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Managing cropland and rangeland for climate mitigation: an expert elicitation on soil carbon in California

Charlotte Y. Stanton[1] · Katharine J. Mach[2] · Peter A. Turner[1] · Seth J. Lalonde[1] · Daniel L. Sanchez[1] · Christopher B. Field[3]

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Abstract Understanding the magnitude of and uncertainty around soil carbon flux (SCF) is important in light of California's efforts to increase SCF (from the atmosphere to soils) for climate change mitigation. SCF depends, to a great extent, on how soils are managed. Here, we summarize the results of an elicitation of soil science and carbon cycle experts aiming to characterize understanding of current SCF in California's cropland and rangeland, and how it may respond to alternative management practices over time. We considered four cropland management practices—biochar, compost, cover crops, and no-till—and two rangeland management practices, compost and high-impact grazing. Results across all management practices reveal underlying uncertainties as well as very modest opportunities for soil carbon management to contribute meaningfully to California's climate mitigation. Under median scenarios, experts expect all the surveyed management practices to reverse SCF from negative to positive, with direct carbon additions via biochar and compost offering the best potential for boosting the soil carbon pool.

1 Introduction

Continuing its streak of nation-leading climate action, California passed legislation in 2016 to reduce its annual greenhouse gas emissions 40% below 1990 levels by 2030 (California Senate

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✉ Charlotte Y. Stanton
charlottestanton@gmail.com

[1] Department of Global Ecology, Carnegie Institution for Science, 260 Panama Street, Stanford, CA 94305, USA

[2] Department of Earth System Science, Stanford University, 473 Via Ortega, Stanford, CA 94305, USA

[3] Stanford Woods Institute for the Environment, Stanford University, 473 Via Ortega, Stanford, CA 94305, USA

2016). If achieved, this reduction—equivalent to 171 $MtCO_2e$ annually—would triple the emissions reductions slated for 2020 (The 2017 Climate Change Scoping Plan Update 2017; California Environmental Protection Agency Air Resources Board 2011). To achieve such a significant reduction, California policymakers are looking to sectors whose climate mitigation potential may be untapped, including natural and working lands, which encompass forests, cropland, rangeland, and wetland. Whereas the potential for natural and working lands to offset emissions may be theoretically large, relying on them for climate mitigation will be complex.

Epitomizing the complexity associated with managing California's land for climate mitigation are soils. Globally, soils store three quarters of the carbon contained in the terrestrial biosphere, where mean carbon residence time exceeds a millennium (He et al. 2016; Paustian et al. 2016). Despite its prospects for longevity, however, soil carbon can decrease when native vegetation is converted to managed land uses (Hicks Pries et al. 2017; Paustian et al. 2016). Worldwide, land-use conversion has depleted one quarter to one half of the soil carbon in the top 1 m of cropland and rangeland soils (Brovkin et al. 2004; Houghton et al. 1983; Koteen et al. 2011; Scharlemann et al. 2014).

The historical depletion of the world's soils has illuminated their potential among California policymakers as a possible cost-effective sink for CO_2 emissions. In addition to climate mitigation, boosting SCF may also provide other incentives for farmers, including improved soil health, higher crop yields, and greater crop resilience (Brown and Cotton 2011; Chabbi et al. 2017; Conant et al. 2001; Lal 2004; Lal et al. 2007; Paustian et al. 1997; Ryals et al. 2015; Ryals et al. 2014). Management practices typically influence SCF by changing the ratio of soil carbon inputs to outputs (Bronick and Lal 2005; Paustian et al. 2016). Four practices that managers commonly use to increase SCF in cropland soils are: biochar and compost amendments, winter cover crop rotations, and no-tillage agriculture, with each practice leveraging a different input or output. For instance, biochar and compost applications increase inputs of recalcitrant and labile carbon, respectively. Annual cover crop rotations add above and below ground biomass through residues and root decay, while no-tillage production systems retain surface residues and limit soil disturbance (Du et al. 2017; Lal 2002, 2016; Olson et al. 2014; Ryals and Silver 2013; Smith 2016). Alternative management practices aimed at increasing rangeland carbon stocks include compost applications and high-intensity grazing, which can stimulate the production of fine, shallow roots (Chen et al. 2015). Nevertheless, there remains great uncertainty in the degree to which these practices affect SCF and their subsequent impact on stocks (Stewart et al. 2009; Zhang et al. 2012).

