Compost Application and “Carbon Farming” in California Agricultural Lands: A Quantitative Systematic Review

ABSTRACT

The possibility of substantially reducing atmospheric carbon by storing it in the soil is acclaimed by some as one key to addressing the climate crisis. Amending soils with compost is a specific practice that holds great promise for carbon sequestration. To quantify the potential of compost application as a sequestration technology, we conducted a systematic review of studies conducted within California. Studies selected for analysis: (1) were conducted in California on agricultural land or rangeland, (2) compared soils amended with compost to appropriate controls, and (3) reported carbon sequestration levels as total soil organic carbon. Eleven published studies met these criteria, from which we extracted data for 30 unique compost versus no-compost comparisons. Results were remarkably varied — ranging from a 250% decline in soil organic carbon (SOC) to a 900% increase. While there was enormous variability in the percent (%) change in SOC, nearly three-quarters of comparisons (22 out of 30) showed an increase in SOC as a result of compost application. Our analysis not only supports the possibility of “carbon farming”, but also makes it clear that the results are too inconsistent to justify some of the claims currently being made about the extent to which soils could significantly reduce global warming.

California’s Exploration of Soil Carbon Sequestration

California is an innovator in both agricultural production and progressive climate policy, and these two initiatives come together in soil — specifically recognizing that improved stewardship of soil can both enhance sustainable food production and reduce greenhouse gases. Of course, the idea of turning to soils as a climate mitigation opportunity did not start in California. In 2015, France announced a bold strategy for soil sequestration of carbon as a major pathway for meeting the Paris COP 21 agreement — committing to a 4% annual increase of soil carbon in the top 30 to 40 cm of soil (4 per 1000 Initiative, 2018). This is part of a broader movement towards a portfolio of farming practices that enrich and rebuild soil organic matter, which is now referred to as “regenerative agriculture” (Hawken, 2019). Some estimates suggest that widely adopted regenerative agriculture, including compost application, green manure, and no-tillage, could sequester and reduce 14.52 – 22.27 gigatons of carbon dioxide equivalent, while being economically profitable (Hawken, 2019).

However, what appears true in principle is not always born out of practice. For this reason, the state of California and nonprofit foundations have recently funded several field trials that implement different practices aimed at improving soil health and then measure the actual effects. For example, the Healthy Soils Initiative, which is a California state-funded incentive program through the California Department of Food and Agriculture (CDFA), promotes the use of compost through technical assistance and grants, along with other regenerative practices (Sanchez, 2019). The Healthy Soils Initiative includes the Healthy Soils Programs

Demonstration Projects, in which farms become sites for applied academic research (CFDA, 2020). One of the larger projects funded by the state is the Marin Carbon Project, which studies composting as a potential form of carbon farming (Marin Carbon Project, 2018). The climate policy initiative behind these efforts is Assembly Bill 32 (AB 32), California's Global Warming Solutions Act of 2006, which aims to reduce California's greenhouse gas emissions to 1990 levels and promote a low-carbon economy statewide by 2030.

In this study, we focus on the application of organic compost to soils as a management practice that boosts carbon storage in soil. If compost additions substantially enhance soil carbon storage, they will not only improve water retention (Serra-Wittling et al., 1996) but also represent a credible carbon sink. Key questions include: (1) whether the type of compost (e.g., manure-based or municipal waste-based) matters; (2) how much compost must be added to see a substantial difference in total soil carbon; and (3) how robust the results are across different soil types and cropping systems. Thanks to the studies mentioned above, as well as other experiments funded by the federal government (USDA/EPA), the California state government (CalEPA, CFDA), the University of California system, philanthropists, foundations, and NGOs, sufficient data now exists to conduct a quantitative systematic review of the effects of composting on soil carbon in California agriculture.

