass (kg) = 0.174 x DBH(cm) (R^2=0.77, p=0.0143)

Lastly, to complete TC and TN estimates in woody vegetation at studied sites, we applied the method by Jenkins et al. (2003) to account for root and foliar biomass C and N contributions. We also accounted for carbon lost due to oven dried methods by correcting for the volatile C fraction (Thomas and Martin, 2012a).

2.4 Data Analysis and Scaling Up

We utilized summary statistics and graphical analysis to describe the field measurement and laboratory results. We then employed data-driven linear mixed effects modeling to determine trends in soil and woody vegetation TC and TN over time (Pinheiro and Bates, 2000). Unique models were developed for TC and TN in soil and woody vegetation, respectively. TC and TN for each component were set as outcome variables, with each site plot set as a group effect to adjust the *P-values* for repeated sampling at the same plot. A forward stepping approach was used to develop the multivariate regression model, with $P \leq 0.1$ set as the criterion for inclusion of the variable in the final model.

To quantify the landscape scale variability, model results for each landform class were combined with the mean width for each landform class surveyed to estimate TC and TN per unit length of stream and at a representative project site 1 km in length. In order to estimate the TC and TN sequestered over decades of riparian revegetation, results from an inventory of stream restoration projects implemented by the Marin Resource Conservation District and partners from 1959 to 2009 (Lewis et al., 2011) were combined with the measurements and modeling from this study.

3.0 Results

3.1 Study Site Characteristics

Surveyed stream restoration project sites (n=42) ranged in age from 0 to 45 years since restoration initiation, with a mean project implementation age of 15 years. Mean project length was 716 m, with a minimum length of 12 m and a maximum length of 4.3 km. Mean project width was 24 m, with a minimum and maximum of 10 m and 60 m, respectively. Bankfull width at the studied sites averaged 7.4 m, with a minimum of 2.4 m and a maximum of 13.7 m. Widths for the studied landform positions (approximately one half of total project site width) are presented in Table 1.

Table 1: Width (meters) of studied site landform positions perpendicular to stream course. Note these are the widths for one streambank or side only and one half of each studied site.

Landform	Mean (Min. - Max.)
Channel	3.32 (0.91-12.2)
Floodplain	9.71 (3.05-29.6)
Upperbank	11.1 (3.05-50.3)

3.2 Soils

We collected soils at a total of 126 soil sampling profiles from one of four dominant horizons for the upperbank and floodplain landform positions and a surface horizon for the channel position. Results from soil sampling and analysis are summarized by dominant soil horizons in Table 2. Total roots, C:N, TC, and TN decreased with depth, while bulk density increased with depth. Trends with depth for the other measured variables were not apparent.

Table 2: Soil sampling and analysis results by diagnostic horizon from surface or horizon 1 which included the active channel landform (N=126) to deeper horizons 2 through 4 at floodplain and upperbank sampling plots (N=84).

	Soil Horizon Mean (Min. - Max.)			
	1	**2**	**3**	**4**
	Mean (Min. - Max.)	Mean (Min. - Max.)	Mean (Min. - Max.)	Mean (Min. - Max.)
Horizon Depth Midpoint (cm)	6.47 (2-14)	22.9 (10-33)	40.9 (32-46)	72.9 (60-85)
Horizon Thickness (cm)	12.6 (4-27)	17.6 (6-32)	18.3 (8-36)	46.1 (20-70)
Total Root (%)	39.9 (0-85)	31.1 (0-85)	19.7 (0-70)	8.87 (0-52)
Total Rock (%)	12.8 (0-80)	10.2 (0-80)	14.3 (0-80)	17.7 (0-80)
Total Sample Weight (g)	565 (148-1,751)	472 (205-1,525)	508 (171-2,014)	696 (121-2,031)
Soil Moisture (%)	2.22 (0.72-5.87)	2.14 (0.50-5.29)	2.16 (0.59-6.78)	2.26 (0.57-6.81)
pH (1:1)	6.26 (4.93-8.17)	6.36 (5.33-7.88)	6.43 (5.34-7.83)	6.57 (5.71-8.38)
Bulk Density (g/cm^3)	1.18 (0.43-1.90)	1.38 (0.73-1.92)	1.40 (0.70-1.84)	1.40 (0.70-1.84)
C:N	13.0 (7.5-18.5)	11.7 (8.40-17.7)	11.5 (7.87-18.4)	11.5 (6.87-16.5)
Total C (%)	1.75 (0.05-7.99)	1.13 (0.06-2.71)	0.88 (0.09-2.91)	0.64 (0.05-2.01)
Total N (%)	0.13 (0.005-0.44)	0.10 (0.006-0.23)	0.07 (0.007-0.24)	0.05 (0.004-0.14)
C Stock (kg/m^2)	2.64 (0.05-9.15)	2.63 (0.12-8.26)	2.29 (0.19-9.16)	4.45 (0.13-14.9)
N Stock (kg/m^2)	0.21 (0.005-0.84)	0.22 (0.01-0.73)	0.19 (0.02-0.74)	0.38 (0.01-1.12)
Labile C Stock (kg/m^2)	0.05 (0.001-0.17)	0.06 (0.004-0.15)	0.05 (0.005-0.20)	0.12 (0.005-0.33)
Humic Acid Stock (kg/m^2)*	0.84 (0.007-2.81)	0.78 (0.005-3.48)	0.64 (0.01-3.38)	1.22 (0.007-6.50)
Fulvic Acid Stock (kg/m^2)*	0.74 (0.02-1.63)	0.61 (0.02-1.39)	0.46 (0.03-1.90)	0.74 (0.02-2.27)
FA:HA ratio*	1.08 (0.48-2.80)	1.10 (0.25-3.0)	1.13 (0.18-3.19)	1.13 (0.24-3.19)