Constraining the uncertainty in soil management is important if emissions from soils will be reliably accounted for in climate mitigation plans and policies. But the process-based models that are commonly used to assess landscape-level soil carbon stocks have a number of shortcomings that can hamper real-time decision-making, including missing data and processes, mismatched scales, and enormous spatial heterogeneity between and within study sites (Ogle et al. 2010; Scharlemann et al. 2014). By building from and complementing available evidence, expert assessment can aid decision-making using tools that are readily available (Stanton et al. 2016). Prominent among such tools is expert elicitation, which documents the subjective probability judgments of experts on an uncertain quantity in a way that minimizes expert bias. Importantly, expert elicitation is not an alternative to research and analysis. But where the state of knowledge is incomplete in supporting ongoing decision-making, it is a well-established method using the best available evidence and expert judgments about it to support policy. Ensuring a valuable contribution from expert elicitation requires careful attention to potential cognitive biases in protocol design, which can build from decision analysis methods developed and vetted over decades (Morgan 2014; Wiser et al. 2016).

Here, we present the results of an expert elicitation survey aimed at characterizing the magnitude of and uncertainty around present-day and future SCF in California's cropland and rangeland, and the expected effects of alternative management practices on SCF over time. Because California's cropland and rangeland together account for approximately 25% of all land in the state, their management for climate mitigation could have a potentially sizeable influence on the state's carbon balance (University of California Agricultural Issues Center 2009). To quantify the potential influence of soil on the state's carbon balance, we juxtapose the expert-elicited probabilities of future SCF alongside California's draft plans to manage approximately 4047 additional hectares each year of cropland and rangeland for climate mitigation through 2030 (The 2017 Climate Change Scoping Plan Update 2017).

2 Methods

2.1 Online survey

The survey was administered through an online platform developed by near zero (http://www.nearzero.org). The survey entailed numerous rounds of review, testing, and revision. Reviewers included a core survey design team and a select group of external specialists. The survey was distributed to experts via personalized web links on January 25th 2017. Two separate waves of personalized reminders were sent before the survey finally closed on February 10th 2017, after which experts were asked to clarify their responses as necessary.

2.2 Survey scope

The survey focused on conventionally managed cropland and rangeland in California. Of California's approximately 40.1 Mha of land, approximately 4.5 Mha are cropland and 5.7 Mha are rangeland (University of California Agricultural Issues Center 2009). Conventionally managed cropland refers to row or field crops (e.g., corn, alfalfa, hay, and vegetables) that are tilled. Conventionally managed rangeland refers to grass-dominated pastures that are moderately grazed (Holechek et al. 2003).

The goal for this survey was to gain insight into the magnitude of and uncertainty around soil carbon in California's cropland and rangeland over time. Accordingly, the survey consisted of six multi-part questions that asked for expert judgment on soil carbon stock and flux in a typical hectare of California cropland and rangeland. Soil carbon stock was specified as the amount of carbon (inorganic + organic) contained in a hectare of land to 1 m depth expressed in $tCha^{-1}$. SCF, as defined earlier, was specified as the net annual change in soil carbon stock, including all forms of carbon, expressed in $tCha^{-1}yr^{-1}$. A transfer of carbon out of the soil pool was specified as a negative flux while a transfer of carbon into the soil was specified as a positive flux. Individual estimates of present-day average stock and flux were derived from five expert-specified subjective probabilities: a minimum value such that there is a 5% probability that the true average falls below this value (5th percentile), second lowest, middle, and second highest values represent the 25th, 50th, and 75th percentiles, respectively, and a maximum value such that there is a 5% probability that the true value falls above this value (95th percentile). Experts were then asked to estimate the possible effects of management practices on SCF. Because our analysis centers on potential changes in SCF over a 50-year time horizon, respondents estimated annual SCF at four points in time: today, 1 year from today, 10 years from today, and 50 years from today for each management practice. At each of these points in time, experts estimated minimum, median, and maximum values, which we aggregated into a pooled estimate for each management practice (Oakley 2017).

The survey encompassed five unique management practices: biochar, compost, cover crops, and no-tillage for cropland; compost and high-impact grazing for rangeland (Table 1). For the practices that involved a biomass amendment, experts were given the precise amount of carbon in the amendment (based on published values) so that expert judgments would be building from the same basis, increasing comparability. The biochar intervention added 20 t of biochar per hectare (containing 10 tC) every 5 years (Stavi 2012). The compost intervention added 20 t of compost per hectare (containing 5 tC) annually (Ryals et al. 2015). The cover crop intervention planted an annual rotation of a winter cover crop mix (e.g., winter peas, common vetch, and rye containing 2.5 tC) (Mitchell et al. 2015; Thomas and Chaney 2010). The compost intervention on rangeland, as on cropland, added 20 t of compost per hectare (containing 5 tC) annually, and high-impact grazing was defined as low-frequency, high-intensity grazing (e.g., 200 cow-calf pairs per hectare annually for approximately 12 h) (Conant et al. 2017; Conant et al. 2001; Loeser et al. 2007; Ryals et al. 2015).