While composting is a long-standing farming practice, its potential in terms of "carbon farming" is a relatively new focus. Only recently have scientists begun to assemble quantitative data on how much carbon can be stored, and what factors underlie variation in the effectiveness of carbon storage. One of the most comprehensive reviews was conducted by Maillard and Angers in 2014, in which they reported on 42 different studies in 49 sites that quantified changes in soil carbon after pure manure application. This is an important distinction to note, as our study used *composted* manure. Notably, none of their studies took place in California. Their manure-based amendments versus untreated soils had an increase of 9.4 Mg C ha^{-1}, but this varied by a standard deviation of 4.1 Mg C ha^{-1} (Maillard and Angers, 2014). They also saw variability in the source of manure, with cattle having the highest SOC stock change and pigs having the lowest (Maillard and Angers, 2014). Importantly, these authors discussed the difficulty in conducting a meta-analysis with so many missing measures of variation. One additional valuable review (Aguilera, 2013) focused on soil carbon in Mediterranean systems -- but the experiments included till versus no-till, and organic farming versus traditional, as well as agricultural waste as opposed to compost, and included data from only 7 studies conducted in California, none of which focused solely on compost application. Ours is the first systematic review focused only on California and only on compost usage.

Structure of Analysis

Search and Screening Methods

We searched for all published studies that reported the impact of compost additions to agricultural systems in California. We were interested in field experiments with actual measurements — not models or non-experimental observations.

To find all relevant literature, we used the following search string: (compost*) AND (carbon sequest*) AND (California*) AND (soil* OR pastur* OR rangeland* OR farm*). We entered this search string in four platforms with no limits on publication date: JSTOR, CAB Abstracts, Wiley, and Proquest. We used the online tool CADIMA to manage the search results. After eliminating duplicates, the effort resulted in 1,200 articles to review.

As a first pass, we read the titles and abstracts to determine if the article concerned a field experiment in California agricultural fields or grasslands with actual (not modeled) measurements of total soil carbon. Studies conducted in a greenhouse, forest, or soil remediation site were also excluded. This initial screening yielded 57 articles to further examine for eligibility. At that stage, we read in detail all 57 articles and required that the following conditions be met for inclusion in our review:

- The experimental design had to include control samples with no compost application, as opposed to simply before and after measurements. In one case, compost was applied to both treatment groups and the study design did not include a compost-free control (Reganold et al., 2010). In this situation, we used the plot with the lower amount of compost added as the control and used the difference in compost application rates as the measure of compost input.
- Studies were excluded for confounding variables in their experimental designs, except for cover cropping. For example, if raw manure in addition to compost were applied, the study was excluded.
- The compost could be derived from municipal waste, green waste, manure, or any combination of these, but it must have been at least partially composted (e.g., application of non-composted manure did not meet our criteria).
- Carbon sequestration levels must have been reported as soil organic carbon (SOC) or the equivalent, total organic carbon (TOC). However, we excluded metrics such as microbial biomass carbon (MBC) or any other subset of total carbon.

Of the 57 papers read in detail, 11 studies satisfied the above criteria. However, two of the studies used the same data, so the one that had the data from the initial experimental was used rather than the subsequent summary report. We additionally identified one additional study that met our criteria (through an informal scan of a Google Scholar, using the same search terms as listed above) for a total of 11 studies.

The final collection of 11 studies conducted their field experiments in a wide range of counties in California, including Alameda, Contra Costa, Fresno, Kern, Kings, Marin, Mendocino, Monterey, Riverside, San Diego, San Joaquin, San Mateo, Santa Barbara, Santa Cruz, Solano, Sonoma, Stanislaus, Tulare, Ventura, Yolo, and Yuba (Figure 1). The duration of the studies ranged from 1–19 years and sample sizes for any given compost versus control comparison ranged from 1–13, with a median of 1 replicate per treatment.