*N=54

3.3 Vegetation

Summary results for restored riparian forest composition and abundance characteristics by landform are presented in Table 3. Bare ground cover was the lowest in the upperbank sites while in contrast, annual ground cover was the highest. In terms of woody species characteristics, shrub ground cover, total woody vegetation density, above ground biomass, and canopy cover were highest in the floodplain landform.

Table 3: Vegetation characteristics by landform class (N = 42 per landform).

Variable	Channel	Floodplain	Upperbank
	Mean (Min. - Max.)	Mean (Min. - Max.)	Mean (Min. - Max.)
Bare Ground Cover (GC) (%)	13.0 (5-35)	10.4 (5-30)	7.1 (5-15)
Litter GC (%)	14.5 (5-35)	17.5 (5-42)	19.9 (5-41)
Annual GC (%)	12.5 (0-55)	20.0 (0-65)	31.2 (0-75)
Perennial Herbaceous GC (%)	29.2 (0-90)	20.7 (0-70)	29.3 (0-80)
Shrub GC (%)	5.59 (0-60)	10.9 (0-50)	4.88 (0-40)
Woody Vegetation Density (#/m^2)	0.45 (0-2.09)	0.99 (0-3.18)	0.39 (0-2.94)
Above Ground Biomass (Kg/m^2)	34.3 (0-528)	60.8 (0-896)	12.0 (0-92.9)
Canopy Cover (%)	59.1 (0-100)	60.9 (0-100)	39.4 (0-100)
Tree Canopy Species Richness (#/plot)	1.05 (0-2)	0.98 (0-3)	0.45 (0-2)

Results from destructive sampling of selected riparian woody species are presented in Table 4. In general, carbon was constant across the different tissue and plant parts while nitrogen values increased from stem bottom to branches or older to younger tissue.

Table 4: Mean, minimum and maximum values for percent carbon and nitrogen results by tissue type for common species.

	Stem Bottom	Stem Middle	Stem Top	Branches
	Mean (Min. - Max.)	Mean (Min. - Max.)	Mean (Min. - Max.)	Mean (Min. - Max.)
C%				
Alnus rubra	47.1 (46.3-47.6)	47.9	47.1 (46.9-47.1)	47.6 (47.1-48.3)
Bacharis pilularis	44.9 (43.6-45.7)	45.2	44.7 (42.4-45.9)	46.3 (46.1-46.5)
Rubus discolor	45.9 (45.7-46.1)	-	45.6 (45.5-45.7)	45.9
Rubus ursinus	46.7 (46.4-47.1)	-	46.5 (46.1-46.9)	46.3 (46.3-46.3)
Salix laseopsis	47.6 (47.4-47.7)	46.9 (46.8-47.1)	47.2 (46.6-47.5)	47.4 (46.7-47.8)
Salix lucida	45.8 (45.4-46.1)	46.1 (45.4-46.8)	46.7 (46.1-47.8)	46.6 (46.3-46.9)
N%				
Alnus rubra	0.39 (0.27-0.45)	0.46	0.49 (0.43-0.53)	0.54 (0.49-0.59)
Bacharis pilularis	0.26 (0.23-0.30)	0.32	0.28 (0.23-0.35)	0.35 (0.31-0.41)
Rubus discolor	0.33 (0.29-0.36)	-	0.51 (0.31-0.71)	0.36
Rubus ursinus	0.71 (0.60-0.82)	-	0.69 (0.50-0.88)	0.77 (0.70-0.84)
Salix laseopsis	0.20 (0.16-0.24)	0.19 (0.16-0.21)	0.22 (0.20-0.24)	0.28 (0.26-0.30)
Salix lucida	0.43 (0.38-0.47)	0.35 0.25-0.44)	0.42 (0.36-0.49)	0.29 (0.22-0.39)

3.4 Total Carbon and Nitrogen by Landform and Project

Results from calculations of carbon and nitrogen stocks for soil and woody vegetation within each landform class are presented in Table 5. For the soil results it is important to keep in mind that channel landform soil sampling was conducted to a depth of 10 cm compared to depths of up to 1 m for the floodplain and upperbank landforms.

Soil carbon stock was greater in the upperbank sites than in the floodplain sites. This is in contrast to the calculated vegetation carbon stock, which was higher in both channel and floodplain sites than in upperbank sites.

