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Grazing and soil carbon:
A social-ecological analysis of adaptive-multi paddock grazing on California rangelands

By

Paige Lauren Stanley

A dissertation submitted in partial satisfaction of the

requirements for the degree of

Doctor of Philosophy

in

Environmental Science, Policy, and Management

in the

Graduate Division

of the

University of California, Berkeley

Committee in charge:

Professor Timothy Bowles, Co-Chair

Professor Lynn Huntsinger, Co-Chair

Professor Nathan Sayre

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Abstract
Grazing and soil carbon:
A social-ecological analysis of adaptive-multi paddock grazing on California rangelands

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Doctor of Philosophy in Environmental Science, Policy, and Management

University of California, Berkeley

Professor Timothy Bowles, Co-Chair

Professor Lynn Huntsinger, Co-Chair

Rangelands are landscapes of uncertainty. Their management as “extensive” yet expansive agricultural landscapes is challenged by high temporal and spatial variability alongside unprecedented climatic, economic, and cultural uncertainties, including reliance on annual grasses with highly seasonal and variable NPP, increasingly common and worsening drought conditions, policy change and impacts, and a growing anti-cattle sentiment among some groups. Cattle overgrazing, along with intensification, has contributed to the significant loss of soil organic carbon (SOC) on rangelands, turning one of the most important terrestrial carbon sinks into a source of CO₂. While well managed grazing could help to sequester SOC and aid in climate change mitigation, the impact of grazing on rangeland SOC on, including how to measure SOC change with such high spatial heterogeneity, is understudied and poorly understood. Further, ultimately climate change mitigation relies on widespread adoption by ranchers, who are situated within complex social-ecological systems and must be responsive not only to ecological uncertainties (such as drought), but also to social and economic uncertainties such as changing social norms, declining profitability, and precarious land access. My dissertation research combined optimizing analytical measurement of SOC on rangelands, an ecological assessment of the impact of different forms of grazing management on SOC, and a social science approach to understand both the factors driving adoption of grazing management practices for SOC sequestration as well as the barriers and challenges ranchers face.

The first chapter of my dissertation examined the challenges of measuring SOC on heterogeneous agricultural landscapes. Using soil samples from California crop and rangelands, I analyzed how spatial heterogeneity, analytical variability, compositing, and statistical analyses affects the power, reliability, and validity of SOC measurements. I demonstrate that (1) spatial heterogeneity is a primary driver of uncertainty; (2) dry combustion analyzers have relatively low uncertainty, although inorganic C can increase error; (3) Student’s t-test and its relatives can be unreliable for drawing inferences about changes in SOC stocks; and (4) in heterogeneous agricultural landscapes, common sample sizes of 10–30 cores cannot reliably detect the modest changes in SOC that a few years of common management interventions are expected to produce. Results highlight the challenges of measuring small SOC changes on highly heterogeneous rangelands. Lastly, I recommend several improvements that will be necessary for reliably monitoring SOC, especially for research and C markets, including using *a priori* spatial information to determine necessary sample sizes, minimizing compositing, and using non-parametric statistical tests in scenarios where t-tests may be unreliable.

Chapters 2 and 3 of my dissertation focused on adaptive multi-paddock (AMP) grazing, which is a form of short-duration, high intensity grazing that centers principles such as adaptive management, animal rotations and incorporating pasture rest. AMP ranchers are often associated with Holistic Management (HM), which is a decision making framework and training program that teaches ranchers AMP grazing practices alongside principles such as systems based thinking for managing complexity, ecological monitoring, and maximizing flexibility and adaptability. Both AMP grazing and HM have been the subject of much research interest, but studies have been conducted in ecological and social science disciplinary silos. In Chapter 2, I investigated the impact of AMP grazing on SOC stocks, SOC stabilization in four functionally distinct soil organic matter fractions, and plant community composition across northern California rangelands. My results demonstrate that, compared to conventionally (CONV) grazed ranches, three of four AMP grazed ranches contain significantly greater SOC in surface soils, and two of four contain significantly greater SOC stocks down to 100cm. The greater SOC on AMP grazed ranches was contained in the MAOM fraction, which is the most persistent form of SOC, with implications for climate change mitigation. Plant community composition varied by site – some AMP grazed ranches had greater composition of perennial vs annual grasses and overall less bare ground, but these findings were not universal.

Lastly, in Chapter 3, I conducted semi-structured interviews with AMP and CONV ranchers to understand how AMP grazing relates to ranchers' mental models, including decision making processes, motivations, barriers, and how the combination of AMP-HM helps these ranchers respond to increasing challenges and uncertainties. Our findings suggest that AMP-HM shifts ranchers' approaches towards ones that involve more 'holistic,' systems based thinking, in two ways: 1) through its emphasis on monitoring combined with increased interaction with their land and animals, which changes the ways ranchers see and understand their management, and 2) by increasing ranchers' agency to operationalize these new mental models through its decision making framework and trainings. Together, these two facets culminate in a common suite of strategies used by AMP-HM ranchers, which they view as key to ranching profitably and sustainably in the face of climatic, economic, and cultural challenges.

Altogether, this dissertation highlights the measurement needs for monitoring, and the grazing management opportunities, for increasing SOC on California rangelands. The social-ecological approach taken in this research also illuminates ranchers' experiences with AMP grazing management and SOC sequestration, which will help improve world applicability of this research. Importantly, results of this work demonstrate the opportunity for sequestering and stabilizing SOC through AMP grazing management on California rangelands – which could bolster climate change mitigation efforts and improve ranchers' ability to sustain future uncertainties.

For mom, gramma, and grampa:
Who sacrificed everything so that I could be anything.

Thank you for believing in me and loving me always – this is for you.

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Introduction

Cattle grazing is the primary use of land both globally and in the United States (Bigelow, 2017; Roser & Ritchie, 2013). Much of this takes place on rangelands, which are grasslands, savannas, and shrublands that are predominately semi-arid and covered by native vegetation (Olson et al., 2001; Rangelands ATLAS, 2021). Human management of grazing cattle on rangelands can either work to protect them, by preventing them from being developed and/or bolstering the ecosystem services they provide, or it can diminish them through overgrazing and overuse. In fact, the health and survival of rangelands and the humans that manage them are deeply intertwined, which is why they are referred to as social-ecological systems (Hruska et al., 2017). This interconnectedness of humans, animals, and rangelands is well illustrated by the case of soil organic carbon (SOC). Soils contain an estimated three times more carbon than the atmosphere (Davidson et al., 2000), more than 30% of which resides in grazing land soils (Derner & Schuman, 2007; Follett et al., 2000; Lal, 2002; Schuman et al., 2002). However, overgrazing has contributed to the loss of ~75 Pg of SOC on rangelands, exacerbating anthropogenic climate change (Sanderman et al., 2017). In turn, well-managed grazing has been shown to sequester SOC and aid in climate change mitigation (Griscom et al., 2017; Liebig et al., 2010; McSherry & Ritchie, 2013; W. R. Teague et al., 2011; Wang et al., 2015).

However, grazing management and associated SOC outcomes have not been well studied on semi-arid rangelands. Much of what is known about SOC and grazing management has arisen from studies conducted on temperate and sub-humid grasslands, and at times those results have been inappropriately extrapolated to global grazing lands, including semi-arid rangelands (see (Moyer et al., 2020)). Considering that rangelands are notoriously heterogeneous “non-equilibrium” environments where precipitation is low and variable, opportunities to reliably increase SOC with grazing management interventions may be more limited (Booker et al., 2013; Oates, 2015). Research is needed to measure the SOC outcomes across the grazing management spectrum on semi-arid rangelands to truly understand the spatially explicit climate change mitigation potential (Buckley Biggs & Huntsinger, 2021; Carey et al., 2020).

Current research on SOC and grazing management practices is further limited by vague grazing terminology and experimental challenges. For example, the majority of applicable studies measure SOC in response to “rotational” grazing, which refers to grazing systems encompassing a range of rotational intensities where animals are moved between pastures, and has historically been considered an improved form of grazing management over continuous grazing (Briske et al., 2011). Rotational intensity is often ill-defined in these studies, despite being crucial to understanding SOC sequestration responses.

Among the most intensive forms of rotational grazing is adaptive multi-paddock (AMP) grazing, characterized by short grazing intervals with moderate-high stocking densities. In AMP grazing, animals are moved frequently to reduce overgrazing of selected grass species and to allow ample plant recovery between grazing events. Furthermore, AMP grazing is non-prescriptive, meaning that land-managers observe ecosystem function and adapt grazing intensity and recovery periods accordingly (Clifford et al., 2020). These features differentiate AMP from other more simplistic grazing systems, such as continuous grazing, low-rotational systems, or other high intensity but non adaptive grazing systems such as mob grazing. AMP grazing has gained scientific interest in recent years due to myriad ecological benefits reported by ranchers and high rates of soil C sequestration compared to other

forms of grazing management measured in temperate grasslands. Aspects of AMP grazing such as adaptivity, short grazing intervals, and pasture rest have been promoted for drought resiliency on rangelands (Roche, 2016), and may also change opportunities to sequester SOC on semi-arid rangelands. However, like grazing management in general, the impact of AMP grazing on SOC sequestration is understudied on semi-arid rangelands.

There are many reasons contributing to the limited research on grazing management in general and AMP grazing specifically on SOC on rangelands. First, rangelands are spatially heterogeneous due to diverse topography, rocky soil horizons, low and patchy soil fertility, and patchiness of grazing and manure deposition (Devine et al., 2020). High spatial heterogeneity combined with the low annual rates of SOC sequestration make accurately detecting and quantifying SOC changes from grazing management very difficult. Second, studies that apply grazing management systems in small experimental plots and measure SOC changes over short time scales are not representative of the long-term SOC changes possible on large rangeland landscapes (Teague et al., 2013). Lastly, real life grazing management is often not set or static: ranchers may change aspects of their grazing management in response to drought or forage conditions (Roche et al. 2015). AMP grazing explicitly centers adaptability as a core management feature, whereby ranchers change aspects of their grazing management in response to monitored outcomes in the short-term. However, adaptation is at odds with traditional experimental research, which requires tightly controlled treatments and reliable replication. Together, these challenges highlight the importance of on-ranch, rather than experimental, research to understand the impacts of AMP grazing management on SOC in working semi-arid rangelands (SARE, 2017).

However, understanding whether and how much AMP grazing can help to sequester SOC on semi-arid rangelands is only one piece of the puzzle. Despite whether a practice is scientifically known to sequester SOC, ultimately climate change mitigation relies on widespread adoption by ranchers, who are situated within complex social-ecological systems and must be responsive not only to ecological factors (such as drought), but also to social factors such as on-ranch economics, rural viability, policy, market structure, community composition, tradition, private vs public land access, etc. (Coppock & Birkenfeld, 1999; Gentner & Tanaka, 2002; Lubell et al., 2013; Peterson & Coppock, 2006; Rowan & White, 1994; Smith & Martin, 1972; Yung & Belsky, 2007). Thus, understanding both the factors driving AMP grazing adoption as well as the barriers and challenges ranchers face is a crucial next step for research that could greatly improve real world applicability.

I took a rancher focused and social-ecological approach to my dissertation work on SOC, AMP grazing, and rangeland social-ecological systems. In doing this, I aimed to make methodological contributions to improve soil C measurement challenges, improve ecological understanding of AMP grazing and its impact on SOC and other rangeland health outcomes, and make theoretical contributions to our understanding of ranchers' mental models and application of adaptive grazing.

The first chapter of my dissertation arose out of a simple question, "How many soil samples do I need to take to measure SOC"? My quest to answer this question led me to a gaping hole in the scientific literature on spatial heterogeneity of rangeland soils, at which point I decided to answer it myself. What began as a simple exploratory sampling campaign turned into seven days of sampling, nearly 700 soil samples collected, and a multi-disciplinary collaborative effort between soil scientists and statisticians. Specifically, we asked:

1. How do the spatial heterogeneity of rangelands and croplands compare in California?

2. How do spatial heterogeneity, analytical variability, and compositing impact the power to detect and accurately quantify SOC stocks and changes on agricultural lands?
3. How does validity of different statistical tests compare, and how does this impact the reliability of our SOC estimates?

For the second chapter of my dissertation, I conducted an on-ranch study comparing the SOC stocks of AMP and conventionally grazed ranches on four paired sites across northern California. I aimed to understand whether AMP grazing may be a viable SOC sequestration strategy on semi-arid rangelands, the persistence of resulting SOC to help inform its long term climate change mitigation potential, and mechanistic drivers including vegetation differences. I asked:

1. Does AMP grazing increase SOC storage relative to CONV grazing on semi-arid California rangelands?
2. How do differences in four soil organic matter pools (dissolved (DOM), free (fPOM) and occluded (oPOM) particulate, and mineral associated (MAOM) organic matter) help explain changes in SOC persistence under AMP grazing?
3. How do plant communities shift in response to AMP grazing, and do these shifts help explain SOC changes?

Though it appears last, the third chapter of my dissertation is actually where this research began. I began by searching for AMP ranchers in northern California who met my ecological criteria for soil sampling. After initial phone interviews with more than 30 ranchers and narrowing my selection, I conducted semi-structured interviews to ask:

1. What are AMP ranchers' decision making processes, and how does this influence their implementation of AMP grazing?
2. How are AMP ranchers' mental models shaped and/or changed under AMP grazing and Holistic Management?
3. What are AMP ranchers' motivations for AMP grazing, and what are the barriers and challenges of this grazing management? How does this compare to more conventional ranchers' grazing management motivations and barriers?

All of my dissertation research took place in northern California, which contains semi-arid rangelands that are spatially diverse and have a long history of grazing. However, its unprecedented rise in land values, development rates, a rising anti-cattle sentiment among the area's urban population, and a strong regional focus on natural climate change solutions have together created unique challenges and opportunities for ranchers in this area. These complex and intertwined factors created the fertile grounds for my dissertation work.

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Chapter 1

Valid inferences about soil carbon in heterogeneous landscapes

1.1. Abstract

Answering research and policy questions about soil organic carbon (SOC) sequestration requires reliably quantifying SOC stocks and changes in stocks. SOC measurement accuracy is limited by the natural spatial heterogeneity of SOC concentrations and soil bulk density, variations in sample preparation, variability of laboratory assays, unmet assumptions in statistical analyses, and the relatively small magnitude of SOC changes over time. Simulations and data from two intensive field sampling campaigns on one rangeland site (662 samples) and seven cropland sites (455 samples) in California, USA, show (1) spatial heterogeneity is a primary driver of uncertainty; (2) dry combustion assays have relatively low uncertainty, although inorganic C can increase error; (3) Student's t-test and its relatives can be unreliable for drawing inferences about changes in SOC stocks; and (4) in heterogeneous agricultural landscapes, common sample sizes of 10–30 cores cannot reliably detect the modest changes in SOC that a few years of common management interventions are expected to produce. To inform policy decisions, investigators should: (1) identify the measurement goal, including the consequences of error; (2) use random sampling with sample sizes adequate to meet that goal, accounting for anticipated spatial heterogeneity, e.g., by conducting pilot surveys; (3) composite samples less than is currently common; (4) assay with dry-combustion instruments; and (5) use nonparametric statistical tests and confidence intervals to control Type I error rates, because Student's t-test and its relatives can be unreliable for SOC (e.g. at low to medium sample sizes or when the distribution of SOC is substantially skewed). Future work should address other critical open challenges, including how to account for rocks and roots, and how to improve bulk density estimates.

1.2. Introduction

Interest in measuring soil organic carbon (SOC) is expanding dramatically because agricultural management interventions that sequester C in soil may help mitigate climate change. Recent policy initiatives and emerging soil C markets designed to accelerate management transitions require practical methods to measure SOC inventories with low uncertainty. Indeed, the high uncertainty of SOC measurements likely contributed to the 2011 collapse of the Chicago Climate Exchange, the only prior U.S. voluntary C market (Gosnell et al., 2011).

Estimating the total SOC in a field or landscape is much more complicated than just measuring the concentration of SOC in a sample of soil. If soil were completely homogeneous and laboratory assays were perfect, measuring SOC stocks would be simple: take a core anywhere in a field, measure its density, and assay its SOC concentration by mass. The total SOC in the field is the product of the C mass concentration, field volume, and density. Changes in SOC stocks could be found by subtraction. But in practice, the accuracy of SOC inventories is limited by heterogeneity of SOC, soil density, and the soil matrix; the presence of subsurface rock fragments, gross organic matter, and other “non-soil”

(i.e., compost); variation in sample preparation and processing; and uncertainties in laboratory assays, among other things.

Reliably detecting and accurately quantifying changes in SOC stocks is challenging because, compared to these sources of variation and uncertainty, the annual changes produced by agricultural management interventions are often small, ranging from less than 0.1% for conversion to no-till (Franzluebbers, 2005) to approximately 0.5% with biochar application (Jones et al., 2012; Majumder et al., 2019). Methods for estimating SOC must be precise and powerful enough to detect such small changes in a heterogeneous medium (Ellert et al., 2002; Homann et al., 1998; Lehmann et al., 2007; Robertson et al., 1997). Current approaches—from sampling design to laboratory and statistical analyses—may be inadequate (Necpalova et al., 2014; Oldfield et al., 2021).

Estimating SOC stocks and changes to those stocks involves many steps and choices (**Table 1**), starting with identifying the goal, e.g., to measure net sequestration over a 5-year period in a particular soil “population” of interest, such as an entire ranch or a single cropland field. The scientific goal must be informed by the consequences of error and uncertainty. For instance, the accuracy needed to reliably detect and quantify changes in SOC stocks on a farm due to management interventions on a timescale of a few years may be higher than the accuracy required for a national SOC “inventory” at a single point in time. The consequences of underestimating changes in SOC stocks on the efficiency of carbon markets could be quite different from the consequences of overestimating changes.

Second, decisions about soil sampling—where, how, how deep, and how many samples—need to be made, so as to meet the intended scientific goals. To draw reliable inferences about a population of soil requires an appropriate sampling design. Systematic sampling designs (e.g., grids, transects, or triangles), where a single randomly chosen point determines every sampling location, are common (Spencer et al., 2011). These designs may be more convenient, but they cannot be used to estimate SOC stocks at the field/landscape scale without making potentially implausible or counterfactual assumptions about how SOC is distributed spatially (Englund, 1990). In contrast, properly designed random samples permit estimates with meaningful uncertainties based on how the samples were selected and analyzed without requiring any assumptions about the spatial distribution of SOC. At the field scale, simple random sampling is technically simple but often logistically inefficient (as opposed to collecting samples in a line along a transect), and can require more samples than other designs to detect SOC changes (Jaap J. de Gruijter et al., 2006).

Whatever accuracy the goal demands, the required sample size depends on the heterogeneity of the landscape, which is affected by edaphoclimatic properties, land use, and management (Fraterrigo et al., 2005). For example, rangelands are thought to have greater SOC heterogeneity than croplands due to more diverse topography, presence of rocky soil horizons, low and patchy soil fertility, and patchiness of grazing and manure deposition (Allen et al., 2010; Bird et al., 2002; Devine et al., 2020). Some management practices known to sequester SOC may even increase spatial heterogeneity (Liu et al., 2011; Zhou et al., 2017). For example, intercropping can create “islands of fertility” in silvopasture (Schlesinger et al., 1995), while practices like no-till and cover cropping, and woody perennials may redistribute C across depths (Syswerda et al. 2011; Tautges et al. 2019; Poffenbarger et al. 2020; Jobbágy and Jackson 2000). Stratifying the soil into more homogeneous domains and independently sampling from those strata can provide more precise estimates and more powerful tests using the same number of samples as other sampling designs (J J de Gruijter et al.,

2016). Identifying the logistical and power tradeoffs of different sampling designs/sizes, and how they change across landscapes of varying spatial heterogeneity, is a critical next step for optimizing SOC measurement.

Third, in order to accurately estimate SOC stocks, choices must also be made about how to collect bulk density samples to estimate soil mass per unit volume. This includes: where and how to collect bulk density samples, whether to use field sampling methods for equivalent soil mass (Wendt & Hauser, 2013), and how to deal with rock fragments and other non-soil components of the samples.

Fourth, many decisions regarding sample processing contribute additional uncertainty, including the removal of gross organic matter; drying temperature, sieve and grind size; and the use of compositing. Compositing, or combining two or more samples and assaying that mixture, reduces the cost of lab analysis, but may increase or decrease overall error (J J de Gruijter et al., 2016; Spertus, 2021). At one extreme, some studies combine all samples collected within an experimental unit into a single composite sample for analysis (e.g., (Carey et al., 2020; Tautges et al., 2019), making it impossible to estimate spatial heterogeneity and uncertainty. Compositing can be optimized to minimize contribution to error within a given budget — given estimates of spatial heterogeneity, analytical error, and cost per laboratory assay (Spertus, 2021). To our knowledge, such an analysis has never been done for an on-the-ground soil sampling campaign.

Fifth, investigators must also choose the analytical assay method, how to calibrate instruments, what standards to use, whether and how to remove inorganic C, and level of analytical replication. The current standard for soil C assays, dry combustion, measures soil C concentrations directly by combusting soil samples and measuring the amount of CO₂ released. Dry combustion is more precise than previous methods (De Vos et al., 2005; Goidts et al., 2009; Roper et al., 2019), but uses small sample masses that must be pretreated to remove inorganic C, which can contribute further to error (Apesteguia et al., 2018; Harris et al., 2001). The extent to which both intra-lab (replicated measurements on the same instrument) and inter-lab (measurements on different instruments) analytical error of dry combustion assays contributes to overall error in measuring SOC is not well known (Chatterjee et al., 2009; O'Rourke & Holden, 2011), limiting the ability to optimize sampling campaigns and the reliability of estimates and inferences.

Finally, investigators must choose how to use measurements to make inferences about SOC changes. Consider assessing whether a farm has sequestered SOC (increased SOC stock) over some interval of time. Typically, this is framed statistically as a test of the null hypothesis that total SOC at the start is equal to total SOC at the end. The choice of the statistical test can increase the likelihood of false positives (Type I errors) and false negatives (Type II errors). A Type I error will conclude that SOC has been sequestered when it has not; while a Type II error will fail to detect genuine sequestration. In a C market, Type I error can lead to allocation of payments without actual SOC sequestration, and possibly even increase net C emissions; while a Type II error can lead to missed opportunities for climate change mitigation (Sanderman & Baldock, 2010) and failing to pay for genuine SOC sequestration. Both types of error could undermine the utility of C markets.

The two-sample Student t-test (and its relatives, such as ANOVA and Student's t confidence intervals) are often used to assess changes in SOC stocks (J J de Gruijter et al., 2016; Kravchenko & Robertson, 2011). Student's t-test assumes that if the total SOC has not changed, SOC at both time points is normally distributed with the same mean and standard deviation. The Student t confidence interval assumes that if total SOC has changed, only the mean has changed, not the distribution: the

distributions at both times are normal and have the same variance. Since SOC generally does not have a normal distribution (Yan et al., 2011) and because agricultural management interventions can redistribute SOC without changing the total (Chappell et al., 2012), Student's t confidence intervals and p-values can have Type I error rates that greatly exceed the nominal significance level (e.g., 5%), and coverage probabilities far lower than nominal (e.g., 95%) (Lehmann and Romano 2010).

When a sample is drawn randomly, nonparametric tests can be used that produce reliable confidence intervals without requiring assumptions about the distribution of SOC (Anderson, 1969; Learned-Miller & Thomas, 2019; Romano & Wolf, 2000; Stark, 2009; Waudby-Smith & Ramdas, 2020).

These methods can take into account biogeochemical constraints, for example, that SOC is between 0 and 18% for mineral soils (United States Soil Survey Staff, 1975). Suitable nonparametric tests and confidence intervals are conservative or exact: the likelihood of Type I error is not larger than the nominal significance level (e.g., 5%), and the chance that confidence intervals include the true amount of SOC sequestered is not less than the nominal confidence level (e.g., 95%). Using suitable nonparametric tests and confidence intervals increases the reliability of inferences about SOC stocks and changes. Stratified nonparametric tests, which might increase power of detection, are the subject of current research.

Below, we investigate some of these choices and how they affect the cost and reliability of inferences about SOC stocks and sequestration. We show how common sampling designs and statistical analyses can be improved to reduce uncertainty. We first examine spatial heterogeneity of SOC and analytical variability using new data from direct sampling campaigns in California croplands and rangelands. We evaluate the relative impact of spatial heterogeneity and analytical variability and the effect of compositing on measurement precision and power. Using simulations, we examine the validity and power of Student's t-test to detect SOC sequestration under simple or stratified random sampling on heterogeneous rangeland topsoil. We compare Student's t-test to a new nonparametric test across a range of hypothetical SOC changes and sample sizes. We find straightforward ways to improve the accuracy and reliability of SOC stock estimates and their change over time, which could yield more reliable assessments of management outcomes and progress towards climate change mitigation goals.

1.3. Methods

1.3.1. Collecting SOC data: rangeland and cropland sampling and laboratory analysis

To explore the spatial heterogeneity of SOC and provide an empirical basis for simulations, we collected soil samples in California range and croplands. We outline our sampling methods briefly below, with more details in supplemental information (**SI 1.1**).

Rangeland samples were collected in December 2019 from a ranch in Paicines, California. The data were collected to quantify spatial heterogeneity of SOC in a constrained setting, controlling for soil type, catenal position, slope aspect, and vegetation—not to quantify SOC stock for the whole ranch. We used soil survey information within the ranch boundaries (SSURGO; Soil Survey Staff et al., n.d.) to identify Auberry Fine Sandy Loam soils. Samples were collected using a stratified transect design with five 100m transects on two adjacent hillslopes stratified by slope position: summit/shoulder (1 transect), backslope (2 transects), and footslope (2 transects). Soils were sampled down to 100cm, or

the point of refusal, and divided into 5 depth ranges (0–10cm, 10–30cm, 30–50cm, 50–75cm and 75–100cm). We attempted to collect 33 samples along each transect, but were limited to 25 samples at one transect, due to time constraints. In all, we attempted to collect 785 samples, but bedrock or rock obstructions limited depth of sampling at some locations (mostly along the summit position), resulting in 662 total samples. Each sample was air-dried, sieved to 2mm, visible plant materials were removed, and soils were ground using a ball mill (**SI 1.1**; Retsch, Newtown, PA).

Cropland soil samples were collected in September and October, 2019, from seven farms across Southern California (**SI Figure 1**) representing various soil types and cropping systems, including two orchards, a vineyard, two intensive cropping systems, and two diversified farms (full soil taxonomy in **SI Table 1**). Samples were collected along transects. At each site, transect locations were selected based on the dominant soil type (Soil Survey Geographic (SSURGO) Database, United States Department of Agriculture, Natural Resource Conservation Service), consistent historic and current management, and cropping system. The number of transects ranged from two at the small diversified farms to six at one of the larger cropland sites. Depth increments varied slightly by site based on tillage depths (0–10, 10–20cm vs. 0–15, 15–30cm) and genetic horizon in the subsurface. In all, 455 samples were collected from the seven farms. Sample were air-dried and sieved to 2mm, visible plant materials were removed, and then soils were oven-dried at 60°C and ground using a ball mill.

Bulk density (BD) samples for crop and rangelands were collected using the pit method (Walter et al., 2016). Cores were collected from the center of each depth increment used for bulk soil samples. For sampling depths greater than 10cm, multiple cores were collected to ensure the sample was representative. At the rangeland site, three 1.5m deep soil pits were dug along each transect (one at each end, and one in the center at 50m) using an excavator, a total of 15 pits. At the cropland sites, one soil pit was dug at the central location of each transect to 1.5m or the point of refusal. Bulk density samples were oven-dried at 105°C until their weight no longer decreased on further drying. Visible rock fragments were removed before weighing the samples and submerged in water to ascertain volume. Rock volume was subtracted from core volume in estimating soil density.

Two different dry combustion analyzers were used to measure C concentrations (TC%) of prepared samples. All cropland soils were analyzed with a Costech ECS 4010 elemental analyzer (Costech, Valencia, CA)—a widely used instrument for dry combustion analysis. Rangeland samples were analyzed on an Elementar soliTOC cube (Elementar, Ronkonkoma, NY; see (Natali et al., 2020)), a relatively new instrument designed to improve precision by combusting higher sample masses (up to 3g of soil vs ~50 mg) while separating total organic C (TOC), residual organic C (ROC), and total inorganic C (TIC) via a temperature ramping method, DIN19539. The ECS 4010 measures only the mass of total C (TC), and thus we compare only TC% between the two instruments.

To quantify the precision and bias of each instrument, we re-analyzed 15 rangeland and 22 cropland samples that had the minimum, median, and maximum TC% for each depth and land-use category (**SI Figure 2**). Five analytical replicates of each sample were performed on each instrument. Samples with high TIC (>0.1%), as measured by the soliTOC, were treated with HCl to remove TIC and re-assayed on the ECS 4010 (**SI Figures 2–3**). Finally, we ran 25 additional replicates of two soil standards with known TC% on each instrument (**SI Figure 4**).

1.3.2. Assessing Spatial heterogeneity of SOC and bulk density

To visualize the relative heterogeneity of TC% by land use, depth, and transect, we used histograms, sample means, and coefficients of variation (CV). While TC% of the non-rocky component of the soil is the focus of this study, we also examined the variability of BD measurements by comparing the CV across depths for rangeland and cropland site 7, which had substantially more BD samples than other cropland sites.

To assess differences in spatial heterogeneity across land uses, depth, strata (transects), and sites, we tested the hypotheses that population TC% distributions were equal across depths and transects on rangeland soils, or depths and sites on cropland soils using a nonparametric test called *permutation ANOVA*, a way of calibrating the ANOVA test statistic to control the rate of false rejections without any assumption about the distribution of SOC (Pesarin & Salmaso, 2010). Details of how the permutation ANOVA was performed are in **SI 1.2**. Code is available at: (redacted for review).

1.3.3. Evaluating analytical variability

We repeated analyses of the same samples to estimate the variability of laboratory assays. For each sample and instrument, analytical error was quantified by the *estimated relative error* (see **SI 1.3** for the formula), which is approximately the CV. We report the median estimated relative error for each instrument. (The estimated relative error measures variability but not bias; we estimated bias from measurements of known standards.) To evaluate whether there were systematic differences in measurements between the two instruments (solⁱTOC and ECS 4010), we used permutation tests for the *two-sample problem*, which asks whether the difference between two samples would be surprising if they were created by partitioning their pooled values into the two groups randomly. We used the difference in means as the test statistic and simulated 10,000 draws from the permutation distribution using the R package **permutter** (see **SI 1.3** for more details).

1.3.4. Quantifying relative uncertainty from spatial and analytical heterogeneity

We quantified the contributions of analytical variability and spatial heterogeneity to uncertainty in estimates of the population mean TC% using the delta method (Goidts et al., 2009), which decomposes the total uncertainty into a sum of the contributions from analytical variability and spatial heterogeneity (**SI 1.4**). If the ratio of the contribution from spatial heterogeneity to total uncertainty is close to 1, spatial heterogeneity contributes more than analytical variability to overall uncertainty, vice versa for a ratio closer to 0. A ratio of 0.5 means analytical and spatial heterogeneity contribute equally to total uncertainty. To assess how compositing affects the relative contributions to uncertainty, we computed the proportion of total uncertainty due to spatial heterogeneity without compositing, and the corresponding proportion when 90 cores are composited to one analytic sample (an extreme degree of compositing). We computed these ratios within depths for both land use types and both instruments.

1.3.5. Comparing how sources of error affect statistical power

We studied how spatial heterogeneity, assay variability, and compositing affect the ability to detect changes in average TC%. Specifically, we approximated the power of the unpaired two-sample t-test when samples are drawn by simple random sampling and there is no compositing, optimal

compositing (derived in (Spertus, 2021), or full compositing. We only examined the power for relatively large sample sizes ($n \geq 90$ cores) because Student's t-test is especially unreliable for small sample sizes (see below).

Comparing compositing strategies requires a budget; if money were no object, measuring every sample separately (i.e., not compositing) minimizes error. Compositing involves a tradeoff between various costs and errors. To explore the tradeoff, we took the marginal cost of collecting a single soil core in the field to be \$20 USD and the cost of laboratory analysis (including sample preparation) in an elemental analyzer to be \$13.60 USD per sample, the average price charged by five commercial labs for TC% analysis. Given these unit costs, the cost to collect, prepare, and analyze 90 cores (without compositing) is \$3,024 USD. Using the same total budget, we explored what the uncertainty would have been had the money been used to take more cores and composite some of them (*optimal compositing*, which maximizes power within the budget) or all of them (full compositing) instead of assaying them individually. The power calculations use the estimates of land-use-specific TC% average and spatial heterogeneity (averaged across sites for cropland) and instrument-specific median relative error to approximate the power to detect a change of a given magnitude.

1.3.6. Power and validity of tests for detecting TC% change

We performed two simulations to estimate the true significance level and power of different two-sample hypothesis tests. The “validity simulation” estimated the significance level of two tests—the chance a test erroneously rejects the null hypothesis when there is no change in total SOC—in four scenarios. The two tests were the usual two-sample Student t-test and a nonparametric test that uses a pre-specified upper bound on TC concentration (See SI 1.6 for details). We set this bound at 10% or 20% TC, which is an established TC range in mineral soils. In each of the four scenarios, SOC means were set exactly equal by shifting their distributions, but the shapes could be different. Specifically, we imposed hypothetical distributional changes that may occur with agricultural management interventions using our empirical crop and rangeland TC data. In the “unchanged normal distribution” scenario, both distributions were normal with SDs of 0.5%; in the “tilled cropland” scenario, the distribution at the first time was the actual topsoil TC% samples from cropland site 5 (right-skewed, Figure 1) and the distribution at the second time was normal with SD 0.5%; in the “change in skew” scenario, the distribution at time 1 was rangeland topsoil samples (right-skewed) and the distribution at time 2 was the same but multiplied by -1 (left-skewed); in the “extreme hotspot” scenario, the distribution at time 1 had 99% of its mass in a normal distribution centered at 2.8% TC (SD: 0.05%) and 1% as a point-mass centered at about 20% TC (Mishra and Riley, 2015; Miller et al, 2016). At the second time, the distribution was normal (SD: 0.05%). We ran both tests at a nominal 5% level 5000 times with sample sizes ranging from 5 to 150 at each epoch and recorded the rate of (false) rejections. We plotted these simulated significance levels along with the nominal 5% significance level (Figure 6).

The “power simulation” estimated the chance of detecting increases in SOC of various magnitudes with sample sizes 10, 30, 90, and 200 using the t-test with unstratified sampling, the t-test with stratified sampling, and the nonparametric test with unstratified sampling. (Stratified nonparametric tests are in development.) The reference population distributions (at time 1) were taken to be the empirical distributions of samples from the rangeland site or from cropland site 5, which had median spatial heterogeneity and the most samples among the cropland sites. The hypothetical change in TC% was an additive shift of the reference distribution, with shifts ranging from 0% (no change) to 60% of

baseline. For example, the baseline average TC% across our cropland sites was 2.7% TC, so the simulated TC% at time 2 ranged from 2.7% to 4.32%. The stratified t-test was used only on rangeland samples. For the purpose of this simulation, we treated each of the 5 transects as if it were a random sample from a distinct stratum. Under this assumption, samples from a transect are representative of the distribution of %TC within the corresponding stratum. This assumption is probably false in a way that favors the stratified Student t-test—within-transect heterogeneity is likely lower and between-transect variation higher than the corresponding quantities in an actual stratified random sampling design. The simulations sampled independently with replacement from each distribution (either pooled or stratified by transect), conducted the tests at nominal significance level 5%, and recorded whether the null was rejected. The nonparametric test requires the user to specify an upper bound on the concentration: a tighter bound leads to a more powerful test, but misspecification can make the test invalid. We ran nonparametric tests with a bound of either 10%, which exceeds the maximum in any of our data (7.8% TC), or 20%, the established bound on TC in mineral soils. We also ran the nonparametric tests at a significance level of 10% to examine how raising the significance level increases power. We ran each simulation 500 times, with 10, 30, 90, or 200 samples drawn from the population at each epoch. For stratified sampling, sample sizes were allocated proportional to “size,” measured by the number of samples in the original transect. All statistical analyses were conducted in R (version 3.6.1). Code is available at [redacted for review].

1.4. Results

1.4.1. Spatial heterogeneity of SOC and bulk density

In both rangeland and cropland soils, TC% generally decreased with depth (Figure 1). In rangeland soils, mean TC% varied from 3.77% in topsoils (0–10 cm) of the summit/shoulder transect to 0.47% at 75–100 cm of the footslope transect. Mean TC% in cropland soils varied from 4.31% at 0–15 cm (at CROP3) to 0.10% at 60–100 cm (at CROP7). Permutation ANOVA found that variations in mean TC% were statistically significant across transects ($p < 1e-4$) and depth ($p < 1e-4$) in rangeland soils and across sites ($p < 1e-4$) and depth ($p < 1e-4$) in cropland soils. Mean TOC% at the rangeland site was similar to TC% (SI Figure 10); most samples had low TIC%.

The spatial heterogeneity of TC% varied with land use, depth, and geographic location (transect and site; Table 2). Heterogeneity of TC%, as measured by the coefficient of variation (CV), was higher in the rangeland site than in the cropland sites. The CV increased with depth in every rangeland transect and in cropland sites with diversified or perennial farming systems (vineyards and orchards), but not in conventionally managed croplands.

Bulk density was highly variable with land use and across sites but generally not with depth. Heterogeneity was particularly high in the rangeland soils, where CV ranged from 0.08 at 30–50cm and 75–100cm to 0.16 at 0–10cm and 50–75cm. Heterogeneity within the cropland sites was lower with CV ranging from 0.04 at 0–15cm and 15–30cm to 0.07 at 60–100cm. Within a given depth, BD varied substantially across rangelands (15 soil pits) and the CROP7 site (16 soil pits), but no consistent patterns emerged (Figure 2). BD for the six other cropland sites combined is plotted in SI Figure 11.

Rangeland SOC stocks were 30.3, 31.6, 22.5, 25.9, and 30.4 Mg C/ha at 0–10, 10–30, 30–50, 50–75, and 75–100cm, respectively. Whole profile stocks (0–100cm) were 141.7 Mg C/ha, SE: 6.7 (SI Table

2). Like most SOC stock estimates, the estimated SE does not reflect uncertainty and variability of bulk density. In section 4.5, we discuss the effect of ignoring rock volume on SOC stock estimates. In croplands, whole profile SOC stocks varied by site from 32.6 Mg C/ha (0–100cm for CROP7) to 230.0 Mg/ha (0–70cm for CROP3) (SI Table 3).

1.4.2. Analytical variability

We compared measurements of 25 analytical replicates of two standard soils on the soliTOC and ECS 4010 dry combustion analyzers. Both instruments showed low variance and a small but consistent positive bias (**SI Figure 4**). Based on analytical replicates of 36 samples measured on both instruments, the estimated median relative errors of the measurements were 0.024 for the soliTOC and 0.061 for the ECS 4010 (**Figure 3**). Permutation tests generally found little evidence of systematic differences between the instruments in replicated TC% measurements, except for samples with TIC% greater than 10% of TC%. In the most extreme case, average replicated TC% measured on the soliTOC was nearly triple that of ECS 4010 for a rangeland sample with ~90% of TC% as TIC%. Removing inorganic C with HCl improved the agreement of measured TOC% between the two instruments (**SI Figure 2**).

1.4.3. Sources of uncertainty and their effects on statistical power

In general, spatial heterogeneity contributes much more uncertainty than analytical variability does, both for rangelands and croplands (**Figure 4**). However, compositing can mitigate or exacerbate the relative contributions to uncertainty from spatial heterogeneity and analytical variability. With no compositing, analytical variability contributes little to the overall uncertainty (**Figure 4**). If all $n = 90$ cores are composited to $k = 1$ analytic sample (“full compositing”), analytical error becomes a major component of the uncertainty in estimates of TC% for cropland soils, especially for the less precise ECS 4010 analyzer (**Figure 4**). The theoretical power of the Student t-test under various compositing schemes reflects this tradeoff (**Figure 5**). The power of the Student t-test to detect TC% change generally depends more on spatial heterogeneity than analytical variability for both instruments, except for full compositing with the ECS 4010, which had much less power (**Figure 5**).

There was relatively little difference in power between optimal compositing and no compositing for any land use or instrument. When spatial heterogeneity is high (e.g., in rangeland) and lab analysis is precise (e.g., with soliTOC), power is maximized by allocating more of the budget to sampling and using some compositing to reduce the number of assays. On the other hand, when spatial heterogeneity is low (e.g., in cropland) and lab analysis is imprecise (e.g., ECS 4010), accuracy is maximized by allocating more of the budget to assays and reducing or avoiding compositing.

1.4.4. Power and validity of tests for detecting TC% change

The nominal significance level of Student’s t-test can greatly understate its chance of making a Type I error, erroneously rejecting the null hypothesis when the hypothesis is true (**Figure 6**). In the validity simulations the t-test always exceeded its nominal level, except when the distributions were both normal. In the “tilled cropland” and “change in skew” scenarios, the level was close to 10% at very small sample sizes, but declined closer to its nominal 5% at larger sizes. In the “extreme hotspot” scenario, the true significance level was always many times higher than the nominal significance level,

and was still above 20% at 150 samples. In contrast, the nonparametric test never erroneously rejected the null hypothesis.