Throughout the survey, experts were instructed to assume that global mean temperature increase stabilizes at 2 °C above pre-industrial levels by 2100, the upper limit of the Paris Agreement. Like the carbon levels involved in the management practices, constraining global temperature increase improved comparability across expert judgements and reduced the number of variables relevant for future outcomes.

2.3 Expert respondents

The success of an expert elicitation survey depends on the credibility of its respondents. Given the focus of our survey on soil carbon in California cropland and rangeland, we targeted experts in relevant fields, including biogeochemistry, soil science, conventional agriculture, conservation agriculture, rangelands, the carbon cycle, California ecosystems, and climate change. The International Soil Carbon Network (http://iscn.fluxdata.org/) provided assistance in identifying experts.

2.4 Implications of alternative cropland and rangeland management practices through time

To evaluate the magnitude and uncertainty of SCF over time, we analyzed five points for each management practice. The points correspond to the 5th, 25th, 50th, 75th, and 95th percentiles of the pooled distribution of experts' probability density functions. To

Table 1 Surveyed management actions and baseline management for California cropland and rangeland

Management action	Baseline management
Cropland	Conventionally managed cropland refers to row or field cropland that is tilled. Examples of row and field crops in California include corn, alfalfa, hay, and vegetable crops. Experts were asked to assume that global mean temperature increase stabilize at 2 °C above pre-industrial levels by 2100.
1 BIOCHAR: 20 tons per hectare added every 5 years over a 50-year time horizon. The biochar is 50% carbon, so 10 tC per hectare are added every 5 years. Experts estimated annual soil carbon flux at years 1, 10, and 50, including the carbon in the biochar.	
2 COMPOST: 20 tons per hectare added annually over a 50-year time horizon. The compost is 25% carbon, so 5 tC per hectare are added per year. Experts estimated annual soil carbon flux at years 1, 10, and 50, including the carbon in the compost.	
3 WINTER COVER CROPS: defined as a mix of winter peas, common vetch, and rye that is seeded before the winter rains and left to decompose, are planted annually. The mix has an average aboveground biomass of 5 t per hectare (or 2.5 tC per hectare). Experts estimated annual soil carbon flux at years 1, 10, and 50, including the carbon in the cover crops.	
4 NO-TILL: Introduced to conventionally managed cropland and maintained as such over a 50-year time horizon. Experts estimated annual soil carbon flux at years 1, 10, and 50.	
Rangeland	Conventionally managed rangeland refers to grass-dominated pastures that are moderately grazed. Experts were asked to assume that global mean temperature increase stabilizes at 2 °C above pre-industrial levels by 2100.
1 COMPOST: 20 tons per hectare added annually over a 50-year time horizon. The compost is 25% carbon, so 5 tC per hectare are added per year. Experts estimated annual soil carbon flux at year 1, 10, and 50, including the carbon in the compost.	
2 HIGH-IMPACT GRAZING: defined as low-frequency, high-intensity grazing. Introduced to conventionally managed rangeland and maintained over a 50-year time horizon. Experts estimated annual soil carbon flux at years 1, 10, and 50.	

examine the implications of these scenarios for California's emissions reduction goal, we multiplied the amount of land the state plans to convert to alternative management by 2030 (4047 $hayr^{-1}$ each of cropland and rangeland) by the average change in SCF between 2020 and 2030 to arrive at the carbon sink potential of converted lands in 2030. We then calculated the share of CO_2 sequestered in 2030 as a percentage of the state's target of 171 M fewer tCO_2eyr^{-1} by then (The 2017 Climate Change Scoping Plan Update 2017).

3 Results

We distributed the survey to 74 experts and received 16 completed surveys, a 22% response rate.[1] The top three fields of expertise among respondents are biogeochemistry, soil science, and the carbon cycle. The response rate was perhaps limited by the survey's geographic focus on California. At the same time, the 16 participating experts span a range of disciplines and perspectives, which is consistent with best practices for expert elicitation (e.g., Kriegler et al. 2009; Zickfeld et al. 2010; McKellar et al. 2017). Table S1 lists the names and affiliations of respondents; Fig. S1 shows the distribution of their expertise across all relevant fields.

Experts' individual and aggregated estimates of current carbon stock and flux are shown in Figs. 1 and 2. The experts' pooled estimate (5th to 95th percentiles) of existing cropland carbon stock ranges from 14.56 to 170.62 tCha^{-1} and annual SCF ranges from − 1.75 to 4.19 tCha^{-1}yr^{-1}. For rangelands, existing soil carbon stock ranges from 27.51 to 169.42 tCha^{-1} and annual SCF ranges from − 0.9 to 1.99 tCha^{-1}yr^{-1}. Observational and modeled carbon stock values in similar climatic zones fall within these ranges indicated by the surveyed experts (Lugato et al. 2014; Martín et al. 2016; Parras-Alcántara et al. 2015).