Table 5: Plot summary data for soil and vegetation results by landform class (N=126 plots, *N=84 plots).

	Mean (Min. - Max.)		
	Channel	**Floodplain**	**Upperbank**
Soil			
C (%)	0.99 (0.05-4.12)	0.97 (0.13-3.05)	1.42 (0.62-2.73)
N (%)	0.07 (0.005-0.28)	0.08 (0.01-0.18)	0.12 (0.06-0.22)
C Stock (kg/m^2)	1.04 (0.05-4.47)	8.82 (0.69-17.9)	16.8 (2.82-36.6)
N Stock (kg/m^2)	0.08 (0.005-0.30)	0.72 (0.05-1.47)	1.42 (0.23-3.01)
C:N	13.1 (7.66-18.2)	12.3 (9.27-15.2)	11.7 (8.92-15.4)
Labile C Stock (kg/m^2)	0.03 (0.001-0.09)	0.23 (0.02-0.53)	0.35 (0.08-0.75)
Humic C Stock (kg/m^2)*	-	2.13 (0.03-6.92)	4.49 (0.42-12.9)
Fulvic C Stock (kg/m^2)*	-	2.08 (0.09-3.75)	3.07 (0.61-5.98)
Woody Vegetation			
C Stock (kg/m^2)	19.2 (0-176)	37.5 (0-295)	9.02 (0-83)
N Stock (kg/m^2)	0.15 (0-1.18)	0.30 (0-2.00)	0.07 (0-0.65)
C:N	150 (68.4-220)	148 (80.8-220)	148 (73.0-220)

Scaling up and combining the results across all landforms provides the opportunity to summarize carbon and nitrogen stocks for soil and vegetation on a per project basis (Table 6). Per square meter, carbon in soils and vegetation are roughly equal, with a wider range for vegetation. In contrast, soil nitrogen stock is greater than woody vegetation nitrogen stock. It is important to recount that eight of the 42 study sites were not restored, with a project age of zero and virtual no woody vegetation. Per meter of streambank restored, woody vegetation carbon stock is greater than soil carbon stock. Similarly, total project mean carbon stock is greater in woody vegetation than in soil. Note that one of the studied sites was 4.3 km long, resulting in the maximum total project values.

Table 6: Total soil and woody vegetation carbon and nitrogen values (N=42 sites, *N=21 sites).

	Mean (Min. - Max.)	
	Soil	**Woody Vegetation**
C (kg/m^2)	26.7 (11.86 -52.43)	21.9 (0-295.5)
N (kg/m^2)	2.2 (0.99-4.22)	0.17 (0-2.0)
Labile C (kg/m^2)	0.6 (0.25-1.30)	-
Fulvic C (kg/m^2)*	5.2 (1.60-9.73)	-
Humic C (kg/m^2)*	6.6 (1.36-19.78)	-
C per Streambank Length (kg/m)	267.7 (75.2-882)	311 (0-2,678)
N per Streambank Length (kg/m)	22.8 (6.3-90.6)	2.1 (0-17)
C Project Total (kg/streambank)	249,106 (1,390-3,865,912)	316,942 (0-6,602,970)
N Project Total (kg/streambank)	22,117 (116.5-379,009)	2,039 (0-42,154)

3.5 Trends in Time and Differences across Landform Positions

Linear mixed effects models for associations of project age and landform position with carbon and nitrogen stock in soil and woody vegetation components are presented in Tables 7a-d. The respective plot data for soil and vegetation stocks that populated these models are presented in Figure 4. Each model contains a positive coefficient for project age that is statistically significant, indicating both carbon and nitrogen are accruing over time in both soil and vegetation at the studied sites. In the case of soil stocks, model coefficients indicate annual increases of carbon and nitrogen are 0.2 kg/m^2 and 0.009 kg/m^2, respectively. Similarly, annual increases of carbon and nitrogen per year in woody vegetation are 0.9 kg/m^2 and 0.007 kg/m^2, respectively.

The relationship between carbon and nitrogen stocks and landform position is less clear. Visually, there are differing trends for both carbon and nitrogen in soil and woody vegetation across three landform positions (Figure 3). In the case of woody vegetation, carbon stocks demonstrate an increase over project age for all three landform positions with the lowest increase in the upperbank position.

Soil carbon stocks increased over time at the floodplain and upperbank positions. Values in first 10-cm of the channel plots where stream flow is intermittent are constant with project age. Carbon soil stocks were greatest in the upperbank. Mechanisms driving soil carbon stocks and accrual in these landscape positions are different due to the difference in plant communities, hydrology and sedimentation processes.

The upperbank position is dominated by annual and in some cases perennial grasses and forbs with minimal to no shrubs and trees. Soils are finer textured relative to the channel and floodplain positions formed from periodic, low-energy flood events. In comparison, floodplain positions are dominated by woody species. Floodplain positions typically support stratified soils aggrading by sediment deposition from relatively high energy flood events. Sediment that is aggrading around and among woody plants is coarser grained sands and gravels (gravelly sands, loamy sands and sandy loams) compared to soils of upperbank positions.

