



Enhancing carbon sequestration in western U.S. rangelands through responsible wool standard and regenerative sheep farming practices

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Abstract

Little is known about soil carbon dynamics and the effects of regenerative grazing practices on sheep ranches in the United States. To address this knowledge gap, we established a soil carbon monitoring program across ten sheep ranches spanning over 1 million hectares of private and federal rangelands in the Western United States. Collectively, these operations manage over 47,000 sheep for meat and wool production. By adopting the Responsible Wool Standard (RWS), these ranches have implemented practices to improve grazing management, land health, and animal and social welfare. From 2020 to 2023, soil carbon levels were measured at a depth of 20 cm. Greenhouse gas emissions, including CO₂, CH₄, and N₂O, were also estimated using the COMET-Farm model at both individual and aggregate levels. Preliminary results indicate that one ranch showed an increase in soil organic carbon (SOC), while SOC levels on the remaining ranches remained relatively stable. COMET-Farm modeling estimates that these ranches have the potential to offset 91,444 metric tons of CO₂ equivalents annually. This study provides a crucial baseline for understanding soil carbon dynamics on sheep ranches and highlights the potential of regenerative grazing and conservation practices to enhance carbon sequestration. It emphasizes the role sustainable sheep grazing systems can play in promoting ecological health while maintaining agricultural productivity.

Introduction

Recent efforts have focused on monitoring greenhouse gas (GHG) emissions and strategies to reduce them, with soil carbon sequestration emerging as a key solution. This process occurs when carbon capture through photosynthesis exceeds losses from respiration, transforming ecosystems into carbon sinks. Conservation practices like no-till farming, cover cropping, regenerative grazing, and optimized fertility management (mineral and organic amendments) not only enhance soil carbon but also improve soil health, reduce erosion, and promote sustainability (Havstad et al., 2007; Derner and Schuman, 2007). Rangelands, which cover vast areas, are particularly suited for carbon sequestration while providing critical ecosystem services like food production, water retention, and biodiversity (Follett and Reed, 2010; Davies et al. 2011; Pyke et al. 2015). Interest in sustainable

practices among ranchers and farmers has grown due to the environmental concerns associated with livestock production. However, research on soil carbon impacts in sheep production, particularly on U.S. rangelands, remains limited. To address this, we developed a soil carbon monitoring program for sheep ranches in the Shaniko Wool Company Farm Group. These farms implement management practices that are deemed regenerative such as rotational grazing, no-till farming, and riparian restoration. Using field sampling and the USDA's COMET-Farm model, which assesses net GHG emissions, we estimate the carbon budget for individual farms and the group as a whole. We hypothesize that these practices will increase soil organic carbon, supporting the role of regenerative livestock production in sustainable land management.

Methods

The soil carbon monitoring program was conducted across ten ranches within the Shaniko Wool Company farm group. However, this study includes data from only seven farms, as three recently joined the group. Collectively, this group grazes across 2.6 million acres (1.05 million hectares) of private lands, Bureau of Land Management (BLM) allotments, and U.S. Forest Service (USFS) allotments. The USFS lands, located at higher elevations, experience cooler temperatures and greater moisture compared to the lower-elevation, drier BLM and private rangelands. Average annual rainfall ranges between 250mm in the drier areas up to 600mm in the higher elevation allotments. Soil types in the ranches present a very high variability as they are located on different areas, from sandy basins to loams and clayey soils. Altogether, the farm group raises over 47,000 sheep and produces approximately 225,000 kilograms of wool annually. The landscapes span diverse ecosystems, ranging from basin shrub-steppe to high-elevation mixed conifer forests and mountain meadows, reaching elevations of over 2,700 meters above sea level. For carbon monitoring, representative sampling sites were selected on each farm based on factors such as topography, soil characteristics, elevation, gradient, vegetation types, and land use. In total, 236 sampling points were established across the participating farms. At each sampling point, five soil cores were collected using a 2-inch bucket auger and combined into a single composite sample per site. Soil was collected at a depth of: 0–20 cm for all sites. Of the seven ranches evaluated in the project, one was sampled four times (2020, 2021, 2022, and 2023), while the other six were sampled three times (2021, 2022, and 2023). Samples were analyzed at the USDA-ARS Soil Laboratory in Corvallis, OR, USA, for soil organic carbon (SOC) using a LECO CN828 analyzer. Because the study sites are located in semi-arid regions, a preliminary "fizz" test (Lal, 2009; Whitlark, 2011) was performed on all soil samples to detect the presence of carbonates. Reactive samples were further analyzed for calcium carbonate content using a pressure-calimeter (Fonnesbeck et al., 2013). Additionally, soil pH was measured using both a 1:1 soil-to-water ratio and a 0.01 M CaCl₂ solution. Bulk density values were obtained from the USDA Web Soil Survey. Soil carbon stocks were estimated using the following formula:

$$\text{Soil C (kg/ha)} = (\%C \div 100) \times \text{BD (g/cm}^3) \times D \text{ (cm)} \times 100,000$$

where %C is the carbon content, BD is the bulk density, and D is the soil depth.

We used the COMET-Farm model for GHG modeling. Due to model limitations, only BLM public lands and private lands were included while USFS public lands were excluded as the model lacks soil data for forested sites. Operational boundaries were delineated and edited using ArcGIS Pro 2.8.0. To meet model size constraints, large shapefiles were divided into parcels smaller than 1,200 acres and imported into COMET-Farm as SHP files. Projects were limited to fewer than 50 parcels and no more than 200 soil units each. Each ranch was modeled separately for grazing land management, cropland management, and animal agriculture. Emissions from these categories were calculated individually and then combined to estimate total emissions for the operations. Historical (pre-1800s general management), baseline (2000–2020), and animal agriculture data were collected through interviews with land managers and incorporated into the parcels. For grazing lands, data collected included vegetation type (modeled as perennial grass), percent daily utilization, grazing periods, rest days, and management practices like fertilization, irrigation, or burning if applicable. For croplands, data included crop species, planting and harvest dates, tillage intensity, field operations, fertilizer or amendment applications, irrigation events, grazing

events, and liming when necessary. For animal agriculture, data collected included class and number of animals, average daily feed, average liveweight, diets, housing, manure management, manure N content, total dry manure produced, and the percentage of pregnant animals.

Each ranch was analyzed separately, as comparisons between ranches were not conducted due to differences in management, history, location, climate, elevation, and soil types. For each ranch, we used a one-way ANOVA to compare the means of soil carbon and nitrogen across its total operations and by lease type (BLM, USFS, and private lands). Normality assumptions were tested by examining residual plots, identifying extreme outliers, and performing a Shapiro-Wilk test. ANOVA and normality analyses were conducted using RStudio (2021.09.0), while regression analyses and plots were generated with SigmaPlot version 15.1.1.26 (2023).

Results

Soil organic carbon

Changes in soil organic carbon (SOC) was not statistically significant ($P > 0.05$) on six of the seven ranches (Figure 1a). Ranch D had an increase in SOC between 2021 and 2022 ($P < 0.001$) as compared to 2020 and remained stable until 2023.