Pooled estimates of expert-specified management effects on SCF over time are shown in Figs. 3 and 4 with summary statistics delineated in Tables 2 and 3. Across cropland and rangeland soils, experts anticipate that conventional management will result in increasingly negative SCF over time. By contrast, across all the management practices on both cropland and rangeland, experts anticipate that alternative practices will bolster soil carbon stocks beginning in the first year of management and continuing over the next 50 years—results which are consistent with current understanding of soil carbon response to disturbance and land-use change (Guo and Gifford 2002).

In the median scenario for cropland soils, the pooled estimates indicate that biochar has the greatest potential to enhance soil carbon stocks (Fig. 3). Here, experts suggest that biochar amendments may increase the size of the soil carbon pool by 0.12 tCha^{-1}yr^{-1} within the first year of management, relative to conventional practices (i.e., no biochar), which is expected to be − 0.07 tCha^{-1}yr^{-1}. After 10 years of biochar, SCF could increase by 0.28 tCha^{-1}yr^{-1} above the SCF expected in conventional agriculture of − 0.08 tCha^{-1}yr^{-1}. Respondents also indicated that compost additions could increase the size of the soil carbon sink by 0.11 tCha^{-1}yr^{-1} in the first year of management and double to 0.22 tCha^{-1}yr^{-1} after 10 years. Relative to biochar and compost, the anticipated median effects of no-till and cover crops in cropland soils are modest. No-till is expected to result in a median SCF of 0.03 tCha^{-1}yr^{-1} after the first year of management and 0.02 tCha^{1}yr^{-1} after 10 years of management, in both cases representing a 0.1 tCha^{-1}yr^{-1} increase in SCF relative to median expectations for conventional cropland. This modest response is consistent with the literature, which suggests minimal SCF potential from no-till agriculture (Powlson et al. 2014). According to the median estimates, cover crops are expected to have a slightly smaller effect in the short term and slightly larger effect in the medium to long term with an 0.07 tCha^{-1}yr^{-1} increase in SCF compared to conventional agriculture after the first year of management, increasing up to 0.09 tCha^{-1}yr^{-1} after 10 years. Relative to values reported in the literature, experts underestimated the potential of cover crops to change carbon stock, which may be due to

[1] One completed survey was dropped from the sample because of self-reported lack of expertise on soil carbon stock and flux in cropland and rangeland.