Our “power” simulation compared the power and actual significance levels of the unstratified Student t-test, stratified Student t-test, and a nonparametric test for detecting SOC shifts, for sample sizes of 10, 30, 90, and 200 from each time (**Figure 7**). Both Student’s t-tests had more power than the nonparametric test to detect shifts in TC% at all sample sizes; the stratified Student t-test was more powerful than the unstratified test. (Stratified nonparametric tests would presumably have higher power than the unstratified nonparametric test; they are the subject of ongoing research.) The power of the nonparametric test improved as the population bounds were tightened and as the level was relaxed: the nonparametric test with 10% max TC and significance level .10 was the most powerful among the nonparametric tests. For example, to have 80% power to detect a relative change of 20% from baseline average TC% on rangeland soils requires about 30 samples with the stratified Student t-test, 90 with the unstratified Student t-test, and 200 with the nonparametric test with 10% max TC and/or a relaxed significance level of 0.1. All tests had more power to detect small changes in cropland soils than in rangeland soils due to lower spatial heterogeneity in croplands. For example, the power of the unstratified Student t-test to detect a 10% change with 90 samples was 80% for cropland soils but only about 30% for rangelands.

1.5. Discussion

1.5.1. Crop and rangelands are spatially heterogeneous

Given the rapid development of C markets, accurate estimates of SOC stocks and the impact of management interventions on SOC stocks are more important than ever. Our study demonstrates how tailoring sampling and analytical decisions to the high spatial heterogeneity often found in managed lands could improve the reliability and efficiency of inferences about SOC stocks and their temporal changes. As expected, SOC at the rangeland site was more heterogeneous than at the seven cropland sites, with roughly twice as large a CV at every depth (**Table 2**). This is consistent with other surveys of California rangelands, though differences in depths, spatial scales, and measures of variability limit quantitative comparisons (Carey et al., 2020; Devine et al., 2020; Silver et al., 2010). This is also consistent with the general notion that rangeland SOC is typically more heterogeneous than croplands because of variation in topography, presence of rock fragments, and patchiness of grazing and manure deposition. This makes accurately estimating SOC change on rangelands more challenging.

Deep sampling is critical for making reliable conclusions about C sequestration and greenhouse gas mitigation (Kravchenko & Robertson, 2011; Kuzyakov & Blagodatskaya, 2015), especially since SOC gains near the surface may be offset by losses at depth (Poffenbarger et al., 2020; Slessarev et al., 2021; Syswerda et al., 2011; Tautges et al., 2019). The CV of SOC in our study tended to increase with depth, while standard deviations decreased. Hence, a given relative change (e.g., 10% gain from baseline TC%) is harder to detect in subsurface soils than in topsoil, but a given absolute change (e.g., 0.5 TC% gain) may be easier to detect. Since detecting an equivalent absolute change in the subsurface requires fewer samples, topsoil heterogeneity should generally guide decisions around sample size.

Though we have emphasized TC% measurements, high variability of BD within sites (**Figure 2**), especially in rangelands, contributes additional uncertainty to SOC stock estimates (Walter et al., 2016). Even where TC% is relatively homogeneous, variability in BD could prevent detection of changes in SOC stocks (Slessarev et al., 2021). Failing to account for BD variability can underestimate uncertainty and lead to erroneous conclusions about SOC stock change.

1.5.2. Analytical variability contributes little to measurement error

Variability in assay measurements contributed far less to measurement error than spatial heterogeneity of SOC, except when samples were highly composited (**Figure 4**). Replicated measurements show that both the soliTOC and ECS 4010 analyzers have estimated median relative error below 0.07.

TC%, however, differed substantially between instruments for samples with high TIC%, (see also **SI Figure 3**). Re-analysis on the ECS 4010 after TIC removal improved agreement between TC% measurements on the ECS 4010 and TOC% on the soliTOC, indicating that TIC should be removed when using elemental analyzers like the ECS 4010. Larger sample masses (~10–20x the mass of traditional dry combustion instruments) may explain the higher precision of the soliTOC, which had about one-third the median relative error of the ECS 4010 (**Figure 3**). Larger analytical subsamples should better represent the entire sample and reduce variability inherent to small subsamples. In the case of the ECS 4010, increased analytical replication may be necessary. SOC monitoring schemes could mitigate analytical error by using the same instrument, ideally in the same lab, for repeated analysis, and by including standards with comparable amounts of TIC, when analyzing samples known to contain TIC.

1.5.3. Sampling design recommendations to reduce uncertainty

Spatial heterogeneity is likely to dominate measurement uncertainty in many scenarios. We recommend three ways to reduce uncertainty in SOC stock estimates and to increase the reliability of inferences about SOC stocks: stratified sampling, minimal compositing (if any), and larger sample sizes.

Stratification generally reduces uncertainty for a given total sample size if the strata are more homogeneous than the population as a whole (J J de Gruijter et al., 2016). In our simulations, stratified sampling had higher power to detect increases in TC% at the rangeland site than simple random sampling (**Figure 7**). The soil samples in our study were taken from strata defined by catenal position, while controlling for soil type and topography. Stratifying on these variables and others, such as historic management and vegetation, can reduce the sampling error in estimates of C stocks and C stock change (Devine et al., 2020), especially in heterogeneous landscapes. Otherwise, far larger sample sizes are required to reliably detect and quantify SOC changes. Preliminary field surveys, geospatial information regarding soil and landscape features, and expert pedological knowledge are useful for defining strata in research settings (Post et al., 2001). Future improvements in algorithm development for stratification (Devine et al., 2020; J J de Gruijter et al., 2016), digital soil mapping, and user-friendly software tools (e.g. Stratifi; <https://www.quickcarbon.org/tools>), could help standardize and ease barriers to stratification for SOC studies.

Compositing can be optimized for any budget to minimize uncertainty, given estimates of the analytical precision, spatial heterogeneity, and the (marginal) unit cost of collecting, preparing, and

analyzing a sample (Spertus, 2021). Without such estimates, it is best to avoid compositing (especially when collecting baseline samples), because it reduces information on spatial heterogeneity, complicates sampling designs and analyses, and increases the contribution of analytical error (**Figure 5**). Compositing also tends to reduce power by decreasing the effective sample size. Compositing is most helpful when SOC is highly heterogeneous, the cost of each laboratory assay is high, and the budget is small. In such cases, investigators should consider optimal, rather than full compositing (Spertus, 2021) and may use an accessible web app to estimate at: <https://scf.berkeley.edu/shiny/bosf/soil-carbon-statistics/>.

Finally, many current sampling designs—both for research and for the sale of C credits—use sample sizes that are too small to allow any test to have a reasonable chance of detecting moderate changes in SOC (Necpalova et al., 2014) or quantifying SOC changes on heterogeneous landscapes on relevant timescales.

To illustrate, assume that compost application on rangelands increases relative TC% by 20% (as per Ryals et al (2014) after 3 years of application). Based on the spatial heterogeneity we observed in rangeland soils, in order to have 80% power to detect such an increase (using stratified sampling and Student's t-test) would require collection and analysis of nearly 100 soil samples at baseline and another 100 samples after the intervention, with no compositing (**Figure 7**).

Most rangeland management interventions, however, such as improved grazing practices, are expected to produce much smaller C gains. For instance, Conant et al (2017) found a relative increase of ~10% from grazing improvements. The smaller the anticipated changes in SOC, the larger the required sample size to reliably detect and quantify them. Similarly, using nonparametric tests—which may be needed to properly control the false positive rate—require larger sample sizes. For instance, it would require more than 200 samples to have an 80% chance of detecting a 10% relative increase in SOC using either the unstratified Student t-test or the nonparametric test (**Figure 7**). No matter the sampling design or statistical test, the sample sizes typical in current campaigns (e.g., 8 samples for USDA GRACEnet; 9 samples composited to 1 for CDFA Healthy Soils Program; Davis et al., 2017) are far too small to have sufficient power to detect changes in rangeland SOC (**Figure 7**).

Our simulations suggest that detecting SOC changes in cropland may be easier than rangelands, but common sample sizes are still inadequate. Nonparametric tests have little chance of detecting reasonable changes with only 10 samples, and Student's t-test is likely to be misleading for such small samples—and lack sufficient power. With only 10 cropland samples, a relative increase of 30%—a very large change, would be needed for Student's t-test to have 80% power (Saby et al., 2008). At the CROP5 site, Student's t-test required ~90 samples to have an 80% chance of detecting a 10% relative change in TC%.

Given that sampling campaigns are routinely underpowered, we suggest *a priori* power analyses to determine site-specific minimum sample sizes (Kravchenko & Robertson, 2011). We also suggest routinely conducting post hoc power analyses to determine whether studies that find no effect of management on SOC had sufficient power to detect expected differences.

1.5.4. Tests must be valid to provide credible evidence of carbon change

Even when sampling is well-designed and executed, statistical analysis matters. Student's t-test and its relatives may erroneously conclude C was sequestered when it was not, at a much higher rate than the nominal significance level. As shown in **Figure 6**, this occurs when even one of the TC distributions is skewed. The Student t-test's false positive rate is particularly high when there are SOC hotspots or the distribution of TC (but not its mean) changes over time. Some management interventions redistribute SOC and create or destroy C hotspots (Baker et al., 2007; Kuzyakov & Blagodatskaya, 2015; Marin-Spiotta et al., 2014). For example, establishing perennial intercrops or hedgerows and spreading high-C inputs such as biochar and compost can create SOC hotspots. Valid inference is crucial to measure SOC sequestration credibly; Student's t-test and related tests and confidence intervals likely often understate the chance of false positives and have an inordinately large chance of false negatives.

How can monitoring and verification campaigns ensure that estimates and inferences are reliable? An important consideration is whether the soil population of interest might have skewed SOC, including from SOC hotspots. If so, it might be possible to stratify the sample so that SOC distributions within strata are not severely skewed. Skewness in the population distribution makes Student's t-test behave particularly poorly. Some practitioners transform skewed data, e.g., by taking logarithms, before analyzing the data. Such transformations can hurt rather than help—unless other, equally strong and equally unverifiable assumptions hold. Moreover, skewness in the population that is sufficient to undermine parametric statistical inferences may not be evident in the data for realistic sample sizes. And selecting a transformation before testing makes interpreting the nominal P-values complicated: “researcher degrees of freedom” needs to be taken into account by adjusting those P-values upward. Larger sample sizes do improve the approximations Student's t-test relies on, but in general, it is not possible to determine how large the sample must be for the approximation to have a particular level of accuracy (Cochran, 1977). If hotspots exist but their locations are unknown prior to sampling, Student's t-test should not be used. In our simulations, nonparametric tests were less powerful than Student's t-test, but they control the false positive rate for any SOC distribution (**Figures 6 and 7**), while Student's t-test can fail for some SOC distributions. Thus, Student's t-test may *appear* more powerful, but it is wrong more often. Our simulations show that using prior geochemical knowledge to bound TC more tightly (e.g. 10% instead of 20%) can increase the power of nonparametric tests, as can testing at a higher significance level (e.g. 10% instead of 5%). Deriving more powerful nonparametric tests is an active research area in Statistics (Romano & Wolf, 2000; Waudby-Smith & Ramdas, 2020), which we hope to extend to stratified soil samples (e.g., Wendell & Schmee (1996)). We have written an R package to facilitate wider use of nonparametric tests, which can be installed from the R console by running `devtools::install_github` (redacted for review).

1.5.5. Study limitations and future research

Our analyses relied on soil samples that were collected using common approaches, rather than all of the sampling practices we advocate here (systematic rather than random samples). This could understate overall spatial heterogeneity if SOC is spatially autocorrelated, making our findings conservative. However, we found little evidence of spatial autocorrelation in our rangeland samples (**SI Figures 5-9**). The simulations provided are a starting point; other expected changes to SOC distributions and deeper soil depths should be examined. The geographic extent of the soil sampling was also limited and thus may not fully represent the heterogeneity of crop and rangelands, but we expect the qualitative conclusions about differences in heterogeneity between rangelands and croplands will be valid more broadly.

Improving measurement of rock fragments and accounting for rock volume in SOC stock estimates should be a research priority. We highlight spatial heterogeneity as a primary driver of uncertainty in SOC stock estimation, but rock fragments can make estimation of bulk density and total soil volume challenging and are an important source of uncertainty. Estimating total SOC stock requires extrapolating to the entire soil population of interest (e.g., a field or pasture from the surface to a particular depth). Simply multiplying the measured SOC concentration of the soil component by the volume of the field (which includes rocks) biases estimates of total C stocks in rocky soils, common in semi-arid rangelands. Current sampling methods are not adequate to estimate total rock volume in rocky soils, in part because large rocks may prevent a core from being taken at all in a particular location or may not fit in a core of a given volume, building bias into the sample. Previous studies have also highlighted rock content as a major source of uncertainty and error in SOC estimates, contributing up to 82% of error in SOC stock estimation on rocky agricultural sites (Beem-Miller et al., 2016). How to best account for rock content and volume remains unresolved (Goidts et al., 2009). Remote sensing and geophysical methods such as ground penetrating radar may be helpful.

1.6. Broader implications for research, C markets, and policy

There have been numerous calls to standardize protocols for measuring SOC (Bispo et al., 2017; Davis et al., 2017; Jandl et al., 2014), but complete standardization may not be practical given differences among project needs and budgets, landscape heterogeneity, and lab constraints. In particular, given the large contribution of spatial heterogeneity to the uncertainty of SOC stock estimates, protocols that require fixed sample sizes are not appropriate. For instance, sampling designs optimized to detect SOC changes for croplands may have little chance of detecting similar changes on rangelands, which typically require larger samples because they are more heterogeneous. Instead, sampling design *processes* should be standardized, such as the use of algorithmic stratification and *a priori* power analyses to select sample sizes adequate to detect plausible changes.

Accurately estimating SOC stocks and stock changes matters for research, policy development and implementation, and program evaluation, whether by academics, NGOs, or governments. The consequences of inaccurate estimates of SOC for the sale of C credits in C markets are large. Current verification sampling protocols used to quantify and generate C credits for C markets cannot reliably estimate SOC sequestration, especially on heterogeneous agricultural lands. This could result in SOC offsets having little connection to the true extent of sequestration (Oldfield et al., 2021). Verification protocols for croplands include Climate Action Reserve's (CAR) Soil Enrichment Protocol, Verra's VM0021, and the Food and Agriculture Organization's (FAO) Global Soil Organic Carbon (GSOC). All three protocols require only three or more samples per stratum, far fewer than required to estimate the impact of management changes on a timescale of years. The protocols also lack details on how to stratify and analyze the resulting data to estimate SOC stocks and stock changes. Especially because they sanction such small sample sizes, these protocols may often reward "false positives" and fail to reward genuine sequestration. We recommend revising the protocols to require substantially more samples tailored to land-specific spatial heterogeneity, and to provide much more detailed and useful guidelines for participants on when, where, and how to sample to minimize uncertainties.

For some purposes, instead of estimating SOC stock changes on *each* participating farm or ranch, it might suffice to estimate the aggregate effect across many farms/ranches, collecting few samples from each, to keep costs down. Alternatively, one might conduct intensive sampling on a random sample of sites or a network of regional research monitoring sites (which could be supported by the development of funding programs like AgARDA or through increases in funding to LTERs or Climate Hub networks). Limiting sampling efforts to a smaller number of dedicated sites representing a range of climates, soil types, and cropping systems could allow for more intensive sampling—with higher power to detect SOC stock changes. This intensive sampling could then be used to calibrate, validate, and improve models such as MEMS 2.0 (Zhang et al., 2021) to estimate SOC change across broader landscapes and generate SOC credits for similar farms and ranches. This may be a more efficient use of resources and could drive more accurate verification, depending on the accuracy of the models. However, both of these strategies represent a shift from paying for *results* to paying for *practices* that are expected—but not guaranteed—to produce results.

1.7. Conclusions

Spatial heterogeneity of SOC is a primary obstacle to accurately measuring SOC stock changes, even with careful sampling design and execution, accurate assays, and rigorous statistical analysis. Attempting to measure or verify SOC sequestration using too few samples, poor sampling design, imprecise laboratory instruments, or inappropriate statistical analysis can undermine climate change mitigation goals. We highlighted errors, quantified uncertainties, and demonstrated potential improvements in design and analysis, using data from California croplands and rangelands. There are several straightforward ways that sampling schemes can be improved. Collecting information on the degree and pattern of heterogeneity before a comprehensive sampling campaign can make it possible to use stratified sampling to advantage. Such information also makes it possible to perform power calculations and identify optimal compositing approaches, ensuring that the campaign has sufficient statistical power to detect anticipated changes in. In general, reliable inferences about the short-term effect of management interventions on soil C require larger sample sizes and less compositing than is commonly used. We demonstrate that Student's t-test has highly inflated false-positive rates in scenarios that may be common in the field and suggest caution when using Student's t-tests and its relatives for verifying changes, especially when sample sizes are small. Nonparametric statistical methods can control false positives for any sample size, without assumptions about SOC distributions; providing more reliable, trustworthy results. The power of nonparametric tests can be increased using transparent, verifiable assumptions (e.g. geochemical constraints on the maximum SOC). Careful planning and continued collaboration between soil scientists and statisticians will help improve accuracy and precision of SOC measurements.

1.8. Data availability and code

All data and code used in this paper are available online at: <https://github.com/spertus/soil-carbon-statistics>. A web application to facilitate investigators with pre-sample planning, including *a priori* power analyses, determining optimal compositing schemes, and budget planning, is available at: <https://scf.berkeley.edu/shiny/bosf/soil-carbon-statistics/>. Our R package to facilitate wider use of nonparametric tests can be installed from the R console by running `devtools::install_github(redacted for review)`.

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1.11. Figures

Figure 1. Histograms TC% by (a) transect and depth in rangeland soils and (b) site and depth in cropland soils. Transect labels in (a) refer to catenal positions and replicates: Bx (footslope, replicate X), By (footslope, replicate Y), Mx (backslope, replicate X), My (backslope, replicate Y), and T (summit/shoulder, no replication). Site labels in (a) refer to cropland sites: CROP1 is a diversified farming system, CROP2 is a vineyard, CROP3 is an orchard, CROP4 and CROP 5 use conventional cropping, CROP6 is a diversified farming system, and CROP7 is an orchard. Depth increments differed between rangeland and cropland sampling schemes. Plotted values are TC%, which is equal to TOC% in samples with zero TIC.

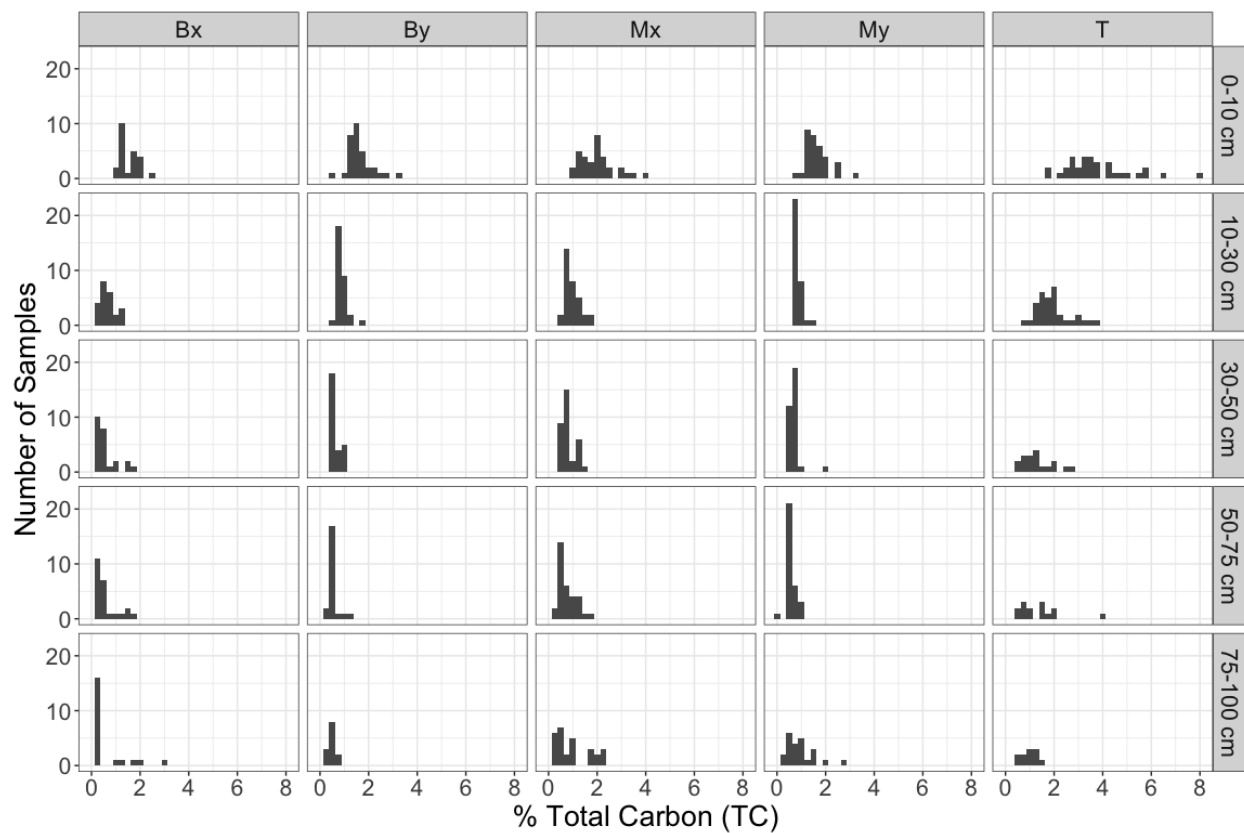
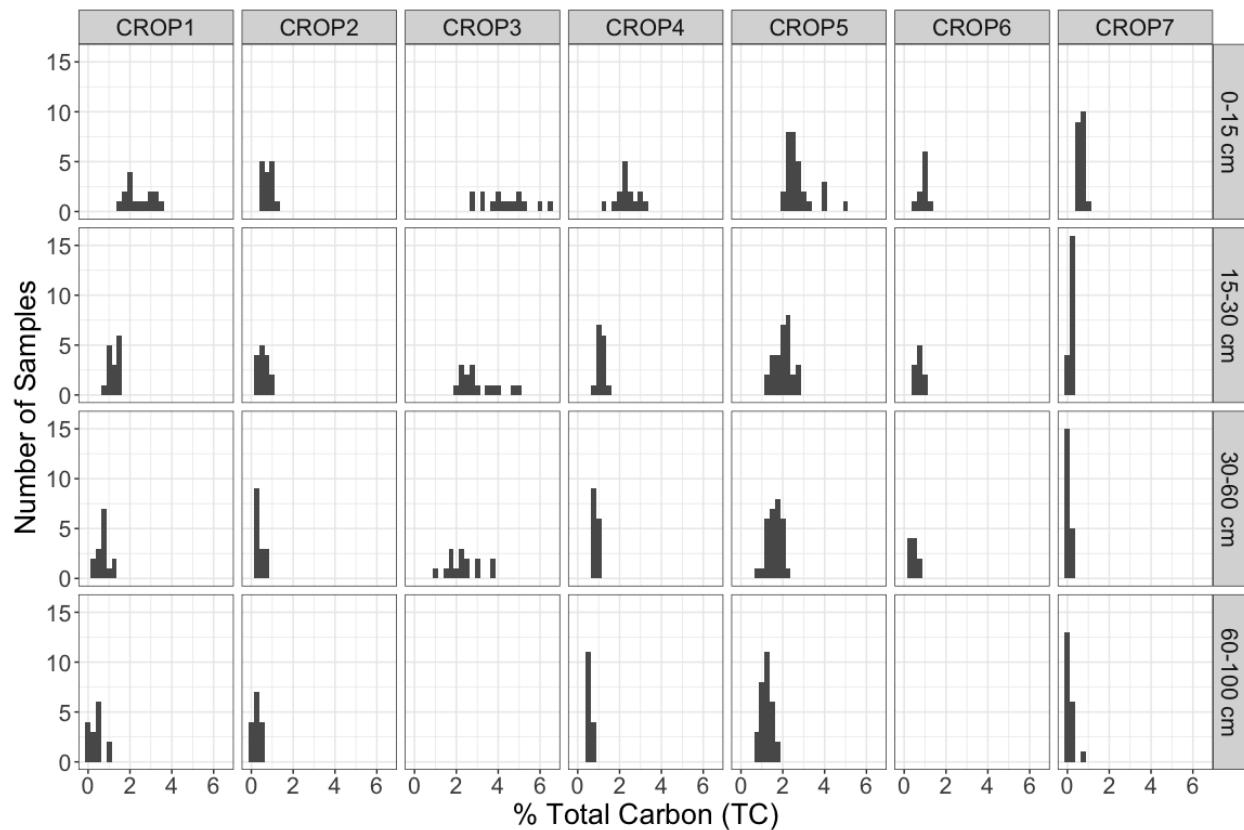


Figure 2. Empirical distributions of bulk density (BD) samples across 16 soil pits on CROP7 (a) and 15 rangeland soil pits (b) by depth (in rows).

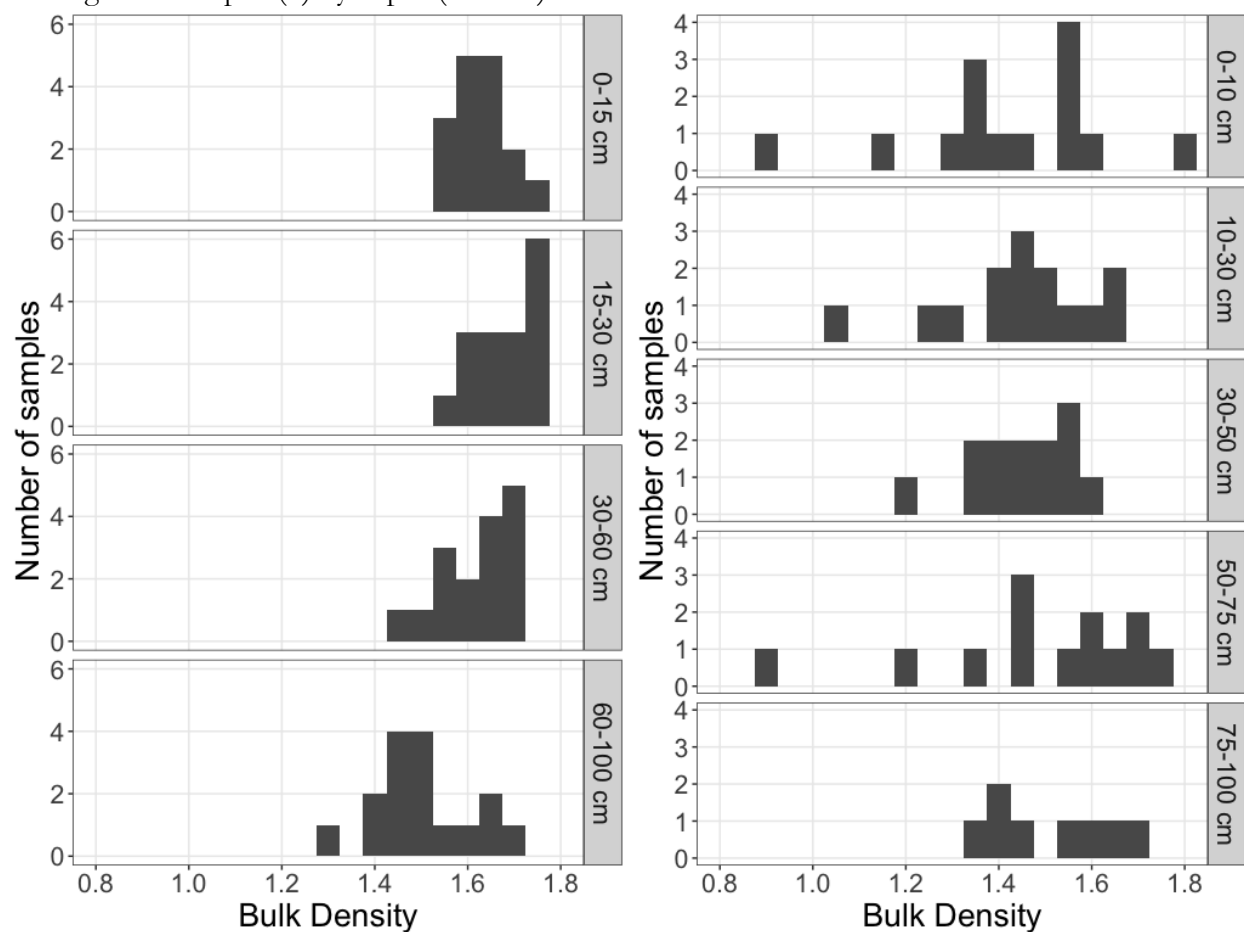


Figure 3. Histogram of relative error of replicated assays computed for each sample run on soliTOC (blue) and ECS 4010 (orange). Histograms bins are 1% relative error wide and stacked. The samples with relative error above 20% on ECS 4010 had high proportions of inorganic C.

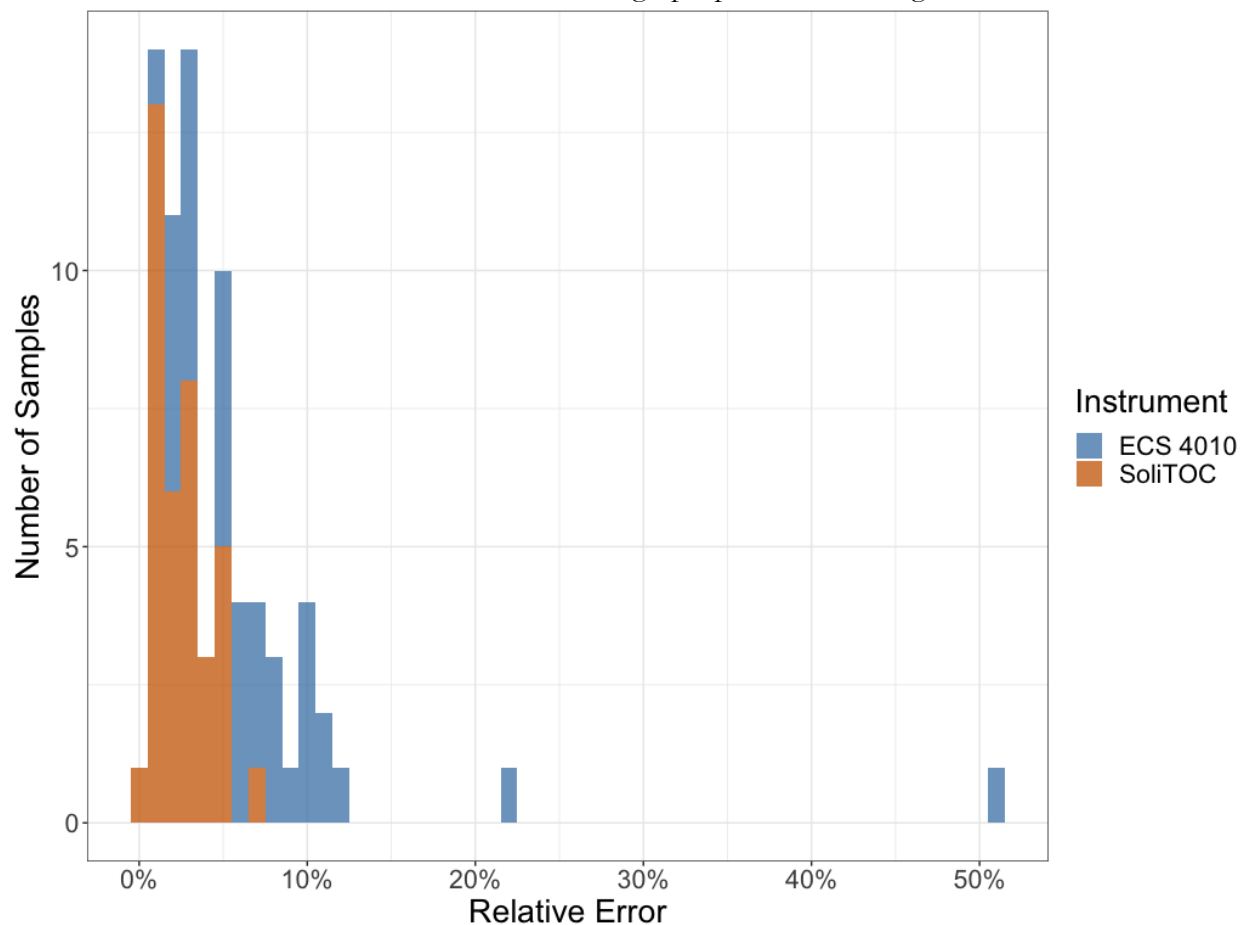


Figure 4. Contributions to the variance of the sample mean from assay uncertainty and compositing. Proportion of variance (y-axis) reflects assaying either all field samples individually (“No Compositing” panels) or 90 field samples together (“Full Compositing”). Different panels correspond to different land uses (in columns) and instruments (in rows). Field heterogeneity is estimated using data from the rangeland site or averages across cropland sites, at various depths (x-axis). Assay variability is estimated either on ECS 4010 (top panels) or soliTOC (bottom panels) elemental analyzers. Rangeland depths: a:0–10cm, b:10–30cm, c:30–50cm, d:50–75cm and e:75–100cm. Cropland depths vary slightly by site (see Figure 1).

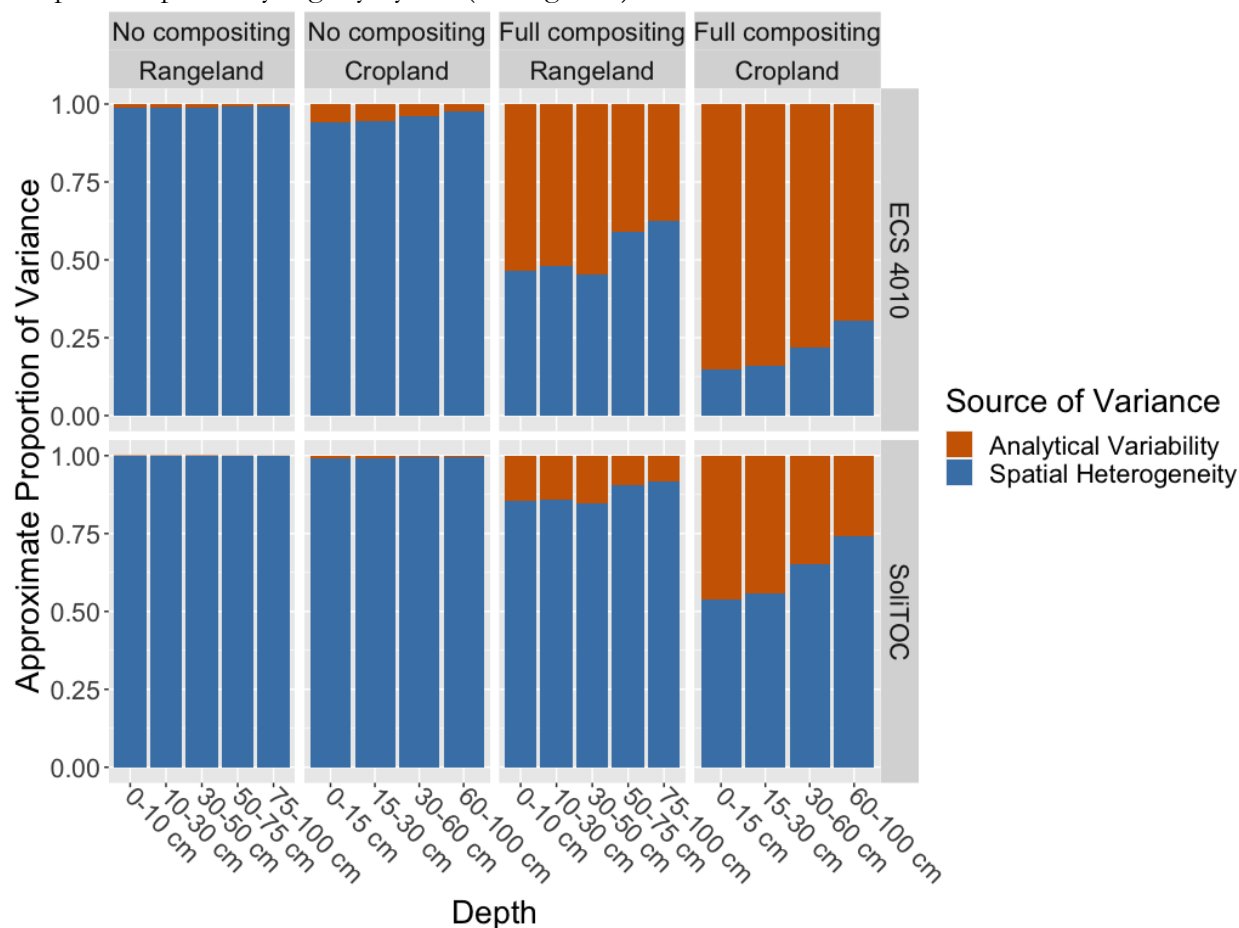


Figure 5. Theoretical power of Student's t-test to detect changes in topsoil TC% (if TC% is normally distributed) for two levels of compositing, for a budget that covers the cost of 90 cores and 90 laboratory analyses without compositing, or 150 cores and one laboratory analysis for full compositing. The X-axis shows the relative change in average TC% from baseline (2.16 TC% for rangeland or 2.04 TC% for cropland); the Y-axis is power. Different panels correspond to different land types (in columns) and instruments (in rows). Colors correspond to the compositing scheme. Optimal compositing for the same budget uses 140 cores composited to 19 analytic samples (SI 1.4).

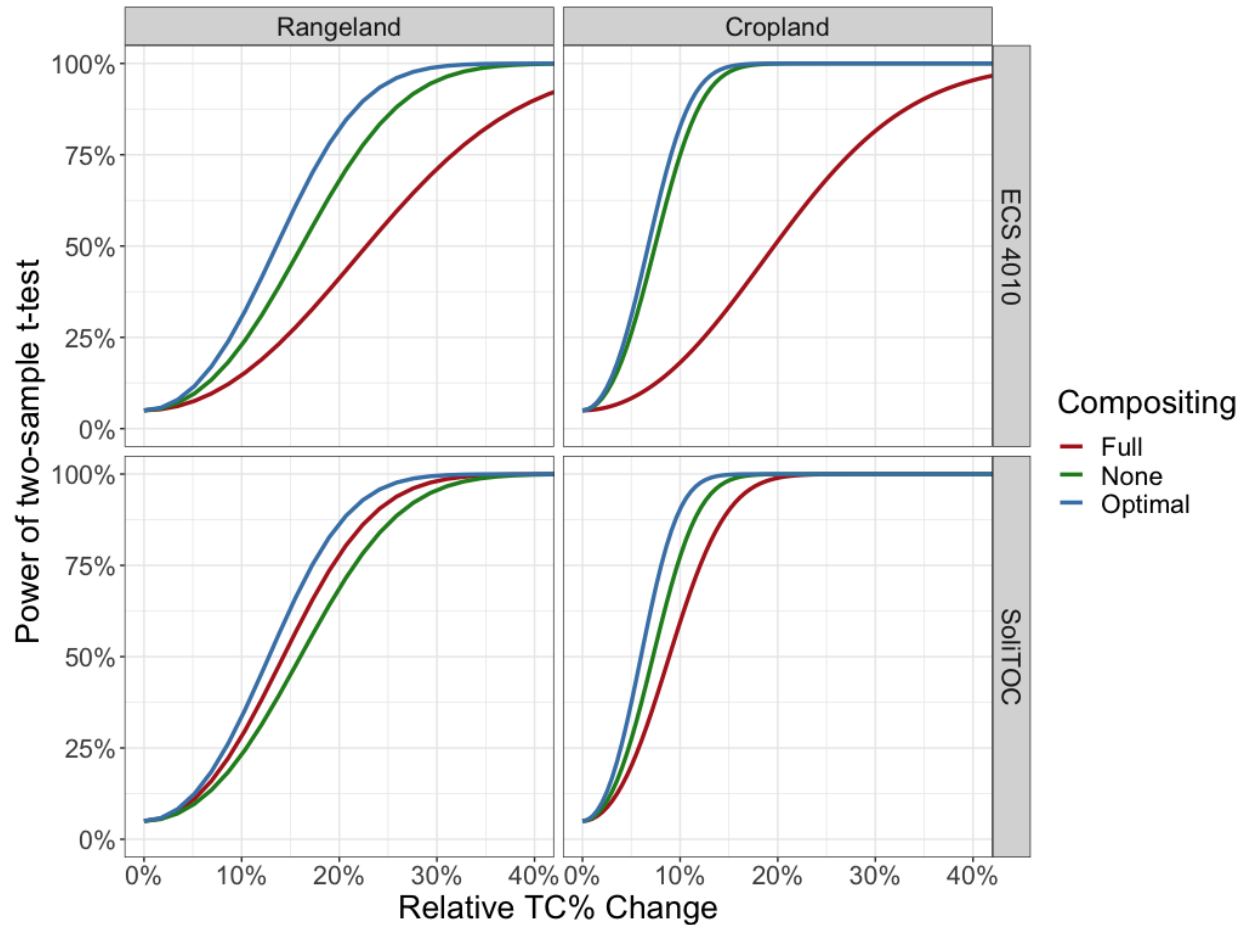


Figure 6. Simulated significance levels of two nominal 5% level tests: the two-sample Student t-test and a nonparametric test. Each panel reflects 5000 simulations at each sample size (x-axis); random samples were drawn independently from each of two distributions that had identical means. The y-axis plots the rate of false rejections of the null hypothesis (the Type I error rate). The solid black line is the nominal 0.05 significance level, which both curves should be at or below.