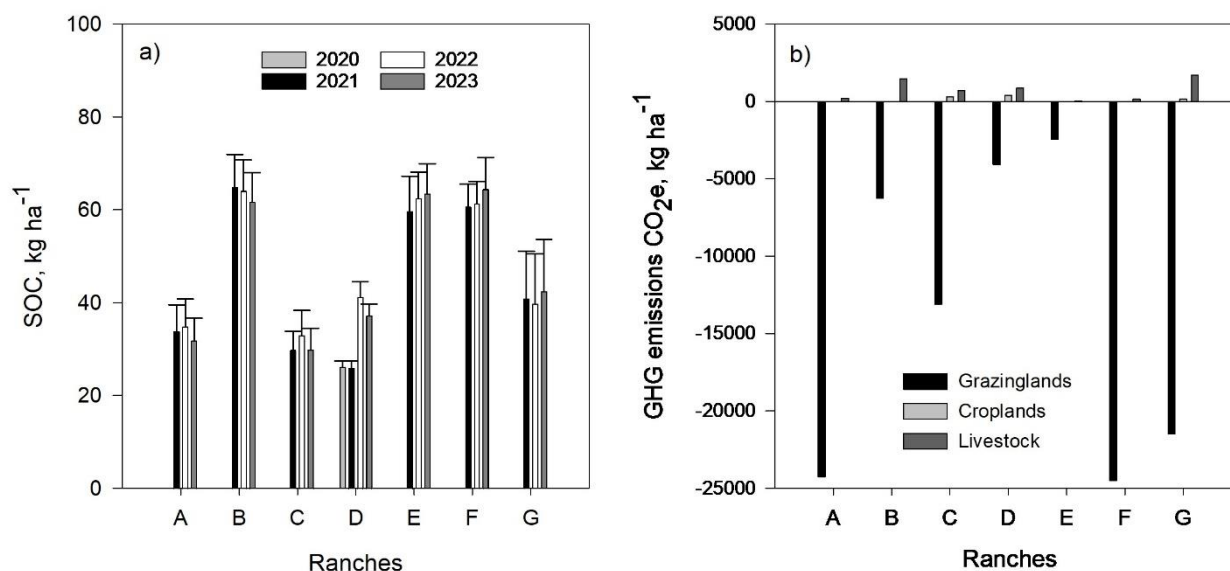


Figure 1. Average soil organic carbon (SOC, t ha^{-1}) change at 0-20cm depth from 2020 to 2023 (a) and GHG emission reduction potential of the ranches (A-G) (b). Bars represent standard error of the mean.

COMET-Farm GHG results

Each one of the ranches presented a large negative emission value in the grazing lands as compared to the smaller positive emissions from the croplands and livestock. The sum of the emissions from the three categories (grazing lands, croplands and livestock emissions) results in a negative emission value for the entire modeled operations. This negative value indicates the potential carbon that can be taken by the soil, demonstrating that all cropland and animal emissions from the ranches can potentially be sequestered by the soil under optimal conditions (Figure 1 b).

Discussion

Among the seven evaluated ranches, only one showed a significant increase in soil organic carbon (SOC) between 2020 and 2023. Three others displayed positive trends in carbon sequestration, while three showed negative trends. Such fluctuations in SOC are expected in the carbon cycle, especially in dry regions where low moisture limits

soil organisms responsible for cycling carbon (Burke et al., 2019). In general, we found that soils high in sand content presented lowest soil carbon, as compared to soils with more silt or clay, highlighting the importance of soil texture in carbon sequestration. Particular attention to soil texture needs to be taken in consideration to better understand carbon sequestration and to better advise land managers. As lands with soils higher in clays will have a different potential to bank carbon as compared with drier sandy soils, common in many regions that are grazed. Longer-term sampling is likely needed to better understand SOC dynamics in these ranches.

COMET-Farm™ modeling suggests that, under current management practices, the ranches can act as carbon sinks, potentially offsetting 91,444 CO₂e kg ha⁻¹ y⁻¹. However, these estimates assume “optimal” rangeland conditions, such as complete plant cover and average rainfall, meaning the results reflect potential sequestration under ideal circumstances. The analysis included only Bureau of Land Management (BLM) allotments and private lands. U.S. Forest Service (USFS) allotments, covering approximately 247,465 hectares (611,500 acres) of forested soils, were excluded due to limited data. Forested soils on USFS lands generally have higher SOC levels than drier rangeland soils, likely due to greater plant cover. This highlights the potential of agroforestry or silvopastoral systems on USFS lands to maintain higher carbon levels while sustaining livestock.

In summary, maintaining adequate plant cover is essential for increasing and sustaining soil carbon sequestration (Lal, 2004). Regenerative practices—such as adjusting livestock numbers, overseeding rangelands, and planting riparian trees—can create favorable conditions for plants to capture atmospheric carbon (Chen et al., 2009). COMET-Farm modeling is a useful tool to project the impacts of these practices over a ten-year period. At the same time, is important to understand that soil carbon sequestration has a limit or saturation point in which no more carbon can be banked in the soils regardless of carbon inputs. This saturation point is associated to the soil texture, soil structure and the biochemical complexity of the organic compounds (Stewart et al., 2007). Furthermore, maintaining adequate soil carbon levels in the upper layers of the soil can eventually assist to improve the vertical transfer of carbon to the deeper layers of soil as a result of the soil mineral properties, plant and microbial activity, favouring banking (sequestering) the carbon to ensure its permanence in the soil (Dwivedi et al., 2017). While current efforts promote healthy, carbon-sequestering ecosystems, further research is needed to determine when these soils might reach the carbon saturation point and avoid carbon losses.

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