Results from the data driven models indicate differences across landscape positions for carbon and soil stocks in terms of starting points (model intercepts) and the rate of change with project age (model slopes). Using soil carbon stocks (Table 7a) as an example, the intercept for

the floodplain and the channel position is reduced below the model constant of 13 kg/m^2 for the upperbank position by -6.2 and -12.7 kg/m^2, respectively (Figure 5). This is consistent with the overall observation that soil carbon stocks are highest in the upperbank position. Similarly, model interactions between project age and landform class describe the respective differences in model slope for the trends with project age at each landscape position. Relative to the coefficient for upperbank position of 0.2 kg/m^2 per year, the rate for floodplain is half that and for channel is zero (Table 7a and Figure 5).

Similar model results for the woody vegetation carbon stock (Table 7c) are presented in Figure 5. In this case, the intercepts are all less than zero indicative of little to no woody vegetation present at unrestored sites. There are still differences, however, in the three positions with channel having the highest intercept indicating the higher likelihood of woody vegetation being present in the position pre-restoration. Differences in the slopes or rates of carbon accrual in woody vegetation, as quantified by the project age landform class coefficients, indicate the rate of change is greatest for the floodplain position relative to the other two positions. This is to be expected because the primary focus of stream restoration and predominance of woody plant establishment is in the floodplain.

During the iterative forward step-wise development of these models, predictive variables that were added and then removed from the model included, woody vegetation density, root density, and soil texture. Woody vegetation and root density had statistically significant direct relationships with project age, and as a result, introduced co-linearity into the models. Soil texture was found to not be statistically significant, despite the field observation in the differences between the upperbank and other two landform positions.

Table 7a: Linear mixed effects model for associations of age and landform position with soil carbon stock (kg/m^2) in revegetated riparian areas of Marin, Napa, and Sonoma counties, Northern California.

Factor	Coefficient	95% CI[a]	P-value[a]
Constant or intercept term for the model	13.8	(11.7, 15.8)	<0.0001
Project age (years)	0.2	(0.1, 0.3)	0.0004
Landform position [b]			
Floodplain	-6.2	(-8.9, -3.5)	<0.0001
Channel	-12.7	(-15.4, -1.0)	<0.0001
Project age Landform class interaction			
Project age and Floodplain	-0.1	(-0.3, 0.02)	0.0908
Project age and Channel	-0.2	(-0.3, -0.1)	0.0038

[a] Adjusted for potential lack of independence due to repeated sampling at the same project plot site.
[b] Referent condition is upperbank landform.

Table 7b: Linear mixed effects model for associations of age and landform position with soil nitrogen stock (kg/m^2) in revegetated riparian areas of Marin, Napa, and Sonoma counties, Northern California.

Factor	Coefficient	95% CI[a]	*P*-value[a]
Constant or intercept term for the model	1.3	(1.1, 1.4)	<0.0001
Project age (years)	0.009	(0.001, 0.02)	0.0278
Landform position [b]			
Floodplain	-0.6	(-0.8, -0.4)	<0.0001
Channel	-1.2	(-1.4, -1.0)	<0.0001
Project age Landform class interaction			
Project age and Floodplain	-0.007	(-0.02, 0.003)	0.1758
Project age and Channel	-0.01	(-0.02, -0.0006)	0.0648

[a] Adjusted for potential lack of independence due to repeated sampling at the same project plot site.
[b] Referent condition is upperbank landform.

Table 7c: Linear mixed effects model for associations of age and landform position with woody vegetation carbon stock (kg/m^2) in revegetated riparian areas of Marin, Napa, and Sonoma counties, Northern California.

Factor	Coefficient	95% CI[a]	*P*-value[a]
Constant or intercept term for the model	-4.9	(-18.8, 8.9)	0.4811
Project age (years)	0.9	(0.2, 1.6)	0.0109
Landform position [b]			
Floodplain	-2.5	(-15.8, 10.9)	0.7129
Channel	3.0	(-10.3, 16.4)	0.6516
Project age Landform class interaction			
Project age and Floodplain	2.1	(1.4, 2.7)	<0.0001
Project age and Channel	0.5	(-0.2, 1.1)	0.1582

[a] Adjusted for potential lack of independence due to repeated sampling at the same project plot site.
[b] Referent condition is upperbank landform.

Table 7d: Linear mixed effects model for associations of age and landform position with woody nitrogen stock (kg/m^2) in revegetated riparian areas of Marin, Napa, and Sonoma counties, Northern California.

