The Potential for Carbon Sequestration due to Compost on Mediterranean Agricultural Lands: A Quantitative Systematic Review

ABSTRACT

It is widely accepted that soil carbon needs to be bolstered, yet the rate and amount of carbon that can be rebuilt is highly variable, uncertain, and dependent on the management practices used. Here, we conduct a quantitative review of composting as a soil treatment in Mediterranean agroecosystems throughout the world. We found 21 published studies, which collectively yielded 58 control-treatment contrasts spread across three continents and five countries. When aggregated, the average percent (%) change in soil organic carbon (SOC) was +46%, with compost increasing SOC in 33 of the 58 experimental contrasts. However, the literature is fraught with uncertainty because sample sizes were often small (the median sample size being less than 1 per treatment), and the durations of the experiments highly variable (from 1 to 19 years). Soil depths and details of compost amendments also varied. Moreover, oftentimes the standard errors or standard deviations were not reported. While the data strongly support the addition of compost as a method for increasing SOC, it will be impossible to estimate composting as a climate mitigation strategy without more standardized experimental approaches and better replication in each study. None of this rejects the value of rebuilding soil carbon, but it does suggest the quantitative outcome of soil improvements are too heterogeneous to yield any generalizations regarding the magnitude of carbon sequestration.

INTRODUCTION

Nations are falling far short of greenhouse gas (GHG) emission targets, and the impacts of climate change are becoming increasingly severe (Nordhaus, 2020). As a result, the importance of sequestering carbon is greater than ever before. One of the potentially largest, but also highly uncertain, possibilities for removing carbon from the atmosphere is carbon storage in soils — a bold strategy first formally implemented in France with the goal of a 4% annual increase in soil carbon (4 per 1000 Initiative, 2018). Some scientists have suggested using regenerative practices to enhance soil carbon, also known as "carbon farming," which could remove up to 22.27 gigatons of carbon from our atmosphere per year (Project Drawdown, 2020). However, skeptics have suggested that the data are highly variable, and that such optimism is unwarranted (Powlson et al., 2011).

Carbon farming entails a variety of land use management practices, such as cover cropping, no-tillage, and the addition of organic amendments such as compost (Dumbrell et al., 2016). In this study, we explored the possibility that compost additions may be sufficiently robust in terms of carbon sequestration to represent a significant carbon wedge in the global carbon budget. One reason for focusing on compost is that independent of ideas about carbon farming, there is increasing pressure and government regulation aimed at keeping organic waste out of landfills, and put to some better use, such as California with AB 32 and AB 1826 (Suddick, 2013; CalRecycle, 2020). Secondly, we focused on Mediterranean ecosystems because they are among the world's most productive agroecosystems due to their benign climate, with dry summers and mild, wet winters, and long growing seasons. Even if the practice is shown to have relatively small effects on soil carbon stores, areas with Mediterranean climates that face water scarcity will still benefit from the practice as compost amendments promote better soil water retention (Serra-Wittling et al., 1996).

In this study, we report the first systematic quantitative review of field experiments involving compost additions to Mediterranean ecosystems. Although meta-analyses are regarded as the "gold standard" for systematic reviews, we were not able to achieve this standard due to many studies failing to report measures of variance. Of the 21 studies analyzed, only 12 provided standard deviations. While there have been related reviews on the subject, they often only consider rangelands (Silver, 2010), and are confounded by additional soil management practices like no-till (Aguilera et al., 2013; Ugarte et al., 2014). Our specific focus in this review was on field experiments in Mediterranean areas that compared an unamended control versus plots treated with compost, and that measured soil organic carbon. In total, we found 21 studies that met these criteria.

METHODS

Search and Screening Methods

To find all relevant literature, we utilized the following search string: (compost*) AND (carbon sequest*) AND (Mediterranean OR California* OR Ital* OR Australia* OR (central AND Chile OR Chilean) OR "Cape Town" OR (South AND Africa*)) AND (agricult* OR farm* OR rangeland* OR pastur* OR cropland*).

This search string was entered to three different platforms with no limits on publication date: CAB Abstracts, Wiley Online, and Proquest. We used the online tool CADIMA to manage the search results and identify duplicates. The first step in our selection process entailed reading the titles and abstracts to determine if the article concerned a field experiment with actual measurements of carbon sequestration. We were not interested in models, or in greenhouse, forest, or soil remediation studies. Once eliminations were done, we then read the full text of the remaining publications. We extracted 21 papers that met the criteria as outlined below:

- The study is a field experiment on agricultural land/cropland or rangeland. Forests, greenhouse, and remediation soils were excluded.
- The study site is within a region characterized by a Mediterranean climate.
- The experimental design includes a control sample with no compost application (as opposed to simply before and after measurements). In one case, compost was applied to both treatments 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, with the exception of cover cropping. For example, if raw manure and compost were applied, the study was excluded.
- The compost was derived from municipal waste, green waste, manure, or a combination of these, but it was at least partially composted (e.g., application of uncomposted manure did not meet our criteria).
- Carbon sequestration levels are reported as soil organic carbon (SOC) or total organic carbon (TOC), terms that are used interchangeably by most authors. However, we did not include metrics such as microbial biomass carbon (MBC) or any other subset of total carbon.