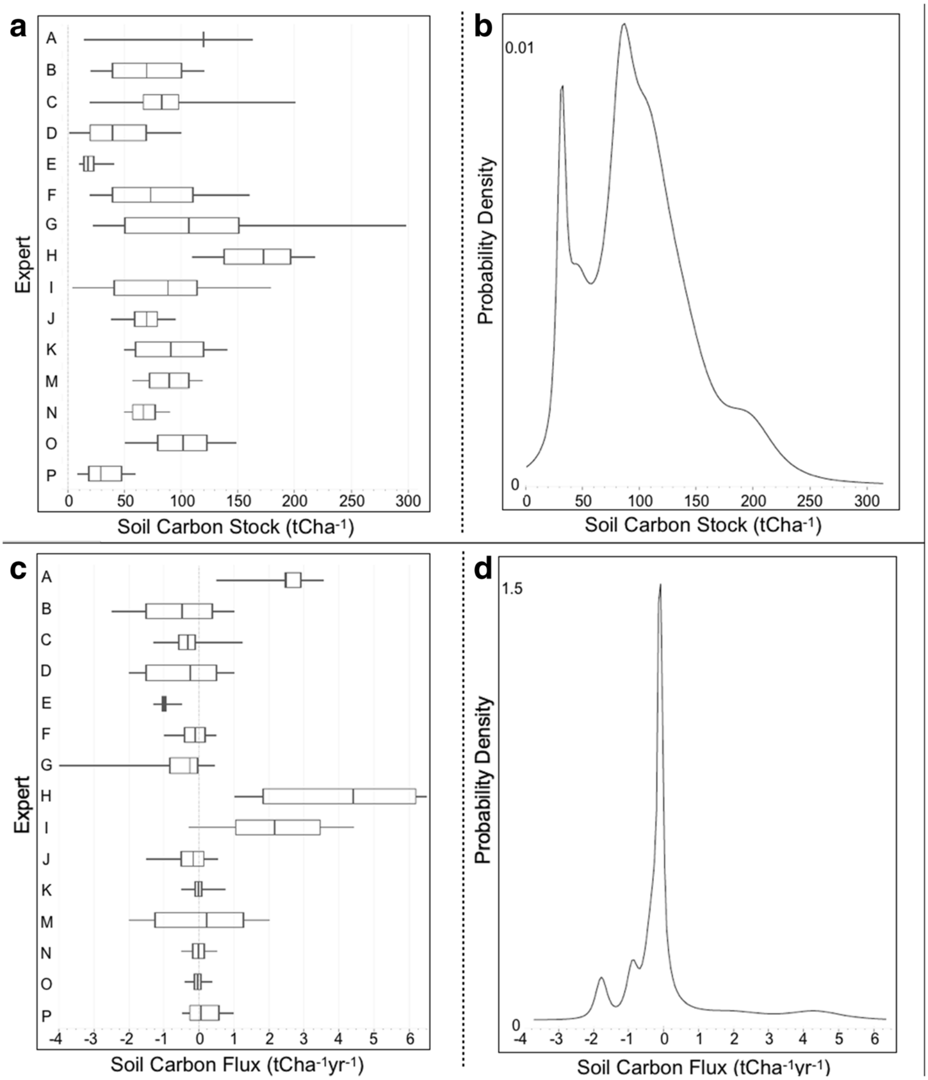

Fig. 1 Individual and pooled estimates of carbon stock and flux to 1 m depth in a typical hectare of California's conventionally managed cropland. Panels **a** and **c** show experts individual responses, where the lowest value represents the minimum value such that there is a 5% probability that the true average falls below this value (the 5th percentile); the second lowest, middle, and second highest values represent the 25th, 50th, and 75th quartiles respectively; and the highest value represents the maximum value such that there is a 5% probability that the true value falls above this value (the 95th percentile). Panels **b** and **d** show the pooled distribution across experts, where the solid line represents the aggregated equally weighted distribution derived from the 5th, 50th, and 95th probabilities specified in (**a**). The median value in the distribution is 77.60 $tCha^{-1}$ for stock and − 0.04 $tCha^{-1}yr^{-1}$

substantial heterogeneity in cover crop species and mixes as well as differences in soil sampling depth across available studies (Poeplau and Don 2015).

In the median scenario for rangeland soils, the pooled estimates indicate that compost could increase the soil carbon pool by 0.77 $tCha^{-1}yr^{-1}$ after the first year of management. This was the greatest absolute SCF response across all the management practices we surveyed in both