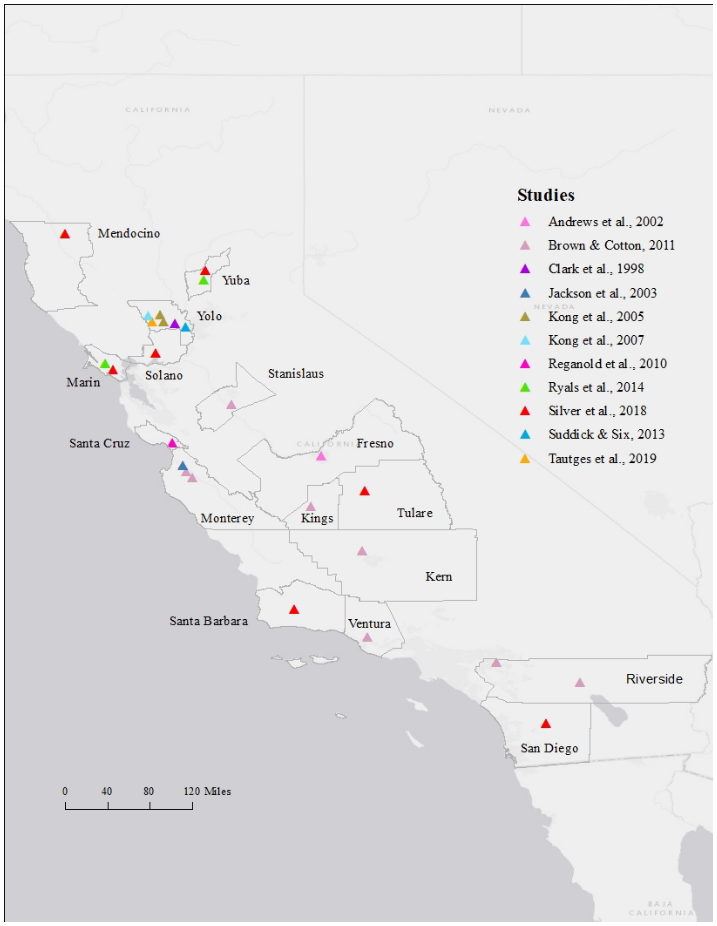

Figure 1. Map of all study sites in California

<u>Data Extraction</u>

Study methods varied greatly among the 11 articles. Soils were sampled at different, and often multiple, depths. Even within a study, different types or rates of compost addition might have been examined, or the experiment may have been conducted in multiple crop systems or locations. To capture all possible measured impacts of compost treatments, we created a separate line of data for each comparison between control and compost-addition. Many of the papers yielded multiple data lines to account for different sampling sites, soil depths, compost application rates, compost types, crops, and sample dates. For studies with repeated samples taken over time, we used only the final sampling date. In total, the eleven publications yielded 30 quantitative comparisons between compost and control treatments with respect to carbon sequestration.

Studies also differed in how they reported their results. Some reported carbon from samples taken at the end of the experiment, others measured carbon at multiple time points, and others reported percent change in carbon as a result of compost application compared to control. Because the majority of the 11 studies provided means without measures of variation, we were not able to calculate effect sizes such as Hedges' *g*. We instead focused on the percent change in SOC as this was the only measure of effect size that could be consistently calculated across all studies. Note that percent change in SOC does not vary in a consistent way with the amount of SOC present at the start of the study (% change in SOC = 229.704 ± 9.332(compost applied); adjusted R2 = -0.04602; p = 0.4473).

When mean SOC values were provided only in graphical form, Web Plot Digitizer was used to estimate values. To ensure consistency, two people independently extracted all data from each study, and any discrepancies were resolved. Supplement 1 reports the raw data from each study, including details about the experimental design, location, crop type, compost type, and rate of application.

Carbon Sequestration Findings

Soil can be extremely variable even within a single field being managed in a uniform way. It is thus not surprising that the response of SOC to composting varied enormously, ranging from a 250% decline to a 900% increase. However, the distribution of the response is clearly shifted in the positive direction (Figure 2A), with nearly three-quarters (22 out of 30) comparisons showing an increase in SOC.