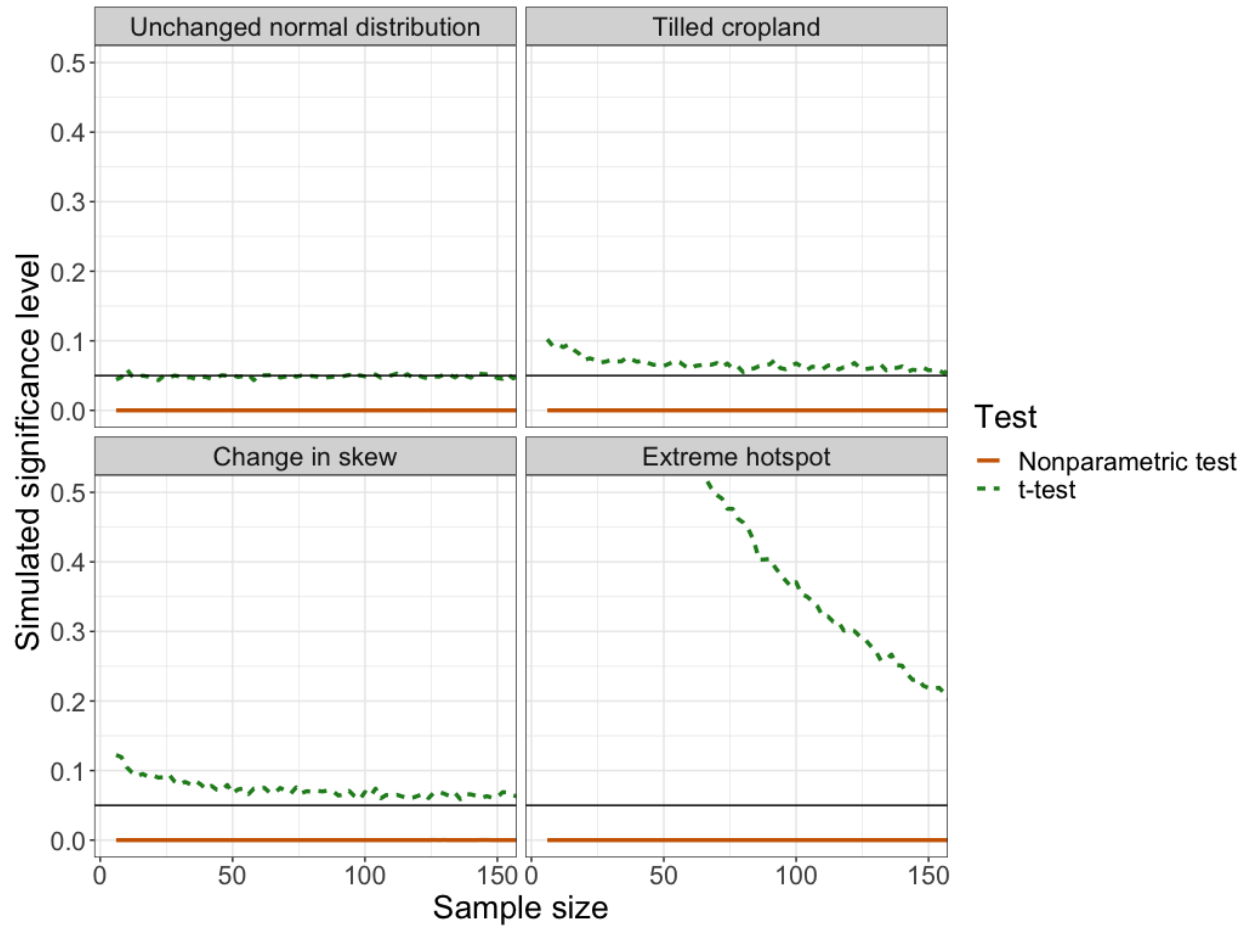
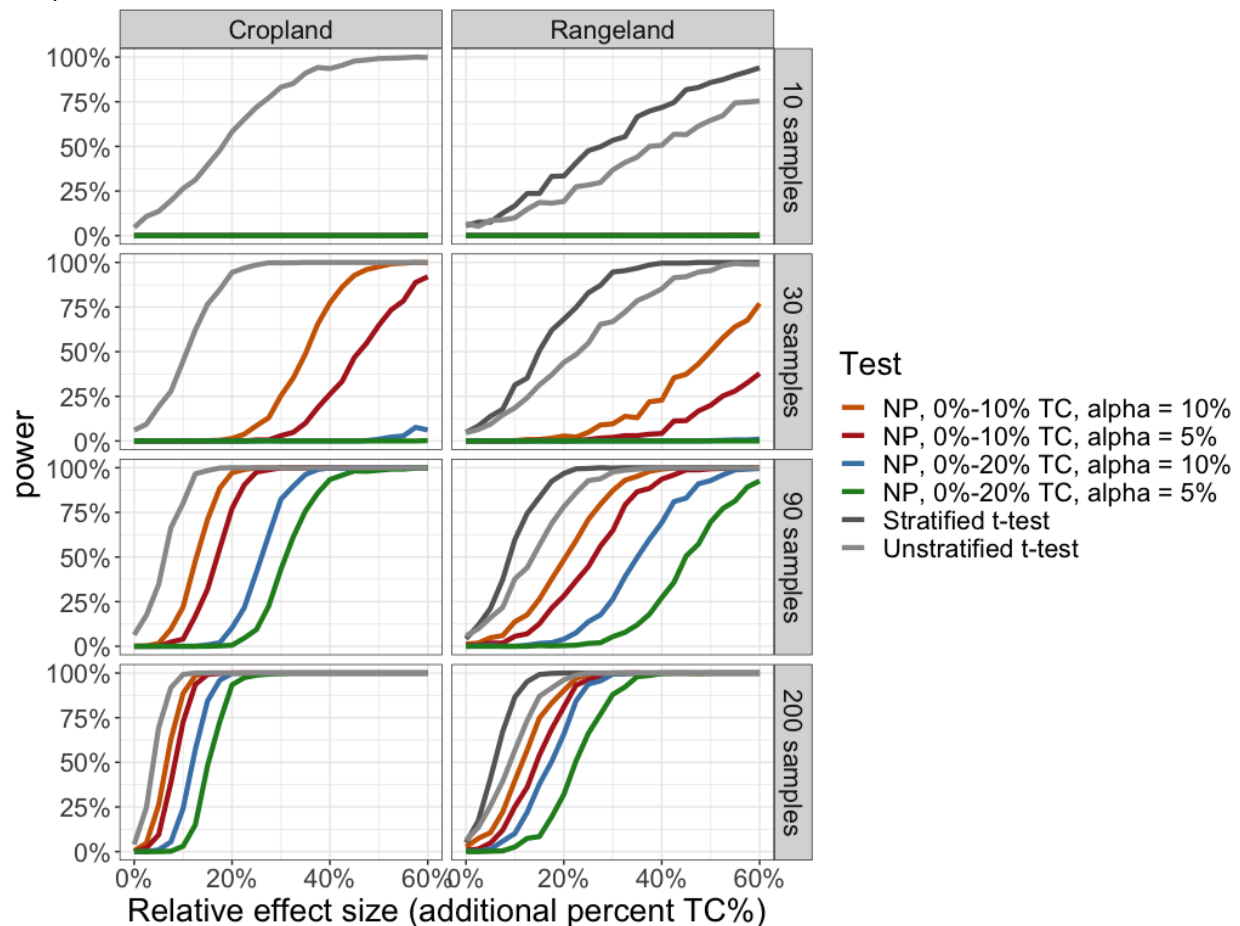


Figure 7. Simulated power of three two-sample hypothesis tests (Student's t-test for unstratified and stratified samples and a nonparametric test for unstratified samples based on Learned-Miller & Thomas (2019)) to detect relative changes in TC% with sample sizes 10, 30, 90, or 200 from each of two populations. The first population distribution is the empirical distribution of TC% measurements for CROP5 (left column) or the rangeland site (right column) topsoil. The second population distribution is the same as the first, but each value was shifted by 0% to 60% of the mean of the first population, 2.7% TC for the cropland samples and 2.2% TC for the rangeland samples. Unstratified samples were simple random samples with replacement from the populations. Stratified samples from rangeland were simple random samples with replacement within transects, independent across transects, with sample sizes proportional to the original number of data in each transect. Stratified samples from cropland were not explored because there were no natural strata in the original data. Four curves are presented for the nonparametric test by varying pre-specified upper bounds on the population (10% TC or 20% TC) and the nominal significance level (5% or 10%); both the Student t-tests used a nominal significance of 5%, which may understate the chance of false positives. NP = nonparametric.



1.12. Tables

Table 1. Key decisions in estimating SOC stocks, in rough chronological order, and considerations associated with each decision. Italicized decisions and considerations are examined in this study.

Key Decisions	Considerations
1. The scientific goal	- Measuring concentrations, stocks, and stock changes are different goals requiring different approaches, different sample sizes, etc. Erroneous conclusions about sequestration can misalign economics and ecology, rewarding non-existent sequestration - or failing to reward genuine sequestration. - Most scientific questions are about a particular “population” subsurface volume, delimited by a map boundary and depth, and possibly by composition (e.g., are rocks considered part of the population?). - To extrapolate reliably from a set of soil samples to a larger population, the samples must be drawn from that population appropriately. - Because some management interventions redistribute SOC vertically, to estimate changes in stocks, the population should include all depths that could be affected. - Different SOC pools have different controls and dynamics, so investigators need to decide what C counts as part of the estimand (e.g. organic, inorganic, biomass < 2mm).
2. Where and how to collect soil samples - Random sample, convenience sample, or systematic sample (grid or transect) - Whether and how to stratify - Sample size - How to account for samples that are uncollectable, e.g., because of rock fragments, root limiting layers, high water table, etc.	- Land use, edaphoclimatic properties and other factors all influence spatial heterogeneity of SOC and potential? management effect sizes. - Systematic sampling is logistically simple, but doesn’t permit reliable inferences about stock or stock changes. - Random sampling permits reliable inferences without additional assumptions. - A stratified random sample may yield higher precision than a simple random sample of the same size when there is prior information about expected variation, e.g., from soil maps. - The power to detect changes in C and the accuracy of estimates increases as the number of samples increases. Not properly accounting for uncollectible samples can bias estimates of SOC stocks, soil volume in a field, soil density, etc.
3. Where and how to collect bulk density samples - Sample specifically to estimate bulk density or use equivalent soil mass - How to account for rocks and gross organic matter in samples	- Bulk density varies spatially and can be correlated with C concentration. Assuming bulk density is constant introduces error. Measurements of bulk density have uncertainty. “Fixed mass” methods may reduce error but are more complex and require more expertise than traditional “fixed depth” methods.

4. Soil processing • Whether and how to composite soil samples • How to deal with visible organic matter • How to account for rocks • How to prepare soil for C assays: Air or oven dry? At what temperature? For how long? Sieve before or after drying, and to what size? Grind with ball mill or mortar and pestle? To what particle size?	• Compositing can reduce lab costs, but may increase bias and make it harder to estimate spatial heterogeneity. • Without consistent treatment of macroscopic organic matter such as root fragments and leaf litter, non-soil can have a large effect on the bias and variability of SOC concentration measurements. • Rock fragments can significantly bias soil bulk density estimates. Their mass and volume need to be accounted for, but can often be beyond the scale of sample collection. • The carbon concentration of soil should not be extrapolated to subsurface rocks or gross organic matter. If rock mass is not in the denominator in calculating C mass density, it should not be in the numerator in extrapolating to find total C in a field. • Inconsistencies in sample preparation contribute to lab-to-lab variability and may lead to false conclusions about SOC changes.
5. Laboratory analysis • Method and instrument, e.g., loss-on-ignition, Walkley-Black, dry combustion? • Sample mass to assay • How to calibrate the instrument; how and how often to run standards • Whether and how to remove inorganic C • Whether and how to replicate measurements	• The least expensive methods, loss-on-ignition and Walkley-Black, are imprecise and sometimes biased. • Very small subsamples (<10 mg) may not represent the average concentration within a core. • Poorly calibrated instruments can bias measurements. • Inorganic carbon can bias measurements of organic carbon for some methods. Inorganic carbon should be quantified separately from organic C or removed. However, removing inorganic C by HCl extraction can bias estimates. • Replication helps measure and reduce variability, at a cost. • Ignoring differences in assay methods or instruments when comparing estimates can lead to erroneous conclusions.
6. How to estimate SOC stocks and make inferences about SOC sequestration • How to combine sample data combined to yield estimates about an entire volume, such as a field • How to quantify the uncertainty in such estimates. Whether and how to check whether the methods are applicable to the data or require assumptions that are unrealistic or false for soil C	• Estimates and tests should account for the sampling design, including stratification, and the uncertainties in intermediate steps, including assays and bulk density estimates. • Estimates and tests should account for the non-soil component of the area of study. For instance, SOC mass concentration should not be extrapolated to the volume occupied by subsurface rocks. • Model-based approaches such as kriging and Gaussian-processes have assumptions that can bias estimates and produce misleading uncertainty estimates. • T-tests, Student-T confidence intervals, ANOVA, and other common statistical procedures may not have their nominal error rates for inferences about SOC, which does not satisfy their assumptions. • Uncertainty estimates based on random sampling are meaningless for samples of convenience and systematic samples (i.e., grid or transect sampling).

Table 2.: Estimates of TC% means and coefficients of variation (CV; in parentheses) for cropland and rangeland. Mean and CV for rangeland sites are listed by transect. Mean and CV for croplands are listed by site. Cropland depths were not always consistent by site. For example, the second sampling depth ranged from 15–30, 15–35, and 15–40 in some cases. We used the most common depth increments here.

CROPLAND								
Depth (cm)	CROP1	CROP2	CROP3	CROP4	CROP5	CROP6	CROP7	Total
	DFS	Vineyard	Orchard	Crop	Crop	DFS	Orchard	
0–15	2.45 (0.26)	0.82 (0.26)	4.31 (0.26)	2.37 (0.21)	2.74 (0.25)	0.94 (0.20)	0.64 (0.21)	2.04 (0.24)
15–30	1.21 (0.19)	0.56 (0.41)	3.05 (0.31)	1.14 (0.15)	2.03 (0.21)	0.73 (0.27)	0.17 (0.36)	1.27 (0.25)
30–60	0.73 (0.39)	0.36 (0.58)	2.36 (0.34)	0.88 (0.13)	1.60 (0.22)	0.50 (0.42)	0.10 (0.44)	0.93 (0.31)
60–100	0.42 (0.77)	0.25 (0.62)	-	0.56 (0.21)	1.22 (0.21)	-	0.12 (1.14)	0.52 (0.38)
RANGELAND								
Depth (cm)	Bx	By	Mx	My	T	Total		
0–10	1.55 (0.27)	1.63 (0.32)	2.02 (0.36)	1.63 (0.32)	3.77 (0.36)	2.16 (0.54)		
10–30	0.67 (0.48)	0.90 (0.27)	0.99 (0.32)	0.86 (0.20)	1.99 (0.36)	1.11 (0.56)		
30–50	0.60 (0.66)	0.64 (0.28)	0.82 (0.33)	0.71 (0.39)	1.32 (0.48)	0.78 (0.53)		
50–75	0.59 (0.75)	0.53 (0.41)	0.75 (0.51)	0.59 (0.36)	1.41 (0.63)	0.71 (0.70)		
75–100	0.65 (1.17)	0.47 (0.27)	1.01 (0.71)	0.94 (0.61)	0.96 (0.34)	0.84 (0.75)		

1.13. Supplementary information

S1. Methods

S1.1. Data collection: soil sampling methods, soil processing, and laboratory assays

The ranch where our rangeland soil samples were collected is approximately 7,670 acres of mixed oak-savannah with slopes of 1-63%, typical of California rangeland. There are 18 distinct soil types on the ranch, ranging from Hanford coarse sandy loam (<1% SOM, 6-18% clay) to Soper gravelly loam (~1% SOM, up to 20% rock by volume) to Diablo clay (2.5% SOM, 45-60% clay). For a full soil taxonomy, see **SI Table 1**. Our population soil of interest, Auberry Fine Sandy Loam, is 18-30% clay with up to 15% gravel; this soil class comprises 280,772 acres of the Central Coast and Sierra Foothills regions of California rangelands.

Sampling at the rangeland site followed a stratified transect design with five 100m transects on two adjacent hillslopes stratified by slope position: summit/shoulder (1 transect), backslope (2 transects), and footslope (2 transects). We chose sampling locations that were accessible, managed consistently at low intensity (i.e., no compost, tillage, or seeding), and had a minimal tree canopy. Transect placement and sampling was non-random. We situated transects to avoid trees and large boulders. At 4 of the 5 transects, we collected 33 1m cores, each divided into 5 depth ranges (a: 0-10cm, b: 10-30cm, c: 30-50cm, d: 50-75cm and e: 75-100cm). We collected only 25 1m cores at one of the footslope transects due to time constraints. In all, we attempted to collect 157 samples at each depth for a total of 785 individual soil samples. Cores were collected down to 1m *or* to the point of refusal (either due to bedrock or rock obstruction). We made up to three total attempts at each sampling point. We first tried to collect the core directly on the transect. If we hit a point of refusal before reaching 1m, we made up to two more attempts: 1m above the transect and 1m below the transect. We only kept soil from a given depth range if the core spanned that entire range. Ultimately, we collected 662 individual soil samples: 123 samples could not be collected across the deepest three ranges, mostly along the summit transect. Each sample was air-dried, sieved at 2mm, and ground on a ball mill (Retsch, Newtown, PA).

The seven farms where our cropland soils were collected ranged from 4 to 694 acres and represented a gradient of clay percentages and cropping systems, including two orchards, a vineyard, two intensive cropping systems, and two diversified farms. Soil types in the cropland data are listed in **SI Table 1**. These soil types comprise 793,653 acres across California. Samples were collected by systematic random sampling, where the initial sampling location was chosen at random and 5 sampling locations were established ~22m apart in a deterministic zig-zag pattern.

After collection, soils were processed according to USDA and SSSA recommendations (Dane & Clarke Topp, 2002). Soils were air dried until they reached a consistent weight. Samples were monitored and weighed over the course of days to weeks: the exact drying time varied from sample to sample. Once dried, soils were sieved at 2mm. All material >2mm was removed, while all material (including visible organic material) <2mm was retained in the sample. Samples were then ground on a ball-mill at 30 Hz until a fine-powdery texture was reached (grind time varied by soil texture and composition).

S1.2. Analyzing C% distributions using permutation ANOVA

The permutation ANOVA test is performed as follows:

- Compute the F statistic¹: the ratio of the sample variance of the means across groups to the sample variance of the deviations from the means within groups.
- Repeat 10,000 times:
 - Shuffle the labels across groups at random
 - Calculate and record the F statistic for that relabeling
- Find the number of values of the F statistic that are greater than or equal to the value for the actual data among the 10,001 values of the statistic for the actual and shuffled data.
- That number, divided by 10,001, is an exact P -value for a permutation test of the hypothesis that the groups amount to taking the soil samples and randomly assigning them group labels -i.e., that the group label (transect, depth, or site) has no connection to soil C.

S1.3. Evaluating analytical variability

Analytical error is quantified by the relative error, defined for a specific sample i as $\sigma_{\delta,i} = SD(R_{ij})/E(R_{ij}) = \sqrt{V(R_{ij})/E(R_{ij})^2}$ where R_{ij} is the j th replicate assay of sample i , and $SD(R_{ij})$, $V(R_{ij})$, $E(R_{ij})$ respectively refer to the (true) standard deviation, variance, and expected value of the measurements, holding the sample fixed. The relative error on sample i is then estimated by the square root of the ratio of the unbiased estimates for $V(R_{ij})$ and $E(R_{ij})$:

$$\hat{\sigma}_{\delta,i} = \sqrt{\frac{1/(n-1) * \sum_j (R_{ij} - \bar{R}_i)^2}{\bar{R}_i^2 - 1/(n(n-1)) * \sum_j (R_{ij} - \bar{R}_i)}} \approx \widehat{SD}(R_{ij})/\bar{R}_i$$

where $\widehat{SD}(R_{ij})$ is the sample standard deviation over replicates of sample i and $\bar{R}_i$ is the sample mean. Note that the ratio $\widehat{SD}(R_{ij})/\bar{R}_i$ is the usual coefficient of variation.

Permutation tests were performed to compare assays made on each instrument. For each sample, the null hypothesis was that there was no difference in the assays made on each instrument. Each of these hypotheses was tested by permutation tests as described in SI1.2 above, replacing the F -statistic with the absolute value of the difference-in-means between the two instruments. Tests that resulted in P -values less than .05 were deemed significant; the assays for the corresponding samples are plotted as histograms in SI Figure 3.

S1.4. Relative uncertainty from spatial and analytical heterogeneity

We quantified the contributions of analytical variability and spatial heterogeneity to the overall uncertainty in population average TC% using the delta method (e.g., Goidts et al. (2009)). Let μ be the true plot mean, σ_p the true plot spatial standard deviation, and σ_δ the true relative error of the laboratory assay. If $\hat{\mu}$ is the sample mean of n cores mixed to form k composite samples, then the delta method approximation of the variance of $\hat{\mu}$ is:

¹ The usual F statistic is permutationally equivalent to the weighted sum of squared within-group means, where the weights are respective within-group sample sizes. We used the latter, but the results would be identical. For details see pages 29-31 of (Pesarin & Salmaso, 2010).

$$V(\hat{\mu}) \approx \frac{\sigma_p^2}{n} + \frac{\mu^2 \sigma_\delta^2}{k}.$$

This is generally quite close to the exact variance derived in (Spertus, 2021). The proportion of total error due to spatial heterogeneity is $\frac{\sigma_p^2}{n} / (\frac{\sigma_p^2}{n} + \frac{\mu^2 \sigma_\delta^2}{k})$. If spatial heterogeneity and assay variability contribute equally to error, this ratio is 0.5. A ratio closer to 1 implies plot heterogeneity contributes more than assay variability to overall error; vice versa for a ratio closer to 0.

Because σ_p , σ_δ , and μ are unknown and vary by plot and lab, we used estimates of those quantities from our data for illustration, substituting sample variances and sample means within depths (averaged across sites for cropland) for σ_p and μ , and the median estimated relative error for the soliTOC or ECS 4010 for σ_δ .

S1.5. Sources of uncertainty and their effects on statistical power

In the optimal compositing scenario (**Figure 5**), 140 cores are taken and 19 composited samples are analyzed. Note that 140 cores cannot be equally allocated into 19 composites. In practice, the numbers can be adjusted to equally composite while maintaining approximate optimality. For example: sample 140 times and analyze 20 composites with exactly 7 cores each. Alternatively, unequal composite sizes can be used by weighting the resulting measurements, but this is more complicated and prone to mistakes in statistical analysis.

S1.6. Power and validity of tests for temporal changes in TC%

For both of our simulation experiments, the t-statistic is the (signed) difference in means divided by the pooled estimate of standard error; the parametric t-test p-value is the corresponding upper tail probability of Student's t-distribution with degrees of freedom given by the Welch-Satterthwaite equation (Welch's t-test). The level- α nonparametric test was based on the non-parametric "Gaffke" test of the population mean proposed by (Gaffke, 2005) (see also (Learned-Miller & Thomas, 2019)). This one-sample test is conjectured to be valid for any bounded distribution; it also tends to be more powerful than other nonparametric tests. We constructed a non-parametric *two-sample* test following an idea described in (Ottoboni et al., 2018). Specifically, we simultaneously ran two one-sample Gaffke tests of (1) whether the population mean at time 1 was below μ_0 and (2) whether the mean at time 2 was above μ_0 . These tests yielded 2 independent P-values, which we combined using Fisher's combining function. We compared this test statistic to the chi-squared distribution with 4 degrees of freedom to obtain a combined P-value. We then maximized the combined P-value over all possible values of the shared mean μ_0 to obtain a valid P-value for the hypothesis that the population means were equal.

S2. Results

We examined spatial correlation of TC% on rangeland using empirical variograms, computed within transects and binned by distance (Diggle & Ribeiro, 2007). Plots of the empirical variograms appear in SI Figures 5-9 below. They do not show a clear pattern of spatial autocorrelation.

S3. References

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S4. Figures

Figure S1. The rangeland site (red arrows) and seven cropland sites (blue arrows) across California



Figure S2. Assays that are not significantly different at a 5% significance level between ECS 4010 and soliTOC, before or after removal of carbonates. Panel titles indicate the sample, and whether the carbon corresponds to TC or TOC (with carbonates removed by HCl for ECS 4010).

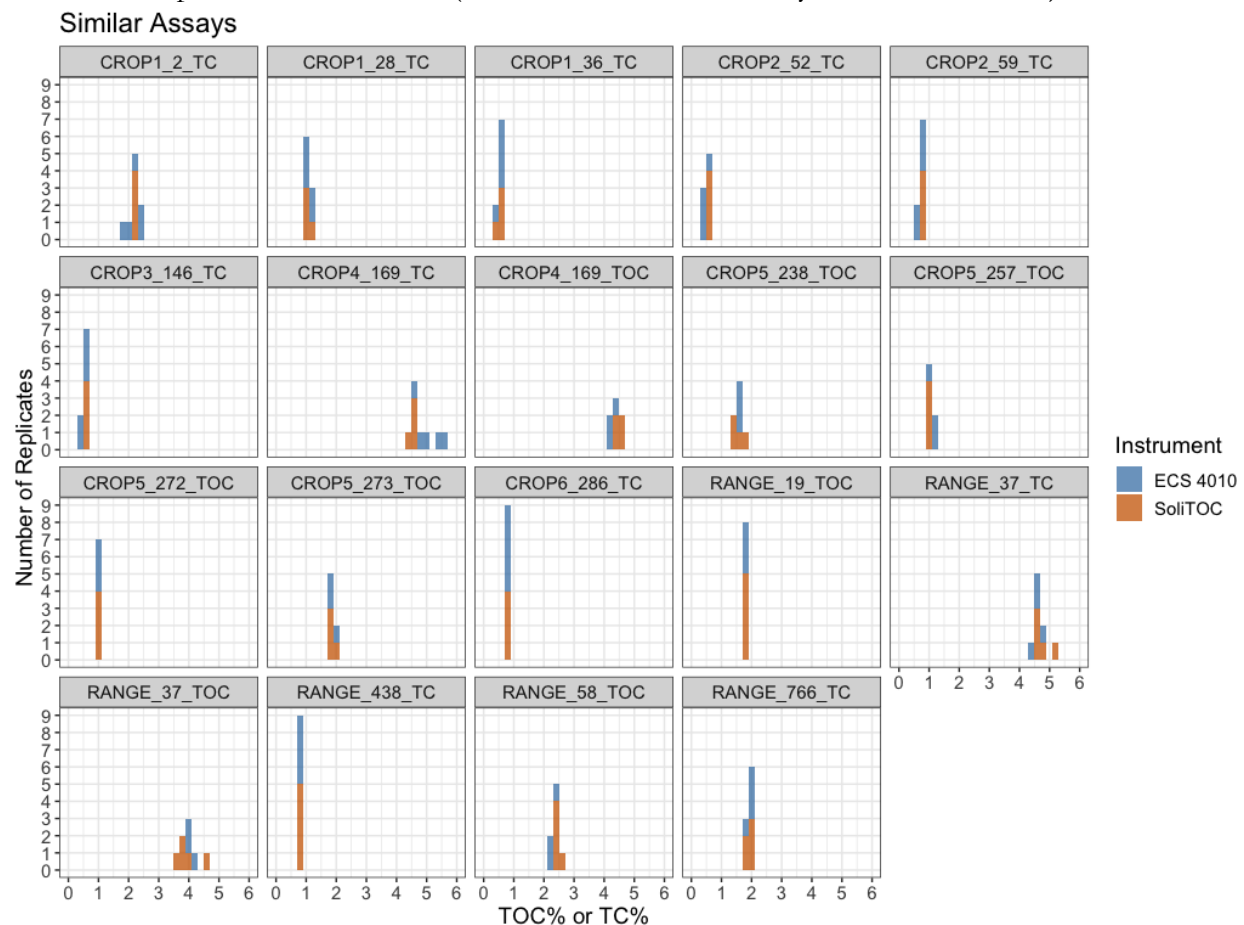


Figure S3. Analyses that are still significantly different after removal of carbonates.

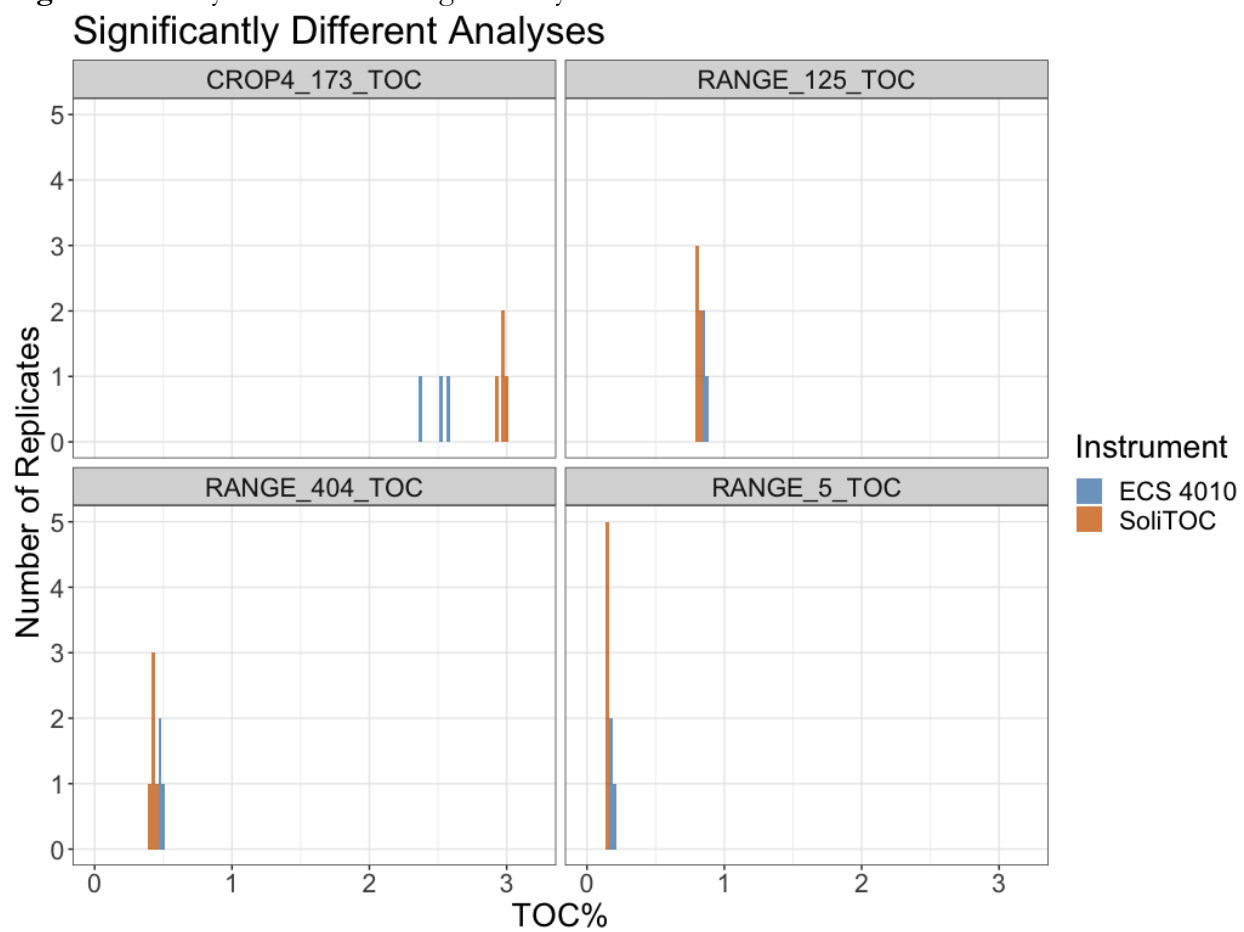


Figure S4. TC% assays from two standard soils replicated 25 times each on the ECS 4010 and soliTOC elemental analyzers.

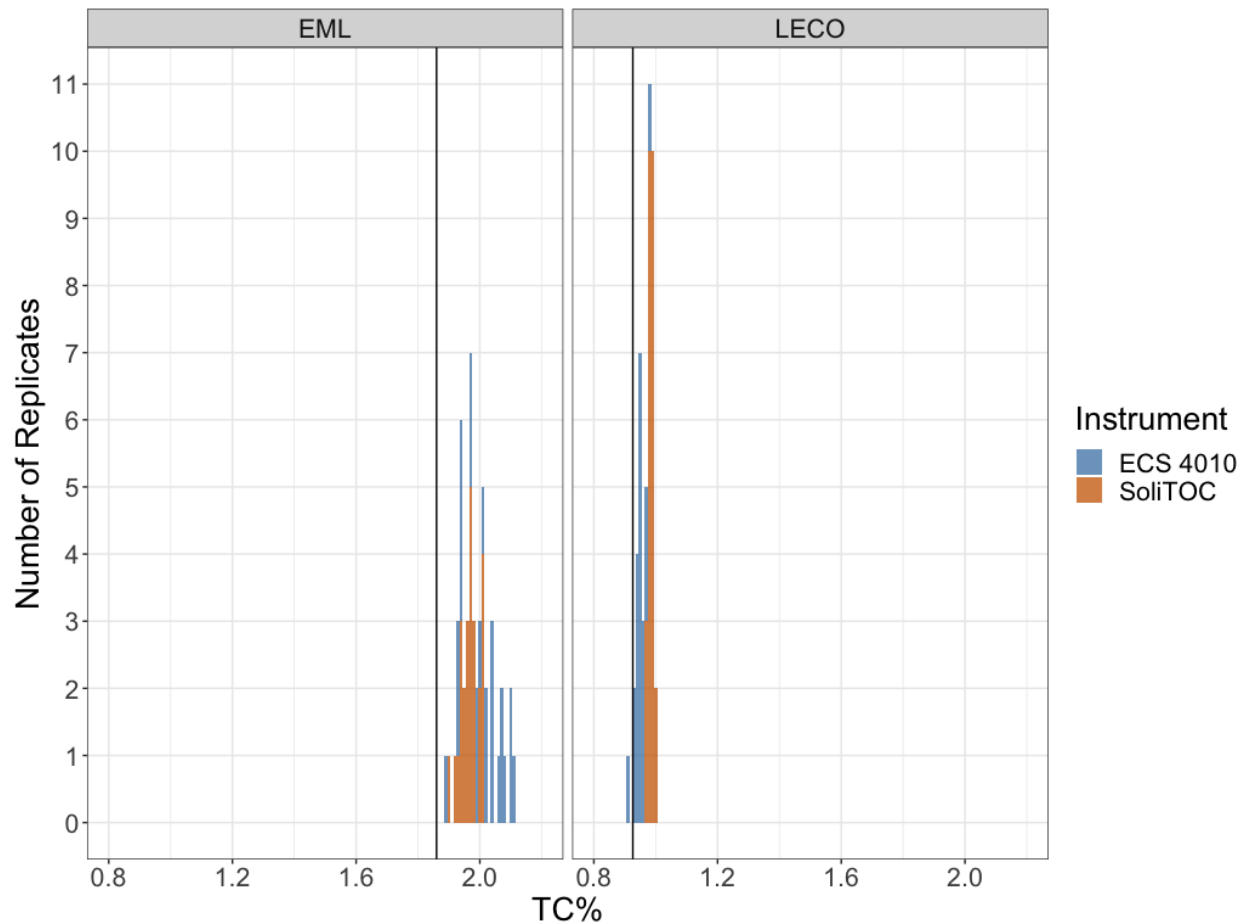


Figure S5. Variogram for topsoils (0-10cm) at the rangeland site, transect Mx.

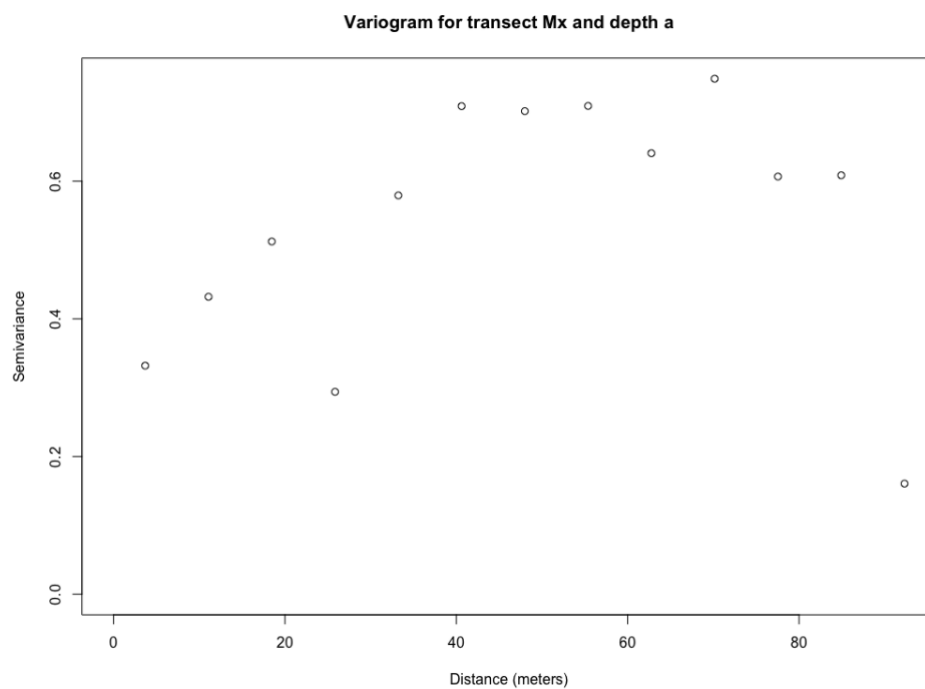


Figure S6. Variogram for topsoils (0-10cm) at the rangeland site, transect My.

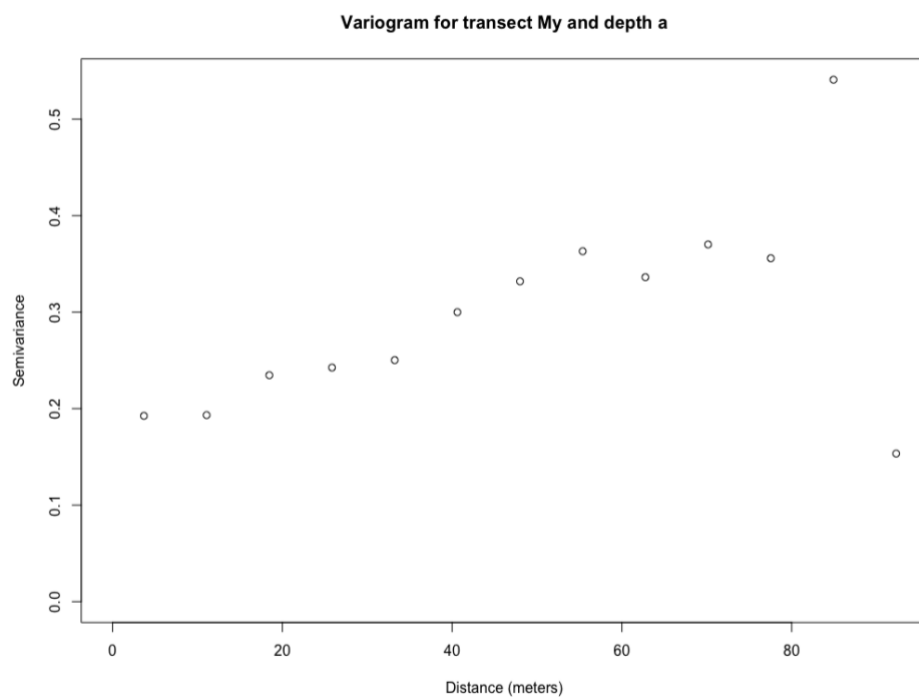


Figure S7. Variogram for topsoils (0-10cm) at the rangeland site, transect Bx.