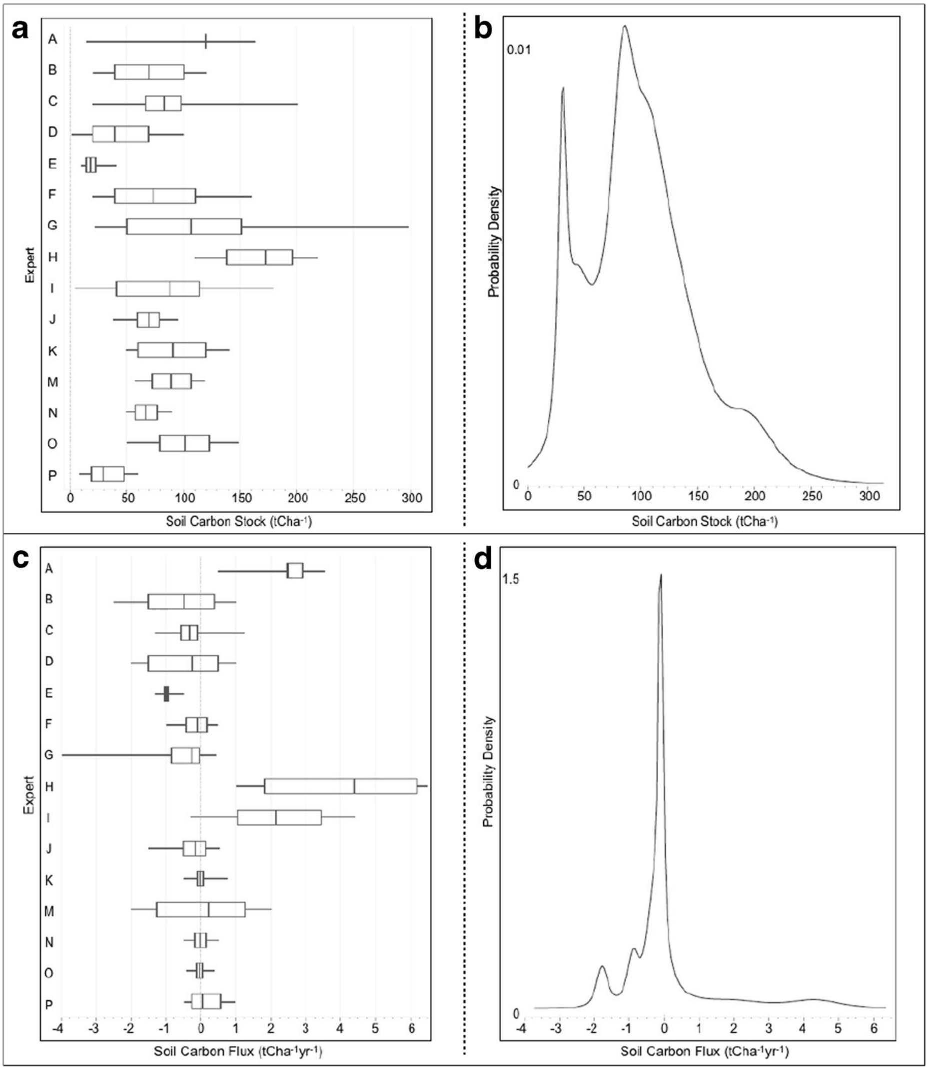

Fig. 2 Individual and pooled estimates of carbon stock and flux to 1 m depth in a typical hectare of California's conventionally managed rangeland. Panels **a** and **c** show experts individual responses, where the lowest value represents the minimum value such that there is a 5% probability that the true average falls below this value (the 5th percentile); the second lowest, middle, and second highest values represent the 25th, 50th, and 75th quartiles respectively; and the highest value represents the maximum value such that there is a 5% probability that the true value falls above this value (the 95th percentile). Panels **b** and **d** show the pooled distribution across experts, where the solid line represents the aggregated equally weighted distribution derived from the 5th, 50th, and 95th probabilities specified in **a**. The median value in the distribution is 79.64 $tCha^{-1}$ for stock and 0.02 $tCha^{-1}yr^{-1}$

croplands and rangelands. Further, experts expected that after 10 years, the SCF on compost-amended rangelands will rise to 0.91 $tCha^{-1}yr^{-1}$ and decrease to 0.61 $tCha^{-1}yr^{-1}$ after 50 years. The experts indicate negligible potential SCF effects driven by high-intensity grazing, citing scant evidence and system-dependence, although because there were no respondents who self-reported themselves as rangeland soil experts, these results should be interpreted with caution.

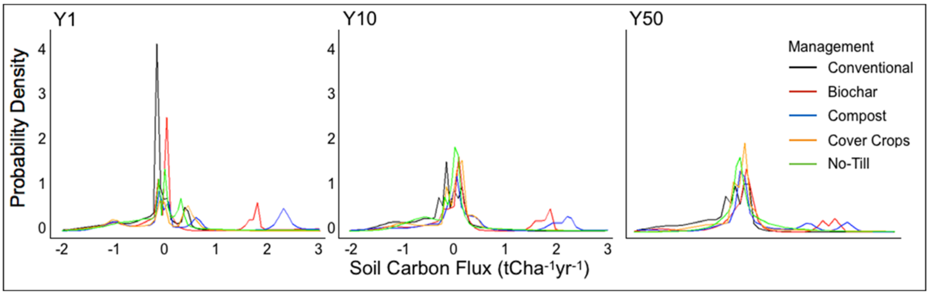

Fig. 3 Pooled estimates of expert-specified soil carbon flux under alternative management practices in a typical hectare of California's conventionally managed cropland over time. The lines represent, for each management practice, the aggregated equally weighted distribution derived from the 5th, 50th, and 95th probabilities specified at years 1, 10, and 50

The implications of these results for California's 2030 target of reducing GHG emissions by 171 $MtCO_2eyr^{-1}$ are shown in Tables 2 and 3. Considering that the state intends to enroll 10,000 $acyr^{-1}$ (4047 $hayr^{-1}$) of managed lands into climate service through 2030, our results suggest that none of the management practices evaluated can have a meaningful impact on the emissions goal set by California policymakers. Only one practice, compost amendments to rangeland soils, would account for more than a quarter of a percent of the 2030 goal (0.42%). Under the median scenario of experts' estimates, cropland soils treated with biochar, compost, no-till, or cover crops could contribute 0.08, 0.06, 0.01, or 0.03% of the 2030 goal. In fact, even if all of California's 4.5 Mha of cropland and 5.7 Mha of rangeland were enrolled into climate service through 2030, given the median estimates and without factoring in full life-cycle impacts, biochar (8.84%), compost on cropland (7.07%), no-till (1.18), and cover crops (3.71%) would contribute less than 10% of the 2030 goal; only compost amendments to rangeland (59.11%) would surpass 10%.