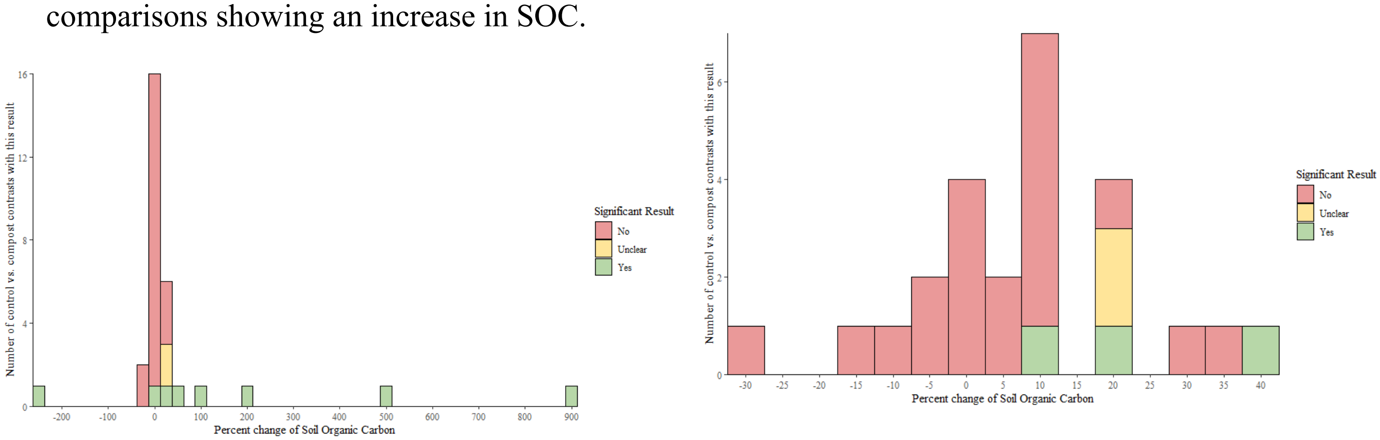

Figure 2. The percent change in soil organic carbon per treatment-control comparison. (A) Histogram for all 30 comparisons. (B) The same histogram but omitting five outliers (defined as values exceeding the first or third quartiles by more than 1.5 times

When all eleven studies were aggregated together (regardless of compost type), the 95% confidence interval overlaps with 0% change, meaning that the variability is so great that it is impossible to draw firm conclusions regarding composting in general in California, given the existing data (Figure 3A). Some of this variability is due to the fact different types of compost were used. For this reason, the data were separated into different treatment categories by compost type. When we did this, the variability was reduced, but the 95% confidence intervals all still overlapped with 0% change (Figure 3A).

Figure 3. Percent change in soil organic carbon as a function of **(A)** various types of compost and **(B)** the additional use of a cover crop. Green squares are means shown with a 95% confidence interval (CI). The red diamonds show the overall mean across all 30 comparisons (center point at 54.488) and corresponding 95% CI (left and right edges). Values in parentheses are the number of comparisons in each category.