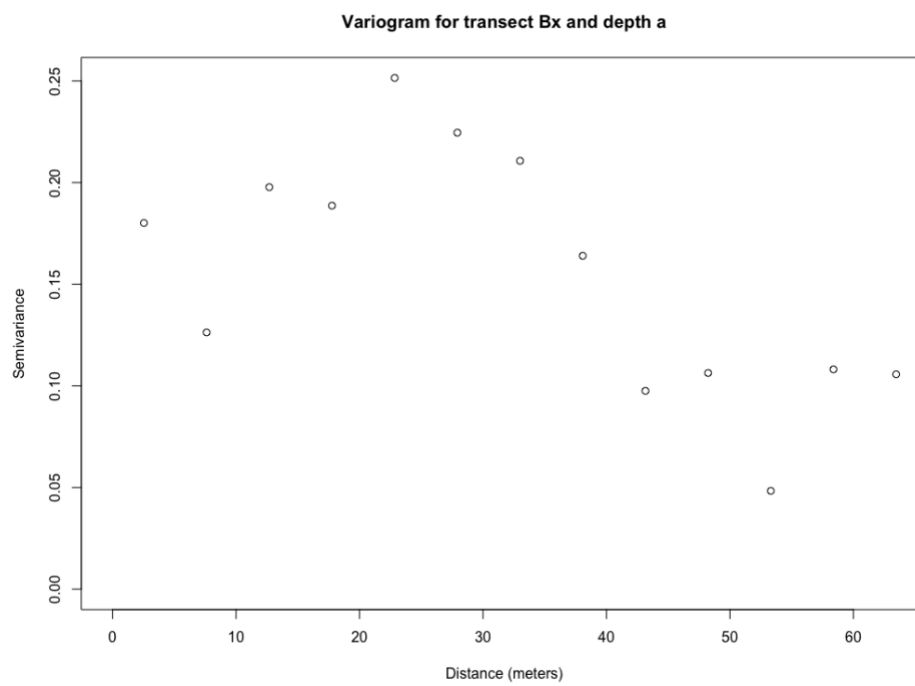


Figure S8. Variogram for topsoils (0-10cm) at the rangeland site, transect By.

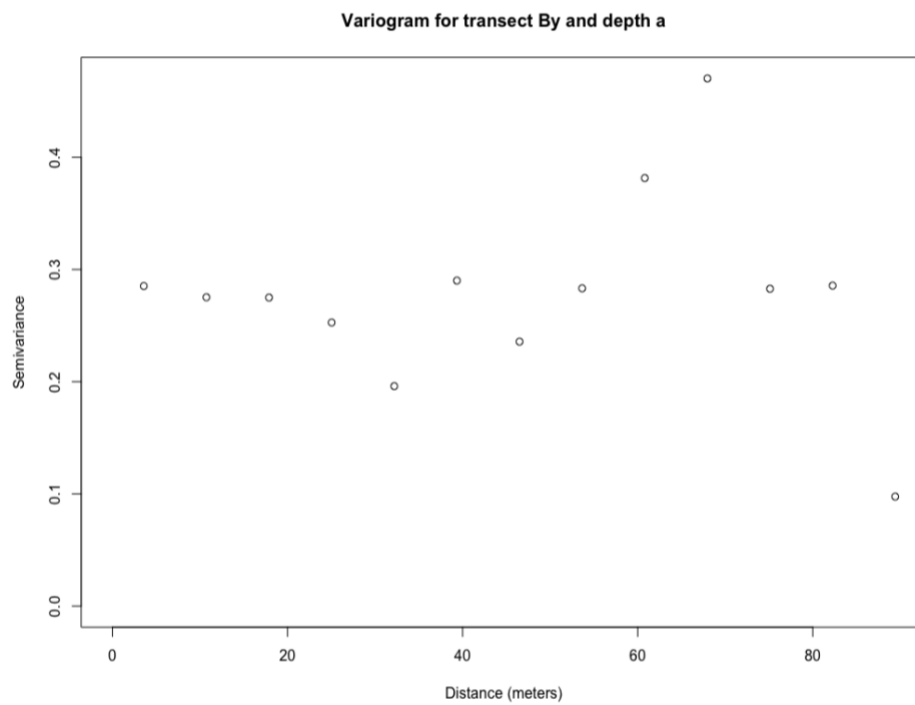


Figure S9. Variogram for topsoils (0-10cm) at the rangeland site, transect T.

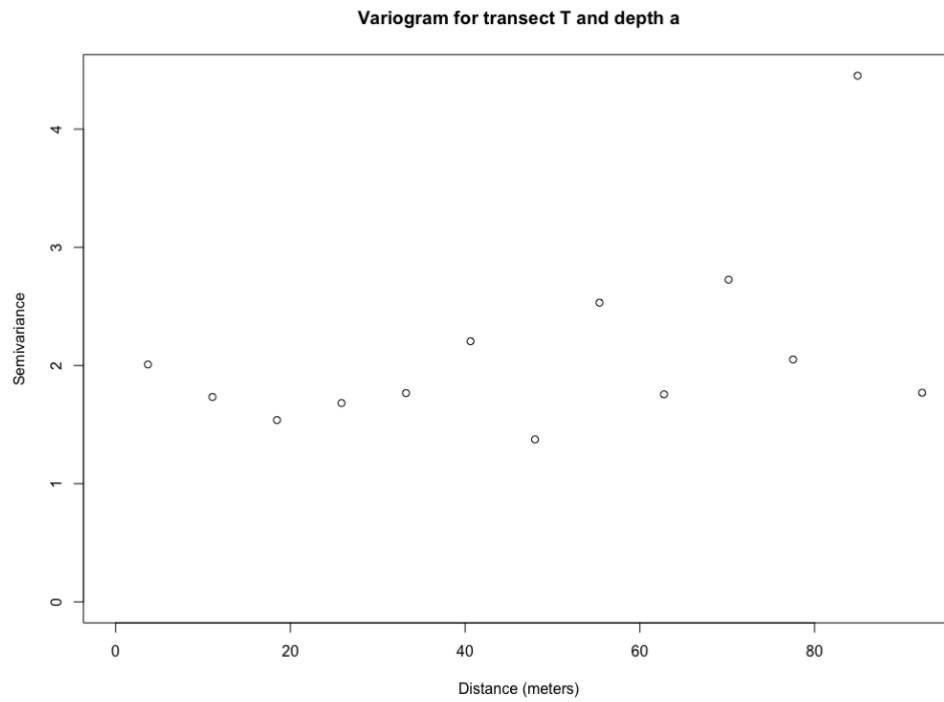
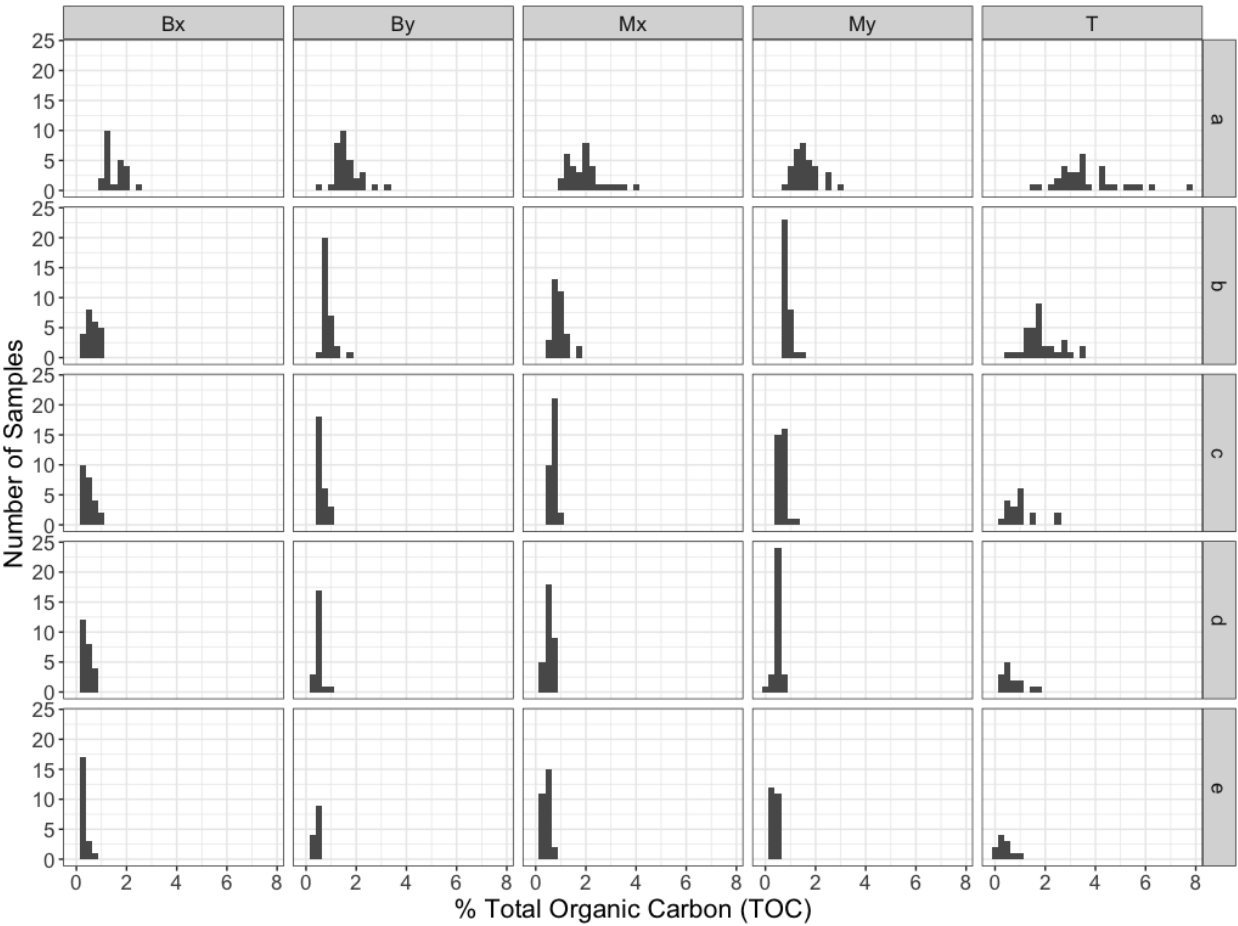
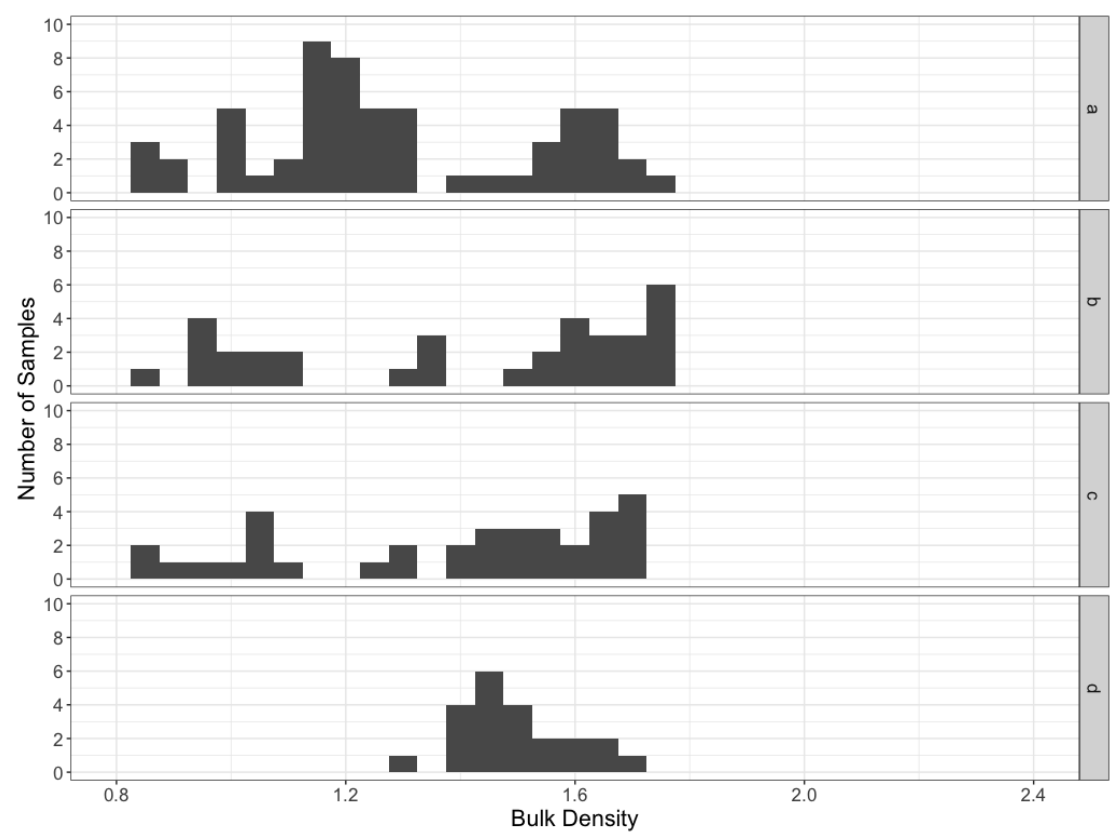


Figure S10. Histogram of TOC% across depths and transects of the rangeland soils



SI Figure 11. Averaged bulk density across cropland sites 1-6.



S5. Tables

Table S1. Rangeland and cropland soil taxonomy

	Soil Series	n	Texture	Cropping System	Series Extent	Taxonomy
RANGE	Auberry	785	Fine Sandy Loam	Rangeland	280,772	Fine-loamy, mixed, semiactive, thermic Ultic Haploxeralfs
CROP1	San Benito	60	Clay Loam	DFS	156953	Fine-loamy, mixed, superactive, thermic Calcic Pachic Haploxerolls
CROP2	Arnold	60	Loamy Sand	Vineyard	96440	Mixed, thermic Typic Xeropsamments
CROP3	Malibu	45	Loam	Orchard	8184	Fine, vermiculitic, thermic Typic Palexerolls
CROP4	Sorrento	60	Sandy Loam	Cropland	115250	Fine-loamy, mixed, superactive, thermic Calcic Haploxerolls
CROP5	Lokern	120	Clay	Cropland	46171	Fine, smectitic, nonacid, thermic Vertic Torrifluvents
CROP6	Elder	30	Sandy Loam	DFS	57185	Coarse-loamy, mixed, superactive, thermic Cumulic Haploxerolls
CROP7	Wasco	80	Sandy Loam	Orchard	156735	Coarse-loamy, mixed, superactive, nonacid, thermic Typic Torriorthents

Table S2. Rangeland total carbon (TC) stocks.

Depth	Stock w/ mean BD (Mg/ha)	Standard Error w/ mean BD ^a	Stock w/ max BD	Stock w/ min BD
A (0-10 cm)	30.3	1.2	35.2	24.9
B (10-30 cm)	31.6	1.4	35.1	27.6
C (30-50 cm)	22.5 ^b	0.9	24.0	21.1
D (50-75 cm)	25.9	1.3	28.8	22.3
E (75-100 cm)	30.4	2.0	32.1	28.3
Whole Profile	141.7	6.7	155.0	124.2

^a Standard error does not reflect bulk density or assay variability (only %TC)

Table S3. Cropland TC stocks

Site	Stock w/ mean BD (Mg/ha)	Standard Error w/ mean BD	Stock w/ max BD	Stock w/ min BD
CROP1	111.3	11.2	118.5	103.4
CROP2	61.4	7.3	64.2	58.1
CROP3 ^a	230.0	18.2	249.8	206.2
CROP6	38.9	44.6	44.6	33.2
CROP7	32.6	35.3	35.3	29.6

^aWe did not have bulk density data for sites CROP4 and CROP5

Chapter 2

Prospects for grazing management to AMP up soil carbon on California rangelands

2.1. Abstract

Despite a lack of research, grazing management is thought to be an ineffective soil organic carbon (SOC) sequestration strategy on rangelands. Semi-arid rangelands in California account for the majority of the state's total land mass, and have lost a significant amount of SOC due to annual grass invasion and historical overgrazing and cultivation. Adaptive multi-paddock (AMP) grazing is a grazing management strategy gaining popular attention because of the large SOC changes measured in temperate and sub-humid grasslands, but little work has been done to understand its efficacy on marginal and semi-arid rangelands, which account for the majority of grazing lands globally. Research has been hampered by the lack of long-term experiments and the highly adaptive nature of AMP grazing, necessitating on-ranch studies. To understand the potential impact of AMP grazing compared to conventional, low-rotational or continuous (CONV) grazing on semi-arid California rangeland SOC stocks, we collected 1440 soil samples at four paired AMP/CONV sites across northern California. We measured differences in bulk SOC down to 100cm, SOC stabilization in four soil organic matter fractions (dissolved [DOM], free [fPOM] and occluded [oPOM] particulate, and mineral associated [MAOM] organic matter) in surface soils (0-10cm and 10-30cm), and plant community composition at each paired site. Three of the four AMP grazed ranches contained significantly greater SOC stocks in surface soils (0-10cm), and two contained greater SOC stocks down to 100cm. The vast majority of these SOC differences between AMP and CONV ranches were in the MAOM fraction, which is the most persistent form of SOC, with implications for climate change mitigation. Plant community composition varied by site – some AMP grazed ranches had greater composition of perennial vs annual grasses and overall less bare ground, but these findings were not universal. This study is the first look into grazing management, and particularly AMP grazing, on SOC outcomes in California rangelands. Our findings suggest that AMP grazing may be a viable SOC sequestration strategy on semi-arid rangelands, though further research is needed to assess site specific constraints and driving mechanisms.

2.2. Introduction

Improved grazing management to sequester soil organic carbon (SOC) on grass and rangelands as a “natural climate solution” has sparked a long standing and ongoing debate (Garnett et al., 2017). Proponents cite improved grazing management as a promising strategy to restore the ~75 Pg of SOC lost from millions of acres of native grazing lands in the last two centuries (Sanderman et al., 2017), which could simultaneously improve productivity and aid in climate change mitigation (Conant et al., 2017). Nearly 40% of grazing lands are characterized as semi-arid rangelands, which are non-equilibrium environments often limited by moisture (Rangelands ATLAS, 2021). However, it is not well understood if grazing management is a viable SOC sequestration strategy on semi-arid rangelands given constraints to SOC accumulation in these systems, including large spatio-temporal variability, scalability, and limited annual plant growth (Booker et al., 2013). Core to this debate are

extremely sparse and conflicting study results on the impact of grazing management on SOC in semi-arid rangelands, and the inappropriate extrapolation of SOC responses from less arid grasslands.

Semi-arid rangelands are particularly prevalent in California, USA, where they make up 62% of the total land area (Saitone, 2003). Like rangelands globally, California rangelands have lost a large quantity of SOC: some estimate SOC losses of 40 Mg C/ha in the top 50cm of rangeland soils, driven mainly by invasion of exotic annual grasses that replaced deeper-rooted perennial grasses and forbs (Burcham, 1957; Koteen et al., 2011). Settler-colonial practices of dividing and fencing large tracts of rangelands into smaller privately owned ranches, replacing native ungulates with domesticated cattle, and overgrazing, may have also contributed to SOC losses on California rangelands (Bailey, 2008; Stromberg et al., 2007).

Grazing management often ranks highly as an opportunity to restore lost SOC on grazing lands generally (Herrero et al., 2016). However, many believe that grazing management is ineffective and/or unreliable at SOC sequestration on non-equilibrium rangelands (Briske et al., 2013), despite a lack of comprehensive on-the-ground research spanning the spectrum of grazing management strategies. On one extreme, continuous grazing is a simplified one-pasture system characterized by set animal stocking rates and no or low rotations among pastures (Briske et al., 2011). “Rotational” grazing refers to grazing systems encompassing a range of rotational intensities where animals are moved between pastures, and has historically been considered an improved form of grazing management over continuous grazing. At the other end of the grazing management spectrum, adaptive multi-paddock (AMP) grazing is among the most intensive forms of rotational grazing, where animals are moved frequently in moderate-high stock densities across lands divided into temporary paddocks. Each paddock is then rested for plant regrowth before being regrazed. Land managers adapt both stocking densities and paddock recovery periods according to seasonality, exogenous shocks and stressors (such as droughts), as well as to meet social and market needs. Compared to low-rotational and continuous grazing management, AMP grazing management is often targeted to soil health improvement and is meant to prevent overgrazing and maintain soil cover. Farmers and ranchers report observing benefits from AMP grazing, such as increased forage productivity, improved forage quality, and perennialization (Sayre, 2001). These benefits are often linked to increased SOC, which has been shown in studies of AMP grazing on temperate and subtropical grasslands (Conant et al., 2003; Machmuller et al., 2015; Mosier et al., 2021; Stanley et al., 2018; Teague et al., 2011). However, to our knowledge, there has been only one study of AMP grazing on semi-arid rangelands in the U.S., which did not measure soil outcomes, but showed no improvement in forage quality or quantity compared to continuous grazing (Augustine et al., 2020). To resolve this debate, the efficacy of AMP grazing to sequester SOC and improve ecosystem health needs to be explored in non-equilibrium, semi-arid rangeland environments (Byrnes et al., 2017), especially in light of some non peer-reviewed evidence suggesting increased perennialization in California under AMP grazing (Henneman et al., 2014; Strohm & Watt, 2019) and higher drought tolerance arising from similar grazing management principles (Woodmansee et al., 2021).

Grazing management can increase SOC in several ways. First, grazing management can increase C inputs by: preventing overuse or overgrazing (the ratio of biomass removal: biomass remaining after a grazing event), which increases above and/or belowground NPP (Derner et al., 2006; Li et al., 2012; McNaughton, 1979); incorporating pasture rest can shift plant community composition toward perennials (Milchunas & Lauenroth, 1993; Piñeiro et al., 2010), which temporally extends above ground NPP and increases root-C inputs (Bai et al., 2012; Derner et al., 2006; Yang et al., 2019); and using short-duration grazing intervals with pasture rest periods, which sometimes increases NPP and

C-rich root exudates (Chen et al., 2015; Dong et al., 2015; Li et al., 2012; Sanderman et al., 2015). Second, changes in grazing management can also reduce the amount of C lost from soil, such as when preventing overgrazing and subsequent bare ground reduce SOC losses by erosion (Piñeiro et al., 2010). Finally, grazing can also affect internal C cycling processes that determine the partitioning of C flows inside the rangeland ecosystem and the stabilization of C in soil. For example, carefully timed grazing can change the quality of plant inputs to soil (Bai et al., 2012; He et al., 2020; McSherry & Ritchie, 2013; Zhou et al., 2017); e.g by decreasing C:N ratios), better distribute animals' manure (Semmartin & Oesterheld, 2001), or stimulate production of mycorrhizal hyphae (Medina-Roldán et al., 2008), which can increase microbial carbon use efficiency (CUE) and lead to relatively higher SOC formation (Piñeiro et al., 2010).

There are several ways AMP grazing specifically could drive SOC sequestration compared to CONV grazing on semi-arid rangelands. For example, AMP grazing could increase SOC inputs and prevent SOC losses by combining fast animal rotations with pasture rest, potentially reducing bare ground and soil erosion and increasing plant litter inputs to soils. AMP ranchers report managing their herds adaptively to target perennial grass establishment and growth (i.e., constructing paddocks around areas of high perennial growth and deferring grazing until after perennial grasses have set seed; *Stanley, unpublished data*), which could also increase SOC inputs. This could be especially important in California, where a study estimated that invasion of annual grasses has reduced SOC by 40 Mg/ha in the top 50cm of rangeland soils (Koteen et al., 2011). It is generally accepted that this has been exacerbated by heavy continuous grazing (Burcham, 1957; Dlamini et al., 2016). However, management strategies to re-establish perennial grass dominance on California rangelands remain notoriously elusive, and studies have shown promising but highly variable perennial response following improved grazing (Bartolome et al., 2004; Carey et al., 2020; Davy et al., 2017; Heady, 1961; Henneman et al., 2014; Stahlheber & D'Antonio, 2013). Lastly, AMP grazing could also drive SOC sequestration by shifting internal soil C cycling processes. For example, concentrating animals together in higher stock densities could more uniformly deposit manure, alleviating N limitations and shifting C:N ratios of soil inputs (Piñeiro et al., 2010). Incorporating analyses of plant community composition changes, bare ground, and soil N alongside SOC measurements is necessary to improve our mechanistic understanding of AMP grazing induced SOC change.

The lack of studies on grazing management and SOC in general is likely, in part, because studies of “rotational” grazing have shown mixed results in semi-arid rangelands (Briske et al., 2008; Briske et al., 2011). Studies of rotational grazing are often complicated by experimental designs that confound stocking rates and densities, small sample numbers, and small experimental blocks sampled over short timescales that have low ability to capture ranch-scale SOC change (Roche et al., 2015). Further, “rotational” grazing is ill-defined and highly variable in practice, ranging from seasonal movement between two-pastures all the way up to multiple movements per day. These limitations have prevented a generalized understanding of the true potential of grazing management to sequester SOC (Briske et al., 2008).

AMP grazing presents additional experimental challenges that have stymied research efforts on rangeland landscapes, despite reported benefits from ranchers. Core to these challenges is the “adaptive” nature of AMP grazing, which is untenable to tightly controlled and replicated experiments. Additionally, we currently lack data on ranchers' application of AMP grazing, including how and when ranchers make rotation decisions, how long to rest between each grazing event, how they change stocking densities to meet their grazing goals, and even how these factors differ among AMP ranchers. Combined with this lack of information on parameters of AMP grazing, researchers are not subject

to the same drivers, constraints, and decision making processes as ranchers, making experimental application of this type of grazing management less meaningful. Together, these challenges highlight the importance of on-ranch, rather than experimental, research to understand the impacts of AMP grazing management on SOC in working semi-arid rangelands (Cheney, 2017).

Driving these research demands is the increasingly urgent need to utilize semi-arid grazing lands to sequester SOC as a climate change mitigation strategy. However, different pools of SOC have varying degrees of persistence — which ultimately confers climate change mitigation potential. Soil C fractionation methods separate SOC in bulk soils into functionally distinct pools, which can provide “more information about the mechanisms driving SOC accrual, its persistence, and vulnerability to disturbance and management practices,” (Mosier et al., 2021). For example, SOC that has been microbially processed can sorb to soil mineral surfaces and form mineral associated organic matter (MAOM), which is thought to be very persistent in soils (Kleber et al., 2007). On the other hand, SOC contained in partially decomposed plant matter, called particulate organic matter (POM), is a more transient soil C pool (Lavalley et al., 2020). Occlusion in soil aggregates is a moderate form of stabilization, which is often measured as a function of soil health broadly (Del Galdo et al., 2003; Haddix et al., 2020). Changes in these distinct pools of SOC can be masked by measuring only bulk SOC — but separating and quantifying SOC stocks in each pool can help to increase the power of detecting SOC changes due to grazing management. This is especially important in rangeland systems where SOC can be extremely heterogeneous, which makes it difficult to detect small SOC changes (Chapter 1). Fractionating SOC into these functionally distinct pools can therefore improve change detection and provide a more useful and thorough understanding of the impact of AMP grazing on SOC.

This study helps to, in part, fill several of these research gaps related to the viability of AMP grazing to sequester SOC, and potentially help meet climate change goals, on rangelands. We conducted an on-ranch study at four paired sites across northern California to ask three main questions: 1) Does AMP grazing increase SOC storage relative to CONV grazing on semi-arid California rangelands? 2) How do differences in four soil organic matter pools (dissolved (DOM), free (fPOM) and occluded (oPOM) particulate, and mineral associated (MAOM) organic matter) help explain changes in SOC persistence under AMP grazing?, and 3) How do plant communities shift in response to AMP grazing, and do these shifts help explain SOC changes? This study is a first step toward answering these questions and improving our understanding of the impact of AMP grazing on semi-arid rangelands.

2.3. Methods

2.3.1. Study Sites

Paired, adjacent AMP/CONV ranches were selected via an iterative snowball networking and screening process from 2018-2020. Networking was initiated with contacts to a key Holistic Management² training center in Northern California. Fifteen ranchers who had completed holistic

² Holistic Management refers to a broader decision making framework attributed to Allan Savory that integrates goal setting, decision making, and financial planning into grazing management. Holistic planned grazing, which we refer to here as adaptive multi-paddock grazing, is the on-the-ground grazing management practice associated with, but distinct from, Holistic Management.

management (or similar, e.g., Ranching for Profit) training and claimed to practice AMP grazing responded to an email solicitation, and initial phone interviews were completed with 12 of those ranchers. We narrowed the qualifying criteria for AMP grazing by focusing on specific management aspects, which were developed in combination with two AMP ranchers outside of the study population. Ultimately five AMP/CONV ranch pairs were chosen based on adherence to the following control and management criteria:

1. Control criteria
 - a. Grazes beef cattle on rangeland in California
 - b. Manages a portion of ranch acreage with grazing only and no other management interventions (no irrigation, compost, other soil amendments, seeding, etc)
 - c. Shares an adjacent fence line with a neighboring “conventionally” grazed ranch (defined below), whose manager/owner was a willing participant (**Figure 1**)
2. Management criteria
 - a. Rancher claimed to make grazing rotation decisions adaptively rather than according to a set regime. This helped to distinguish AMP grazing from other high-intensity but non-adaptive forms of grazing management
 - b. Has completed AMP, Holistic Planned Grazing, or similar grazing management training
 - c. Uses a grazing plan (either formally (e.g., PastureMap/Gaia), or informally)
 - d. Subdivides land into smaller paddocks throughout the grazing season (>10 paddocks)
 - e. Incorporates targeted pasture rest
 - f. Uses monitoring (formally (e.g., Point Blue Conservation Science, NRCS) or informally (e.g., using visual indicators)) outcomes (e.g., forage recovery, ocular vegetation cover, residual dry matter, SOC) to drive adaptive management decisions on temporal rotations and recovery lengths
 - g. Has been using this management for 3 or more grazing seasons

We decided *not* to set stocking density, pasture rest, and rotation thresholds both because these do not appear in HM trainings and because the application of AMP-HM grazing is highly variable and changes seasonally on California rangelands. Rather, we focused on ranchers’ self-reported, intentional use of animal movement, pasture rest, higher than average regional stock densities, and adaptability to reach their management goals. Eight AMP ranches met the finalized criteria, but three were excluded because CONV neighbors could not be identified within close enough vicinity. We consulted local extension agents, natural resource advisors, experienced rangeland ecologists and existing grazing management literature (Bush, 2006) in California to inform our understanding of CONV grazing management. We ultimately defined CONV grazing broadly as the suite of traditional grazing practices common to California, including year-round continuous grazing and low-rotational systems (i.e., rotation among 5 or fewer pastures) (Huntsinger et al., 2007; Roche et al., 2015). We chose to prioritize proximity of AMP/CONV neighbors rather than maximize the number of pairs to ensure that differences in soil outcomes could be reasonably attributed to differences in management and not differences in other inherent soil properties. Ranch pairs are described in **SI Table 1**.

Five AMP/CONV ranch pairs were chosen based on these criteria. We were unable to collect enough soil samples at one site due to high rock content. Sampling was conducted April-July 2020 on the four remaining paired sites in three distinct ecoregions of Northern California: Central Coast Rangeland, Northern Coast Rangeland and Sierra Nevada Foothills (**Figure 2**).

2.3.2. Soil sampling

Sampling locations on each ranch were determined by initial pasture walks with ranchers, where we could identify pastures in each ranch pair with the same soil type (based on U.S. NRCS soil survey data; Soil Survey Staff, 2022), slope aspect, ecological site descriptions, and that met our other control and management criteria. We determined sample sizes based on a preliminary power analysis using spatial heterogeneity information from prior samples collected on a nearby coastal rangeland site. Samples were collected using a stratified transect design with three 50m transects constructed along each adjacent ranch pair, stratified by slope position: summit/shoulder, backslope, and footslope (3 transect per ranch * 2 ranch/pair * 4 pairs = 24 total transects). Soils were sampled down to 1m and divided into 4 depth ranges (a: 0-10cm, b: 10-30cm, c: 30-50cm, d: 50-100cm). Based on our power analysis, we attempted 25 samples along each transect for the 0-10 and 10-30cm depths, and 5 per transect down to 100cm. In all, we attempted to collect 1200 topsoil samples (a and b depths) and 240 deep soil samples (c and d depths) for a total of 1440 individual soil samples. Cores were collected down to 100cm *or* to the point of refusal (either due to bedrock or rock obstruction). Ultimately, we analyzed 1424 individual soil samples: 6 samples could not be collected due to rocks, and 10 were either damaged or lost.

Samples were collected with hand-augers of known volume and separated by depth. All samples were transported back to the Berkeley Agroecology Lab at the University of California, Berkeley, air dried, and stored in air-tight bags until processing. Samples were then sieved to <2mm, finely ground on ball-mill (Retsch, Newtown, PA), and stored for analysis.

2.3.3. Bulk density and equivalent soil mass

We collected bulk density data at our first sampling site (HH) using a modified core method. We collected three topsoil BD samples at each transect: two 0-30 cm samples at each end (at the 0 and 50m marks) and one 100cm sample in the center (25m mark). We drove a specially manufactured steel cylinder into the soil at each location with a 30lb sledgehammer, and extracted the cylinder with a Hi-jack car lift. Partial pits were dug to allow us to extract the cylinder at deeper depths. Due to the high-clay content of these samples, we were unable to reach below 80cm. We assumed our measured BD at 50-80cm was consistent from 80-100cm.

At each of the three other sites, we used the equivalent soil mass method (Haden et al., 2020; Wendt & Hauser, 2013), rather than traditional bulk density sampling, to compare SOC stocks on the basis of equivalent soil mass. Briefly, rather than collecting separate samples for TC% and BD, we collected each sample with a bucket auger of known volume. The total soil collected at each depth increment within a single soil core (0-10, 10-30, 30-50, and 50-100cm) was weighed in-field. Then a subsample was collected from each depth increment and weighed field-wet. Subsamples were transported back to the lab, air-dried, and then reweighed. Soil water content was calculated based on the difference between wet and dry weight of the subsamples, which was then used to extrapolate the dry weight of the whole depth increment. “Apparent” BD was calculated for each sample using the dry soil mass and volume, and used as input for ESM calculations.

2.3.4. Vegetation survey

To measure the impact of AMP vs CONV grazing on plant community composition, we collected line-point intercept data following the method of (Herrick et al., 2005). Briefly, we made a “controlled drop” of a pin flag in 0.5m intervals along each 50m transect. We recorded the first species intercepting the top of the pin flag (i.e. “top-hit”). If the pin did not intercept a live plant, we recorded the hit of the pin flag at the soil surface (i.e., either bare ground or plant litter). In total, we recorded 300 vegetation intercepts per ranch and 2,400 overall.

Vegetation surveys also generally include categories of woody biomass such as trees and shrubs. This is especially important in California rangelands, which are often interspersed with oak trees. However, our transects were designed to be the basis of both plant community composition and soil sample collection. Because trees are known to heavily influence SOC stocks and heterogeneity, we stratified and placed transects outside of areas of high tree density at our sites. This means that our data only represent the impact of grazing management on the “grassy” portions of California rangelands. We attempted to identify the species of every intercept, although some plants were too immature to identify at the species level. We opted to categorize our line-point intercept data into common functional groups of interest in California rangelands: perennial grasses and forbs, annual grasses and forbs, litter, and bare ground.

We calculated the percentage cover of each functional group as:

$$\text{Percent cover, functional group } A = \left(\frac{\# \text{ hits functional group } A}{\text{total \# of points}} \right) \times 100$$

2.3.5. Lab analysis

2.3.5.1. Bulk SOC%

We analyzed samples for TC% and N% on an Elementar soliTOC cube (Elementar, Ronkonkoma, NY), a relatively new instrument designed to improve measurement precision by combusting higher sample masses (up to 3g of soil vs ~50 mg) and separating total organic C (TOC), residual organic C (ROC), and total inorganic C (TIC) via a temperature ramping method, DIN19539 (Natali et al., 2020). Our prior work showed this instrument to have lower error than more traditional dry combustion instruments (Chapter 1). This negated the need to extract inorganic C prior to combustion. Topsoil samples were analyzed at 300mg and deep soil samples were analyzed at 500mg. Unfortunately, we were unable to obtain reliable TN% measurements on soliTOC.

2.3.5.2. Size and density fractions: mass and TC%/N% (DOM, fPOM, oPOM, MAOM)

Topsoils (0-10 and 10-30cm depths) were composited in groups of five along each transect for fractionation analysis (i.e. cores 1-5, 6-10, etc were composited by depth). This resulted in a total of 240 composite samples for fractionation (5 samples per transect * 2 depths * 24 transects). Soils were fractionated by size and density into four functionally distinct pools: dissolved organic matter (DOM), free particulate organic matter (fPOM), occluded particulate organic matter (oPOM), and minerally associated organic matter (MAOM).

We fractionated following the (Haddix et al., 2020) protocol, but modified for our high-clay samples at one site. This method separates POM before and after aggregate dispersion into “free” and “occluded” POM versus other common methods which separate POM after aggregate dispersion into

“light” and “heavy” fractions. We chose this method because it provides information on how grazing management may be forming or disrupting soil aggregates, which may offer short-term OM protection.

Briefly, we added 40mL of DI H₂O to oven-dried samples (previously 2mm sieved and composited) and shook on low on an oscillating shaker for 15 mins. We then centrifuged at 3400rpm for 15 mins, which yielded the DOM fraction as supernatant. We poured off the DOM through a filtration unit with a 20 µm nylon filter. Everything captured on top of the filter was added to the fPOM fraction, while all supernatant filtered through the filter was kept as DOM. DOM was analyzed for TC% and N% on an Elementar varioTOC (Elementar, Ronkonkoma, NY).

We filled the centrifuge tube containing the remaining pellet (mixed fPOM, oPOM and MAOM) with 1.85g cm³ sodium polytungstate (SPT), vortexed, and centrifuged for 30 mins at 3400rpm. We then aspirated the fPOM and SPT mixture through a filtration unit with a 20 µm nylon filter. The fPOM was then rinsed 3x to remove all SPT. The remaining pellet with oPOM and MAOM was then rinsed of any remaining SPT three times by centrifuging with DI H₂O. For heavy clay soils (>60% clay) at site 1, the protocol was modified to include three more rinses and a series of dispersants and flocculants to thoroughly remove SPT.

We dispersed aggregates in the remaining soil (oPOM + MAOM) by shaking on a reciprocal shaker with sodium hexametaphosphate and glass beads for 18h. After shaking, the fractions were separated into oPOM (>53 µm) and MAOM (<53µm) by wet sieving.

All fractions were mass recovered to within +/- 5% of the original soil mass. Samples over or under-recovered were refractionated until within this threshold. The fPOM, oPOM and MAOM fractions were oven-dried at 60°C, ground, and analyzed on an Elementar varioEL for TC/TN% (Elementar, Ronkonkoma, NY). TC% on all composited samples was recovered to an average of 102% of original bulk TC%.

There was no significant inorganic C detected in our bulk soil samples on the solⁱTOC. Because varioEL only reports TC% for our fractionated soils, we report fraction and bulk soils on the basis of TC%, which is equivalent to TOC for the purposes of SOC stock calculations.

2.3.5.3. Texture

Surface soils (0-10 and 10-30cm) were analyzed for texture following a rapid pipette method (Soil Survey Laboratory Methods Manual, 1992). Briefly, 5g of soil was shaken overnight on a reciprocal shaker with 40mL of 0.5% sodium hexametaphosphate. Sand and clay fractions were pipetted at time intervals determined by the temperature and particle sizes. Each fraction was oven dried at 105°C and weighed. Percent sand and clay were determined based on Stoke’s Law, which was used to quantify soil texture.

2.3.6. Soil data analysis

We calculated ESM-based SOC stocks using the (Haden et al., 2020) method. In addition to “apparent” BD, ESM calculations require four things to ultimately determine cumulative SOC stock on the basis of equivalent mineral soil mass: 1) a choice of reference soil, 2) depth increments, 3)

SOC%, and 4) SOM%. The CONV grazed ranch within each ranch pair was chosen as the reference soil mass because all AMP ranches were historically CONV grazed. We estimated SOM retroactively using Van Bemmelen's factor of 0.58 g SOC/g SOM (McBratney & Minasny, 2010) and the measured TOC% for each sample. We used the Haden et al. (2020) example R-code, which uses a cubic-spline interpolation function to calculate cumulative SOC stocks (g C/cm²) on the basis of equivalent, cumulative mineral soil mass for each soil core at each site.

We analyzed the impact of grazing management (AMP vs CONV) on cumulative SOC stocks and bulk TC% using general linear models separately for each site. Site, grazing management, and their interaction were treated as fixed effects. We compared models with additional fixed effects for clay and transect. The effect of transect was not significant and so was not included in the final model. We chose to exclude clay as a covariate in our model for two reasons: 1) Site as a random intercept accounted for much of the variability associated with clay, and 2) the high clay vertisol site (Site 1, >61% clay) drove a mild negative overall correlation between clay and SOC, which is contrary to the positive correlations at every other site and to known relationships between clay and SOC. In our exploratory models including clay as a covariate, it was not a significant predictor of cumulative SOC stocks.