Factor	Coefficient	95% CI[a]	*P*-value[a]
Constant or intercept term for the model	-0.03	(-0.1, 0.1)	0.5019
Project age (years)	0.007	(0.002, 0.01)	0.0061
Landform position [b]			
Floodplain	-0.03	(-0.1, 0.08)	0.6086
Channel	0.02	(-0.08, 0.13)	0.6703
Project age Landform class interaction			
Project age and Floodplain	0.017	(0.01, 0.02)	<0.0001
Project age and Channel	0.003	(-0.002, 0.008)	0.2196

[a] Adjusted for potential lack of independence due to repeated sampling at the same project plot site.
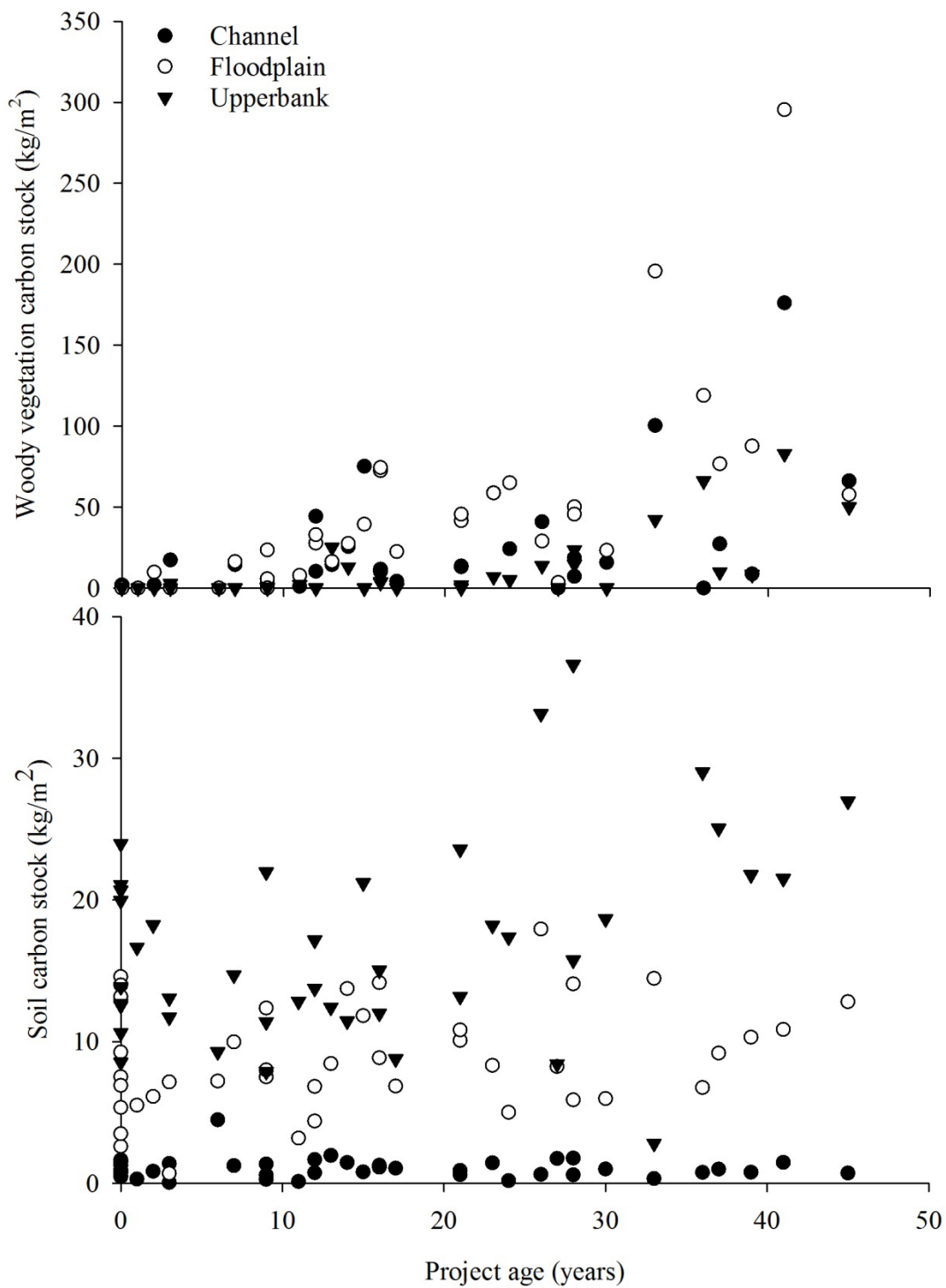[b] Referent condition is upperbank landform.