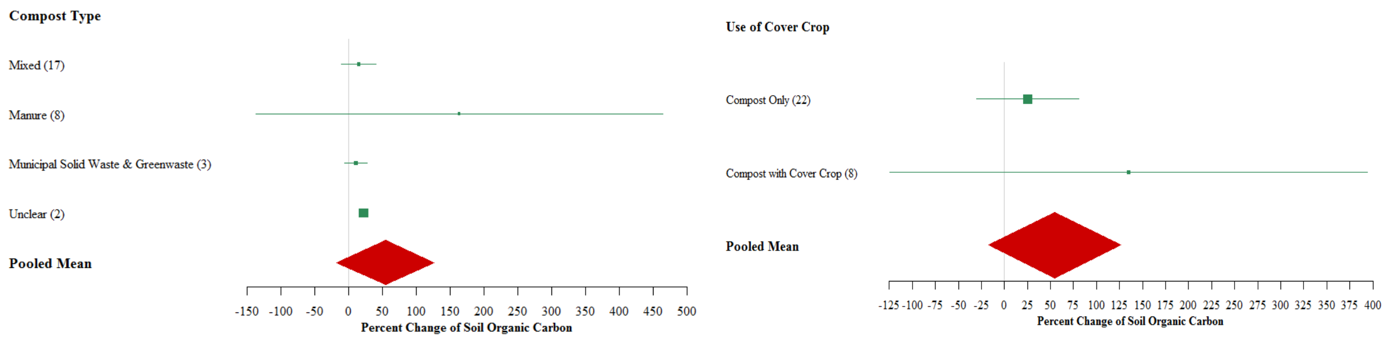

Figure 3. Percent change in soil organic carbon as a function of **(A)** various types of compost and **(B)** the additional use of a cover crop. Green squares are means shown with a 95% confidence interval (CI). The red diamonds show the overall mean across all 30 comparisons (center point at 54.488) and corresponding 95% CI (left and right edges). Values in parentheses are the number of comparisons in each category.

One shortcoming of the studies to date is sample size. There are too few studies (only 11 for California — and they span 20 counties (Figure 1) and 18 different crops (Table 1). Complications also arose due to cover crops and different compost types. Secondly, within each study, the sample sizes were small. The largest sample size was 13 for the 30 contrasts summarized in *Figure 2*.

We also investigated the impact of the amount of compost on percent change in soil organic carbon. Across the studies, the amount of compost applied ranged from 4 – 25.9 Mg C ha^{-1}. Despite this wide range, there was no evidence of a significant relationship between the amount of compost applied and % change in SOC. Note, however, that a recorded change of +900% resulting from a 373 kg N ha^{-1} compost application (Kong et al., 2007) was excluded from the analysis of this relationship because the units reported for the compost application rate were not comparable to the others (Mg C/ha). Again, the lack of a significant relationship is not surprising due to the variability in the myriad other factors that likely obscure any trend due to the amount of compost applied. Among the 11 publications we examined, none investigated whether the amount of compost applied made a difference in terms of soil carbon sequestration. Finally, we asked whether the percent change in SOC increased with the number of years that compost was applied (Figure 4). The relationship was weak but significant.

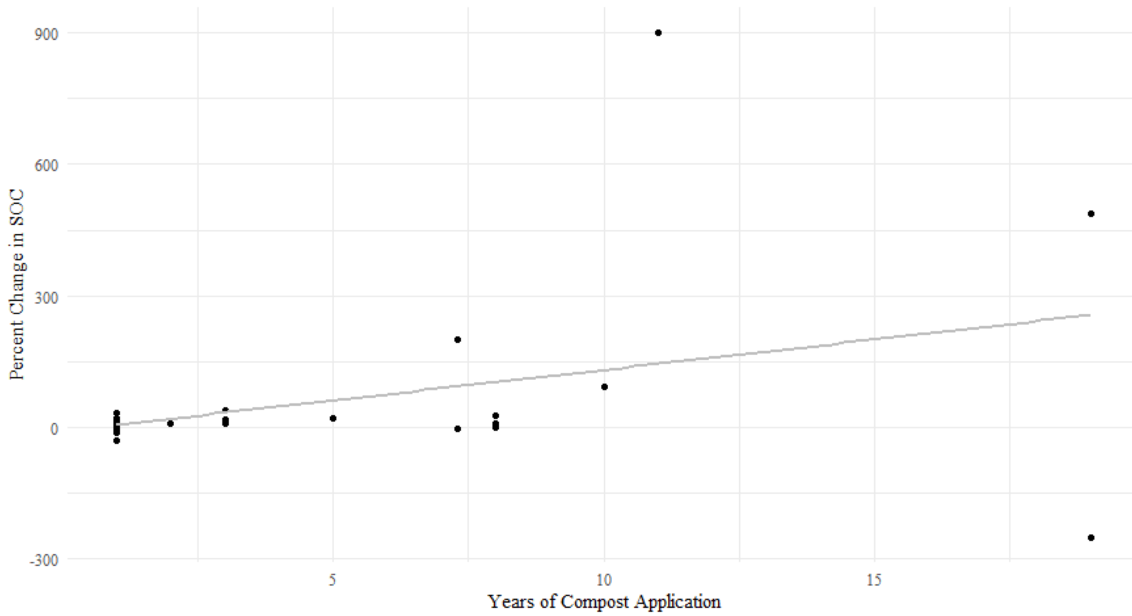

Figure 4. The effect of years of compost application on the percent change in SOC. % change in SOC = -7.389 + 13.895(years of compost); adjusted R2 = 0.102; p = 0.04757. There is a weakly significant relationship between increasing years of compost and increased percent change.