We calculated the TC stocks in each of our four fractions using our ESM adjusted BD output for the 0-10 and 10-30cm depths. Because composite samples were fractionated but ESM-BD was calculated for the original, individual samples, the ESM-BDs associated with each of the five samples of the composite fractionated sample were averaged. We analyzed the impact of grazing management (AMP vs CONV) on the SOC and N stocks and C:N ratios of each fraction using the same linear model structure used for bulk TC stocks.

2.4. Results

2.4.1. Texture and site characteristics

Site characteristics, including time under management, acreage, and general management characteristics are reported in **Table 1**. Results from our texture analysis largely parallel SSURGO soil maps at each site. Ranches within pairs all categorized as the same textural class: soils at three ranch pairs were within 3% clay of their ranch neighbors, and Site 1 ranch pair soils were within 9%. Soils categorized as clay, loam, loam/sandy loam, and loam/sandy loam/silt loam at Sites 1, 2, 3 and 4, respectively (**SI Table 2**). This establishes that soils were similarly textured with each ranch pair and that any differences in SOC are unlikely due to textural differences.

2.4.2. Bulk SOC stocks

Bulk SOC stocks varied across Northern California, ranging from a low of 71.6 Mg C/ha at Site 2 to a high of 199.2 at Site 3 (**Table 2**). Average whole-profile SOC stock (0-100cm) across all sites was 121.7 Mg C/ha. Soil organic carbon stocks, separated by depth, are plotted in **Figure 3**.

Linear model results show that, considered together, AMP grazed ranches contained significantly greater SOC stocks in the top 0-50cm of soil compared to CONV grazed ranches. There was no clear difference in SOC stock between grazing management types below 50cm (**Table 3**). Ranch pair

location and the interaction of site and grazing management were significant factors for cumulative SOC stocks at all depths in our model. This indicates that generally, differences in SOC stocks across sites were larger than differences between grazing management regimes within each pair, and the effect of AMP grazing differed across sites (**Table 3**).

There was a statistically clear positive effect of AMP grazing on SOC stocks at two of the four sites. At sites 2 and 4, the AMP grazed ranch in each pair had significantly greater cumulative SOC stocks at all depths down to 100cm (**Table 3**). On average, there was 25% (20.9 Mg C/ha) and 38% (37.9 Mg C/ha) more cumulative SOC down to 100cm on AMP versus CONV ranches at sites 2 and 4.

The effects of AMP grazing on SOC stocks were more variable and less clear at sites 1 and 3. At site 1, there were no significant differences in cumulative SOC stock at any depth between AMP and CONV grazed ranches. At site 3, SOC tended to be higher on the AMP grazed ranch in the surface (0-10cm; $p = 0.10$), but the CONV grazed ranch had greater cumulative SOC stocks at-depth (**Table 3**).

2.4.3. Bulk soil TC% and bulk density

Bulk TC% varied from site to site. Site 3 had the highest average TC% (3.78%), and Site 1 had the lowest (1.65%) (**Table 2**). TC% declined with depth at all sites. Adaptive multi-paddock grazed ranches had clearly greater TC% in the 0-10cm ($p=2.06E-14$) and 10-30cm ($p=8.45E-09$) depths compared to CONV ranches, but differences in TC% at depths lower than 30cm were less clear (**Table 3**).

Bulk TC% trends generally followed SOC stocks, indicating that differences in SOC stocks between grazing management pairs were due to differences in SOC content and not changes in BD. Sites 2 and 4 showed clear differences in TC% down to 30cm (**Table 3**). Compared to their CONV neighbors, AMP grazed ranches had 24% greater TC% in the 0-10cm depth at both sites, and 30% and 34% greater TC% in the 10-30cm depth at sites 2 and 4, respectively (**Table 2**). Similar to SOC stock results, the differences in TC% between AMP and CONV grazed ranches were more variable at sites 1 and 3. There was no clear difference in TC% between AMP/CONV ranches at site 1. At site 3, the AMP grazed ranch had higher TC% in the surface ($p=0.04$), but less at-depth ($p=6.04E-05$) than the CONV grazed neighboring ranch.

We report fixed-depth (FD) bulk density as a standalone metric to gain understanding of how grazing management impacts soil density. Equivalent mineral soil mass was used to quantify and compare SOC stocks at each site. Fixed-depth bulk density was different across sites and grazing management pairs at each site (**Table 3**). Bulk density on the AMP grazed ranch at site 1 was variable across depths: the AMP grazed ranch had higher BD in 0-10cm soils ($p=1.09E-07$) and 30-50cm soils ($p < 2.2E-16$), but lower BD in the 50-100cm soils ($p=1.55E-04$) compared to the CONV grazed neighboring ranch. At sites 2 and 4, AMP grazed ranches had significantly lower BD in the 0-30cm soils, but there were not statistically clear impacts at depths lower than 30cm. This corresponded to 23% and 10% average lower BD in the 0-10cm depth and a 5% and 9% average lower BD in the 10-30cm depth at sites 2 and 4, respectively (**Table 2**). At site 3, the AMP grazed ranch had lower BD than the CONV grazed neighboring ranch in the surface 0-10cm, but higher BD at lower depths (**Table 3**). We report both ESM and BD bulk densities in **Table 2**.

2.4.4. Soil organic matter fractions: C stocks

The MAOM fraction was by far the largest reservoir of SOC at all sites, containing an average of 77% of total SOC stocks (0-30cm). The oPOM and fPOM fractions contained an average of 15% and 7.5% of total SOC stocks, respectively. The DOM fraction contained very little SOC, averaging only 0.00000002% of SOC stock across sites (**Table 4, Figure 4**).

With the exception of DOM, site and the interaction of site and grazing management were significant factors for soil organic matter fraction-C stocks in our model, indicating that fraction-C stocks at each site were both different from one another and differently impacted by AMP grazing management.

There was an overall positive response in MAOM-C stock on AMP grazed ranches compared to CONV grazed ranches in both 0-10cm ($p=0.02$) and 10-30cm ($p=4.22E-04$) depths (**Table 5**). At three of the four sites, AMP ranches had higher MAOM-C stocks. However, the effect of AMP grazing on MAOM-C stocks was only statistically clear at sites 2 and 4: AMP grazed ranches at both sites had significantly greater MAOM-C stocks in the 0-10 (site 2, $p=3.52E-04$; site 4, $p=0.03$) and 10-30cm (site 2, $p=4.89E-05$, site 4, $p=1.62E-03$) depths (**Table 5**). At site 1, MAOM-C at the AMP grazed ranch tended to be greater in 10-30cm depth ($p=0.10$), but there was no clear difference among AMP and CONV grazed ranch in the surface. There were no clear differences in MAOM-C stocks between AMP and CONV grazing at site 3.

There was a general positive response in oPOM-C stocks on AMP grazed vs CONV grazed ranches in surface soils ($p=0.02$). At three of the four sites, AMP ranches contained greater oPOM-C stocks in both depths, but this difference was only significant at site 2 (0-10 cm, $p=0.01$). At site 1, the CONV ranch had clearly higher oPOM-C stocks (**Table 5**).

Trends in fPOM-C stocks varied by site. AMP ranches at three of the four sites showed slightly elevated fPOM-C stocks compared to their CONV neighbors, but the difference was only statistically clear at site 4 (0-10 cm, $p=0.0004$; 10-30 cm, $p=0.006$). At site 4, fPOM-C stock at the AMP ranch was 13 times greater than the fPOM stock at the neighboring CONV ranch in the surface soils. We observed the opposite trend at site 2, where the AMP grazed ranch had lower fPOM-C stocks in the surface compared to the CONV neighbor (0-10 cm, $p=0.01$) (**Table 5**).

There were no observable differences in DOM-C stock among pairs of grazing management neighbors at any site (**Table 5**).

2.4.5. Soil organic matter fractions: N stocks

Pools of soil N stocks were similarly distributed among soil organic matter fractions as C stocks. Across all sites, 76%, 12%, 13%, and 0.00000003% of total soil N stocks were contained in the MAOM, oPOM, fPOM and DOM fractions, respectively. Across sites, there was greater variability in each fractions' N stock than C stocks. For example, Site 3 had overall higher oPOM-N stock at 0-10cm than any other site, and site 4 contained much greater fPOM-N than any other site (**Figure 5**).

With the exception of DOM, ranch pair location and the interaction of site and grazing management were significant factors for soil organic matter fraction C stocks in our model, indicating that fraction-

N stocks at each site were both different from one another and differently impacted by AMP grazing management.

AMP ranches generally had greater MAOM-N stocks compared to their CONV grazed neighboring ranches in both 0-10cm ($p=0.03$) and 10-30cm depths ($p=0.004$; **Table 5**). The effect of AMP grazing on MAOM-N stock was statistically clear at site 2 in both 0-10cm ($p=6.89e-6$) and 10-30cm depths ($p=6.92e-8$). There were no clear differences in MAOM-N stock between AMP and CONV grazing at any other site.

oPOM-N stock was elevated in the 0-10cm soils of AMP grazed ranches ($p=0.007$), but the impact was not statistically clear at 10-30cm. At site 1, the CONV grazed ranch had significantly greater oPOM-N stocks in both depths (0-10cm, $p=0.002$; 10-30cm, $p=0.008$). oPOM-N stocks were greater on AMP grazed ranches at every other site, but this relationship was only statistically clear at sites 2 (0-10cm, $p=0.003$; 10-30cm, $p=0.05$) and 3 (0-10cm, 0.04). There were no clear differences in oPOM-N stock between AMP and CONV grazing at site 4 (**Table 6**).

The impacts of AMP grazing on fPOM-N stocks varied by site. At some sites, the AMP grazed ranch had greater fPOM-N stocks (i.e., site 2, 10-30cm and site 3), while the CONV grazed ranches had greater fPOM-N stocks at other sites (e.g., in the 10-30cm depth of site 1 and in the 0-10cm depth of site 2). The only statistically clear effect was observed at site 4, where the CONV grazed ranch had 104% and 109% more fPOM-N in the 0-10cm ($p=6.14e-5$) and 10-30cm ($p=1.45e-4$) depths, respectively than the AMP grazed neighbor (**Table 6, Figure 5**).

There were no clear differences in DOM-N stocks between AMP and CONV grazed ranches at any of the four sites.

2.4.6. Soil organic matter fractions: C:N ratios

Across all sites, C:N ratios were the lowest in the DOM fraction, followed by MAOM, oPOM and fPOM. DOM-C:N was variable across sites and ranged from a low of 2.8 at site 2 to 10.3 at site 4. The C:N ratio in MAOM ranged from 8.8 at site 1 to 12.6 at site 4. The fPOM fraction had the highest C:N ratio at all sites, ranging from 16.8 at site 3 to 33.3 at site 2. There were no consistent trends of C:N in each fraction with depth (**Table 7, Figure 6**).

The impact of AMP grazing on the C:N ratios of each fraction differed by site. Most statistically clear relationships were observed at sites 2 and 4, but the C:N trends were opposite. C:N ratios of MAOM and oPOM fractions were lower at the AMP grazed ranch compared to CONV at site 2, while C:N was greater in these fractions on the AMP grazed ranch at site 4 compared to the CONV neighboring ranch (**Table 8**).

At site 1, the AMP ranch had a significantly higher MAOM-C:N (0-10cm, $p=0.002$). DOM-C:N was generally lower on AMP ranches across three of the four sites, and this relationship was statistically clear at sites 3 and 4. There were no clear differences in fPOM-C:N between grazing management pairs at any site (**Table 8**).

2.4.7. Vegetation

Statistical analysis for vegetation data is not yet completed, and thus only summary statistics are presented. Vegetation community composition differences were more pronounced across sites than across grazing management differences within sites (**Figure 7**). Percent cover of perennial grasses varied widely across sites, ranging from 7.7% to 60.3% of total cover. Two sites were dominated by annual grasses and forbs (sites 2 and 4), while the other two were dominated by perennial grasses and forbs (sites 1 and 3). Most hits intercepted live plants, and where live plants were not observed, soils were generally covered by litter. Bare ground was rare and made up less than 3% of cover at all sites.

At two of the four sites, the AMP grazed ranches were associated with greater perennial vs annual plant cover (sites 2 and 3), more live plant cover, and less bare ground. We did not observe differences in vegetation community composition between AMP and CONV grazing at site 1. At site 4, a large stand of perennial grasses at one transect drove higher percent cover of perennial plants at the CONV ranch compared to the AMP grazed ranch (data not shown).

2.5. Discussion

Understanding the impacts of grazing management on rangeland vegetation and SOC sequestration is crucial to informing long-standing scientific debates and to optimizing rangeland management for multiple ecosystem outcomes, including climate change mitigation and biodiversity. Our study is the first of its kind to study the vegetation and SOC impacts of a promising grazing management strategy, AMP grazing, on semi-arid, non-equilibrium rangelands in California.

2.5.1. SOC and vegetation characteristics of California rangelands

Beyond our primary goal of examining the vegetation and SOC response to grazing management on rangelands, our large dataset and use of ESM methods add to the scientific understanding of California rangelands in general. The three coastal rangeland sites had greater SOC stocks (average cumulative 0-100cm: 134.9 Mg C/ha) than the valley site (average cumulative 0-100cm: 82.05 Mg C/ha) - both of which are in close agreement to previous literature for California rangelands (Carey et al., 2020; Silver et al., 2010). Coastal rangelands generally have a higher composition of perennial grasses and forbs than valley rangelands in California (Barry et al., 2020; J W Bartolome, 1987). We observed this trend at two of the coastal rangeland sites compared to the one valley site: coastal sites 1 and 3 were, on average, covered by 61% perennial grasses and forbs, while valley site 2 had only 12.5% perennial cover. Site 4 had noticeably lower perennial grass cover (28%) compared to the other coastal sites.

The small body of literature on rangeland SOC pools combined with varying fractionation methods complicates comparisons with our fractionation results. Additionally, many other studies only report fractionated SOC pools in 0-10cm soils, while we fractionated soils down to 30cm. However, our findings are relatively consistent with other studies where comparisons are possible. We found that the MAOM pool contained an average of 58% of total SOC down to 10cm across our sites, while other studies report ~60-70% in European grasslands (Cotrufo et al., 2019; Lugato et al., 2021), ~57% in Southeastern U.S. grasslands (Mosier et al., 2021), and 45-67% in similar California grasslands (Ryals et al., 2014). Compared to Ryals et al. (2014), soils in our study contained less SOC in oPOM (18% vs ~28%), though fractionation methods were slightly different.

2.5.2. Site-wise case studies comparing SOC on AMP vs CONV ranches

Our results show greater SOC stocks on some, but not all, AMP grazed ranches compared to CONV grazed ranches on semi-arid California rangelands, indicating that impacts of AMP grazing on SOC may be site specific. Out of four paired sites across northern California, three AMP grazed ranches had greater SOC in the surface soils (sites 2, 3, 4), and two AMP grazed ranches had greater whole-profile SOC stocks (sites 2 and 4) compared to their CONV grazed neighboring ranches. One site showed no clear differences (site 1). Given the nuances of each pair of AMP and CONV ranches, we consider each pair to be a case study in possible impacts of AMP grazing on working California rangelands.

Site 1 was the only ranch pair where we did not observe any differences in SOC stocks between AMP and CONV grazing management. Though generally SOC and clay are positively correlated, we suspect that the extremely high clay content (>65% clay) of the Vertisol soils at this site constrains management induced SOC accumulation. Despite the high clay content, 0-30cm SOC stocks at this site were among the lowest of all sites in this study. Prior studies of SOC changes on Vertisol soils have shown that SOC is responsive to major disturbances like tillage, but less intensive management changes to increase NPP and soil C inputs, such as residue management and crop rotations, often have no measurable SOC impact (Jha et al., 2020; Muñoz-Romero et al., 2017). This was additionally supported by our vegetation data at this site, which showed no observable differences in bare ground or plant community composition, suggesting that NPP inputs to soil were similar within the pair. Similarly, a study of the impacts of grazing intensity on SOC in semi-arid Australian rangelands showed no effect on their Vertisol soil site (Waters et al., 2017). In addition to the possible soil textural constraints to increasing SOC inputs, it is possible that the grazing intensity differences between AMP and CONV were not stark enough to create measurable differences in SOC at this site.

At sites 2 and 4, AMP grazed ranches had 25% (20.9 Mg C/ha) and 38% (37.9 Mg C/ha) greater whole-profile SOC stocks, respectively, indicating that effect sizes are similar at responsive sites. Though no study to our knowledge has directly measured the effect of grazing management on SOC on California rangelands (Byrnes et al., 2017), effects of this magnitude were unexpected, given results from other studies and factors moderating SOC accumulation on California rangelands. For example, a similar management-based study in the U.S. Southeast showed a 13% average increase in SOC stocks under AMP vs continuous grazing (Mosier et al., 2021), and a study of compost application on proximal California rangelands showed 18% and 9% increases in SOC stocks at valley and coastal sites, respectively (Ryals et al., 2014). Compared to these results, we expected SOC gains from AMP grazing management to be smaller, especially considering California's Mediterranean climate (e.g., limited rainfall), and dominance of non-native annual grasses, which have very short growing seasons compared to grasslands in other ecoregions (Booker et al., 2013).

Given this knowledge, it is unlikely that changes of this magnitude are wholly attributable to AMP grazing. These SOC changes from AMP grazing could be the result of increases in soil C inputs, decreases in soil C outputs, or changes in internal soil C cycling processes that more efficiently form and stabilize SOC. Previous studies in northern California estimate maximum NPP inputs at 2-5 Mg C/ha/yr, and in some cases only 10% of NPP-C is incorporated into soils (Li et al., 2012). This means that five years of AMP grazing could reasonably sequester ~2.5 Mg C/ha in surface soils. Even if AMP grazing cannot account for the total difference in SOC stocks at these sites, we speculate that a

portion of the observed differences is likely due to AMP grazing, especially in surface soils that change more rapidly. We expected to observe any SOC stock differences primarily in surface soils (0-30cm) because California rangelands are dominated by annual grasses whose rooting depths are concentrated in this zone (Gordon & Rice, 1992). Three of the four AMP grazed ranches in our study had greater SOC stocks in the 0-10cm depth, and none of the AMP ranches had lower SOC than the CONV grazed ranches in surface soils at any site.

Site 2 was a valley rangeland, where AMP grazing had only been established for less than 5 years. However, the AMP grazed ranch contained more perennial vs annual grass, and more overall living grass cover. This suggests that at this site, AMP grazing could have contributed to greater SOC stocks through shifting plant communities – potentially increasing belowground NPP from perennial roots – increasing soil cover by reducing overuse – which both increases NPP inputs and reduces SOC losses compared to bare soil. At site 3, the AMP grazed ranch contained 4.3% (2.1 Mg C/ha) greater SOC in the surface soil despite a history of tillage compared to the neighboring CONV ranch. Both sites 3 and 4 were coastal rangeland sites, where the AMP grazing practices had been established for 10-20 years. The AMP grazed ranches at these sites had less bare soil and greater percent cover by living plants than the CONV grazed ranches, and at site 3 the AMP grazed ranch also had a greater proportion of perennial grass cover than annuals compared to the neighboring CONV ranch. Thus, greater SOC in the AMP grazed ranches at these sites may have arisen out of more pasture rest and fast grazing rotations – potentially reducing SOC losses and increasing SOC inputs. At site 4, this may have resulted in greater SOC stocks under AMP grazing management even though cover of perennial grasses was greater on the CONV grazed ranch.

2.5.3. MAOM drives SOC sequestration from AMP grazing

We expected that fractionating and quantifying SOC from functionally distinct SOM pools would help us detect SOC changes from grazing management that may be masked by analyzing only bulk soils (Six et al., 2002). However, we only detected consistent differences in SOM pools at the same sites where there were clear changes in bulk SOC from AMP grazing (sites 2 and 4).

While fractionations did not uncover smaller, harder-to-detect SOC changes compared to our bulk SOC results, it did provide information about which SOC fractions were most different between AMP and CONV ranches. MAOM was consistently more responsive to AMP grazing than the other, more labile fractions: AMP grazed ranches had greater MAOM-C stocks by 26% (25.8 Mg C/ha) and 43% (42.9 Mg C/ha) in 0-30cm at sites 2 and 4, respectively. Differences in MAOM-C stocks were detected after less than five years of AMP grazing at site 2 and 10-20 years at site 4, indicating SOC changes in this fraction can happen quickly and may continue for more than a decade in response to AMP grazing in California rangelands.

Particulate organic matter (POM) fractions, especially fPOM, are thought to be the youngest forms of SOC and most sensitive to management changes (Gregorich et al., 2006; Poeplau et al., 2018), but we did not find consistent differences in fPOM and oPOM in our study. Compared to MAOM, patterns of oPOM and fPOM-C stock differences between AMP and CONV grazing were inconsistent and generally small in magnitude, even when statistically significant. For example, the AMP grazed ranch at site 2 had statistically greater oPOM-C stock than the CONV grazed neighbor ranch, but the absolute difference was only 1.73 Mg/ha. Despite their small magnitudes, the fact that AMP grazed ranches contained greater oPOM and fPOM-C stocks at different sites (versus universally

greater MAOM-C stocks at responsive sites) suggests site-dependent SOC accumulation mechanisms. Another possibility is that POM and DOM fractions are in fact sensitive to management changes, but turnover rapidly and were not detected at our point-in-time sampling.

2.5.4. Hypothesized drivers of MAOM formation under AMP grazing

Though our point-in-time data cannot determine how AMP grazing drives MAOM formation, hypothesizing pathways of MAOM formation under AMP grazing may be useful considering that changes in MAOM constituted most of the bulk SOC differences in our study.

MAOM is thought to form via microbial transformation of SOM or from high-quality soil leachates (i.e., DOM, root exudates), which then sorb to soil mineral surfaces. On the other hand, POM generally forms from the partial decomposition of plant litter products, which either become briefly protected (on a timescale of months) in soil aggregates (oPOM) or remain free in the soil matrix (fPOM) (Cotrufo et al., 2013, 2015; Poeplau et al., 2018). Because AMP grazing management is tailored to prevent overuse and overgrazing, one straightforward mechanism that could drive SOC sequestration from AMP grazing is increased plant inputs to the soil. However, we detected the strongest and most consistent SOC increases in MAOM, which suggests that aboveground, structural plant litter inputs may not drive SOC changes from AMP grazing in California.

Current theoretical frameworks describe MAOM formation along two pathways: 1) an *in vivo* microbial turnover pathway, where high carbon use efficiency (CUE, i.e., low C:N ratio) soil inputs are preferentially and rapidly assimilated by microbes and sorbed to mineral surfaces, or, 2) a DOM-leachate direct sorption pathway, where C is leached from plant materials as DOM and directly sorbed to mineral surfaces, or a combination of both mechanisms, (Cotrufo et al., 2015; Lavallee et al., 2020; Robertson et al., 2019; Sokol, Sanderman, et al., 2019). Considering our vegetation and SOM results, we discuss two potential mechanisms by which AMP could drive MAOM formation along these theoretical pathways: 1) shifting plant communities to higher perennial cover, and 2) increased concentration and better distribution of manure.

Though not yet statistically validated, we found a greater percentage coverage of perennials on AMP grazed ranches at two sites (Sites 2 and 3), suggesting that shifting plant community composition may be a driver of MAOM formation. Vegetation is an important explanatory driver of SOC stocks on California rangelands (Carey, Weverka, et al., 2020), and shifting plant community composition from annual grasses to perennial grasses could increase MAOM formation along both theoretical pathways outlined above (Cotrufo et al., 2015; Robertson et al., 2019). We hypothesize that greater perennial root inputs increase MAOM formation primarily via the microbial turnover pathway. Perennial grasses and forbs, relative to annuals, allocate more of their biomass to below-ground roots (Brown et al., 1998; Walker et al., 2017). Root litter inputs and exudates are highly effective contributors of SOC sequestration via MAOM formation compared to above ground plant litter inputs because they have lower C:N ratios and are in close spatial proximity to soil microbes and mineral surfaces (Austin et al., 2017; Bird et al., 2008; Sokol, Kuebbing, et al., 2019). Even within the same plant functional group, previous studies have established that grazing management can change root biomass allocation, exudation, and chemistry (Derner et al., 2006; Gao et al., 2008; Johnson & Matchett, 2001; McNaughton et al., 1998; Pucheta et al., 2004; Wilson et al., 2018). Taken together, AMP grazing may change SOC by shifting plant communities towards perennials, which drive root-mediated MAOM formation. Our data provide some support for this as a potential strategy: at site 2, the AMP grazed ranch had greater perennial grass coverage, greater MAOM-C and MAOM-N stocks,

and lower C:N ratios than the neighboring CONV grazed ranch. Bulk SOC stocks were also greater throughout the whole 0-100cm soil profile, which is most likely explained by deeper penetrating perennial grass roots. However, further studies are needed to clearly determine whether AMP grazing mediates SOC changes via plant community composition shifts.

Increased perennial cover may also drive MAOM formation via the DOM-leachate direct sorption pathway. With this strategy, shifting plant community composition toward perennials could increase high quality (i.e. lower C:N) plant-derived soil inputs, which then leach nutrients as DOM and sorb to soil mineral surfaces, either directly or first by microbial transformation, to form MAOM (Cotrufo et al., 2015; Lavalley et al., 2020; Robertson et al., 2019; Sanderman et al., 2014). Notably, because of their different phenologies, annual grasses produce greater aboveground biomass more quickly than perennials (i.e. contribute greater seasonal plant litter), but then quickly senesce - when up to 77% of plant N is translocated to seeds (Eviner & Firestone, 2007). Because annual grasses grow only seasonally and form plant litter with high C:N, they support smaller microbial communities (Parker & Schimel, 2010) and lower carbon use efficiency (CUE). On the other hand, perennial grasses are slower growing, but retain more temporally consistent live plant tissues, which lowers litter C:N and supports greater microbial communities and CUE, which support greater MAOM formation (Cotrufo et al., 2015; Eviner & Firestone, 2007). This process - whereby perennial plants change both litter chemistry and temporal soil inputs - suggests that shifting plant community composition toward perennials could contribute to greater and more dynamic DOM pools, which are then efficiently processed by microbes and stabilized as MAOM (Cotrufo et al., 2015; Robertson et al., 2019).

Increased manure-derived DOM leachates could also drive MAOM formation from AMP grazing. Contrary to our results at site 2, we observed greater SOC in MAOM at the AMP grazed ranch at site 4 that was not associated with perennialization or greater N stocks. This suggests that MAOM formation at this site may be driven by other factors. We suspect that this could be explained via a manure-derived and DOM-mediated MAOM formation mechanism. In AMP grazed systems, animals are concentrated at higher stock densities and rotated quickly, which more evenly distributes manure across the soil surface in each paddock (Paine et al., 1999; Wang et al., 2021). Improved (i.e., less patchy) spatial distribution of manure could increase manure-derived DOM (Semmartin & Oesterheld, 2001), potentially increase microbial biomass and/or shift microbial communities, and result in greater MAOM-C formation and overall higher SOC stocks (Jagadamma et al., 2014). While manure-derived DOM may form MAOM directly (without microbial mediation), studies of manure application often show increased microbial biomass and elevated SOC (Conant et al., 2001). Though few studies have examined changes in SOM fraction pools from manure deposition, those that have suggest that manure aids in MAOM-C formation (Mikha et al., 2017). Lastly, DOM is able to deliver C to deep soil horizons, which may help explain the greater SOC stocks at-depth in the AMP grazed ranch at site 4, even in the absence of deep-rooted perennials (Kalbitz et al., 2005). This may be plausible given the higher coastal precipitation and coarser textured soils at this site, which may increase DOM-C movement throughout the soil profile (Rothstein et al., 2018).

Importantly, more research is needed to determine the pathways of MAOM formation under AMP grazing. Likely none of the mechanisms described above alone describe AMP-induced SOC change, nor are they mutually exclusive or universal. For example, at site 3, the AMP grazed ranch had greater perennial cover compared to the CONV grazed neighboring ranch, but this did not translate to greater whole-profile SOC stocks. It is also possible that reduced bare ground and increased living plant cover on AMP grazed ranches in this study (at sites 2, 3 and 4) could contribute to increased SOC stocks.

Whatever the mechanisms involved, MAOM seems to be driving SOC differences under AMP grazing at responsive sites across California rangelands.

2.5.5. Study limitations and future research

Necessitated by time constraints, we used a space-for-time study approach, which is a technique that attempts to extrapolate ecological trends (i.e., SOC change from AMP grazing) from sites of different treatment longevities (i.e., AMP ranches that were previously CONV grazed vs CONV grazed neighbors), rather than collecting measurements from the same site over time (i.e., measuring SOC on AMP ranches over five years) (Pickett, 1989). This is a common ecological approach because repeated temporal sampling is not always possible, is sometimes prohibitively expensive, or expected SOC changes occur too slowly to detect in the short-term.

However, concerns have been raised because space-for-time approaches rely on the assumption that differences in space are the result of ecological processes over time, rather than other drivers of spatial differences such as past management (Damgaard, 2019; Pickett, 1989). SOC is heavily influenced by past land management, soil texture, vegetative cover (i.e., the presence of trees), and other factors. We attempted to minimize the influence of these factors on spatial differences at our sites by establishing strict control criteria (i.e., no soil amendments or other management interventions), choosing sites that had not (to our knowledge) been previously tilled, that had all been historically CONV grazed prior to AMP grazing establishment, and shared the same soil type and ecological site description. However, despite our best efforts, it remains possible that other drivers not considered here could have attributed to SOC differences in ranch pairs.

It is generally accepted that space-for-time approaches are more reliable for detecting general trends than for inferring mechanisms, especially when results are consistent with prior research. The greater SOC stocks on AMP vs CONV grazed ranches in our study generally align with results of other studies of AMP grazing in other climates. We did not speculate on rates of SOC accrual from AMP grazing, which we believe requires repeated temporal sampling. In an attempt to explain differences in SOC between AMP and CONV ranches, we speculated on possible mechanisms and drivers of SOC accumulation from AMP grazing in our measured rangeland sites, but more research is needed to say for certain.

There are several other important limitations to this work. We sampled intensively at four sites concentrated in Northern California, which is not representative of all rangelands generally or in California. More work is needed on rangelands in other regions of California and the U.S. West. We stratified our sampling sites outside of areas of high tree density to minimize variability of SOC within ranch pairs. However, California rangelands are often oak-savannas, meaning we likely underestimated SOC stocks at sites with high tree density. We attempted but were unable to identify grazing exclosures at each site, which would have improved our understanding of baseline SOC stocks on rangelands. Our sampling density was informed by *a priori* power analysis using spatial heterogeneity information from a California rangeland site, but it is possible that our study was underpowered to detect small SOC changes at some sites.

This study was a first glance at the impacts of AMP grazing on SOC on California rangelands. Our results raise many more questions that we look to future research to answer.

2.6. Conclusions and implications

We collected 1440 soil samples from eight working ranches on four sites across northern California to assess differences in SOC with grazing management. To our knowledge, this is the largest and most comprehensive single assessment of SOC on California rangelands to-date. We incorporated many current methodological gold-standards: we used improved ESM methods to more reliably calculate SOC stocks compared to traditional BD methods, fractionated SOC into functionally distinct pools to assess SOC persistence, and incorporated deep soil sampling to more accurately capture SOC response to grazing at-depth.

Our data show differences in SOC stocks between AMP and CONV grazed ranches in California, suggesting that grazing management may be a viable opportunity for SOC sequestration on California rangelands. This creates an opportunity to re-evaluate conclusions about the efficacy of grazing management and SOC sequestration on rangelands, given the prior lack of on-the-ground research (Booker et al., 2013; Buckley Biggs & Huntsinger, 2021). While more research is needed to improve our understanding of when, where, how, and under what conditions AMP grazing influences SOC on rangelands, our results have several implications.

Our finding that the largest SOC differences were in the MAOM fraction on AMP grazed sites has important climate change mitigation implications. Compared to POM, MAOM is thought to be a more persistent pool of SOC because it is better protected from decomposition through association with soil minerals (Lavalley et al., 2020). This means that MAOM-C is less likely to re-enter the atmosphere under changing environmental conditions associated with climate change (though some studies have suggested that MAOM may be more dynamic than previously thought; (Jilling et al., 2018; Keiluweit et al., 2015). On the other hand, while MAOM has greater climate change mitigation power, it is also more likely to saturate than POM (Cotrufo et al., 2019). However, hypothetical MAOM saturation is unlikely to inhibit MAOM accumulation on California rangelands in the near future because of the large SOC deficit and relatively slow SOC accumulation rates associated with grazing management (Dynarski et al., 2020; Stewart et al., 2007; Viglizzo et al., 2019).

California has invested heavily in agricultural SOC sequestration to augment its GHG reduction goals. In the absence of grazing management and SOC research, California's flagship agricultural GHG reduction program, the Healthy Soils Program Incentives Program (HSPIP), has focused much of its funding on compost application projects (Petek, 2021). HSPIP only funds one practice related to grazing management: "prescribed grazing," defined by NRCS as "Managing the harvest of vegetation with grazing and/or browsing animals with the intent to achieve specific ecological, economic, and management objectives" (NRCS, 2017). In fact, since prescribed grazing became an HSP listed practice in 2018, it has only been approved for funding on five projects to date (CDFA, 2021). Given our new findings and the fact that prescribed grazing is not targeted to SOC outcomes, we see an opportunity for HSPIP to incorporate grazing management practices with promising SOC benefits such as AMP grazing. Grazing management such as AMP grazing may be a more accessible way for ranchers to engage in SOC sequestration, because it is likely cheaper than compost application and uses tools already available to them – their cattle.

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2.8. Figures

Figure 1. Example adjacent fenceline required for site selection and illustrative transect placement.



Figure 2. Approximate locations of the four paired adaptive multi-paddock and conventionally grazed ranches across Northern California.

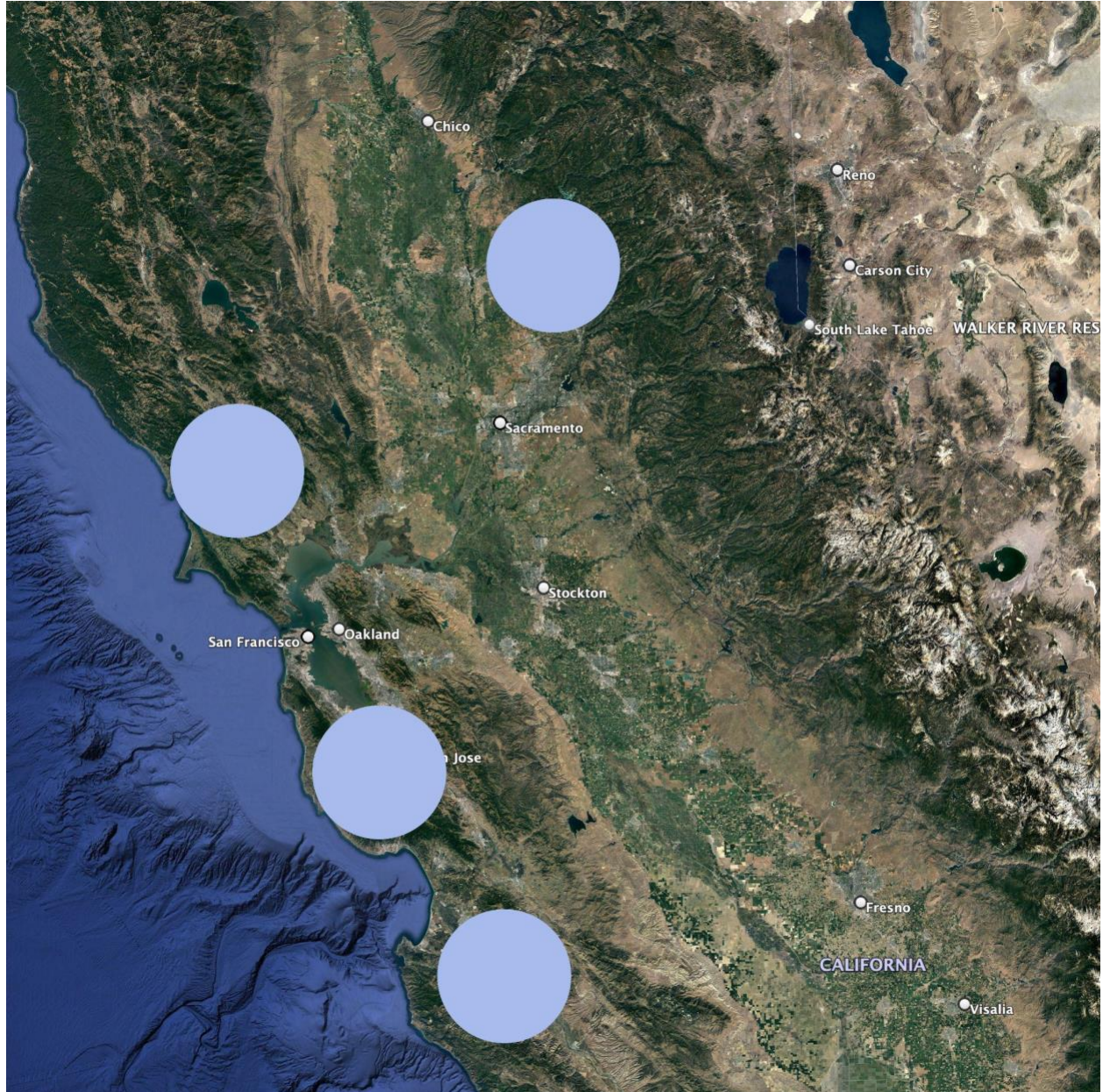


Figure 3. Bulk soil organic carbon stock (Mg C/ha) by site and depth. Note, these are SOC stocks separated by depth (reported in Table 1), but statistical comparisons were made on the basis of cumulative SOC stocks (Table 3).

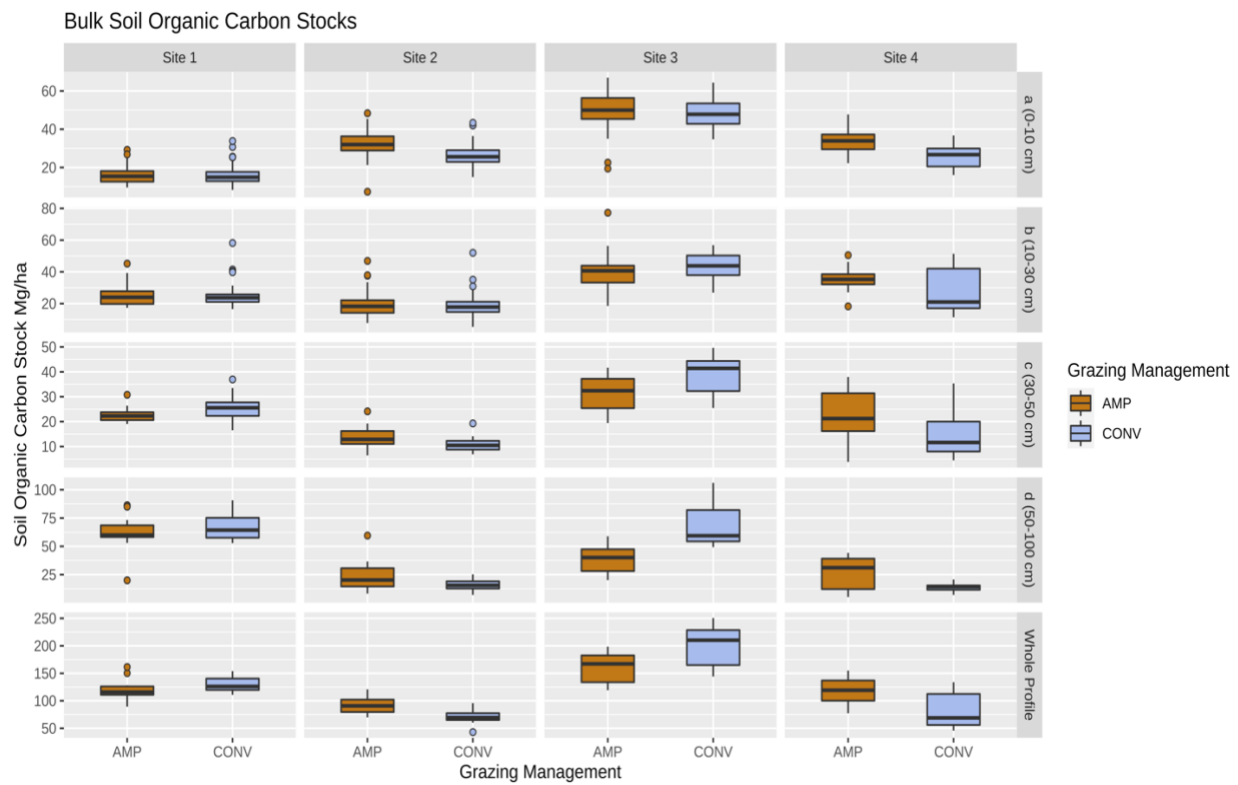


Figure 4. Soil organic carbon stocks (Mg C/ha) by site (sites 1-4), depth (a:0-10cm; b:10-30cm), and grazing management (adaptive multi-paddock (AMP) and conventional (CONV)) in each fraction: mineral associated organic matter (MAOM), occluded particulate organic matter (oPOM), free particulate organic matter (fPOM), and dissolved organic matter (DOM).