Figure 4: Measured values for carbon stock as a function of project age grouped by landform position for woody vegetation (upper) and soil (lower). Note the difference in the y-axes scales between the upper and lower graphs.
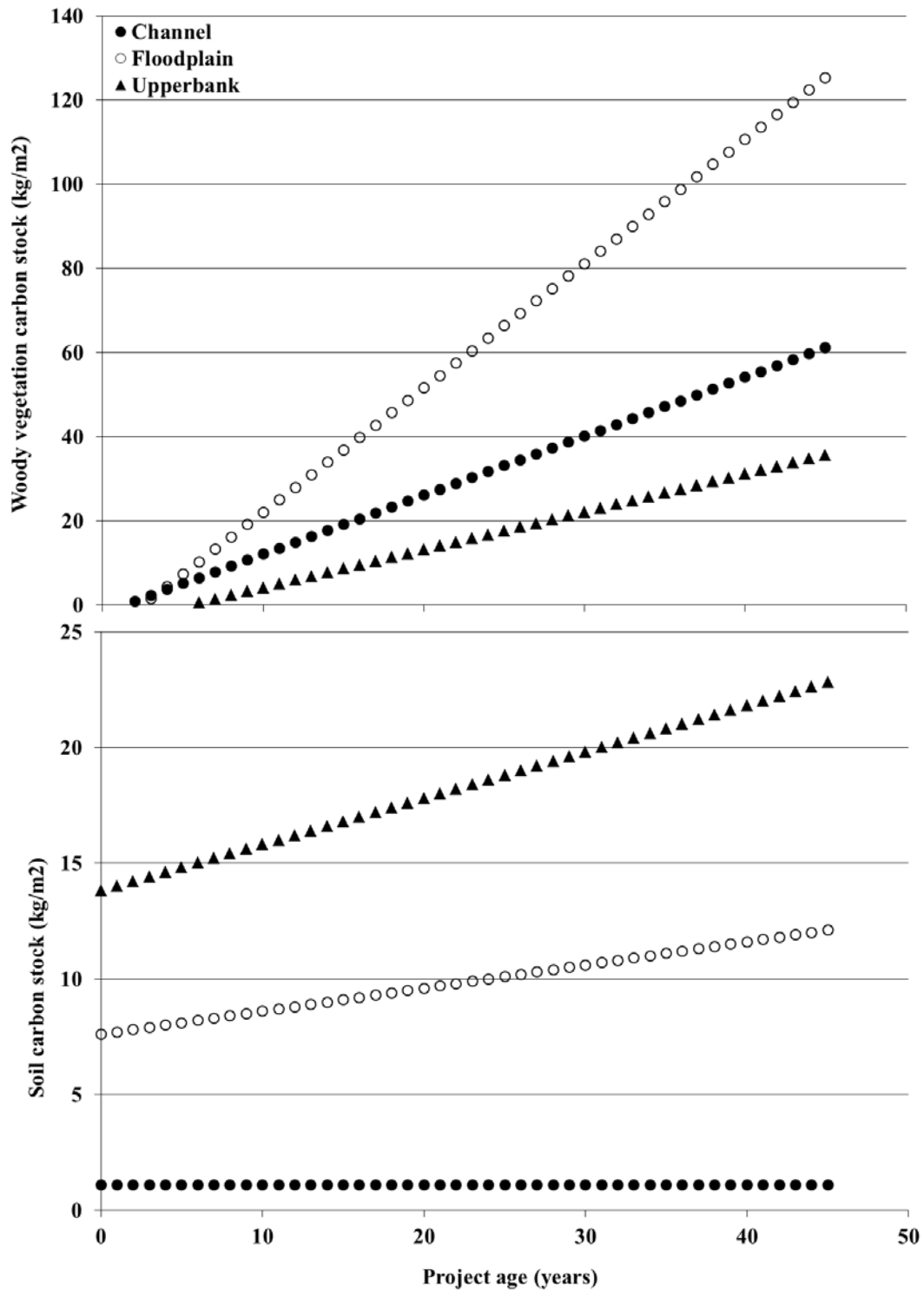
Figure 5: Trends in carbon stock (kg/m^2) for woody vegetation (upper) and soil (lower) in the channel, floodplain, and upperbank positions based upon data driven linear mixed effects model. Note the difference in the y-axes scales between the upper and lower graphs.

3.6 Confirmation of Sequestration and Permanence

Additional confirmation of soil C accrual is provided by an increase in the soil carbon and nitrogen ratio over time (Figure 6). The C:N ratio is a proxy for organic matter quality and resistance to microbial decomposition to CO_2. As C:N ratio increases decomposition rates generally decrease. In all three landform positions, ratios increase from lows of 8 to 10 in early project ages to lows of 12 to 14 at project ages over 40 years. Many of the greatest values, those above 16, measured at sites across the project age gradient, represent litter and organic matter encapsulated in the soil through deposition and aggradation.

Figure 6: Soil carbon and nitrogen ratio (C:N) as a function of project age and grouped by landform position.

Further characterization of soil organic matter quality with fulvic and humic acid extraction suggests that SOM becomes more resistant to microbial decomposition over time. Results from the fulvic acid (FA) and humic acid (HA) extraction methods indicate that the ratio of FA to HA decreases with restoration project age for the upperbank and to a lesser degree for the floodplain position (Figure 7). Carbon extracted with HA is more recalcitrant and longer lasting carbon in soil relative to FA extractable carbon. Ratios are above 2.0 with maximums approaching 3.5 at time zero or project age of zero. They decrease to values below 1.5 in the oldest projects studied with project ages of 36, 41 and 45 years of age. Lower FA:HA values at floodplain positions likely reflects the different source and quality of organic matter, consisting largely of litter and particulate carbon deposition in floodplains and grass root exudates at the upperbank.