Cover crops represented a confounding variable that made it difficult to differentiate sequestration sources. Four of the 11 papers used cover cropping, usually on a rotation basis. When cover crops were not used, the sequestration only increased by 25.3%, but that increase was less variable. The studies that used cover crops had a higher change in SOC at 134.9%, but with a huge confidence interval, likely due to the small number of comparisons in this category (Figure 3B). While the all results were insignificant, they were skewed in the positive direction (Figure 3B).

The Potential for Carbon Management

With 1500 – 2000 Pg C of the world's carbon stored in just the top 1-meter soils (Janzen, 2005), it is not surprising that managing agriculture for enhanced soil carbon has been receiving much attention as one of many "wedges" of carbon sequestration (Gryze, 2008). The incentive for carbon farming is augmented in California because a recently passed organic waste law, AB 1826, mandates that all businesses producing more than 4 cubic yards of commercial solid waste per week must compost their waste rather than sending it to landfills (CalRecycle, 2020). If farms in California's Central Valley could use such waste to boost soil carbon, it could be an incentive to develop a circular economy of restaurant waste. In addition, modeling has suggested that, in California grasslands, this carbon will remain in the soil long-term and sequestration will increase over time (Ryals et. al, 2016). From our analysis, as years of compost application increased, the percent change of SOC did as well — which is empirical support for the prior modeling predictions.

If baseline soil carbon levels are assessed prior to compost application on different cropping systems and managed properly, California farmers could immensely benefit from AB 32 in the form of carbon credits from carbon farming (Suddick, 2013). While our analysis showed evidence for carbon storage in soils, the results were not as clear as one might hope. Hence, if carbon farming was to be eligible for carbon credits, there would need to be more research conducted to address the variability we report. For the purpose of providing rough estimate calculations, we can ignore the variability and simply use the average change over all 30 experimental contrasts. When we do this, we find the average amount of soil carbon stored is 0.36 tons per acre per year. As of May 2020, California carbon credits were at $17.77/ton (CARB and MELCC, 2020) and as of 2018, the average farm size in California was 350 acres (CDFA, 2019). So, farmers could receive an average of $2,245.06 per year in carbon credits if this was implemented, or $6.41 per acre per year.

Research Recommendations

We found relatively few California agricultural and rangeland studies that compared the effects of compost additions with appropriate controls. Those that we did find were of limited duration and geographic scope (*Table 1*). Among the 11 total papers, the average study duration was approximately 6.5 years, and only two studies spanned more than 10 years. Five of the studies were located on the UC Davis Russell Ranch Sustainable Agriculture Facility in Yolo County, while only two of the studies examined field sites across the geographic range of California (Brown and Cotton, 2011; Silver et al., 2018). Implementing credits for carbon farming will require additional studies that span California's diverse climates and soil types (Brynes, 2017). Furthermore, the average sample size per comparison was less than 4, with a median of 1 replicate per treatment. If carbon farming via compost application is to be implemented for carbon credits, there needs to be long-term studies with larger sample sizes spanning the entire state.

Optimal application rates also need to be investigated more thoroughly, as none of the 11 studies examined the effects of different application rates at the same site. Unsurprisingly, given the many variables that differed across the 11 studies, we found no significant relationship between compost application rate and carbon sequestration. Cost is a common barrier cited among farmers for widespread application, so to understand the optimal range for maximizing sequestration while minimizing costs to farmers will be vital.