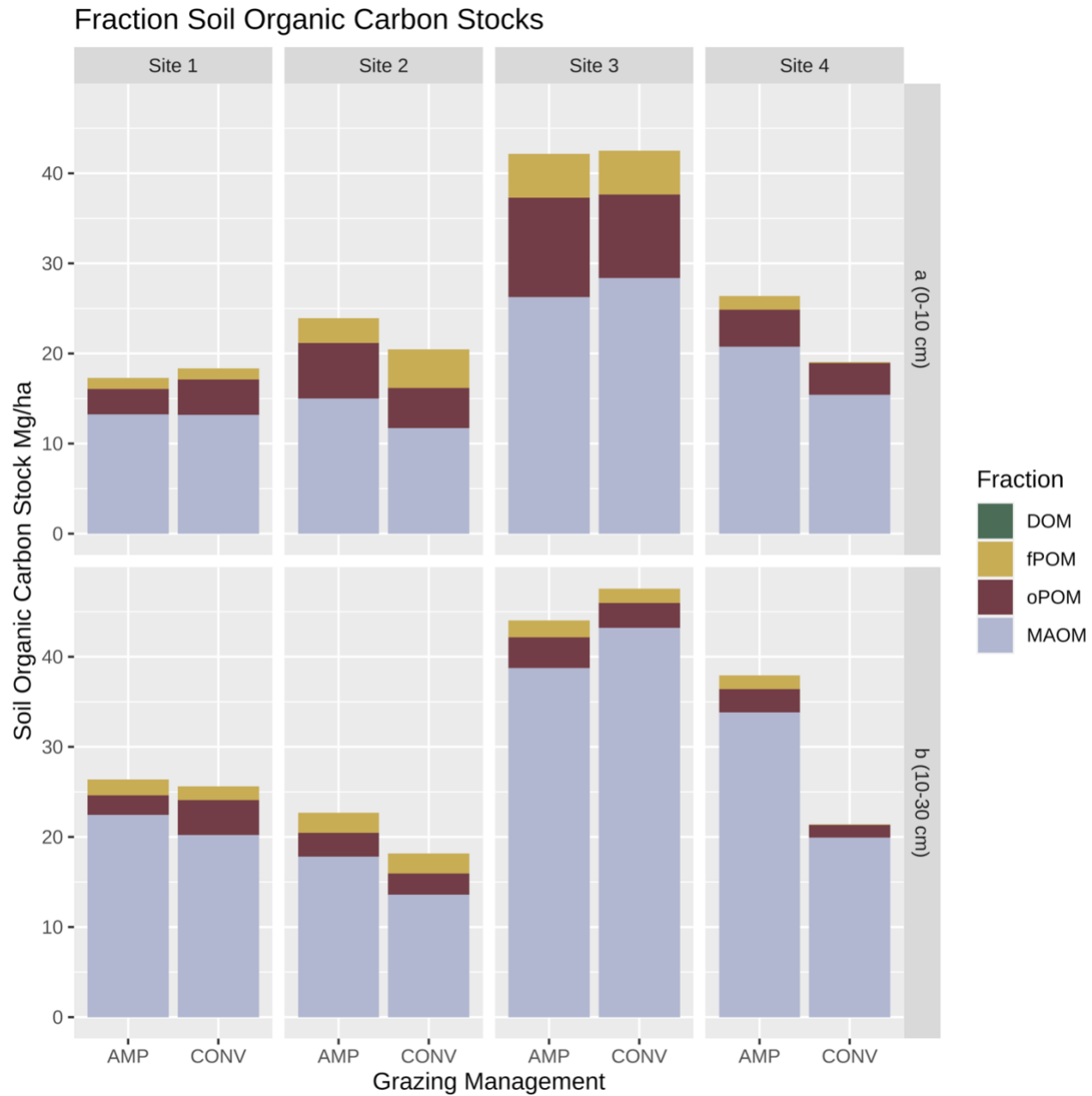


Figure 5. Soil nitrogen (N) stocks by site and depth in each fraction: mineral associated organic matter (MAOM), occluded particulate organic matter (oPOM), free particulate organic matter (fPOM), and dissolved organic matter (DOM).

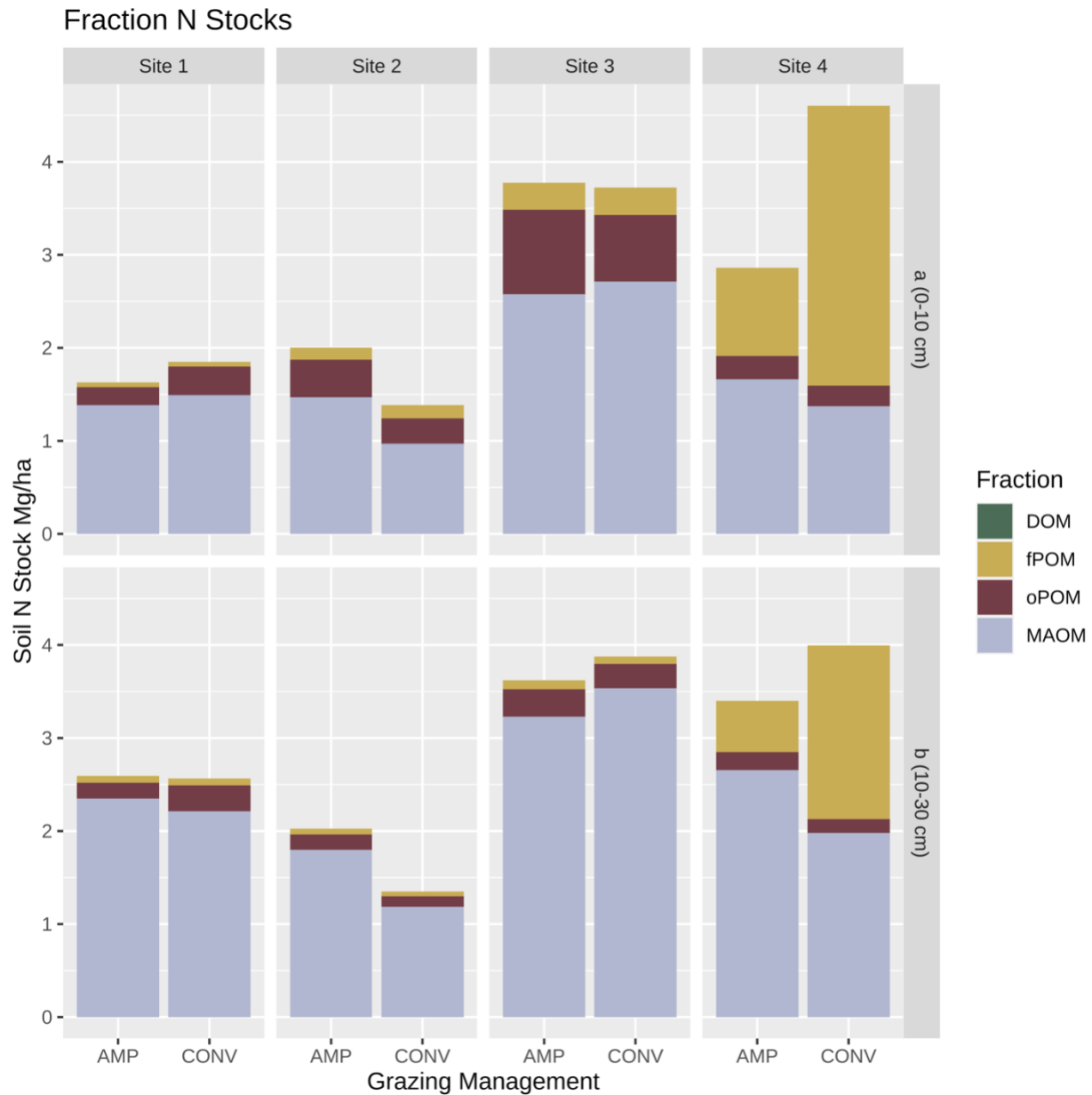


Figure 6. Carbon-to-nitrogen (C:N) ratios of each fraction by site and depth. Fractions are: mineral associated organic matter (MAOM), occluded particulate organic matter (oPOM), free particulate organic matter (fPOM), and dissolved organic matter (DOM)

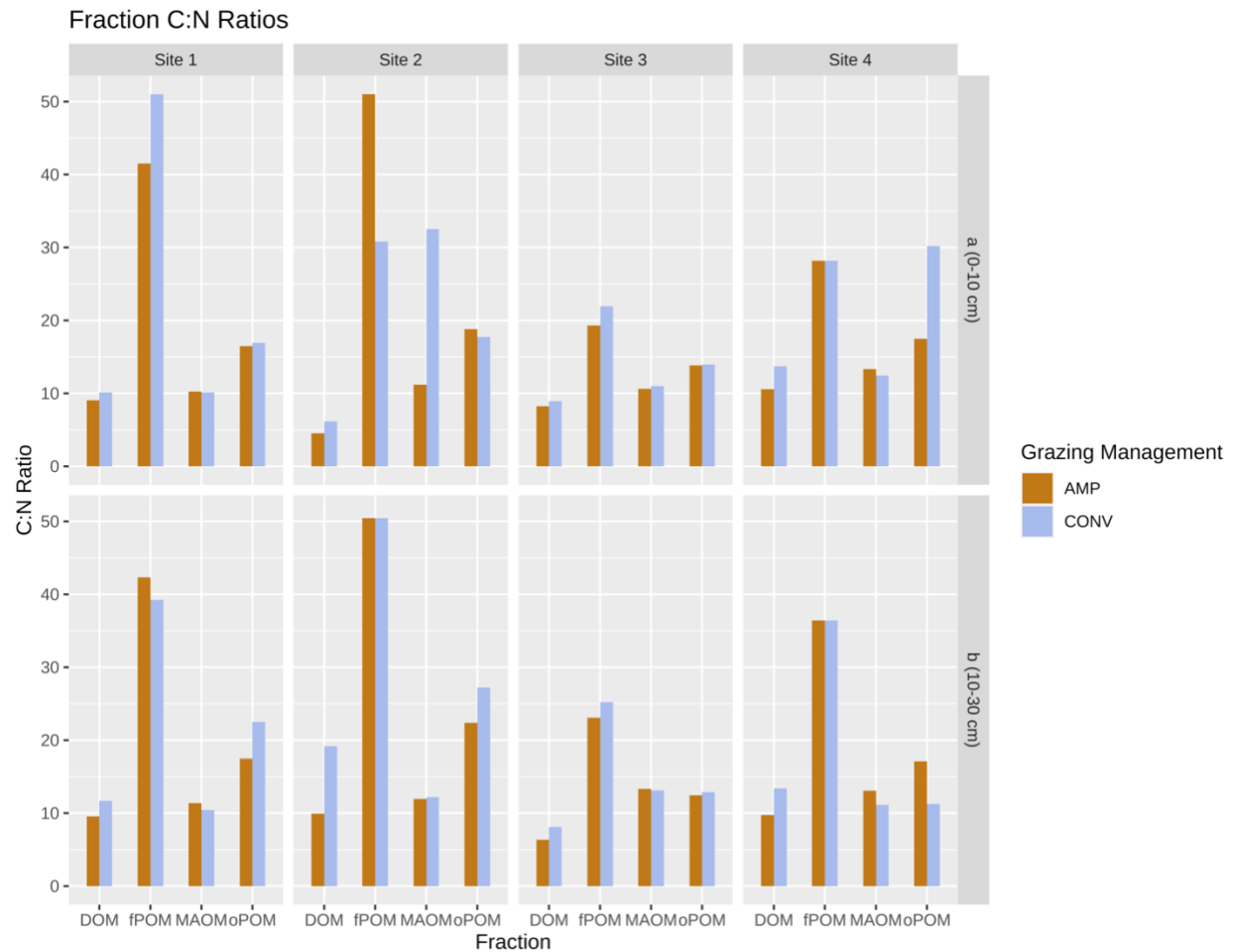


Figure 7. Comparative percent cover by vegetation functional group on conventionally (CONV) and adaptive multi-paddock (AMP) grazed ranches at four sites on Northern California rangelands.



2.9. Tables

Table 1. Grazing management characteristics of ranches across the four study sites. Quantitative characteristics were categorized representatively grouped to protect ranchers' anonymity. Max stocking density is reported for ranchers who were able to estimate their maximum grazing intensity during the growing season. Rotation schedule and rest duration are averages for each season reported by the ranchers. NR = not reported, NA = not applicable.

Site	Mgmt category	Acres	Cattle # and type	Length of mgmt	# temporary paddocks	Max stocking density	Rotation schedule (days)	Rest duration (days)
Site 1	AMP	>10,000	>2000 cow-calf + yearlings	>20 years	>100	NR	Spring: 1-1.5 Dry: <10	Spring: 45 Dry: 90
	CONV	100-300	<50 cow-calf	>20 years	NA	NA	NA	NA
Site 2	AMP	1,000-5,000	300-1000 birth-finish	0-5 years	>100	75 AU/ac for <1 day	Spring: 1-2 Dry: varies	Spring: 30-40 Dry: 60-70
	CONV	1,000-5,000	300-1000 cow-calf	>20 years	NA	NA	NA	NA
Site 3	AMP	1,000-5,000	300-1000 cow-calf + yearlings	10-20 years	>100	100 AU/ac for <1 day	Spring: <1-1 Dry: <30	Spring: 25 Dry: 180
	CONV	100-300	50-100 cow-calf	>20 years	NA	NA	NA	NA
Site 4	AMP	5,000-10,000	1000-2000 birth-finish	10-20 years	NA rotates with horses	10 AU/ac for 2 days	Spring: 2-5 Dry: <21	Spring: 30 Dry: 90
	CONV	100-300	<50 cow-calf	>20 years	NA	NA	NA	NA

Table 2. Mean bulk soil organic carbon (SOC) stock (Mg C/ha), total carbon (TC)%, equivalent soil mass bulk density (g/cm³), and fixed-depth bulk density (g/cm³) by site, grazing management, and depth. Standard deviations are reported in parentheses. Fixed-depth (FD) bulk density is reported as a standalone metric: equivalent mineral soil mass was used to calculate SOC stocks.

Bulk SOC Stock (Mg C/ha)								
	Site 1		Site 2		Site 3		Site 4	
Depth	AMP	CONV	AMP	CONV	AMP	CONV	AMP	CONV
a (0-10 cm)	15.8 (4.17)	15.9 (4.72)	32.4 (5.96)	26.6 (5.32)	50.4 (8.33)	48.3 (7.56)	33.3 (5.78)	25.4 (5.39)
b (20-30 cm)	24.6 (5.83)	24.5 (6.17)	19.2 (7.24)	18.7 (6.58)	39.9 (8.49)	44.0 (7.78)	35.5 (4.91)	26.8 (12.7)
c (30-50 cm)	22.5 (3.03)	25.2 (5.42)	13.6 (4.67)	11.0 (3.17)	31.5 (6.80)	38.7 (8.25)	22.6 (9.95)	15.0 (10.1)
d (50-100 cm)	61.9 (17.7)	66.9 (12.3)	23.6 (13.4)	15.9 (5.02)	39.2 (12.4)	68.2 (17.6)	25.7 (15.2)	13.7 (3.63)
Whole Profile	120.8 (20.1)	128.9 (14.7)	92.5 (15.9)	71.6 (13.7)	161.5 (28.2)	199.2 (36.1)	118.5 (24.4)	80.6 (30.8)
TC%								
	Site 1		Site 2		Site 3		Site 4	
Depth	AMP	CONV	AMP	CONV	AMP	CONV	AMP	CONV
a (0-10 cm)	1.65 (0.41)	1.68 (0.47)	2.34 (0.43)	1.83 (0.39)	3.78 (0.61)	3.53 (0.54)	2.37 (0.27)	1.86 (0.60)
b (20-30 cm)	1.09 (0.20)	1.13 (0.25)	1.06 (0.20)	0.78 (0.24)	1.93 (0.34)	1.99 (0.34)	1.53 (0.20)	1.09 (0.60)
c (30-50 cm)	0.89 (0.12)	0.98 (0.21)	0.59 (0.19)	0.45 (0.15)	1.36 (0.32)	1.66 (0.26)	0.96 (0.32)	0.64 (0.53)
d (50-100 cm)	0.68 (0.20)	0.74 (0.13)	0.32 (0.11)	0.24 (0.11)	0.56 (0.23)	0.99 (0.26)	0.45 (0.24)	0.21 (0.08)
Equivalent Soil Mass, Mineral Soil Bulk Density (g/cm ³)								
	Site 1		Site 2		Site 3		Site 4	
Depth	AMP	CONV	AMP	CONV	AMP	CONV	AMP	CONV
a (0-10 cm)	0.94 (0.04)	0.94 (0.04)	1.46 (0.07)	1.45 (0.06)	1.38 (0.04)	1.37 (0.04)	1.42 (0.19)	1.41 (0.17)
b (20-30 cm)	1.10 (0.11)	1.10 (0.10)	1.23 (0.04)	1.23 (0.04)	1.11 (0.01)	1.12 (0.01)	1.25 (0.09)	1.25 (0.08)
c (30-50 cm)	1.28 (0.01)	1.28 (0.01)	1.24 (0.06)	1.24 (0.06)	1.16 (0.01)	1.16 (0.01)	1.31 (0.19)	1.31 (0.18)
d (50-100 cm)	1.80 (0.01)	1.80 (0.004)	1.42 (0.28)	1.42 (0.28)	1.39 (0.04)	1.39 (0.04)	1.27 (0.10)	1.27 (0.10)
Fixed Depth Soil Bulk Density (g/cm ³)								
	Site 1		Site 2		Site 3		Site 4	
Depth	AMP	CONV	AMP	CONV	AMP	CONV	AMP	CONV
a (0-10 cm)	1.01 (0.10)	0.93 (0.09)	1.19 (0.16)	1.50 (0.17)	1.19 (0.17)	1.35 (0.14)	1.31 (0.16)	1.45 (0.19)
b (20-30 cm)	1.12 (0.10)	1.11 (0.13)	1.12 (0.14)	1.18 (0.21)	1.17 (0.11)	1.13 (0.08)	1.15 (0.09)	1.26 (0.15)
c (30-50 cm)	1.52 (NA)	1.28 (0.01)	1.25 (0.27)	1.24 (0.27)	1.28 (0.15)	1.16 (0.08)	1.21 (0.15)	1.31 (0.22)
d (50-100 cm)	1.66 (NA)	1.75 (0.08)	1.24 (0.25)	1.45 (0.29)	1.42 (0.11)	1.39 (0.09)	1.30 (0.12)	1.27 (0.15)

Table 3. Total soil organic carbon stocks, total carbon (TC%) concentration, and bulk density (BD) for bulk soils at 0-10, 10-30, 30-50 and 50-100cm depths. Fixed-depth (FD) bulk density is reported as a standalone metric: equivalent mineral soil mass was used to calculate SOC stocks. p-values reported for sitewise models were Bonferroni corrected.

	Cumulative Bulk SOC stock					Bulk TC%					FD BD				
	MSE	F value	Dg. Freedom	Pr(>F)		MSE	F value	Dg. Freedom	Pr(>F)		MSE	F value	Dg. Freedom	Pr(>F)	
a 0-10 cm	Grazing	2281.60	62.37	1	1.39E-14***	14.05	61.52	1	2.06E-14***		2.56	111.98	1	< 2.2E-16***	
	Site	28591.60	781.65	3	< 2.2E-16***	114.33	500.68	3	< 2.2E-16***		5.24	229.11	3	< 2.2E-17***	
	Grazing * Site	485.10	13.26	3	2.18E-08***	2.46	10.76	3	6.80E-07***		1.00	43.65	3	< 2.2E-18***	
	<i>Sitewise</i>	Site 1	Site 2	Site 3	Site 4	Site 1	Site 2	Site 3	Site 4		Site 1	Site 2	Site 3	Site 4	
	Effect of AMP	-0.13 (0.73)	5.74 (0.93)	2.13 (1.30)	7.91 (0.91)	-0.03 (0.07)	0.51 (0.07)	0.25 (0.10)	0.51 (0.08)		0.09 (0.02)	-0.31 (0.03)	-0.16 (0.03)	-0.14 (0.03)	
	Pr(>F)	0.86	5.48E-09	0.10	7.30E-15	0.69	1.71E-11	0.04	1.72E-09		1.09E-07	< 2.2E-16	3.24E-09	2.40E-06	
b 10-30 cm	Cumulative Bulk SOC stock					Bulk TC%					FD BD				
	MSE	F value	Dg. Freedom	Pr(>F)		MSE	F value	Dg. Freedom	Pr(>F)		MSE	F value	Dg. Freedom	Pr(>F)	
	Grazing	216.30	29.31	1	8.97E-08***	3.51	34.15	1	8.45E-09***		0.12	7.12	1	0.01**	
	Site	14529.90	560.37	3	< 2.2E-16***	30.98	301.79	3	< 2.2E-16***		0.21	12.38	3	7.32E-08***	
	Grazing * Site	1079.70	19.74	3	3.328E-12***	2.24	21.80	3	2.12E-13***		0.19	11.34	3	3.06E-07***	
	<i>Sitewise</i>	Site 1	Site 2	Site 3	Site 4	Site 1	Site 2	Site 3	Site 4		Site 1	Site 2	Site 3	Site 4	
c 30-50 cm	Effect of AMP	0.01 (1.52)	6.40 (1.45)	-2.04 (2.21)	16.60 (2.23)	-0.04 (0.04)	0.28 (0.04)	-0.06 (0.06)	0.44 (0.07)		0.02 (0.02)	-0.06 (0.03)	0.04 (0.02)	-0.11 (0.02)	
	Pr(>F)	0.99	1.91E-05	0.36	7.21E-12	0.32	4.52E-12	0.29	4.26E-08		0.34	0.04	0.01	5.20E-08	
d 50-100 cm	Cumulative Bulk SOC stock					Bulk TC%					FD BD				
	MSE	F value	Dg. Freedom	Pr(>F)		MSE	F value	Dg. Freedom	Pr(>F)		MSE	F value	Dg. Freedom	Pr(>F)	
	Grazing	1596.30	5.78	1	0.02*	0.02	0.16	1	0.69		0.13	4.19	1	0.04*	
	Site	26744.90	96.85	3	< 2.2E-16***	5.00	54.23	3	< 2.2E-16***		0.19	6.27	3	5.74E-04***	
	Grazing * Site	1841.30	6.67	3	3.53E-04***	0.54	5.88	3	9.24E-04***		0.15	4.84	3	3.35E-03**	
	<i>Sitewise</i>	Site 1	Site 2	Site 3	Site 4	Site 1	Site 2	Site 3	Site 4		Site 1	Site 2	Site 3	Site 4	
d 50-100 cm	Effect of AMP	-3.02 (3.38)	13.25 (3.49)	-8.71 (7.52)	25.98 (8.32)	-0.09 (0.06)	0.15 (0.06)	-0.30 (0.13)	0.32 (0.16)		0.23 (0.002)	0.01 (0.10)	0.12 (0.05)	-0.09 (0.07)	
	Pr(>F)	0.38	7.68E-04	0.26	4.15E-03	0.61	0.13	0.10	0.22		< 2.2E-16	0.92	0.01	0.18	
d 50-100 cm	Cumulative Bulk SOC stock					Bulk TC%					FD BD				
	MSE	F value	Dg. Freedom	Pr(>F)		MSE	F value	Dg. Freedom	Pr(>F)		MSE	F value	Dg. Freedom	Pr(>F)	
	Grazing	642.00	1.05	1	0.31	0.04	1.06	1	0.30		0.10	4.01	1	0.05*	
	Site	52372.00	85.80	3	< 2.2E-16***	1.71	51.60	3	< 2.2E-16***		1.04	39.90	3	< 2E-16***	
	Grazing * Site	8017.00	13.13	3	2.62E-07***	0.58	17.60	3	2.89E-09***		0.10	3.69	3	0.01*	
	<i>Sitewise</i>	Site 1	Site 2	Site 3	Site 4	Site 1	Site 2	Site 3	Site 4		Site 1	Site 2	Site 3	Site 4	
Effect of AMP	-8.05 (7.75)	20.90 (5.53)	-37.71 (11.98)	37.93 (10.14)	-0.07 (0.07)	0.08 (0.04)	-0.43 (0.09)	0.23 (0.07)	-0.21 (0.10)		-0.09 (0.02)	-0.21 (0.10)	0.03 (0.04)	0.04 (0.05)	
	Pr(>F)	0.31	7.99E-04	4.00E-03	8.40E-04	0.39	0.21	6.04E-05	5.38E-03		1.55E-04	0.05	0.44	0.47	

Table 4. Mean soil organic carbon stocks (Mg C/ha) for each fraction by site (sites 1-4), grazing management (adaptive multi-paddock (AMP) and conventional (CONV)), and depth (a:0-10cm; b:10-30cm). Fractions include mineral associated (MAOM), occluded particulate (oPOM), free particulate (fPOM), and dissolved (DOM) organic matter. Standard deviations are reported in parentheses.

MAOM C stock (Mg C/ha)								
	Site 1		Site 2		Site 3		Site 4	
Depth	AMP	CONV	AMP	CONV	AMP	CONV	AMP	CONV
a (0-10 cm)	13.2 (2.89)	13.2 (3.02)	15.0 (2.25)	11.7 (1.60)	26.2 (3.13)	28.4 (4.64)	20.8 (3.92)	15.4 (5.92)
b (20-30 cm)	22.4 (4.29)	20.2 (2.71)	17.8 (2.24)	13.6 (2.09)	38.7 (4.85)	43.2 (6.78)	33.8 (6.56)	19.9 (11.7)
oPOM C Stock (Mg C/ha)								
	Site 1		Site 2		Site 3		Site 4	
Depth	AMP	CONV	AMP	CONV	AMP	CONV	AMP	CONV
a (0-10 cm)	2.80 (0.95)	3.96 (1.41)	6.19 (1.77)	4.46 (0.981)	11.0 (1.93)	9.28 (2.77)	4.08 (0.886)	3.54 (1.21)
b (20-30 cm)	2.20 (1.04)	3.91 (1.10)	2.68 (0.738)	2.34 (0.730)	3.43 (1.62)	2.75 (0.665)	2.57 (2.65)	1.42 (0.535)
fPOM C Stock (Mg C/ha)								
	Site 1		Site 2		Site 3		Site 4	
Depth	AMP	CONV	AMP	CONV	AMP	CONV	AMP	CONV
a (0-10 cm)	1.25 (0.473)	1.23 (0.481)	2.74 (0.881)	4.29 (1.54)	4.85 (1.64)	4.83 (2.72)	1.51 (1.20)	0.115 (0.034)
b (20-30 cm)	1.74 (1.20)	1.53 (1.24)	2.17 (0.896)	2.20 (1.20)	1.90 (0.820)	1.60 (0.505)	1.52 (1.60)	0.064 (0.029)
DOM C Stock (Mg C/ha)								
	Site 1		Site 2		Site 3		Site 4	
Depth	AMP	CONV	AMP	CONV	AMP	CONV	AMP	CONV
a (0-10 cm)	7.27 E-9 (2.70 E-9)	7.49 E-9 (3.33 E-9)	8.88 E-10 (1.41 E-09)	3.10 E-10 (3.79 E-10)	4.44 E-09 (2.49 E-09)	3.69 E-09 (1.50 E-09)	8.62 E-09 (2.86 E-09)	8.09 E-09 (6.89 E-09)
b (20-30 cm)	9.87 E-9 (5.60 E-9)	1.19 E-8 (4.52 E-9)	4.98 E-10 (7.20 E-10)	6.64 E-10 (1.16 E-09)	2.70 E-09 (2.15 E-09)	2.60 E-09 (1.23 E-09)	9.66 E-09 (6.46 E-09)	6.64 E-09 (4.97 E-09)

Table 5. Linear model (ANOVA) results of the a) overall impact of AMP grazing and b) sitewise comparisons of AMP grazing on fraction (MAOM, oPOM, fPOM, DOM) soil carbon stocks by depth. Sitewise comparisons show the effect of AMP grazing with standard errors in parentheses and Bonferroni adjusted p-values. Significant differences are bolded.

	MAOM C stock				oPOM C stock				fPOM C stock				DOM C stock				
	MSE	F value	Dg. Freedom	Pr(>F)	MSE	F value	Dg. Freedom	Pr(>F)	MSE	F value	Dg. Freedom	Pr(>F)	MSE	F value	Dg. Freedom	Pr(>F)	
a 0-10 cm	Grazing	80.04	5.99	1	0.02*	15.68	6.08	1	0.02*	0.14	0.07	1	0.79	5.03E-18	1	0.49	
	Site	1313.97	98.42	3	<2.2E-16***	289.76	112.38	3	<2.2E-16***	107.11	56.87	3	<2.2E-16***	3.71E-16	3	4.45E-16**	
	Grazing * Site	82.60	6.19	3	6.28E-04***	14.13	5.48	3	1.5E-03**	10.94	5.81	3	1.00E-03**	1.39E-18	3	0.94	
	Sitewise	Site 1	Site 2	Site 3	Site 4	Site 1	Site 2	Site 3	Site 4	Site 1	Site 2	Site 3	Site 4	Site 1	Site 2	Site 3	Site 4
	Effect of AMP	0.06 (1.08)	3.26 (0.71)	-2.13 (1.44)	5.34 (1.83)	-1.15 (0.44)	1.74 (0.52)	1.76 (0.87)	0.55 (0.39)	0.02 (0.17)	-1.55 (0.46)	0.01 (0.84)	1.40 (0.31)	-2.19E-10 (1.11E-9)	5.78E-10 (3.76E-10)	7.53E-10 (7.50E-10)	5.27E-10 (1.93E-9)
	Pr(>F)	0.95	3.52E-04	0.15	0.03	0.05	0.01	0.21	0.17	0.91	0.01	0.99	4.00E-04	0.84	0.14	0.32	0.79
b 10-30 cm	MAOM C stock				oPOM C stock				fPOM C stock				DOM C stock				
	MSE	F value	Dg. Freedom	Pr(>F)	MSE	F value	Dg. Freedom	Pr(>F)	MSE	F value	Dg. Freedom	Pr(>F)	MSE	F value	Dg. Freedom	Pr(>F)	
	Grazing	469.90	13.21	1	4.22E-04***	0.38	0.22	1	0.64	7.07	6.50	1	0.01*	7.40E-19	1	0.83	
	Site	3526.10	99.12	3	<2.2E-16***	7.99	4.64	3	4.3E-03**	10.16	9.34	3	1.46E-05***	6.79E-15	3	<2E-16***	
	Grazing * Site	433.40	12.18	3	5.86E-07***	11.95	6.94	3	2.50E-04***	3.31	3.04	3	0.03*	3.23E-17	3	0.12	
	Sitewise	Site 1	Site 2	Site 3	Site 4	Site 1	Site 2	Site 3	Site 4	Site 1	Site 2	Site 3	Site 4	Site 1	Site 2	Site 3	Site 4
Effect of AMP	2.23 (1.31)	4.19 (0.79)	-4.49 (2.15)	13.90 (3.46)	-1.71 (0.39)	0.33 (0.27)	0.68 (0.45)	1.15 (0.70)	0.20 (0.44)	-0.02 (0.39)	0.30 (0.25)	1.46 (0.41)	-2.04E-9 (1.96E-9)	-1.66E-10 (3.52E-10)	1.05E-10 (6.39E-10)	3.02E-9 (2.11E-9)	
Pr(>F)	0.10	4.89E-05	0.18	0.03	6.12E-04	0.22	0.14	0.45	0.65	0.95	0.23	5.79E-03	0.31	0.64	0.87	0.16	

Table 6. Linear model (ANOVA) results of the a) overall impact of AMP grazing and b) sitewise comparisons of AMP grazing on fraction (MAOM, oPOM, fPOM, DOM) soil nitrogen stocks by depth. Sitewise comparisons show the effect of AMP grazing with standard errors in parentheses and Bonferroni adjusted p-values. Significant differences are bolded.

	MAOM N stock				oPOM N stock				fPOM N stock				DOM N stock				
	MSE	F value	Dg. Freedom	Pr(>F)	MSE	F value	Dg. Freedom	Pr(>F)	MSE	F value	Dg. Freedom	Pr(>F)	MSE	F value	Dg. Freedom	Pr(>F)	
a 0-10 cm	Grazing	0.54	4.98	1	0.03*	1.06E-01	7.68	1	6.53E-03**	7.91	26.10	1	1.36E-06***	9.04E-19	1	0.07668	
	Site	12.26	112.31	3	<2.2E-16***	2.22E+00	160.47	3	<2.2E-16***	25.12	82.91	3	<2.2E-16***	4.56E-18	3	8.93E-09***	
	Grazing * Site	0.73	6.72	3	3.28E-04***	1.30E-01	9.40	3	1.36E-05***	7.92	26.15	3	7.17E-13***	4.01E-19	3	0.24211	
	Sitewise	Site 1	Site 2	Site 3	Site 4	Site 1	Site 2	Site 3	Site 4	Site 1	Site 2	Site 3	Site 4	Site 1	Site 2	Site 3	Site 4
	Effect of AMP	-0.11 (0.12)	0.50 (0.083)	-0.14 (0.12)	0.29 (0.15)	-0.11 (0.03)	0.13 (0.03)	0.19 (0.07)	0.03 (0.03)	0.01 (0.01)	-0.01 (0.02)	3.68E-04 (0.06)	-2.06 (0.40)	-1.29E-10 (2.07E-10)	2.60E-10 (1.75E-10)	4.19E-10 (1.77E-10)	1.44E-10 (2.15E-10)
	Pr(>F)	0.35	6.89E-06	0.25	0.29	2.06E-03	2.67E-03	0.04	0.24	0.55	0.48	0.995	6.14E-05	0.54	0.15	0.10	0.51
	MAOM N stock				oPOM N stock				fPOM N stock				DOM N stock				
b 10-30 cm	Grazing	2.36	8.70	1	0.003873**	9.98E-04	0.12	1	0.73	3.13	22.84	1	5.39E-06***	3.53E-20	1	0.73	
	Site	18.06	66.63	3	<2.2E-16***	1.11E-01	13.63	3	1.21E-07***	9.64	70.46	3	<2.2E-16***	9.06E-18	3	1.08E-14***	
	Grazing * Site	1.57	5.80	3	0.001006**	4.00E-02	4.89	3	3.10E-03***	3.30	24.09	3	4.2E-12***	4.58E-19	3	0.2	
	Sitewise	Site 1	Site 2	Site 3	Site 4	Site 1	Site 2	Site 3	Site 4	Site 1	Site 2	Site 3	Site 4	Site 1	Site 2	Site 3	Site 4
	Effect of AMP	0.14 (0.16)	0.61 (0.08)	-0.30 (0.18)	0.68 (0.29)	-0.10 (0.03)	0.05 (0.02)	0.03 (0.04)	0.04 (0.04)	-0.003 (0.02)	0.02 (0.01)	0.01 (0.01)	-1.32 (0.27)	-2.73E-10 (2.61E-10)	1.55E-11 (3.91E-11)	9.49E-11 (1.32E-11)	3.32E-10 (2.67E-10)
	Pr(>F)	0.40	6.92E-08	0.39	0.40	7.75E-03	0.05	0.42	0.28	0.88	0.18	0.32	1.45E-04	0.31	0.69	0.48	0.22

Table 7. Carbon-to-nitrogen (C:N) ratios for each fraction by site, grazing management, and depth. Fractions include mineral associated (MAOM), occluded particulate (oPOM), free particulate (fPOM), and dissolved (DOM) organic matter. Standard deviations are reported in parentheses.

MAOM C:N ratio								
	Site 1		Site 2		Site 3		Site 4	
Depth	AMP	CONV	AMP	CONV	AMP	CONV	AMP	CONV
a (0-10 cm)	9.4 (0.43)	8.8 (0.49)	10.2 (0.55)	13.1 (5.40)	10.2 (0.31)	10.4 (0.50)	12.5 (0.45)	11.2 (0.76)
b (20-30 cm)	9.7 (0.83)	9.1 (0.64)	10.1 (1.32)	11.6 (0.45)	12.0 (0.85)	12.2 (0.89)	12.6 (0.28)	9.7 (1.0)
oPOM C:N ratio								
	Site 1		Site 2		Site 3		Site 4	
Depth	AMP	CONV	AMP	CONV	AMP	CONV	AMP	CONV
a (0-10 cm)	14.6 (0.94)	13.2 (2.47)	14.8 (1.44)	16.0 (0.70)	12.6 (0.50)	12.9 (0.56)	16.2 (0.83)	16.2 (4.15)
b (20-30 cm)	12.9 (2.49)	14.6 (2.95)	16.6 (3.21)	20.6 (3.90)	10.8 (0.97)	10.7 (1.28)	12.6 (1.76)	9.43 (1.47)
fPOM C:N ratio								
	Site 1		Site 2		Site 3		Site 4	
Depth	AMP	CONV	AMP	CONV	AMP	CONV	AMP	CONV
a (0-10 cm)	26.0 (8.61)	28.0 (9.23)	26.3 (9.71)	23.0 (3.67)	16.8 (1.71)	17.5 (2.68)	22.8 (4.54)	23.2 (4.42)
b (20-30 cm)	26.8 (7.90)	23.6 (8.86)	33.3 (10.4)	32.0 (12.70)	19.9 (2.21)	19.4 (3.07)	25.3 (5.34)	24.4 (6.34)
DOM C:N ratio								
	Site 1		Site 2		Site 3		Site 4	
Depth	AMP	CONV	AMP	CONV	AMP	CONV	AMP	CONV
a (0-10 cm)	7.12 (0.99)	6.70 (1.49)	2.80 (0.80)	3.33 (1.60)	5.62 (2.00)	7.17 (1.38)	9.05 (0.86)	10.3 (1.70)
b (20-30 cm)	8.04 (1.07)	7.98 (1.81)	3.49 (2.77)	3.78 (4.73)	5.09 (0.80)	6.32 (1.11)	8.49 (0.83)	9.15 (2.14)

Table 8. Linear model (ANOVA) results of the a) overall impact of AMP grazing and b) sitewise comparisons of AMP grazing on fraction (MAOM, oPOM, fPOM, DOM) soil CN ratios by depth. Sitewise comparisons show the effect of AMP grazing with standard errors in parentheses and Bonferroni adjusted p-values. Significant differences are bolded.

	MAOM CN ratio				oPOM CN ratio				fPOM CN ratio				DOM CN ratio				
	MSE	F value	Dg. Freedom	Pr(>F)	MSE	F value	Dg. Freedom	Pr(>F)	MSE	F value	Dg. Freedom	Pr(>F)	MSE	F value	Dg. Freedom	Pr(>F)	
a 0-10 cm	Grazing	2.59	0.67	1	0.42	0.00	0.0001	1	0.99	0.90	0.02	1	0.88	16.23	8.14	1	5.16E-03**
	Site	49.02	12.65	3	3.51E-07***	71.36	20.38	3	1.31E-10***	513.26	12.84	3	2.92E-07***	221.25	111.02	3	<2.2E-16***
	Grazing* Site	26.11	6.74	3	3.20E-04***	9.02	2.58	3	0.06	37.32	0.93	3	0.43	5.79	2.90	3	0.038*
	Sitewise	Site 1	Site 2	Site 3	Site 4	Site 1	Site 2	Site 3	Site 4	Site 1	Site 2	Site 3	Site 4	Site 1	Site 2	Site 3	Site 4
	Effect of AMP	0.66 (0.17)	-2.91 (1.40)	-0.27 (0.15)	1.35 (0.23)	1.43 (0.6)	-1.23 (0.41)	-0.23 (0.19)	0.005 (1.09)	-1.96 (3.26)	3.25 (2.68)	-0.68 (0.84)	-0.34 (1.64)	0.41 (0.46)	-0.53 (0.46)	-1.55 (0.63)	-1.28 (0.49)
	Pr(>F)	2.46E-03	0.19	0.32	9.08E-06	0.18	0.02	0.26	1.00	0.55	0.24	0.43	0.84	0.38	0.26	0.08	0.06
b 10-30 cm	MAOM CN ratio				oPOM CN ratio				fPOM CN ratio				DOM CN ratio				
	MSE	F value	Dg. Freedom	Pr(>F)	MSE	F value	Dg. Freedom	Pr(>F)	MSE	F value	Dg. Freedom	Pr(>F)	MSE	F value	Dg. Freedom	Pr(>F)	
	Grazing	6.05	8.48	1	4.34E-03**	11.33	1.89	1	0.17	64.09	1.04	1	0.31	9.40	1.80	1	0.18
	Site	37.56	52.61	3	<2.2E-16***	401.45	67.05	3	<2.2E-16***	850.69	13.80	3	1.01E-07***	164.07	31.35	3	9.31E-15***
	Grazing* Site	25.79	36.13	3	<2.2E-17***	68.79	11.49	3	1.26E-06***	11.43	0.19	3	0.91	2.23	0.43	3	0.73
	Sitewise	Site 1	Site 2	Site 3	Site 4	Site 1	Site 2	Site 3	Site 4	Site 1	Site 2	Site 3	Site 4	Site 1	Site 2	Site 3	Site 4
	Effect of AMP	0.57 (0.27)	-1.51 (0.36)	-0.17 (0.32)	2.91 (0.28)	-1.77 (1.00)	-3.96 (1.30)	0.09 (0.41)	3.19 (0.59)	3.23 (3.06)	1.30 (4.24)	0.42 (0.98)	0.90 (2.14)	0.06 (0.56)	-0.29 (1.41)	-1.23 (0.35)	-0.67 (0.59)
	Pr(<>F)	0.18	1.00E-03	0.60	1.09E-10	0.34	0.02	0.83	9.39E-06	0.30	0.76	0.67	0.68	0.92	0.84	0.01	0.27

Table 9. Percent cover of each vegetation functional group on conventional (CONV) and adaptive multi-paddock (AMP) grazed ranch pairs on rangeland sites across Northern California.