Figure 7: Soil fulvic and humic acid ratio as a function of project age for floodplain and upperbank landform positions.

3.7 Site and Regional Scales

A representative revegetation project site that is 15 years old, 1 km long, and characterized by the mean values for landform widths, and the carbon and nitrogen stocks for soil and woody vegetation, contains approximately 551 tonnes of carbon and 46 tonnes of nitrogen in the soil and 1,055 tonnes of carbon and 8 tonnes of nitrogen in the woody vegetation.
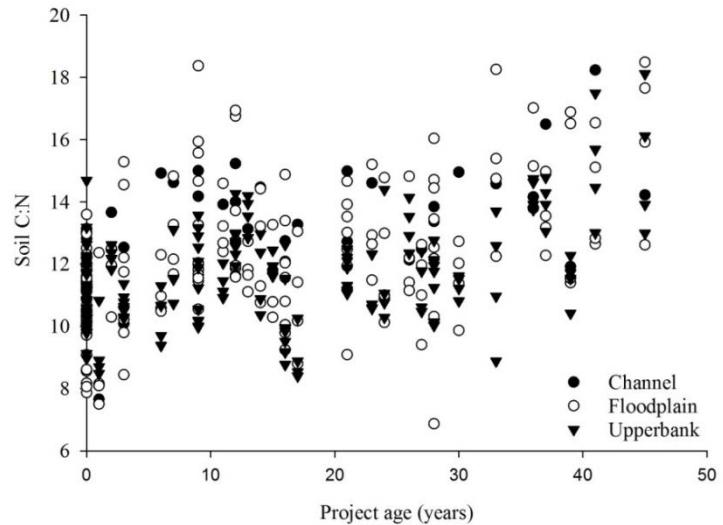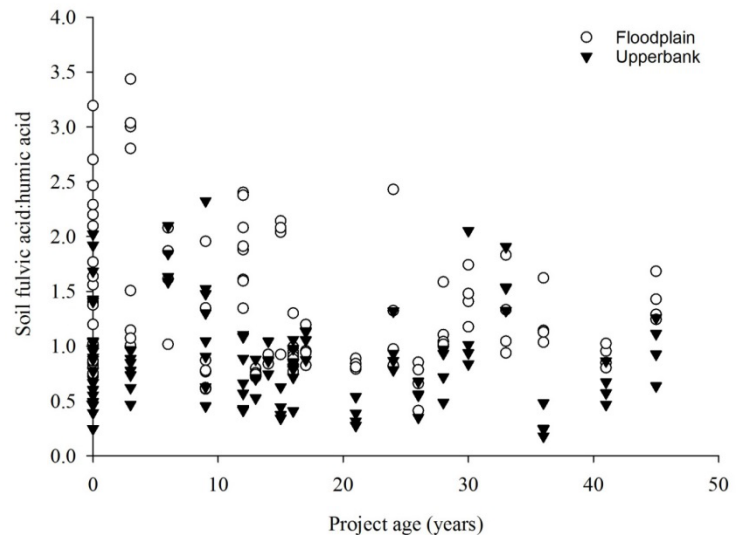
Based upon that project age and using the LME coefficients to calculate carbon and nitrogen accumulation, approximately 96 tonnes and 4 tonnes of soil carbon and nitrogen have accrued above baseline, respectively. Similarly, 1,312 tonnes and 9 tonnes of woody vegetation carbon and nitrogen have accrued. Forecasting additional accumulation in similar manner indicates that in an additional 30 years, or at project age 45 years, approximately 190 tonnes of carbon and 7 tonnes of nitrogen in soil and 2,624 tonnes of carbon and 17 tonnes of nitrogen in woody vegetation could be sequestered within this 1 km representative site.

At the scale of Marin County, an earlier inventory of stream revegetation projects through 2009 documented 41 kms of revegetated stream, with project ages ranging from 6 to 45 years (Lewis et al., 2011). Calculations, using the mean values from studied sites and data driven model results for soil and woody carbon and nitrogen, indicate totals of 25,262 tonnes of carbon and 1,956 tonnes of nitrogen in the soil and 55,003 tonnes of carbon and 439 tonnes of nitrogen in woody vegetation have accrued as a function of these stream restoration projects.

4.0 Discussion

The conservation practices related to stream restoration often target woody vegetation establishment. As implemented practices and planted shrubs and trees mature over multiple decades, atmospheric carbon and nitrogen may be sequestered into the soil profile and woody biomass, reducing available greenhouse gases. This has been well documented for temperate forests by quantifying the carbon sequestered in living trees. On California's Mediterranean rangelands, stream and river corridors are hot spots for tree and woody species growth because of available water in the soil profile to support their growth.

The mean carbon stock values (Table 6) for above and below ground portions are confirmation of the capacity of Mediterranean streams to be sinks for carbon. In comparison to broad landscape estimates for mixed woodland and grassland above and below ground carbon (Lenihan et al. 2003, Williams et al. 2011 and Zhu and Reed, 2012), they are two to three times greater.