There also seems to be sequestration rate effects by compost type. For example, it seems that manure changed the carbon stocks at a much higher amount, which is interesting for future policy recommendations. However, there was a huge confidence interval and only 8 data lines on the category, so there is a need for more research investigating manure effects on sequestration. This higher sequestration from manure-based compost is especially important in California where there is an abundant supply from the over 5 million cows in the state (USDA NASS, 2020).

ACKNOWLEDGEMENTS

We are thankful for Peter Karieva (University of California, Los Angeles) and Michelle Marvier (Santa Clara University) for their advising and assistance in editing and data analyses, as well as for their helpful comments and suggestions. This work was done for the University of California Los Angeles Institute of Environment and Sustainability (IoES) practicum. Lastly, we would like to thank our client, Sustainable Conservation, who brought this topic to us.

TABLES

Table 1. Number of study sites, counties, and crops showing the variation of the different references.

Reference	Number of Study Sites	County in California	Crop
Brown and Cotton, 2011	8	Riverside (2), Ventura (1), Kern (1), Kings (1), Stanislaus (1), Monterey (2)	Grapes, lemons, mango, almonds, apricots, row crops
Kong et al., 2005	1	Yolo	Maize-tomato, wheat-tomato
Tautges et al., 2019	1	Yolo	Maize-tomato, wheat-tomato
Jackson et al., 2003	1	Monterey	Crisphead lettuce and broccoli
Suddick and Six, 2013	1	Yolo	Lettuce, winter cover crop, bell pepper, and Swiss chard
Ryals et al., 2014	2	Yuba (1), Marin (1)	Grassland
Silver et al., 2018	14	Santa Barbara, Tulare, Solano, Yolo (2), San Joaquin, Contra Costa, Mendocino, San Diego, Sonoma, Yuba, Stanislaus, Marin, Kings, San Mateo	Grassland
Kong et al., 2007	1	Yolo	Maize-tomato, wheat-tomato
Clark et al., 1998	1	Yolo	Tomato, safflower, and corn, with oats, vetch, wheat, or bean
Andrews et al.	1	Fresno	Tomato, melon
Reganold et al., 2010	13	Santa Cruz	Strawberries; followed by broccoli, lettuce, or a cover crop

Table 2. A conversion from relevant metric measures to standard Imperial

Metric	Standard Imperial
1 Mg	1.10231 ton
1 hectare	2.47105 acres
1 cm	0.393701 inch

REFERENCES

Aguilera, E., Lassaletta, L., Gattinger, A., & Gimeno, B. S. (2013). Managing soil carbon for climate change mitigation and adaptation in Mediterranean cropping systems: A meta-analysis. *Agriculture, Ecosystems & Environment, 168*, 25-36. doi:10.1016/j.agee.2013.02.003

Byrnes, R., Eviner, V., Kebreab, E., Horwath, W. R., Jackson, L., Jenkins, B. M., . . . Wheeler, S. (2017). Review of research to inform California's climate scoping plan: Agriculture and working lands. *California Agriculture, 71*(3), 160-168. doi:10.3733/ca.2017a0031.

California Department of Food and Agriculture. (2020). HSP Demonstration Projects. Retrieved May 19, 2020, from https://www.cdfa.ca.gov/oefi/healthysoils/DemonstrationProjects .html

CalRecycle. (2020, March 17). Mandatory Commercial Organics Recycling. Retrieved May 30, 2020, from https://www.calrecycle.ca.gov/recycle/commercial/organics/

California Air Resources Board (CARB) and Québec's ministère de l'Environnement et de la Lutte contre les changements climatiques (MELCC). (2020, May 28). *California Cap-and-Trade Program, and Québec Cap-and-Trade System May 2020 Auction #23* (CA-QC Joint Auction Summary Results Report). Retrieved May 30, 2020, from https://ww3.arb.ca.gov/cc/capandtrade/auction/may-2020/summary_results_report.pdf

CDFA (2018). *California Agricultural Statistics Review 2017-2018*. Retrieved from:www.cdfa.ca.gov/statistics/PDFs/2017-18AgReport.pdf.