Percent Cover by Vegetation Functional Group								
	Site 1		Site 2		Site 3		Site 4	
Functional Group	AMP	CONV	AMP	CONV	AMP	CONV	AMP	CONV
Perennial Grasses & Forbs	60.3%	60.3%	17.3%	7.7%	67.0%	55.7%	23.7%	32.3%
Annual Grasses & Forbs	28.7%	32.3%	80.7%	73.7%	33.0%	39.7%	62.3%	55.7%
Bare	1.7%	0.3%	0.0%	0.0%	0.0%	0.7%	0.3%	3.0%
Litter	9.3%	7.0%	2.0%	18.7%	0.0%	4.0%	13.7%	9.0%

Chapter 3

Landscapes of uncertainty: Rethinking adaptive grazing in California with Holistic Management

3.1. Abstract

Unprecedented climatic and economic uncertainties challenging ranchers grazing on California rangelands requires reenvisioning “adaptive” grazing beyond reactionary measures. Shifting research focus toward increasing ranchers’ adaptive capacity, where flexibility, monitoring, and diversification are key features, will help support ranchers sustain this future of uncertainty. Within this context, Holistic Management (HM), a decision making framework used by some ranchers to manage complexity, is of particular interest because it emphasizes systems-based thinking, maximizing flexibility and adaptability, ecological monitoring, and goal setting. Many HM ranchers are associated with the use of a particular grazing management strategy called adaptive multi-paddock (AMP) grazing, which is characterized by the combination of moderate-high animal stock densities, fast rotations, pasture rest, and iterative monitoring and adaptive management. We interviewed a small group of AMP-HM ranchers in Northern California to 1) examine how their on-the-ground implementation of AMP grazing relates to their mental models as shaped by HM, including embedded decision making processes, motivations, barriers, and catalysts, and 2) understand how AMP-HM helps these ranchers respond to increasing challenges and uncertainties. We also report numerical information on their implementation of AMP grazing. Our findings suggest that AMP-HM shifts ranchers’ approaches towards ones that involve more ‘holistic,’ systems based thinking, in two ways. First, AMP-HM shifts ranchers’ mental models through its emphasis on monitoring combined with increased interaction with their land and animals, which changes the ways ranchers see and understand their management. Second, AMP-HM increases ranchers’ agency to operationalize these new mental models through its decision making framework and trainings. Together, these two facets culminate in a common suite of strategies used by AMP-HM ranchers, which they view as key to ranching profitably and sustainably in the face of climatic, economic, and cultural challenges. These include building flexibility into herd sizes and structures to increase temporal and spatial mobility, diversifying ranch enterprises to increase financial flexibility, building reliable natural resources bases through targeted soil health improvements, reducing input costs and improving profitability – all of which have been recommended rangeland management practices for decades. These findings suggest that AMP-HM may hold promise in helping ranchers approach strengthening adaptive capacity and succeed in a future of uncertainties.

3.2. Introduction

Ranchers managing semi-arid rangelands are facing more climatic, economic, and cultural uncertainty than ever before, sparking a new wave of inquiry into their currently used adaptation strategies to inform opportunities for the future. California ranchers face additional uncertainties that are only exacerbated by widely recognized challenges such as worsening climate change and low profit margins (Byrd et al., 2015). These include unprecedented appreciation of land values and rising costs (NASS, 2021), reliance on annual grass dominated rangelands with highly seasonal and variable NPP,

increasingly common and worsening drought conditions (Larsen et al., 2014), policy change and impacts, and a growing anti-cattle sentiment (Dimock et al., 2021) among some groups.

There is a strong body of literature cataloging ranchers' singular responses to specific independent stressors like drought. For example, research has well documented ranchers' reactionary responses to recent extreme droughts, including reducing herd size (destocking), purchasing additional feed, creating drought management plans (Kachergis et al., 2014; Macon et al., 2016; Woodmansee et al., 2021), and how these responses are influenced by ranch and rancher characteristics (Roche et al., 2015). In response to economic stressors like record high land appreciation and rising costs, studies show that ranchers commonly supplement their incomes with off-farm work, or in extreme but increasingly common cases, sell their ranches (Sulak et al., 2009). Some estimate decadal ranch turnover rates as high as 45% in some areas (Gosnell & Travis, 2005). Lastly, some ranchers have turned to on-ranch management strategies like compost application to increase productivity as a buffer against changing socio-economic conditions (Gomez et al., 2021).

Little research, however, has studied how and why some ranchers are able to successfully respond to, and in some cases mitigate, simultaneous sociological, ecological and economic challenges through more “holistic” approaches that strengthen their adaptive capacity (L. Roche, 2016). Building adaptive capacity on grazed rangelands entails being flexible enough in the short-term to withstand disturbance events, and having the long-term ability to adapt to changing conditions, complex challenges, and uncertainties (Fazey et al., 2010; Folke et al., 2001; Olsson et al., 2004). Rather than *a la carte* practices such as destocking in response to drought, a “holistic” approach to increasing adaptive capacity entails adopting a diversified suite of interconnected and mutually reinforcing practices – both at the ranch enterprise and on-the-ground grazing levels (Petersen-Rockney et al., 2021). According to (Darnhofer et al., 2010), flexibility, monitoring and learning, and diversification are key components of adaptive capacity.

Dealing with the inevitably large complexity embedded in holistic approaches to strengthen adaptive capacity in this way depends on the mental models of those making decisions, or their understanding of how the system works. This includes understanding the cause and effect relationships between their management interventions and ecological and economic outcomes (Lynam & Stafford Smith, 2004). Despite the increasing importance of understanding ranchers' mental models and how they change in the face of complex challenges, they remain understudied because they are difficult to study and capture in the short timescales of most research. (Lynam & Stafford Smith, 2004) characterize mental models as “crucial slow variables,” meaning they change slowly but are critical for understanding long-term change. The overwhelming emphasis on large quantitative methods in social science combined with the short timescales of most research has contributed to this lack of understanding of ranchers' mental models. Quantitative surveys benefit from large sample sizes and can discern large-scale and generalizable patterns, such as the common adaptation practices used by ranchers, and how these choices correlate with ranch characteristics and rancher demographics. However, these studies are limited in their ability to inform our understanding of ranchers' mental models and embedded decision making processes, including both how they change in response to challenges and uncertainties, and how ranchers operate within them to make specific management decisions (Nathan F. Sayre, 2004). This is especially important for informing our understanding of how and why some ranchers, rather than *a-la-carte* practice adoption, take holistic approaches to increase adaptive capacity. Building on current theoretical frameworks (Briske et al., 2015), in depth qualitative work is necessary to understand how ranchers' mental models interact with their on-ranch management decisions with the proper flexibility and context specificity.

Within this context, Holistic Management (HM), a decision-making framework conceived of and popularized by Allan Savory, a controversial biologist from Zimbabwe (Savory & Butterfield, 2016; Sherren & Kent, 2017), is of particular interest because of its adaptive management approach, which mirrors the features of adaptive capacity. Allen et al. (2011) define adaptive management as “an approach to natural resource management that emphasizes learning through management,” and, “has explicit structure, including careful elucidation of goals....procedures for the collection of data followed by evaluation and reiteration.” HM can be thought of as a framework for adaptive grazing management on rangelands, because of its explicit emphases on “holism,” paradigm shifts (i.e., shifting mental models), monitoring and feedback loops, embedding flexibility to maximize adaptability to changing conditions, and a suite of ranch and grazing management practices that purportedly improve environmental outcomes. HM training is offered to ranchers through a series of courses offered by the Savory Institute and other similar organizations such as Holistic Management International and Ranching-for-Profit. It emphasizes a “triple bottom line” approach to “holistically” harmonize management goals and tradeoffs on dynamic landscapes in complex scenarios. It provides a framework for ranchers to explicitly define their ecological, economic, and social/personal goals, create detailed plans for executing these goals, iteratively check their decisions against these goals using context checks and ecological measurement and monitoring, and adapt their management accordingly (Gosnell et al., 2020).

In practice, HM is often accompanied by a grazing management approach commonly termed adaptive multi-paddock grazing (AMP, but has alternatively been referred to as Holistic Planned grazing or management intensive grazing) (Mann & Sherren, 2018). Adaptive multi-paddock (AMP) grazing is among the most intensive forms of rotational grazing, where animals are moved frequently in moderate–high stock densities across lands divided into multiple temporary paddocks. Each paddock is then rested for plant regrowth before being regrazed, a commonly recommended rangeland management practice. AMP ranchers often use mobile electric fencing to divide pastures into small temporary paddocks to achieve desired rest and rotation intervals, though some also achieve this through herding and range riding. Land managers adapt (re- and proactively) both stocking densities and paddock rest periods according to seasonality, exogenous shocks and stressors (such as droughts), and to meet social and market needs. HM and AMP grazing have been the subject of previous research, but often as independent phenomena and within social and ecological disciplinary silos.

Together, AMP and HM form a very different approach to conventional ranching and rangeland management. They form both a theoretical and applied basis for the application of adaptive grazing management, attributes of which may be desirable to help ranchers respond to the complex challenges facing grazing on rangelands, such as the holistic approach to managing complexity, systems thinking, and embedded monitoring (Lynam & Stafford Smith, 2004; Mann et al., 2019; Sayre, 2001). However, an unknown but likely small (<10% total) population of ranchers globally have adopted AMP and/or HM, despite successes reported by adoptees, warranting further investigation.

In this paper, we provide a narrow but deep investigation into a small subset of ranchers using both HM and AMP grazing in California. Using semi-structured interviews, our goal was to identify the core pillars of these approaches, what they do, how and why ranchers use them, and why some have found it to be successful. We then examine how their on-the-ground implementation of AMP grazing relates to their mental models as shaped by HM, including embedded decision making processes, motivations, barriers, and catalysts. We explore the ways in which ranchers’ – through HM trainings, on-the-ground grazing implementation, and iterative learning, monitoring, and adapting – have shifted

their mental models, ultimately providing agency to successfully increase flexibility and respond to increasing social, economic, and ecological challenges and uncertainties of the social-ecological systems in which they are embedded.

3.3. Methods

3.3.1. Study structure, goals, and defining terminology

This quantitative research was carried out as part of a larger social-ecological analysis of AMP grazing in California. The overarching goals of this broader analysis were to 1) measure the ecological outcomes of AMP versus more conventional (CONV) grazing on selected Northern California ranches, including soil carbon sequestration, plant community composition, and soil water function, and, the topic of this paper, to 2) understand the decision making processes underpinning AMP ranchers' grazing management and how it is shaped by HM, focusing on why and how they apply this mode of grazing management to meet their goals. This nested study structure necessitated using both ecological and grazing management criteria to define the ranchers and ranches used to conduct the research addressing both study goals, which we describe below.

We used different terminology to meet our ecological and social study goals. While we recognize this can create confusion, we felt it was important not to conflate the application of a specific grazing management regime with the underlying decision making framework used by ranchers. In an effort to reduce this confusion but simultaneously respect their separate but related nature, we clarify our definitions and assumptions here at the outset.

In this study, we analyze the relationship and interactions between ranchers' mental models and their grazing management in-practice. We were interested in the influence of HM on ranchers' mental models, because it is a framework that structures decision making and goal setting, and AMP grazing as the grazing management-in-practice. We use AMP-HM throughout this study as a useful shorthand for the combination of both.

3.3.2. Interviewee selection criteria

In this study, conventional grazing and graziers (CONV) are defined broadly as those relying on traditional practices and have not taken HM trainings. This includes continuous year-round or season-long grazing, rotational systems among 5 or fewer pastures, and commonly residual dry matter-based decision making (Huntsinger et al., 2007; L M Roche et al., 2015). We defined AMP-HM and CONV grazing management and developed corresponding selection criteria in consultation with local farm and livestock Cooperative Extension agents, California-based rangeland ecologists, and a small group of ranchers outside of the study population.

We selected AMP-HM ranchers using the following criteria:

1. Has completed Holistic Management, or similar, grazing management training (i.e., Holistic Management International or Ranching-for-Profit)
2. Makes grazing rotation decisions adaptively rather than according to a set regime. This helped to distinguish AMP grazing from other high-intensity but non-adaptive forms of grazing management such as mob or cell grazing.

3. Uses a grazing plan (either formally (e.g., PastureMap/Gaia), or informally) to premeditate and guide grazing decisions throughout the year
4. Subdivides land into smaller paddocks throughout the grazing season (>10 paddocks)
5. Incorporates targeted pasture rest
6. Uses monitoring to drive adaptive management decisions on temporal rotations and recovery lengths. This includes both formal monitoring by scientists and organizations (e.g., Point Blue Conservation Science, NRCS, Savory Institute Ecological Outcome Verification) or informal monitoring using visual indicators, including forage recovery, ocular vegetation cover, and residual dry matter
7. Has been using this management for 3 or more grazing seasons
8. Uses higher than average animal stock densities (either seasonally or year-round) to meet intended ranch outcomes

We decided *not* to set arbitrary stocking density, pasture rest, and rotation thresholds both because these do not appear in HM trainings and because the application of AMP-HM grazing is highly variable and changes seasonally on California rangelands. Rather, we focused on ranchers' self-reported, intentional use of animal movement, pasture rest, seasonally intensive stock densities, and adaptability to reach their management goals.

We identified ranchers who met these criteria using an iterative snowball networking and screening process from May 2018 – January 2020. We first consulted with a key Holistic Management training center in California to connect us with AMP-HM ranchers who met our criteria and who might be willing to participate in the study. Fifteen ranchers who had completed Holistic Management (or similar) training and claimed to practice AMP-HM grazing responded to an email solicitation. We conducted initial phone interviews with 12 of these AMP-HM ranchers and six of their CONV rancher neighbors.

We interviewed CONV neighboring ranchers wherever possible. These ranchers and their grazing management were not the focus of the study, but we include them to provide additional perspective and context to our AMP-HM rancher interviews. CONV ranches were selected from neighboring ranches to pair with AM-HM ranches, with the following criteria:

1. Uses either continuous year-round or season-long grazing, or low-rotational grazing among 5 or fewer pastures
2. Does not have HM training or refer to it as affecting practices

We identified seven rancher pairs with proximate properties based on management and ecological criteria (paired AMP-HM/CONV ranchers) to meet overall study goals. Two CONV rancher interviews were excluded from analysis because they declined to be recorded, and two more were excluded because they are considered “hobby” ranches as defined by (Peterson & Coppock, 2006). This resulted in a sample of seven AMP-HM ranchers and three CONV ranchers.

Our sample population is not a “representative” sample of AMP-HM ranchers in California. Our goal was not to interview all AMP-HM ranchers in California, but rather to gain a deeper understanding of the ranchers in our narrow sample, including their motivations, decision making processes, and mental models under the AMP-HM framework.

3.3.3. Semi-structured interview protocols and qualitative data analysis

We conducted semi-structured interviews from September 2019 – January 2020. Our interview protocols focused on six main categories: 1) ranch history and characteristics, 2) detailed grazing management practices and underlying decision making, 3) ecosystem responses and feedback, 4) management motivations, challenges, and barriers, 5) information networks and communities, and 6) economics and resources (**Table 1**). Interviews ranged from 30 minutes to 2 hours.

Interviews were audio recorded and digitally transcribed verbatim. Qualitative data was analyzed through a five step iterative coding process. We first listened to each interview and transcribed, then listened through recordings a second time and annotated each transcript with notes. Upon a third pass, we coded interviewee responses into categories defined by our interview protocol (**Table 1**). We then revisited our interview notes and transcripts, and recoded into emergent themes that arose from the interviews in aggregate. We then passed through each transcript a final time to identify key quotes within our emergent themes. We incorporate ranchers' quotes throughout the results to center these ranchers' experiences and journeys in their own words.

3.4. Results

3.4.1. Quantitative ranch characteristics

The ranchers we interviewed included a variety of ranch ownership situations, operation scales, histories, and enterprises. We did not find patterns that helped distinguish ranchers by grazing management: AMP-HM ranchers did not consistently operate larger ranches or own more private acres compared to CONV ranchers in this study.

It was common for ranchers to operate across several landbases, combining grazing on small privately owned home ranches with grazing opportunities from public leases with state parks and organizations or other private leases. Two AMP-HM ranchers and one CONV rancher owned ranches >1000 acres, while most other ranches in the sample only owned base acres ranging from 11-300 acres. Operational characteristics and herd sizes varied widely among ranchers in our sample, ranging from 50-2500 cow-calf pairs (**Table 2**).

3.4.2. Quantitative grazing management characteristics

To quantify parameters of on-the-ground AMP-HM grazing management in our study, we cataloged quantitative management data from our interviews (**Table 3**). Six of the seven AMP-HM ranchers had been AMP-HM grazing for less than 12 years, while one had been AMP-HM grazing for more than 25 years. All CONV ranchers had been grazing conventionally since they began ranching, all more than 15 years ago. When asked to describe their grazing management, including number of temporary paddocks, stocking densities, etc., AMP-HM ranchers rarely reported a single definitive value. Rather, they emphasized the variability of these values both seasonally and as a core feature of their adaptive management and HM approach.

Despite managing across a variety of rangeland ecotypes in California, AMP-HM ranchers reported relatively consistent ranges for grazing rotations and pasture rest. During the growing season, AMP-

HM ranchers moved their cattle every 1-2 days and aimed for 25-45 days of rest, on average. However, their use of stocking density varied by up to 10-fold. Some AMP-HM ranchers reported using very high stocking densities with very fast rotations to meet their goals during peak grass growth (e.g., 112 AUs in 1 acre for only a few hours), while others use more moderate densities (100 AUs in 10 acres for 2 days). Generally, AMP-HM ranchers reported constructing more than 100 temporary paddocks during the grazing season, except one rancher who manages fewer acres (necessitating fewer paddocks), and another who primarily herds animals on horseback via range riding.

In addition to short term adaptability within a single growing season, all AMP-HM ranchers also discussed how they adapt their grazing rotations, pasture rest, and stocking densities throughout the year in response to seasonal precipitation. Generally, grazing rotations become slower (up to 20-30 days) and pasture rest periods longer (60-90 days) as conditions become more dry, which limits grass growth and forage availability (**Table 3**).

In comparison, two CONV ranchers reported rotating animals between five permanently constructed pastures, but did not set target rotation frequencies or pasture rest periods. The third CONV rancher grazed more intensively, rotating every 2-5 days on a set schedule, and resting pastures for 10-20 days between grazing events.

3.4.3. Qualitative emergent themes

We identified seven key themes that emerged from our qualitative interview data (**Table 4**):

1. HM is considered a useful decision making framework by ranchers
2. AMP-HM ranchers prioritize strategies to increase adaptive capacity on their ranches, using synergistic approaches (both grazing and ranch-enterprise related) to increase temporal, spatial, and financial flexibility in response to ecological, economic, and social uncertainties
3. AMP-HM ranchers view their management as a continual process of iterative improvement, relying on closed feedback loop of continued education, experimentation, and monitoring outcomes
4. AMP-HM ranchers are not an elite subgroup: they are constrained by systemic challenges
5. There are some unique challenges to AMP-HM in California, which may limit adoption
6. Motivations for ranchers' AMP-HM adoption were not uniform: ranchers are driven to AMP-HM via many, idiosyncratic reasons
7. A set of common tools act as positive catalysts, shifting ranchers' mental models and reinforcing AMP-HM among adoptees

3.4.4. Theme 1: HM is a useful decision making framework for ranchers

At the outset of our interviews, we set out to gain an understanding of AMP grazing, including AMP ranchers' underlying decision making processes. However, throughout our interviews it became clear that ranchers' AMP grazing management was inseparable from HM. In fact, all AMP ranchers we interviewed discussed HM at some point independently and without prompt.

Many AMP-HM ranchers echoed the sentiment illustrated by the quote in **Table 4** (Theme 1): the HM decision making framework was a useful tool to implement a systems approach on their ranches, taking complex financial, social, and ecological contexts into consideration. Prior to their HM approach, ranchers report their economic and ecological goals were often at odds. But through the HM-mediated process of explicitly identifying their long-term goals, learning tools to reach these goals,

tying social and economic contexts into their decision making, monitoring their ecological outcomes, and learning the importance of adapting in response, ranchers report feeling more fulfilled in economic, ecological, and personal spheres.

In this way, HM seems to be a key precursor of AMP management. While animal movement, pasture rest, and the flexible use of high animal stocking densities are taught as grazing tools in HM, the specific typology of AMP grazing seems to arise primarily as a function of HM ranchers' emphasis on monitoring and adaptation. In the words of one rancher,

And, you know, one of his greatest insights [Allan Savory] has been the decision making framework, which is, I mean, I tell people, look, I don't care what you do. Use, I mean on the land use this decision making process, format, and then monitor what you're doing. If you're monitoring what you're doing, I kind of think you're gonna move towards this thing, which, as we've already discussed, is not self-evident on how to do it. (R1)

3.4.5. Theme 2: Strategies for increasing adaptive capacity using AMP-HM

Without being asked directly, AMP-HM ranchers collectively described a variety of strategies they use to increase adaptive capacity. This includes both decisions directly tied to their grazing management and in their business models.

Flexibility is central to ranchers' AMP-HM approach. Ranchers reported efforts to move animals across their ranches very quickly during the growing season, often choosing to leave more grass behind than necessary as a way to over-cautiously prevent overgrazing and grassbank forage in case of drought. They expressed making decisions about when to rotate, stocking density, paddock size, and length of pasture rest on a day-to-day basis, taking into account a myriad of social and ecological factors including: precipitation, grass regrowth in previously grazed paddocks, forage utilization within current paddocks, grass maturity in planned future paddocks, growth needs of different grass species, seasonal wildlife habitats, and planned weekend breaks for ranch staff (**Table 4, 2d**). For example, Rancher 3 explained:

And so now we're grazing for animal and soil performance, we're not grazing according to A, B, C like pattern 1, 2, 3 where it's almost more like pulse grazing, we might go from pasture one to pasture 10, and then back to pasture one, depending on how much grass there is and how wet it is, and performance.

All seven AMP-HM ranchers discussed the difficulty of ranching in California, where already temporally variable annual grass growth is increasingly exacerbated by drought. Several ranchers expressed a desire to rapidly stock large herds of cattle in the spring to take advantage of the rapid forage growth, and rapidly destock as resources become more scarce in the summer and with first signs of drought (**Table 4, 2a**).

Because our grass here comes on so quickly, like between April and June, we're like we don't have enough cows. Everytime. We're like, we don't have enough cows, we don't have enough sheep, we need to

hire more. And then like July 4th comes and we're like "sell all the cows" so it's just so fast. (R2)

In response to these challenges, 6/7 AMP-HM ranchers reported shifting their herd sizes and types to improve spatial and temporal mobility. This included shifting the composition of their cattle herds away from cow-calf pairs toward more diversified or solely yearling enterprises (**Table 4, 2a**). Rancher 1 illustrated by saying:

We've moved from a cow-calf year round enterprise to a stocker enterprise, which is seasonal... It was a business decision. And actually, drought pushed us in that direction....because there have been some pretty serious droughts.

AMP-HM ranchers also aim to increase economic flexibility by diversifying income streams and reducing external inputs. For example, several AMP-HM ranchers we spoke to have chosen to diversify their herds by either newly incorporating sheep or growing their existing sheep herds, shifting their overall composition of cattle:sheep (**Table 4, 2c**). Incorporating sheep provides a second form of income when cattle markets are unfavorable and also increases spatial mobility on hard-to-reach grazing locations.

However, maximizing the number of animals produced was not their profitability strategy. Instead, AMP-HM ranchers opted for overall smaller herds cattle, which they could graze sustainably year-round on their land base with few inputs, as opposed to larger herds which required expensive hay feed. Reducing herd sizes to more carefully match their animals (in number, breed, and species) to their available natural resources was part of a concerted effort to reduce their external input costs and increase overall profitability (**Table 4, 2a, 2b**).

But [redacted] has 80 cows on 200 acres, that's like, less than three acres per cow. He's feeding the crap out of them for three months or four months of the year, and I'd rather have 40 cows and never feed them. (R3)

I'll get [people asking] like, "how's the Savory program going?" And then I'll explain that it's going great, and that it helped me a lot, and then we got rid of our hay bill and that always blows their mind that it got rid of the hay bill. Not the whole bill, but a large chunk of it... Yeah, we're down to seven loads of hay vs. 22, I think, when I got here...So that's, that's another thing is I haven't been growing the herd because I'm trying to get the genetics of this environment right. We're doing seven loads of hay and you're moving all the time. I need the herd that can handle that. (R2)

In contrast, one interviewed CONV rancher turned to the opposite strategy. Their profitability approach prioritized producing the maximum number of animals by increasing inputs, primarily irrigation, and the rancher expressed frustration at not having access to more irrigation water.

We've added some irrigation on one piece.... we'd like to do some more additional improvement but we don't have money to do it. You probably can't maximize our pastures, maximize production, the way

that this irrigation system is set up right now and the way our water availability is. Two thirds of it only gets water once every two weeks. And so, yeah, we're always behind on the water. And until we can pour more water to it, we're never gonna be able to maximize production. (R10)

3.4.6. Theme 3: Education and experimentation

All AMP-HM ranchers described their grazing as an iterative and lifelong process of continued improvement, whereby they constantly seek new information (Table 4, 3c), test their hypotheses through on-ranch experiments (Table 4, 3a, 3d), monitor their outcomes (Table 4, 3b), and change their decisions accordingly. These ranchers don't solicit grazing management help from traditional channels such as NRCS, but instead network and engage in vast online communities, attend specialized regenerative agriculture and HM conferences (i.e., Regenerate, EcoFarm), and seek out targeted advice from trusted experts with experience in AMP-HM systems. AMP-HM ranchers are also highly motivated to experiment with both their grazing management and other aspects of their ranch management, including changing grazing intensities to reduce weedy species, taking penetrometer measurements under windrows, and testing outcomes of different combinations of practices like seeding, microbial inoculation, and compost application. Here is an example of a rancher experimenting with pasture rest durations during the growing season and reflecting on their monitored outcomes (Table 4, 3a, 3b):

We've tried different things, trying to understand how this best works... Early on, we tried to use shorter recovery periods during the grazing season. And it didn't produce bigger plants. I think we just weren't giving the plants enough recovery. But we were giving plenty of recovery in the dormant season. So we were seeing some good things, but not as much, so we've kind of shifted to a little bit longer or twice as long recovery periods during the growing season. (R1)

In addition to the experiments they've been able to carry out, these ranchers also repeatedly discussed practices and ideas they aspired to try in the future.

3.4.7. Theme 4: AMP-HM ranchers are constrained by systemic challenges

AMP-HM ranchers expressed constraints imposed by systemic challenges that are well-documented among ranchers both broadly and in California. For example, like many California ranchers, these ranchers often cannot afford to purchase contiguous land bases and are instead forced to cobble together several grazing leases to reach profitable scales. In cases of insecure land access, including short-term leases, ranchers feel disenfranchised in implementing AMP-HM management because they may not be able to reap the long-term benefits (Table 4, 4a). In one extreme example, an AMP-HM rancher had recently lost access to their largest land lease (accounting for more than half of their total managed acres) despite positive ecological outcomes arising from their management, jeopardizing their ranching future, stating:

That's what they want to do...It's their ball. And all the people who were monitoring, they're really happy with how the land is responding. Yeah. I mean, if I don't [find another lease], I can't

keep my little business, my guys together. So, I really want to do that. And, you know, I'm trying to think about, okay, it's an opportunity, it's painful, but what can you do? (R1)

Both AMP-HM and CONV ranchers expressed significant economic challenges associated with ranching in California (**Table 4, 4b**). For example, several ranchers illustrated scenarios where they were forced to sell animals in sub-optimal market conditions because of worsening drought or even to pay looming debt. Infrastructure and labor are additional challenges shared among all California ranchers in our interviews (**Table 4, 4c, 4d**), though we came across several examples of AMP-HM ranchers finding ways to partially mitigate these challenges. For example, it is commonly assumed that labor and fencing costs are prohibitive to adoption of AMP-HM grazing. AMP-HM ranchers openly acknowledge the increased labor needs and expenses associated with their management, but have reportedly managed to still increase overall profitability by drastically reducing other input costs. To our surprise, none of the AMP-HM ranchers interviewed reported mobile electric fencing as a significant economic or infrastructural challenge. When asked directly, one rancher responded,

Oh my God, no. Last year we spent \$800, that's with batteries and all sorts of stuff. Then I budgeted it in this year, like another 1500 bucks. No, that isn't, that has not been a barrier. (R2)

Though AMP-HM ranchers are generally less reliant on permanent interior fencing, poor perimeter fencing and water development are infrastructural challenges they share in common with CONV ranchers (**Table 4, 4d**).

3.4.8. Theme 5: Unique challenges to AMP-HM that may limit adoption

We found several unique challenges associated with AMP-HM compared to more conventional forms of grazing management in California. First, 4/7 interviewed AMP-HM ranchers expressed that they've been subject to institutional disapproval of their grazing management (**Table 4, 5a**). They reported scenarios ranging from feeling shunned from prominent grazing institutions, opposition to discussing AMP-HM at institutional gatherings, and hearing prominent rangeland experts actively advising against the use of AMP-HM (**Table 4, 5a**).

I get more pushback from the University of California. There's some rangeland consultants out there that would really love to see me just crash and burn. .. I go to meetings and they slam their hand down on the table, and say "the Society for Range Management hasn't accredited these kinds of things, and they have no business writing range land plans at all" (R1)

Some ranchers also reported difficulties finding land owners willing to let them try AMP-HM on their grazing leases because of local antipathy. One rancher recalled knowledge of a scenario involving direct censorship of a public employee after organizing a rancher-requested HM meeting:

I know a guy who was put on two weeks of administrative leave, because he --and the ranchers asked for it-- he organized a meeting with a group of ranchers and Allan Savory and he was put on administrative leave from NRCS. This was back in the day. So it's

like that's the kind of stuff that happened and that's why people didn't pursue it. (R5)

Second, AMP-HM ranchers consistently discussed frustration with the steep learning curve of AMP-HM grazing (**Table 4, 5c**). In early adoption, they struggled with learning which ecological cues to consider, which grazing levers to adjust in response, how to recover from management mistakes, and how to balance social and personal needs. One rancher described it by saying, “it’s been like, drinking out of a fire hose, basically,” (R2) illustrating the challenge of applying their newfound knowledge from HM trainings on-the-ground, and with few local communities of practice to rely on (**Table 4, 5d**). In the words of one rancher:

But the literature on this was pretty scant. I mean, you know, you had your, Savory, you had your Joel Salatin has been around for a while and some folks but there just was not any guidance. (R6)

Instead, AMP-HM ranchers turn to their robust online communities as well as ranchers and instructors they met in their HM training courses. As they gain experience and become more comfortable with the process of monitoring outcomes, changing management, making mistakes, and starting again, these ranchers come to understand and find meaning in AMP-HM as a life-long journey of iterative learning, rather than a formulaic method.

So, the cons are that, you know, you make a lot of mistakes cause you're trying a lot of new things. But you get better at, you know, the mistakes you're making are generally small. If you're monitoring, you can correct them really, pretty quickly. And there's, you know, it's kind of a little blip on the screen. (R1)

The lack of local communities of practice poses other challenges, including lack of collaborative distribution opportunities (**Table 4, 5d**). For example, in response to low profit margins of beef wholesale markets, some ranchers have opted to form cooperatives within their regional ranching communities and sell their product collaboratively in higher-margin direct-to-consumer outlets. This was not possible for the AMP-HM ranchers, however, because their neighbors do not share their management approach. As one rancher put it:

That means your whole region needs to be like I am THE only holistic grazer. Like the only. (R2)

Lastly, AMP-HM ranchers reported difficulties implementing their ideal management across non-contiguous ranch leases (**Table 4, 5b**). Non-contiguous leases are a known challenge for California ranchers. However, it seems to especially challenge AMP-HM management: when ranchers manage separate herds on spatially discrete ranches, they found it difficult to rotate animals as frequently and intensively as they would have liked. According to one rancher managing more than 5 separate grazing leases in separate locations:

But maybe the thing that's most likely to be good is really high stock densities applied systematically across the landscape. And that has been super challenging for me to do. It wouldn't have been very much of a challenge if I had 12,000 acres on one ranch. It virtually has been, you know, almost impossible.

3.4.9. Theme 6: Idiosyncratic motivations for AMP-HM

One key focus of our semi-structured interviews was to understand the motivations underlying adoption of AMP-HM. All of the AMP-HM ranchers we interviewed had unique, and often highly personal, reasons for adopting and maintaining AMP-HM on their ranches. Motivations were diverse, and no singular motivation applied uniformly to all AMP-HM interviewees. We grouped “motivators” into four groups, though they are interrelated: philosophical, ecological, economic, and connectivity to land and animals. In constructing these groups, we pulled on rancher responses to questions directly involving motivations as well as motivational reflections throughout the interviews.

The motivations we describe below are also influenced by unique rancher contexts. Of the seven AMP-HM ranchers we interviewed, two adopted AMP-HM during a familial ranch transition, two were relatively new ranchers (< 10 years) who began ranching with AMP-HM, and three transitioned to using AMP-HM >10 years ago from more CONV grazing systems.

We describe the first group of motivations as “philosophical” (Table 4, 6a). AMP-HM ranchers collectively reflected on large societal challenges they felt compelled to, in some way, address within their ranching contexts. These conversations spanned issues of climate change, struggling rural communities and declining ranching viability, the connections between industrial agriculture, public health, and environmental degradation, and a deep desire to contribute to a regenerative food system of the future.

There really should not be these stark distinctions that we've drawn between wild landscapes or wild lands and then working landscapes and so I think grazing lands offer like the easiest opportunity to be able to merge those, but then even in crop and orchard production, there's a lot of opportunity to merge those and I think just for fate, all purposes, whether it's health of the environment, human health, through healthy food and human health through social well-being, we need to break down those...can those walls that have basically been set up and we need to start to blend those lines more and more. So that's I guess, yeah why. Like in terms of, yes, how I came about that cause I definitely was not raised with that or exposed to that and like, through education. So it's been a combination of a lot of observation and conversations on the ground and just the opportunity to attend so many different events, that it's just become a connecting of the dots like process. (R5)

This sentiment was similarly echoed by the majority of AMP-HM ranchers we spoke to. Some sought out HM courses specifically for this reason, while others admitted to recognizing these issues but thinking about them separately from their management prior to HM. For many, HM’s explicit linkage of society and culture to ecology, grazing, and its decision making framework to incorporate these issues into their everyday decisions was an “epiphany” moment which allowed them to connect philosophy and practice.

And I grew up in a Catholic family, and had a big kind of emphasis on social justice and the common good....And finally, finally I stumbled on to, you know, Wendell Berry kind of helped me understand

the connections between agriculture, and culture, and civilization. And I was, it was, you know, one of those epiphany moments. (R1)

We describe the second group of motivations collectively as “ecological” (**Table 4, 6b**). This includes scenarios of ranchers recognizing declining rangeland conditions under their prior management, a longing to restore previously observed diversity of plants and animals on their ranches, a deep appreciation and reverence for “Mother Nature,” and an understanding that healthy soils are their primary resource base.

And sometimes you get it wrong. You know, you might have heard me say the analogy of Mother Nature's like our dance partner, and once in a while we'll always step on each other's toes. If you keep stepping on each other's toes over and over, you're going to get a new dance partner, pretty quick. Because it doesn't work that way. Usually, you might step on each other's toes once or twice and figure it out. Okay. You follow me. You know. The same way with Mother Nature. She'll put you out of business if you keep stepping on her toes. It's really true. (R3)

All seven AMP-HM ranchers tied their ranching philosophies and management decisions back to a fundamental focus on promoting healthy soils. They emphasized their desire to increase soil health both as an important virtue of regenerative agriculture, and strategically to increase their productivity by shifting away from inputs and instead relying on improved functionality of healthy soils to sequester carbon, hold more water longer, and increase grass growth.

It is the ecosystem we need to manage, not the pastures. And I used to think as a cattleman that I thought I was a you know, grass grower and a water steward and now it's really about the land and the soil. You know you can do whatever you want everywhere else and if you don't have a living soil, you're out of luck. (R6)

Some AMP-HM ranchers described reaching an economic breaking point on their ranches where they knew they'd soon be forced to either sell their ranches or make a radical change (**Table 4, 6c**). The two ranchers whose stories we highlight below to illustrate “economic” motivations both opted to make radical ranch enterprise changes by turning to AMP-HM. One rancher, after taking over management of their family's ranch, realized that the ranch could no longer economically sustain its yearly hay purchases.

Then after looking at the books and adding up the hay bill, I realized that we had to make a dramatic change. For one I wanted better grass because I was trying to finish animals for the beef company. So I was like, "how do I do that?" Researched every book I could, conferences, and then I found the Holistic Management Program...So I dove in pretty much headfirst into the holistic grazing thing because I knew we have a lot of property. I was like, "Hi, I need help. My dad thinks I'm crazy, but we can't buy any more hay. So I need to make it work better." (R2)

These economic motivations are closely related back to the types of ecological motivations we describe above. For example, the second rancher's story we highlight here involved a historic drought that drove severe ecological, economic and psychological hardships and ultimately catalyzed a radical change in their approach to ranching.

So 2013 and 14, we had like the worst drought ever. And I never want to be stuck in a position like that again. So I leave a lot more residual than I ever have. And like December 1st is my critical rain date. If we don't get an inch or two of rain by December 1st, I'm starting to sell animals. And this year rain, you know, I was like, preparing to sell mama cows and stuff. And it rained on November 29th. Last time in 13 and 14, I waited. And then it didn't rain in January. And then it didn't rain. And I was out of money, had skinny cattle, horrible pastures, like nothing left on the pastures. And February 2nd, it started raining. We had a spring, it was a decent spring. But I don't ever want to be in that situation again. (R3)

The remaining motivations we encountered throughout our interviews were collectively related to ranchers' feelings of joy and connectedness to their animals and landscapes (**Table 4, 6d**). These ranchers expressed being drawn to AMP-HM because it gave them an opportunity to be outside, spend much more time with their animals, and guided them through monitoring ecological outcomes. In the words of one rancher,

I just want to be out there on land riding, doing what I love, like that's why I do this because I love being out there. Like it's so fun to see the country and to really get to observe it and observe the cattle. I think more people actually want that than even acknowledge or recognize that they want it and if our support systems and economics were different like we could just get that realization.

In contrast, one CONV rancher expressed the opposite sentiment, stating, "We do a rotation system. It's not really super fun."

3.4.10. Theme 7: Positive catalysts reinforcing AMP-HM

Several sets of tools seemed to catalyze AMP-HM management by either reducing barriers or facilitating faster learning. For example, all AMP-HM interviewees reported leveraging funding opportunities such as USDA-NRCS EQIP or CDEA for more flexible infrastructure, primarily for improved water distribution (**Table 4, 7a**). Interestingly, despite their emphasis on soil health, none of the AMP-HM ranchers we interviewed reported applying to CDEA's Healthy Soils Program funding. These ranchers did not rely on "pay-for-practice" mechanisms tied to their grazing management, but rather operationalized infrastructural funding, like many other ranchers, to meet their management goals.

Several ranchers also reported the use of helpful tools and technologies that either made implementation of AMP-HM easier or allowed them to optimize their application of AMP. For example, many AMP-HM ranchers discussed that using low-stress livestock handling techniques

helped them move their animals more easily, enabling more flexible and intensive rotations. In discussing their application of low-stress livestock handling, one rancher reported:

My animals are really calm. I have almost no death loss, which isn't necessarily tied to holistic management, but my expression of it, it's a great deal to do with livestock handling. I think it, it opens up opportunities that a lot of ranchers aren't, you know, exploring. (R1)

Though not all, several AMP-HM ranchers in our interviews also employed grazing record keeping apps such as PastureMap or Gaia. Using these apps to record and visualize their rotations, stocking densities, and pasture rests helped them more efficiently plan and scale up their management (**Table 4, 7b**).

AMP-HM is knowledge and experience intensive, but AMP-HM ranchers feel isolated from traditional grazing and rangeland groups. Consequently, they did not view traditional information channels as helpful resources for AMP-HM management.