4 Discussion and conclusion

Notwithstanding the straightforward narrative that emerges from the median scenarios, considerable uncertainty across all of the management practices is reflected in the range spanning the lower and upper percentiles (6–12 $tCha^{-1}yr^{-1}$; Tables 2 and 3). This uncertainty, even

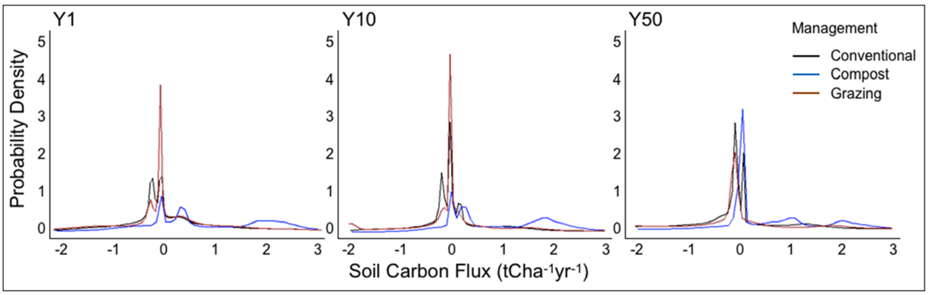

Fig. 4 Pooled estimates of expert-specified soil carbon flux under alternative management practices in a typical hectare of California's conventionally managed rangeland over time. The lines represent, for each management practice, the aggregated equally weighted distribution derived from the 5th, 50th, and 95th probabilities specified at years 1, 10, and 50

Table 2 Expert-specified effects of management actions on soil carbon flux in California cropland over time

	Soil carbon flux $tCha^{-1}$ yr^{-1}			Implications for 2030 target	
	(a) after 1 year	(b) after 10 years	(c) after 50 years	(d) $MtCO_2yr^{-1}$ in 2030	(e) % of 171 $MtCO_2$
Conventional cropland					
5th	− 1.48	− 1.46	− 1.67	− 1.20	− 0.70
25th	− 0.39	− 0.44	− 0.47	− 0.35	− 0.20
50th	− 0.07	− 0.08	− 0.10	− 0.06	− 0.04
75th	0.34	0.23	0.19	0.21	0.12
95th	5.22	6.57	8.48	0.02	0.01
Biochar on cropland					
5th	− 1.14	− 1.11	− 1.18	− 0.91	− 0.53
25th	− 0.15	− 0.09	0.05	− 0.08	− 0.05
50th	0.05	0.20	0.26	0.14	0.08
75th	1.87	2.09	3.31	1.67	0.97
95th	9.46	10.34	10.99	8.29	4.85
Compost on cropland					
5th	− 5.48	− 5.52	− 5.62	− 4.50	− 2.63
25th	− 0.26	− 0.17	− 0.07	− 0.16	− 0.09
50th	0.04	0.16	0.17	0.11	0.06
75th	2.18	2.12	1.92	1.74	1.02
95th	5.40	5.83	6.92	4.68	2.74
No-till on cropland					
5th	− 1.23	− 1.04	− 0.59	− 0.88	− 0.52
25th	− 0.24	− 0.21	− 0.05	− 0.18	− 0.10
50th	0.03	0.02	0.09	0.02	0.01
75th	0.31	0.24	0.65	0.21	0.12
95th	4.47	5.05	5.74	4.02	2.35
Winter cover crops on cropland					
5th	− 5.36	− 5.57	− 5.70	− 4.51	− 2.64
25th	− 0.57	− 0.24	− 0.15	− 0.26	− 0.15
50th	0.00	0.09	0.07	0.06	0.03
75th	0.45	0.44	0.44	0.36	0.21
95th	5.84	6.66	8.34	5.29	3.09

Here, the 5th, 25th, 50th, 75th, and 95th percentiles are drawn from the pooled estimates shown in Fig. 3. If 4047 $hayr^{-1}$ of cropland are enrolled for carbon mitigation beginning in 2020, the amount of CO_2 sequestered in 2030 is shown in (d) and as a percentage of the state's target of 171 M fewer tCO_2eyr^{-1} by 2030 in (e)

among soil experts, may be explained in part by the heterogeneity of cropland and rangeland soils, which in California span approximately 10° of latitude (Steenwerth et al. 2002). Expert G underscored the uncertainty by noting: *"I do not find it very useful to think about a typical soil or farm … When I talk about soil carbon sequestration to farmers, I always tell them that these average published rates may very well be meaningless for their particular farm because of the local climate or particular soil conditions (particularly true for California where there is diversity in both of these factors)."* Expert F echoed the same sentiment, albeit more sparingly, for rangeland, which may exhibit spatiotemporal variability (Sayre et al. 2013): "*Not sure how to imagine 'typical' rangeland."* Indeed, macro and micro-scale heterogeneity across California could complicate the state's efforts to implement effective accounting of soil-based emissions mitigation. Creating site-specific baselines will also be challenging if there is no "average" cropland or rangeland on which to reliably forecast SCF. This heterogeneity and related problems, including the practical complexities of measuring soil carbon, insufficient availability of landscape-level soil data, and a limited ability to measure underlying processes,