CDFA. (2019). *California Agricultural Statistics Review, 2018-2019* (Rep.). Retrieved June 1, 2020, from https://www.cdfa.ca.gov/statistics/PDFs/2018-2019AgReportnass.pdf

Gryze, S. D., Albarracin, M. V., Catalá-Luque, R., Howitt, R. E., & Six, J. (2008). Modeling shows that alternative soil management can decrease greenhouse gases. *California Agriculture, 63*(2), 84-90. doi:10.3733/ca.v063n02p84.

Hawken, P. (2019). *Drawdown: The most comprehensive plan ever proposed to reverse global warming*. Vancouver, B.C.: Langara College.

Janzen, H. H. 2005. Soil carbon: A measure of ecosystem response in a changing world? Can. J. Soil Sci. 85: 467–480.

Kohl, C., McIntosh, E.J., Unger, S., Haddaway, N.R., Kecke, S., Schiemann, J., & Wilhelm, R. (2018). Online tools supporting the conduct and reporting of systematic reviews and systematic maps: a case study on CADIMA and review of existing tools. *Environmental Evidence, 7*(8). https://doi.org/10.1186/s13750-018-0115-5.

Maillard, É, & Angers, D. A. (2013). Animal manure application and soil organic carbon stocks: A meta-analysis. *Global Change Biology, 20*(2), 666-679. doi:10.1111/gcb.12438

Marin Carbon Project. (2018). Retrieved May 29, 2020, from https://www.marincarbonproject.org/about

Owen, J. J., Parton, W. J., & Silver, W. L. (2015). Long-term impacts of manure amendments on carbon and greenhouse gas dynamics of rangelands. *Global Change Biology*, *21*(12), 4533–4547. doi: 10.1111/gcb.13044.

Ouédraogo, E., Mando, A., & Zombré, N. P. (2001). Use of compost to improve soil properties and crop productivity under low input agricultural system in West Africa. Agriculture, Ecosystems & Environment, 84(3), 259–266. doi: 10.1016/s0167-8809(00)00246-2.

Platt, B., Goldstein, N., Coker, C., Brown, S. (2014). State of Composting in the U.S.: What, Why, Where & How. Retrieved from: https://ilsr.org/state-of-composting/.

Ryals, R., Eviner, V. T., Stein, C., Suding, K. N., & Silver, W. L. (2016). Grassland compost amendments increase plant production without changing plant communities. *Ecosphere*, *7*(3). doi: 10.1002/ecs2.1270.

Sanchez, D. L., Houlton, B. Z., & Silver, W. (2019). UC experts can lead on carbon dioxide removal. *California Agriculture, 73*(2), 69-72. doi:10.3733/ca.2019a0009

Serra-Wittling, C., Houot, S., & Barriuso, E. (1996). Modification of Soil Water Retention and Biological Properties by Municipal Solid Waste Compost. *Compost Science & Utilization, 4*(1), 44-52. doi:10.1080/1065657x.1996.10701817

Silver, W. L., Ryals, R., & Eviner, V. (2010). Soil Carbon Pools in California's Annual Grassland Ecosystems. *Rangeland Ecology & Management*, *63*(1), 128–136. doi: 10.2111/rem-d-09-00106.1.

Suddick, E. C., Ngugi, M. K., Paustian, K., & Six, J. (2013). Monitoring soil carbon will prepare growers for a carbon trading system. *California Agriculture, 67*(3), 162-171. doi:10.3733/ca.v067n03p162.

USDA National Agricultural Statistics Service. (2020). NASS - Quick Stats. USDA National Agricultural Statistics Service. https://www.nass.usda.gov/Quick_Stats/Ag_Overview/stateOverview.php?state=CALIFORNIA. Accessed 2020-05-31.

"4 per 1000" Initiative. (2018). Retrieved June 01, 2020, from https://www.4p1000.org/