Yeah, I really haven't had a lot to do with NRCS. Or Cooperative Extension. They're really nice people. But I just, just haven't, and I would have worked more with them and not so much on questions of how to do some of this stuff, because none of the NRCS people or Cooperative Extension seem very interested in this. But in terms of, you know, working with them to, you know, for infrastructure purposes. (R1)

As a result, AMP-HM ranchers rely heavily on their AMP-HM networks for support (**Table 4, 7c**). These networks serve as important catalysts in these ranchers' learning and troubleshooting, and provide inspiration when they see others' success with AMP-HM. This seemed to be especially important for the female AMP-HM ranchers we spoke with, who reported feeling even more marginalized because of their gender. In her words, "Yeah, and also no one really talks to me because I'm like, a girl." In contrast, one male AMP-HM rancher reported the opposite sentiment, that he's accepted into some traditional ranching groups *despite* his AMP-HM approach because he's a well-respected cowboy in the community [rancher ID redacted for anonymity]:

Well, it has been helpful that I'm a pretty decent cowboy. So, you know, they still invite me to brandings, you know, we get along fine.

In turn, in addition to the networking channels that nearly all AMP-HM interviewees reported finding useful such as their HM training groups and instructors, Ranching for Profit, and HM-centered social media groups, women AMP-HM ranchers also found support in networks such as "Girls with Grass" and "Women in Ranching" groups.

Lastly, "seeing" the first signs of ecological improvement seemed to be a critical aspect for AMP-HM ranchers, catalyzing a pathway of positive reinforcement. Several AMP-HM ranchers reported feeling frustrated and discouraged early in their adoption, making many mistakes and not seeing any changes on their ranches.

Which again, you know, pushes back on any incentive to do this, it's like, you know, your first steps are almost a negative. (R1)

However, once AMP-HM ranchers saw the first signs of improvement, they reported feelings of excitement, accomplishment, and a new sort of connectedness to nature. This seemed to be an important catalyst for continued AMP-HM – a moment that marked a shift in their mental models and reinforced their desire to continually learn and improve their grazing (**Table 4, 7d**).

That was the first pasture that we've managed holistically, really densed them up and moved them every day, and then got off of it. So that was the first pasture that we really did that with, and I, it was, it was like, there was just so much more growth per square foot than there was before. And it was all different plants and it just looked really good and so that was exciting. (R2)

3.5. Discussion

3.5.1. Shifting mental models and the agency to operationalize change underscore AMP-HM success

In a recent review of HM, (Gosnell et al., 2020) concluded with a call to future research, stating, “The core question that has to be asked about HM is not just about ecological outcomes...; it is about how a social-ecological regime like HM can help bring about necessary shifts in the systems, structures, assumptions and worldviews in order to support a sustainable society.” Our results from in-depth rancher interviews suggest that AMP-HM works by shifting ranchers’ mental models in several key ways. Mental models are internally constructed worldviews that influence our understanding of how the world works and provide the mechanism for filtering and interpreting information (Jones et al., 2011; Lynam & Stafford Smith, 2004). AMP-HM is not a singular practice or prescription; it involves deep paradigm shifts in the ways ranchers see themselves as agents of change, their ranches within social-ecological contexts, and how they approach learning and adapting to changing conditions (Gosnell et al., 2019; Mann & Sherren, 2018). Using our qualitative data, we illustrate two key ways in which AMP-HM works to update ranchers’ mental models.

First, AMP-HM’s core emphasis on iterative learning through monitoring is a central feature contributing to changing AMP-HM ranchers’ mental models. Lynam and Stafford Smith (2004) point out that the local ecological knowledge constituting ranchers’ mental models determines “what observations are made, where and how those observations are made and how they’re interpreted.” AMP-HM – as a decision making framework *and* grazing management strategy – changes ranchers’ opportunities for making these observations in several ways: 1) HM teaches ranchers on-the-ground monitoring strategies for both biological and financial outcomes (as illustrated in the Savory Institute’s online course, “105: Monitoring your Decisions,” and in chapters of Savory and Butterfield, 2009), 2) the HM framework closes management-monitoring feedback loops by providing mechanisms and platforms for internalizing those outcomes and checking them against their ecological and financial goals, and 3) features of AMP require ranchers to interact with their land and animals more frequently, physically getting boots and eyes on the ground to make monitoring observations. Previous work has similarly identified the importance of shifting mental models under HM (Gosnell et al., 2019), and

how monitoring plays a fundamental role (Nathan Freeman Sayre, 2001), though to our knowledge our study is the first to capture ranchers' experiences and of shifting mental models under AMP-HM.

(Nathan Freeman Sayre, 2001) notes that careful monitoring speeds up the learning process by "reveal[ing] the effects of management decisions well before they are apparent to the naked eye, greatly increasing one's ability to avoid lasting damage and to encourage range improvement." We suspect that the combined emphasis on monitoring (including the tools, knowledge and iterative checking against goals) with the increased, often day-to-day, interaction with land and animals under AMP-HM allows ranchers to more quickly connect their management decisions with ecological outcomes. Ultimately, this culminates in the shifted mental models that are necessary to make and sustain the types of "holistic" grazing practice and operational shifts that they describe.

The shifting mental models of AMP-HM ranchers is reflected in the ways in which they recall "seeing" the land differently with monitoring over time (**Table 4**, Theme 7d). [Gosnell et al. \(2019\)](#) also captured this phenomena among ranchers transitioning to "regenerative" grazing with HM: introduction to the principles of HM and elucidating the linkages between their management and ecosystem outcomes through farm assessments allowed these ranchers to "see" the land differently – an epiphany which created a new mental model and inspired radical behavioral and cognitive change. While this has also been observed outside of HM, HM seems to provide a template that increases ranchers' ability to form new mental models. For example, (Rissman & Sayre, 2012) document interesting shifts in conventional ranchers' mental models and perceptions after observing improved rangeland conditions following grazing rest during a severe drought. Upon observing these changes, ranchers voluntarily and dramatically reduced their stocking rates and in some cases simultaneously improved profitability compared to their prior approach.

Many of the AMP-HM ranchers we spoke to were also making efforts to partner with scientists and monitoring bodies like Point Blue Conservation Science to monitor biological outcomes beyond their reach (i.e., soil carbon sequestration).

Point Blue, and you, and [redacted], I have all these people kind of looking over my shoulder, helping me see things that I never would have seen, and I'm not really prepared to understand all the variations on a theme. (R1)

These new mental models are also exemplified by AMP-HM ranchers' discussions of how they now view ecology and economics as reinforcing, rather than competing goals as they once did. For example, R4 reported:

"I wanted to try and figure out a way that I could raise more pounds of beef. And the way to do it was to, you know, graze more intensely, so that I could grow more forage. And then, really about six or seven years ago, when I started with the Marin Carbon Project, I started focusing on soil health, it was like, oh, really, I'm not a grass farmer. I'm a soil, I'm trying to create more awesome soil" (R4)

It is not immediately clear whether these ranchers' appreciation of their natural resource base as an economic tool *arose* out of monitoring, or if this connection was emphasized as a pillar of HM and

drove monitoring. In either case, AMP-HM ranchers in our study seem to have all come to the same conclusion: that improving their ecological conditions (with a specific emphasis on soil health) translates to higher profitability. These ranchers see healthy soils as a foundation, fundamental to their mental model.

Reducing inputs by bolstering ecosystem functioning such as soil health has been promoted in the forms of “ecological intensification,” agroecology, and diversified farming systems (FAO, 2018; Kremen et al., 2012; Spiegel et al., 2018). Interestingly, AMP-HM ranchers’ increased profitability seems to arise not from increasing animal numbers, but rather from their concerted efforts to reduce their cost to income ratio. Most AMP-HM ranchers we interviewed achieved this by successfully reducing external input costs, especially related to hay. AMP-HM ranchers achieved this by focusing on growing more and healthier grasses, and sometimes even by *reducing* the sizes of their herds to better match their yearly forage availability. Emboldened by their new mental models, these AMP-HM ranchers had the confidence and tools to risk changing their approach to profitability – weaning themselves off of their inputs and focusing on improving their ecological outcomes. Importantly, AMP-HM is associated with some increased costs in other areas, such as mobile electric fencing (and associated needs such as solar panels) or water development. However, these costs differ in their periodicity and volatility: costs such as hay are annual and highly volatile, while infrastructural costs associated with AMP-HM are often one-time fixed costs. Ranchers we interviewed did not report mobile electric fencing as a significant input cost, and primarily rely on grants and funding opportunities to help mitigate the costs of water development. Together, these factors may have contributed to their success in ultimately reducing their total annual input costs relative to their profits.

Despite these ranchers’ ultimate successes, all AMP-HM ranchers we interviewed pointed to the initially steep learning curve as a challenge. This is important because it highlights that even ultimately successful AMP-HM ranchers make mistakes along the way, but that they find a way to learn from them and persist. Once the management-monitoring feedback loop is built into AMP-HM ranchers’ approaches, it seems to inspire continued curiosities that push them to overcome the learning curve challenge. Visualizing positive ecological feedback from their management as well as becoming more intimately familiar with and connected to their land and animals thus likely reinforces ranchers’ incentives to monitor (Stinner et al., 1997).

Oh man. Well, I love learning. And I can be pretty enthusiastic about the things I want to learn about....I was really, you know, immersed in looking at stuff, and the animals, and the land, and the plants, and how they grew, and how they regrow. And then I was, you know, through all these means of finding or connecting with teachers around the world. As I was doing this, and I just started finding fascinating connections between, you know, animals and their management, and then Allan [Savory], and then people in South Africa, and all over the place, I was, so I was on fire and just loving it but you know, I wasn't naturally inclined to business.
(R1)

Second, AMP-HM increases ranchers’ agency, or feeling of control over their management and outcomes, which is necessary to operationalize their new mental models on-the-ground (Gosnell et al., 2019). This is a crucial aspect in AMP-HM ranchers’ behavioral shifts: without the tools to translate and mobilize their new mental models into tangible actions, they may not feel empowered

to assume the risk embedded in the associated behavioral change, instead causing them to revert to old ways (Burton & Wilson, 2006; Knapp & Fernandez-Gimenez, 2009). The combination of AMP-HM's emphasis on "holistic" systems thinking (Mann et al., 2019) and the framework for synthesizing multiple information streams (financial, social, and ecological) layered onto the monitoring-driven mental model shifts, acts as a complete set of tools needed to succeed under AMP-HM. As illustrated from an excerpt of a quote in **Table 4**,

The reason why Holistic Management felt right to me is because those were all the pieces that I couldn't figure out how to work together. Yeah, like how do I manage the land? How do I manage the books? How do I manage the animals? The feed? And like so Holistic Management kind of is an umbrella of how to manage it all and that was what was so attractive to me because it organized for me all the things that I felt were separate, and it was like, "No, you have to manage them all together and you have to have like a North Star and that kind of helps you gauge everything" and it, and it made it just made sense in my brain. (R2)

In fact, previous studies report that both of these aspects – paradigm shifts and holistic thinking – are explicit teaching objectives of HM trainers (Mann and Sherren, 2018).

Reinforcing these new mental models is the way in which HM embeds its approach into larger societal contexts. While unclear if the effect is directly or indirectly mediated by HM, the shift in ranchers' mental models under AMP-HM seems to accompany a sense of purpose and activism. For example, AMP-HM ranchers often connected their efforts to reduce external inputs and build more robust natural resource bases with mitigating climate change, building soil health, increasing biodiversity, and building highly local and regenerative agricultural systems. Early studies of HM similarly reported that adoption of HM increased farmers' awareness of biodiversity, causing them to incorporate it as a goal of their management (Stinner et al., 1997). This "sense of purpose" that AMP-HM ranchers feel above and beyond themselves likely entrenches their new mental models.

3.5.2. Ranchers increase adaptive capacity under AMP-HM to ranch viably in uncertain times

Decades of literature has documented that the ranching lifestyle is a primary motivation for ranchers to persist: maximizing profitability is not a primary motivation, and ranchers will often endure financial hardships (including taking off-ranch jobs) to maintain their ranches (Smith and Martin, 1972). The AMP-HM ranchers we interviewed were no exception. [emphasis added]

I guess that my passion is that I like challenges, and it's not about the money. I mean sure I want to be financially secure. But the passion is I mean, when you get the bug of ranching you want to ranch or be farming you want to grow... **Like if somebody gave me \$10 billion tomorrow and said, you don't need money anymore. I'd still ranch.** You know? I might go on a few more big vacations a year. But I wouldn't do a lot more different than I am now. (R3 - emphasis added)

While taking off-ranch jobs to subsidize their ranching lifestyles was reported by the majority of the CONV ranchers we interviewed, AMP-HM interviewees collectively went the opposite direction. Either they adopted AMP-HM as a strategy to prevent selling the ranch or taking off-ranch jobs, or to quit off-ranch jobs and reach their ultimate goal of full-time ranching. In other words, many of these ranchers have turned to AMP-HM *in order to ranch viably*. This is supported by previous literature, in which HM adopters attribute improved profitability to their AMP-HM approach (Stinner et al., 1997).

The types of common decisions made by AMP-HM ranchers – a culmination of their shifted paradigms and operationalized actions – suggest purposeful strategies to strengthen their adaptive capacity is crucial to their ability not only to continue ranching, but to ranch profitably and sustainably, amidst significant uncertainties. Adaptive capacity entails strategies that work at different times scales to increase short-term flexibility and longer-term adaptation, but synergistically increase ability to cope with uncertainties (Allen et al., 2011). Short-term flexibility is embedded in AMP practices themselves and in the ways in which they change on a day-to-day basis during the growing season. For example, stocking animals more densely in paddocks, rotating quickly, and increasing pasture rest periods results in AMP-HM ranchers using significantly less land at any given time, increasing flexibility to grass-bank forage across the ranch to hedge against unexpected drought. They often also make decisions and changes to each of these aspects of their grazing management on a day-to-day basis based on their observed outcomes, which reduces response time and increases flexibility of potential response options (Darnhofer et al., 2010). In combination, these AMP-HM ranchers have made operational shifts to proactively plan and *adapt* their management and operations in the long-term to increasing climatic and economic uncertainties. Common ranch enterprise shifts among our interviewees included shifting from cow-calf to yearlings, matching animal numbers to year-round forage capacity to reduce inputs, and diversifying their ranch operations (i.e., incorporating sheep and chickens, building on-ranch agro-tourism enterprises, etc). These shifts collectively worked to increase their spatial, temporal, and even financial mobility, allowing them the flexibility necessary to successfully adapt and reorganize in the face of ecological and economic challenges.

Many of the individual adaptation strategies reported by AMP-HM ranchers in this study are not new or novel. In fact, previous studies have recommended practices employed by our interviewees, like incorporating yearlings to improve temporal flexibility (Torell et al., 2010), using flexible stocking rates (rather than set, conservative stocking rates) to adjust to variable precipitation (Ritten et al., 2010), enterprise diversification (Joyce et al., 2013), incorporating smaller livestock to increase spatial mobility (Polley et al., 2013), or suites of combinations of these practices (Briske et al., 2015; Joyce et al., 2013; Kachergis et al., 2014). However, adoption of these proactive adaptation strategies remains notoriously limited among ranchers. For example, in a survey of 507 California ranchers, 24% reported incorporating pasture rest, and only 11% and 3% reported adjusting stocking rates and diversifying their livestock, respectively (Macon et al., 2016; L. Roche, 2016).

3.5.3. Limitations, implications and future work

Our small sample size limits the ability to understand if the features of AMP-HM ranchers and their management in our study are generalizable to the broader AMP-HM population (which is likely a small group overall). Our findings are largely complementary to prior studies of HM, but further research is needed deepen our understanding, namely studies including larger populations of AMP-HM ranchers to improve generalizability, studies including ranchers who've considered but failed to

adopt or chosen not to adopt AMP-HM to better understand barriers, and social-ecological studies which explicitly link ranchers' mental models and decision making processes to measured ecological outcomes. We hope to expand on the latter in our future work. Additionally, the role of gender is greatly understudied in rangeland sciences. Our interviews revealed some potentially telling linkages between gender, social norms, and rangeland management that deserve exploration in future research.

Lastly, future studies will need to include technical assistance providers and institutional actors (i.e., academics, rangeland consultants, and prominent rangeland organizations) who play a role in the social norms and agenda setting of rangeland management. This is critical because our results suggest that antipathy toward HM, likely by association with Allan Savory, has become a variable of importance. Ranchers we interviewed and reports from other studies show that above and beyond skepticism from their peers, AMP-HM ranchers have been subject to stigma from the academic community (Gosnell et al., 2019; Sherren & Kent, 2017). The intense criticism and rejection they've received from these actors has ostracized them from rangeland communities they desired to be a part of and even prevented them from publicly associating themselves with AMP-HM. This behavior is antagonistic and counteracts the current efforts to study and manage rangelands as social-ecological systems, where ranchers themselves are co-producers of knowledge. Preventing criticisms of Allan Savory and the Savory Institute (Nordborg, 2016; Sherren & Kent, 2017) from further damaging relationships with AMP-HM ranchers could be a first step in rebuilding these relationships. Rebuilding these relationships may also offer future opportunities to revisit the ecological outcomes of AMP-HM, especially because these ranchers seem motivated to submit their ranches to academic ecological monitoring.

3.6. Conclusions

Our in-depth interviews with AMP-HM ranchers in Northern California provide new insights about their mental models and associated decision making processes, including motivations, barriers, and catalysts for their management. We identified seven emergent themes from our interviews: 1) the HM decision making framework is a useful tool for ranchers to organize complexity; 2) AMP-HM ranchers use a series of strategies to increase adaptive capacity, including diversifying their herds and reducing external inputs; 3) AMP-HM ranchers view their approach as a process of iterative improvement, relying on a closed feedback loop of continued education, experimentation, and monitoring of outcomes; 4) like most ranchers, AMP-HM ranchers are constrained by systemic challenges like insecure land access and limited infrastructure; 5) AMP-HM ranchers face several unique challenges that may limit adoption, including a steep learning curve and institutional rejection that isolates them from important communities; 6) myriad motivations drive ranchers' transition to AMP-HM, all of which relate to their desire to ranch viably; and 7) there are several positive catalysts reinforcing AMP-HM, including low-stress livestock handling and seeing improved ecological and/or economic outcomes resulting from their management.

Our interviews suggest that AMP-HM's combination of training in "holistic" thinking, decision making framework, monitoring, and grazing management tools successfully shifts ranchers' mental models, creating new ways of "seeing" and thinking about their landscapes and their role in managing them. Among the ranchers we interviewed, this was often accompanied by a sense of purpose and activism, and a shift towards viewing their ecological and economic goals as reinforcing rather than opposing – leading them to focus on improving their soil health and ecological outcomes and reduce their inputs as their "new" profitability approach. Second, the collective decisions arising from

ranchers' shifted mental models align with strategies to strengthen adaptive capacity. This includes actions in their AMP grazing management such as adaptive rest and rotations and actions at the enterprise level, such as diversifying their herds to include more yearlings or smaller ruminants. These strategies work synergistically to improve AMP-HM ranchers' ability to ranch viably in the face of increasing ecological, economic, and social uncertainties.

Many of these emergent themes relate back to the core principles of HM, suggesting that HM-AMP offers a strategy for ranchers to both shift their mental models towards ones that involve more 'holistic,' systems based thinking, and to operationalize these models into on-the-ground actions that work to synergistically increase day-to-day flexibility and long-term adaptation. We identify the needs for future research, and suggest a way forward in rebuilding relationships between AMP-HM ranchers and the broader rangeland academic community.

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3.8. Tables

Table 1. Categories and example questions extracted from the semi-structured interview guide used for rancher interviews.

1. Ranch History and Characteristics	
Ranch History	Can you tell me about the history of your ranch?
Ranch Characteristics	- How many acres do you graze, and do you own or lease this land? - What other (if any) types of agricultural production take place on the ranch (besides beef cattle?) - What type of beef operation takes place on the ranch (e.g., cow-calf, stocker, finisher), and how many animals do you have?
2. Detailed Grazing Management Practices	
Detailed Grazing Management	- Can you please describe your grazing management? (<i>open ended</i>) <i>Follow up questions</i> - Do you rotate your cattle across your ranch? If so, how often, and how do you decide when to move them? - How does your grazing change seasonally? - Do you subdivide your ranch into smaller paddocks? If so, how many, what sizes, and how do you decide? - If you rotate your cattle, how much rest does each paddock receive? - What do you call your grazing management?
3. Ecosystem responses and feedbacks	
Ecosystem responses and feedbacks	- Do you manage specifically for any type of environmental outcomes? - Have you noticed any environmental changes on your ranch that you attribute to your grazing management? - What environmental responses do you seek when informing grazing management decisions (e.g., when to rotate animals, how long to rest pastures)? - Do you measure any of these outcomes, or have you had any monitoring done on your ranch?
4. Management motivations, barriers	
Motivations	- What motivated you to graze this way? - How did you learn about this grazing management strategy and what about it appealed to you? - Why do you prefer this grazing strategy?
Barriers	- What challenges do you face in your grazing management? - What barriers do you face that prevent you from reaching your grazing management goals?
5. Information networks and communities	

Information networks	• Where do you go when you have questions about grazing? ○ Do you consult with organizations, Cooperative Extension, or other institutions? ○ What other ways do you receive useful information that helps you in your grazing management?
Communities and neighbors	• Do you consider your grazing management to be different from others in the region? • Do you feel like your grazing management practices have impacted nearby ranches? • Have you experienced social challenges or negative reinforcement related to your grazing management?
6. Economics and resources	
Economics	• Is ranching your main occupation? ○ If not, what proportion of your income is on vs. off-ranch? • Do you have certifications that you find useful? • Have you relied on any grants or funding to help you achieve your desired grazing management or ranch goals?

Table 2. Ranch characteristics operated by interviewees. Quantitative characteristics were representatively grouped to protect ranchers' anonymity.

Rancher ID	Management category	Acres managed	Enterprises and ownership by acreage	Number and type of cattle
R1	AMP-HM	>10,000	• 1-5 • private and public leases	• >2000 • cow-calf + yearlings
R2	AMP-HM	1,000-5,000	• 1 • all privately owned	• 300-1000 • birth-finish
R3	AMP-HM	1,000-5,000	• 5-10 public + private leases • <500 acres privately owned	• 300-1000 • cow-calf + yearlings
R4	AMP-HM	5,000-10,000	• 5-10 public + private leases • <50 acres privately owned	• 1000-2000 • birth-finish
R5	AMP-HM	500-1,000	• 1-3 private leases • <200 acres privately owned	• 0-300 • cow-calf
R6	AMP-HM	5,000-10,000	• 1 • privately owned	• 0-300 • cow-calf
R7	AMP-HM	<500	• 1 • privately owned	• 0-300 • cow-calf
R8	CONV	<500	• 1-5 • private leases	• 0-300 • cow-calf
R9	CONV	>10,000	• 1-5 • private leases	• 2,500 • yearlings
R10	CONV	1,000-5,000	• 1 • privately owned	• 0-300 • cow-calf

Table 3. Grazing management characteristics of interviewed AMP ranchers. Quantitative characteristics were categorized to protect anonymity. Overall cattle stocking rate is calculated as the total AUs divided by the total grazed acres. Max stocking density is reported for ranchers who were able to estimate their maximum grazing intensity during the growing season. Rotation schedule and rest duration are averages for each season reported by the ranchers. NR = not reported

Rancher ID	Length of management (years)	# permanent pastures	# temporary paddocks	Overall cattle stocking rate	Max stocking density	Rotation schedule (days)	Rest duration (days)
R1	>20	25-50	>100	5-10 ac/AU	NR	Spring: 1-1.5 Dry: <10	Spring: 45 Dry: 90
R2	0-5	25-50	>100	5-10 ac/AU	75 AU/ac for <1 day	Spring: 1-2 Dry: varies	Spring: 30-40 Dry: 60-70
R3	10-20	25-50	>100	0-5 ac/AU	100 AU/ac for <1 day	Spring: <1-1 Dry: <30	Spring: 25 Dry: 180
R4	10-20	10-25	NA, rotates with horses	15-20 ac/AU	10 AU/ac for 2 days	Spring: 2-5 Dry: <21	Spring: 30 Dry: 90
R5	0-5	0-10	0-50	15-20 ac/AU	NR	Spring: 1-2 Dry: 14-30	Spring: 30-45 Dry: 45-70
R6	5-10	0-10	>100	10-15 ac/AU	20-50 AU/ac for 1 day	Spring: 1-4 Dry: <30	Spring: 30 Fall: 90-180
R7	0-5	10-25	>100	0-5 ac/AU	112 AU/ac for a few hours	Spring: 0.5 Dry: <20 days	Spring: 30 Dry: 60

Table 4. Illustrative AMP-HM (adaptive multi-paddock and holistic management) and CONV (conventional) rancher quotes categorized by emergent theme.

Theme 1: HM is a useful decision making framework for ranchers			
"I was so overwhelmed by all the things you have to think about to run a property, that I was searching for something to help me compartmentalize all that stuff, like the financial part, and the grazing planning part, and the land planning part. The reason why Holistic Management felt right to me is because those were all the pieces that I couldn't figure out how to work together. Yeah, like how do I manage the land? How do I manage the books? How do I manage the animals? The feed? And like so Holistic Management kind of is an umbrella of how to manage it all and that was what was so attractive to me because it organized for me all the things that I felt were separate, and it was like, "No, you have to manage them all together and you have to have like a North Star and that kind of helps you gauge everything" and it, and it made it just made sense in my brain. Like, they could have called it anything. Like I don't give a shit what it's called, but I just needed a way to organize the complexity of owning a property." (R2)			
Theme 2: Strategies for increasing adaptive capacity			
<i>Changing herd size & type (a)</i>	<i>Improving soil health to reduce external inputs (b)</i>	<i>Diversifying with smaller ruminants (c)</i>	<i>Flexible grazing management (d)</i>
"So '14, we had the worst drought ever. And I never want to be stuck in a position like that again. So I leave a lot more residual than I ever have. And like December 1st is my critical rain date. If we don't get an inch or two of rain by December 1st, I'm starting to sell animals." (R3)	"My ideal thing is I don't want to buy hay. I don't want to pay when I can go to animal grazing. That's the other reason to consider going to stockers is that if you're putting too much pressure on, you get rid of the animals and start building up the soils and building up the plant base." (R6)	"Our management with them [sheep], has been putting them in areas where we can't necessarily reach with the cows." (R2)	"My first trigger is when I get down to 60% of the forage, you need to move. With the steers, it's pretty much every day. So I just kind of go okay, this paddock was a little bit too small today, we left less than 60% of the forage. So we'll make the next paddock next week a little bigger and move them with the cows. It changes, you know." (R6)
Theme 3: Education, experimentation, and monitoring			
<i>Experimenting with grazing (a)</i>	<i>Monitoring outcomes (b)</i>	<i>Continuing education (c)</i>	<i>Experimenting beyond grazing (d)</i>
"We've tried different things, trying to understand how this best works...Early on, we tried to use shorter recovery periods during the grazing season. And it didn't produce bigger plants. I think we just weren't giving the plants enough recovery. But we were giving plenty of recovery in the dormant season. So we were seeing some good things, but not as much, so we've kind of shifted to a little bit longer or twice as long recovery periods during the growing	"When the NRCS guy would come out to monitor, I would sit out there with him and ask like, 100 questions, and then I got my report and I was like, "Oh, this is helpful." Like because I didn't know any of this. I didn't know what to look for." (R2)	"I talk to ranchers around the world...I talk directly to them or if I know them, go to a few conferences, not too many, the Ranching for Profit thing was kind of what I did for about five years. And that, that was a great network of ranchers. You know, hear about people, YouTube soil scientists from around the world." (R1)	"I have lots of plans and hopes to do some seeding, some like annual cover crop type seeding, and some soil inoculation, and some compost applications, and a whole bunch of other things, too." (R5)

season.” (R1)			
Theme 4: AMP-HM ranchers are constrained by systemic challenges			
<i>Insecure land access (a)</i>	<i>Debt/economics (b)</i>	<i>Labor (c)</i>	<i>Infrastructure (d)</i>
"Since I've had it I've been trying to build up— just try and let plant material grow and then try and knock some down. It gets tough because it's in the context of other grazing properties I have that are totally unstable. And so the grazing has not been to the level that I would like it to be." (R5)	"They're, they're like fighting each other, the amount of cattle that I need to be able to pay my bills is forcing me to make decisions that are compromising or slowing soil health." (R3) "I mean, the economics are really tough. For ranching, especially as everything gets more and more expensive. And if you're not doing well financially, then it's hard to innovate and put that time towards innovation." (R4) "We just, we have so much debt right now, and there's just no way it's gonna happen. So you kind of limp along." (CONV rancher)	"There's a lot more busy work. So I mean, there's a certain part of kind of going, "God, it's a boat load of work to do it this way." But what you get out of it is significant greater, like anything. But you know, you kind of look at some of my neighbors and say, "Well, that's kind of nice. You just turn your cows out and they eat until it's dirt and then they start feeding them and go down to Baja or whatever, This definitely takes more day to day attention" (R6) "I think I would say that a lot of people don't want to deal with the labor of rotational grazing" (CONV rancher)	"For us, if we had a permanent water system, then a little more cross fencing, then it would be a more proactively managed regenerative situation" (CONV rancher) "And it was a lot of work because the fences were a mess. And so they wouldn't get through the electric fence they'd get through the ends. And then everywhere we went, we had to set up chargers and ground rods and all that stuff and just go field to field. Now I have a massive charger I finally bought this year up here and now it's like, this is easy. Once you have the infrastructure.” (R7)”
Theme 5: Unique challenges			
<i>Institutional disapproval (a)</i>	<i>Non-contiguous leases (b)</i>	<i>Learning curve (c)</i>	<i>Small communities of practice (d)</i>
"It can be frustrating for sure. Even just covering certain topics at the summit, or at different meetings or conferences or events is just like pulling teeth I feel like. Around grazing management. And in conversations about the development of grazing plans, they're just like "Don't have prescribed grazing plans." Seriously some NRCS people are just like, "No, don't put in a rotation, there's no benefit to that." So the prescription can literally be season long." (R5)	"I wish I had a larger and more stable land base to demonstrate on. Like if my other grazing properties were more stable and consistent... I feel like I could be so much further and really be able to like, show some stuff" (R5)	"I'd say learning curve is a challenge, when you don't have anyone on your team that's done it before where you're all kind of learning together." (R2) "So, the cons are that, you know, you make a lot of mistakes cause you're trying a lot of new things. But you get better at, you know, the mistakes you're making are generally small." (R1)	(discussing the possibility of being able to market and distribute beef collectively), "That would mean your whole region needs to be like I am, but I am THE only holistic grazer.” (R2)

Theme 6: Idiosyncratic motivations for AMP-HM			
<i>Philosophical (a)</i>	<i>Ecological (b)</i>	<i>Economic (c)</i>	<i>Connectivity to land and animals (d)</i>
"But it's something that I'm just driven to do it, I need, I think we need as a society to kind of figure these things out, as we manage so much of the Earth's surface is rangeland, that's what we're doing so, what are we doing, if we're not trying to do it as well as we can?" (R1)	"I'm trying to create more awesome soil. And then that's going to ultimately grow more grass, and then ultimately convert that to more protein that I can sell." (R3) "It's the ecosystem we need to manage, not the pastures. And I used to think as a cattleman that I thought I was a, you know, grass grower and a water steward, and now it's really about the land and the soil. You know, you can do whatever you want everywhere else and if you don't have a living soil, you're out of luck." (R6)	"I built the ranch at the same time I was doing my day job. I was moonlighting like crazy. I was at a breaking point where I was either gonna get a divorce or die of a heart attack. And I grew up on the ranch where we were basically broke, you know, did it so you can make it again, do it again the next year. I never want to be like that. So to leave a safe secure job where I had a 401k and great benefits all that was a big deal." (R3) "So I think that what motivated us to do it more intensively was because we want it to improve our soils and improve our plants and improve our weight gains on our our animals, because we sell meat." (R4)	"I enjoy it. I like going out and being with the cows twice a day, right? It just chills me out. And there's no better sound than like, when they're all kind of, you know, ready to go and you move it up. And then it's just the silence of them eating—250 cows eating. I could just lie down in them. There's no better... so I just really like it personally, you know, and so that's my holistic framework." (R7)
Theme 7: Positive catalysts reinforcing AMP-HM			
<i>Leveraging opportunistic funding (a)</i>	<i>Techniques and Technologies (b)</i>	<i>AMP-HM Networks (c)</i>	<i>Changing mental models (d)</i>
All AMP-HM ranchers have leveraged funding opportunities from bodies such as USDA, California Fish and Wildlife Service and CDFA to fund flexible infrastructural improvements (i.e., removing interior fencing, improving perimeter fencing, developing mobile water sources), allowing them to more easily and effectively implement AMP-HM.	<u>Low-stress livestock handling</u> "From a stockmanship standpoint, it's been kind of fun. I've been really using low stress livestock handling principles for the last two years, and the difference I see in the way my cattle handle is phenomenal. Seeing them stick together more, it's just been cool to see them graze differently." (R5) <u>PastureMap</u> "I knew we weren't utilizing lots of pieces that we could. So when I took the classes and started holistically managing, I think it was only like five or 600 acres that I would say we managed holistically, and I plugged them into PastureMap to help make sure we didn't go back too early." (R2)	"But the literature on this was pretty scant. I mean, you know, you had your Savory, you had your Joel Salatin but there just was not any guidance. Then [names redacted] introduced me to a community which gave me more confidence in what I was doing, and more impetus to double down on what I was doing. But it's kind of like you're working on your research and then all of a sudden you come into some colleagues and that kind of steps it up just because there's a community that validates what you're doing. Seeing the success, hearing the stories, and just not feeling you're completely alone. It's more on an inspirational basis" (R6)	"And once you finally learn how to see that stuff, that's the thing is my eye is changing. I'm starting to see stuff that I didn't, that I would have never noticed before." (R2)

Conclusion

From the beginning, I aimed to conduct dissertation research that was timely, interdisciplinary, and that contributed to furthering collective understanding of grazing management and SOC sequestration on rangelands to address the challenge of my generation: climate change. Core to my work was centering ranchers, because beyond academia, the success of efforts to bolster working lands as a natural climate solution depends on ranchers as applied agents of change, despite the complex challenges they currently face. I strived to strike a balance in my work, linking rigorous, novel scientific research with an applied, rancher-forward and policy relevant approach. In an effort to meet these goals, I situated this dissertation work at the nexus of rangeland ecology, soil biogeochemistry, and rancher sociology. Three basic questions drove my dissertation research: 1) How do we measure SOC on rangelands to maximize power, accuracy, and efficiency to detect and quantify SOC changes?; 2) How can adaptive multi-paddock grazing management be used to increase SOC sequestration on California rangelands, and; 3) How are ranchers' mental models shaped by holistic management, and how does this translate to their on-the-ground AMP grazing management practices?

Data on SOC sequestration is only as reliable as the sampling and measurement methods used to collect them. However, despite decades of soil C research, there remain critical gaps in our understanding of how best to measure SOC, including measurement requirements of different landscapes arising from differences in spatial heterogeneity, and other major sources of error. For example, though rangelands are generally accepted as having high variability compared to other managed landscapes, little is known about the spatial heterogeneity of SOC in order to inform properly powered sampling campaigns. In Chapter 1, we found that the spatial heterogeneity of SOC is a primary obstacle to accurately measuring SOC changes. Compared to error arising from laboratory analysis or compositing, spatial heterogeneity of SOC on crop and rangelands is the primary driver of uncertainty when measuring SOC. Rangelands were twice as heterogeneous as croplands across our samples in California, which makes accurately detecting and quantifying SOC changes on rangelands more challenging. We found that error associated with lab analysis was small in general, but there are differences in precision and accuracy across different dry combustion instruments. We also evaluated the impact of compositing, or combining multiple soil samples to reduce analysis costs, and found that compositing can mitigate or exacerbate the relative contributions to uncertainty from spatial heterogeneity and analytical variability. In our analyses, we demonstrate that compositing is most effective when spatial heterogeneity is high and lab analysis is precise, but that researchers should never fully composite, and should aim to minimize compositing when lab analysis is imprecise. Lastly, conclusions of SOC change based on conventional statistical methods such as the Student's t-test and its relatives (i.e., ANOVA) may not be reliable when sample sizes are small or when SOC is not normally distributed. These results have several important implications, especially in light of rapidly developing SOC monitoring protocols to generate the sale of C offsets on crop and rangelands. First, many current sampling designs – both for research and C markets alike – collect too few samples to detect and quantify SOC sequestration on heterogeneous landscapes, especially rangelands. Attempting to measure or verify SOC sequestration using too few samples, poor sampling design, imprecise laboratory instruments, or inappropriate statistical analysis can therefore undermine climate change mitigation goals. We suggest several ways that SOC measurement can be improved, including collecting and using *a priori* spatial heterogeneity information to calculate necessary sample sizes, generally taking many more samples than is currently common, and using nonparametric statistical methods. These improvements will increase reliability of SOC measurements, ensuring accurate research and benchmarking against climate goals.

In Chapter 2, I applied the lessons learned from Chapter 1 to conduct an on-ranch study comparing the SOC stocks of AMP and conventionally grazed ranches at four paired sites across northern California. Results indicate that at three of four sites, AMP grazed ranches contained significantly greater SOC stocks in surface soils, while two contained significantly greater SOC down to 100cm. The largest differences in SOC stocks were found in the MAOM fraction, which indicates that SOC accumulation from AMP grazing may be persistent and important for helping to meet climate change mitigation goals. Though statistical analysis is needed, our data also suggest that AMP grazing may mediate SOC changes by reducing bare ground and shifting plant community composition. Despite California's millions of acres of rangelands, long history of grazing, and emphasis on natural climate solutions, this was the first study of its kind to study the impacts of different grazing management strategies on SOC. I hope that this catalyzes research interest in this area to fill lingering gaps, including site-specific requirements and limitations for grazing management-induced SOC changes.

Finally, in Chapter 3, I gleaned how Holistic Management and AMP grazing work to synergistically shape new mental models among ranchers. First, AMP-HM shifts ranchers' mental models through its emphasis on monitoring combined with increased interaction with their land and animals, which changes the ways ranchers "see" and understand their landscapes and resulting outcomes of their management. Second, AMP-HM increases ranchers' agency to operationalize these new mental models through its decision making framework and trainings. These new mental models manifest in a suite of common grazing management and ranch enterprise strategies that hold promise in helping ranchers approach strengthening adaptive capacity and succeed in a future of uncertainties. This includes actions in their AMP grazing management such as adaptive rest and rotations and actions at the enterprise level, such as diversifying their herds to include more yearlings or smaller ruminants. AMP-HM ranchers also described how their profitability strategies had shifted from "productivist" approaches, where economic and ecological goals were often at odds, towards an approach that emphasized improving their natural resources bases and reducing inputs, ultimately fostering alignment between their economic and ecological goals and improving profitability. Despite the successes reported by adoptees in this study, it remains true that AMP-HM adoption among ranchers is low in general. Our interviews reveal that AMP-HM ranchers face unique constraints that could partially explain low adoption, including steep learning curves and feelings of ostracization from important academic rangeland communities. Future work will be needed to deepen our understanding, including expanding in-depth interviews to a larger population of AMP-HM ranchers to improve generalizability, to connect these mental models to measured ecological outcomes, and to unpack potentially telling linkages among rangeland management, gender, and social norms.

I collected more than 2,000 soil samples on grazed California rangelands over the course of my dissertation research, which laid the foundation for a lifetime of research on grazing management and SOC sequestration on rangelands. I look forward to collecting thousands more as I look to the future of my work. There are several key research avenues that I view as crucial next steps. First, the potential for grazing management to sequester SOC on semi-arid rangelands remains chronically understudied. Further, the majority of studies have been conducted on small experimental plots, and thus are not well representative of the real-life scales, challenges, and timeframes of grazing management and SOC change on working rangelands. Often, they are also informed by sampling designs that are underpowered, limiting reliability. In my future work, I plan to expand the scope of my sampling sites to cover a wider gradient of rangelands in the western United States and to lengthen the duration of sampling to better understand SOC changes over relevant timescales. These steps will be important to better understanding where and when AMP grazing may provide opportunities to sequester SOC

on working rangelands. Second, I plan to link expanded on-ranch results with lab experiments to better understand the mechanistic basis for *how* AMP grazing works to increase SOC in some cases. This is the next step for linking SOC outcomes to specific attributes of AMP grazing, and grazing management in general, which is necessary for tailoring site specificity. I believe these next steps lay the immediate groundwork for ultimately building verified, reliable, spatially explicit, and mechanistically grounded models for estimating and predicting SOC change on rangelands with management interventions like grazing. Long-term model development will alleviate significant barriers, including expensive and destructive SOC measurement, preventing the understanding and use of working landscapes like rangelands as natural climate solutions. I look forward to building on this work to meet my long term research goals of exploring the interactions between grazing management, working rangelands, and rancher decision making to aid in SOC sequestration and climate change mitigation, and to building better relationships between ranchers and academics to link their rural livelihoods to healthy rangeland ecosystems.