Study results indicate that soil and woody vegetation carbon and nitrogen increase in relationship to restoration project age. Observed soil stocks for carbon and nitrogen at unrestored sites are generally greater than in the woody vegetation component. However, as implemented revegetation projects mature over time, the quantity of carbon and nitrogen in woody plants can be as much as one to three times greater than the amount in soils. This is because the rate of increase is greater for woody vegetation than for soil.

These two pools of carbon have potentially different levels of permanence. Carbon sequestered in soil is generally considered more permanent than carbon in vegetation. Carbon residence time is typically greater in soil compared to vegetation because vegetation is susceptible to disturbances such as fire, disease, climate change and land conversion. Thus, even though vegetation appears to have more carbon, soil organic carbon stocks are perhaps more permanent in managed landscapes.

Across the studied landforms, soil carbon and nitrogen accumulation was greatest in the upperbank relative to the channel and floodplain positions. It is likely that the combination of fine roots from grasses and fine textured soils contributes to greater accumulation and storage of carbon in the upperbank soil relative to the other positions. This is because grasses have most of their biomass below ground. In floodplains, dense woody vegetation has coarse woody roots and the canopy prevents grass growth, thus it is difficult to imagine soil organic matter accumulating via decomposition of roots. The trapping effect of woody vegetation likely promotes sedimentation of particulate organic matter that is ultimately sequestered in soil. Thus, soil organic carbon accumulation in the floodplains is likely due to sedimentation. Soil organic carbon is perpetually low in the channel landscape position because of an inability to trap soil due to continual scouring by streamflow. By comparison, woody vegetation carbon and nitrogen amounts and accrual were greater in the floodplain and channel than in the upperbank position. This is consistent with the design and implementation of restoration projects where the revegetation of woody species is focused primarily on the floodplain and channel positions and not the upperbank.

A representative project site 1 km long with a 45 year old revegetation project could contain as much as 748 tonnes of soil carbon and 3,671 tonnes of woody vegetation carbon, or total of 4,419 tonnes of carbon and 16,217 tonnes carbon dioxide equivalents (CO_2e). Marin's Climate Action Plan 2015 Update has the goal of reducing greenhouse gas emissions by an additional 84,160 tonnes CO_2e (ICF International, 2015). This amount could be offset with the

implementation of 5.2 km of stream revegetation. Not included in this offset calculation are the 54 tonnes of soil nitrogen and 24 tonnes of woody vegetation nitrogen that could accumulate at this site, because calculating and estimating nitrogen offsets is limited due to the continual cycling of nitrogen through soil, plants, and the atmosphere.

Regionally, within 41 kms of revegetated stream in Marin County (Lewis et al 2011), there is an estimated 25,262 tonnes of soil carbon and 55,003 tonnes of woody vegetation carbon and correspondingly 1,956 tonnes of soil nitrogen and 498 tonnes of woody vegetation nitrogen in projects with ages ranging from 6 to 45 years of age.

The 4,419 tonnes of accrued carbon at the 1 km representative site, in terms of greenhouse gas emission, equates to the energy used by 1,478 homes or emissions from 3,411 passenger cars in one year (US EPA, 2015). At the regional scale, the combined 80,265 tonnes of sequestered carbon equals the emissions from 61,959 passenger cars or the energy used by 26,853 homes in one year. This does not include any potential offset from the accrued nitrogen. Additionally, these greenhouse gas emission offsets are additive and complementary to improvements in water quality and wildlife habitat, and other environmental services already confirmed for stream revegetation.

Achieving these levels of potential carbon and nitrogen accrual and mitigation comes with a price tag for project implementation. Design, permitting, materials, and labor costs to install the simplest stream revegetation projects are on the order of $316 per linear meter or $316,000 for a 1 km long project (Scolari, 2015). This covers the costs for sprigging 1,280 willow sprigs in two rows and 3 meters on center, planting 275 additional trees and shrubs, and installing tree protectors, fencing, erosion cloth, and irrigation. If project sites require more complex erosion control and channel habitat restoration, costs can be three to ten times more per linear meter of activity. Unit cost of carbon accrued for the less expensive approach to revegetated streams at the 1 km long site with a project age of 45 years are $71.5 per tonne of carbon or $19.50 per tonne CO2e. Currently, carbon markets are offering approximately $12.75 per tonne of CO_2e (CPI, 2015).

Study results add to the understanding of the role that stream and riparian areas have in providing environmental services and how restoration and revegetation facilitate those services. In addition to enhancing water quality and quantity and providing habitat for aquatic and terrestrial plants and animals, restored and functioning riparian areas are sinks for carbon and nitrogen. Confirming that stream restoration and the revegetation of riparian areas leads to the accrual and sequestration of carbon and nitrogen provides additional endorsement for implementation of these conservation practices in partnership with private and public land managers. While market rate payments are not currently high enough to fully cover implementation costs, the ability of voluntary and regulatory markets to support riparian restoration should be buoyed by the confirmation of the amount of carbon and nitrogen these practices can accrue over time.

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