Table 3 Expert-specified effects of management actions on soil carbon flux in California rangeland over time

	Soil carbon flux $tCha^{-1}$ yr^{-1}			Implications for 2030 target	
	(a) after 1 year	(b) after 10 years	(c) after 50 years	(d) $MtCO_2yr^{-1}$ in 2030	(e) % of 171 $MtCO_2$
Conventional rangeland					
5th	− 1.33	− 1.52	− 1.79	− 1.21	− 0.71
25th	− 0.24	− 0.24	− 0.35	− 0.20	− 0.11
50th	− 0.01	− 0.02	− 0.04	− 0.01	− 0.01
75th	0.52	0.53	0.46	0.43	0.25
95th	2.28	2.75	3.59	2.16	1.26
Compost on rangeland					
5th	− 5.07	− 5.62	− 5.64	− 4.49	− 2.63
25th	− 0.01	0.05	0.01	0.03	0.02
50th	0.77	0.91	0.61	0.72	0.42
75th	2.22	1.97	2.03	1.66	0.97
95th	5.70	5.53	5.79	4.55	2.66
High-impact grazing on rangeland					
5th	− 1.65	− 1.94	− 2.24	− 1.53	− 0.90
25th	− 0.28	− 0.32	− 0.35	− 0.25	− 0.15
50th	0.01	− 0.01	− 0.04	0.00	0.00
75th	0.61	0.56	0.53	0.47	0.27
95th	2.21	2.91	4.00	2.25	1.32

Here, the 5th, 25th, 50th, 75th, and 95th percentiles are drawn from the pooled estimates shown in Fig. 4. If the state target of 4047 $hayr^{-1}$ of rangeland are enrolled for carbon mitigation beginning in 2020, the amount of CO_2 sequestered in 2030 is shown in (d) and as a percentage of the state's target of 171 M fewer tCO_2eyr^{-1} by 2030 in (e)

hamper model-based assessments of SCF to inform policy-making as well as implementation and monitoring of management practices through time.

Further complicating a robust emissions accounting of soil management practices, particularly the practices involving organic amendments, is the need to factor in emissions generated throughout the entire life cycle and amendment quality. Experts P and F emphasized this point in their estimation of the effects of biochar and compost (including compost on cropland and rangeland) on SCF, with Expert P writing: "*I don't think the most important issue is C gain with amendments on the amended field, but what is the overall C balance. I would say overall, you have to lose small amounts because of reduced inputs in large regions to have a gain in one specific field. There is no free lunch in soil C.*" Different assumptions about carbon loss where the amendments were sourced may therefore explain the multimodal distribution evident in Figs. 3 and 4 that show secondary modes for biochar (1.76, 1.87, 1.83 $tCha^{-1}yr^{-1}$), compost in cropland (2.26, 2.20, and 2.08 $tCha^{-1}yr^{-1}$), and compost in rangeland (1.86, 1.84, 2.00 $tCha^{-1}yr^{-1}$). Yet another salient factor is the quality of biochar and compost, which affects decomposition. As Expert O noted: "*[The] decomposition rate depends on compost quality.*" Different assumptions among experts about the decomposition rate of the organic amendment may further explain the bimodal distributions depicted in Fig. 3.

The application frequency of biochar (5 years) and compost (annually) further underscore the complexities of direct carbon additions. For instance, because the carbon in biochar is more recalcitrant than compost, biochar should have a greater sequestration efficiency than compost (Hua et al. 2014). This outcome is reflected in the experts' responses, whereby the implied sequestration efficiency of biochar and compost reported by experts were 11 and 3.5%, respectively. This means that for compost to achieve sequestration at levels commensurate with biochar, 40% more compost annually would be needed. Such a massive application rate would likely push against the bounds of what farmers would consider acceptable.

Taken together, these elicitation results suggest very modest opportunities for soil carbon management to contribute to California's climate mitigation agenda as well as underlying uncertainties. While all the management practices we evaluated reverse SCF from negative to positive, direct carbon additions, regardless of source, offer the greatest potential for boosting the soil carbon pool. Overall, these results can help to inform ongoing efforts by state policymakers to consider cropland and rangeland management for climate mitigation, under different scenarios, by explicitly accounting for the uncertainty in their decision-making.

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