Data Extraction and Analysis

From the 21 published articles that met our criteria, we extracted all relevant qualitative and quantitative data. While nearly all of the publications focused solely on one field experiment, one of them (Paulin, 2005) included three distinct relevant experiments. Thus, the 21 publications yielded a total of 23 studies. The 23 experiments were located in California, Italy, Spain, Southern Turkey, and Australia (*Figure 1*). Studies conducted in California accounted for 11 of the 23 studies analyzed and included 9 counties spanning from Mendocino County in northern California to Riverside County in southern California. The remaining studies were as follows: 6 in Italy, 3 in Spain, 2 in Western Australia, 1 in Victoria, Australia, and 1 in Turkey.

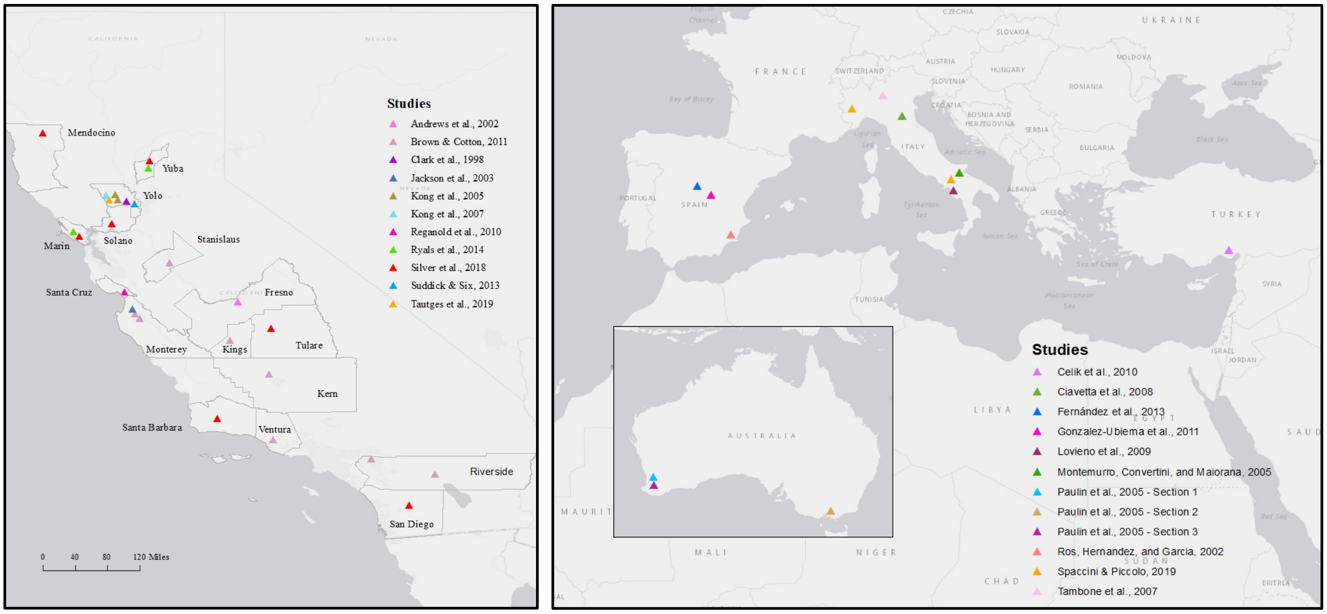

Figure 1. Maps of all study sites. **(A)** shows the California map. **(B)** shows the Meditereanean region and Australia.

The duration of the studies ranged from 1 – 19 years and sample size for any given compost versus control comparison ranged from 1 – 14, with a median of 1 replicate per treatment. In the Supplemental Materials, we provide qualitative descriptions of each experiment as well as the data we extracted from each study. Quantitative data included the SOC stocks of the control and amended plots, the number of samples taken, sampling depth, and whether or not the result was deemed significant. When mean SOC values were only reported in graphical form, Web Plot Digitizer was used to estimate values.

Since the majority of the field experiments provided means without measures of variation, we were not able to calculate effect sizes such as Hedges' g. Additionally, there existed a lack of uniformity across the studies in how researchers reported their results. Some reported carbon from samples taken at the end of the experiment, while others measured carbon at multiple points throughout the duration of the study. However, to ensure consistency, we only included values from the final year of each study in our analysis. We focused on the percent (%) change in SOC as this was the only measure of effect size that could be calculated across all studies. Percent change was calculated from the final control SOC value and the final treatment SOC value, whether they were reported in g/kg, Mg C/ha, or % C. The percent change in SOC did not vary in a significant way with the initial amount of SOC in the beginning of the study (linear regression: R2, n.s. % change in SOC = 68.407 ± 2.187(compost applied); adjusted R2 = 0.07485; p = 0.1286) Magnitude of change was only calculated for studies that reported SOC in Mg C/hectare, as our team considered this to be the most useful unit when considering the potential for carbon credits or other incentive programs. To ensure consistency, two individuals from our team each independently extracted all data from each study, and any discrepancies were resolved.

We created a separate line of data for each comparison between control and compost addition. Many of the papers yielded multiple data lines, or control versus compost contrasts, 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 only used the final sampling date, as our main interest was long-term carbon sequestration. In total, the 21 publications yielded 58 relevant comparisons of compost treatment versus control (Supplement 1)

Results

On average, compost application did indeed sequester carbon dioxide with an average percent change in soils of 46% (*Figure 3*). The data gathered presented a majority of positive percent change values, with 33 of 58 being positive percent changes. However, there were values ranging from -250% to 900%, as indicated in *Figure 2*. It should be noted that each line of data from all the studies were given an equal weight, regardless of how well the study was conducted. For example, if one study based their results on solely one sample while another used ten samples, this wasn't accounted for in the calculations.

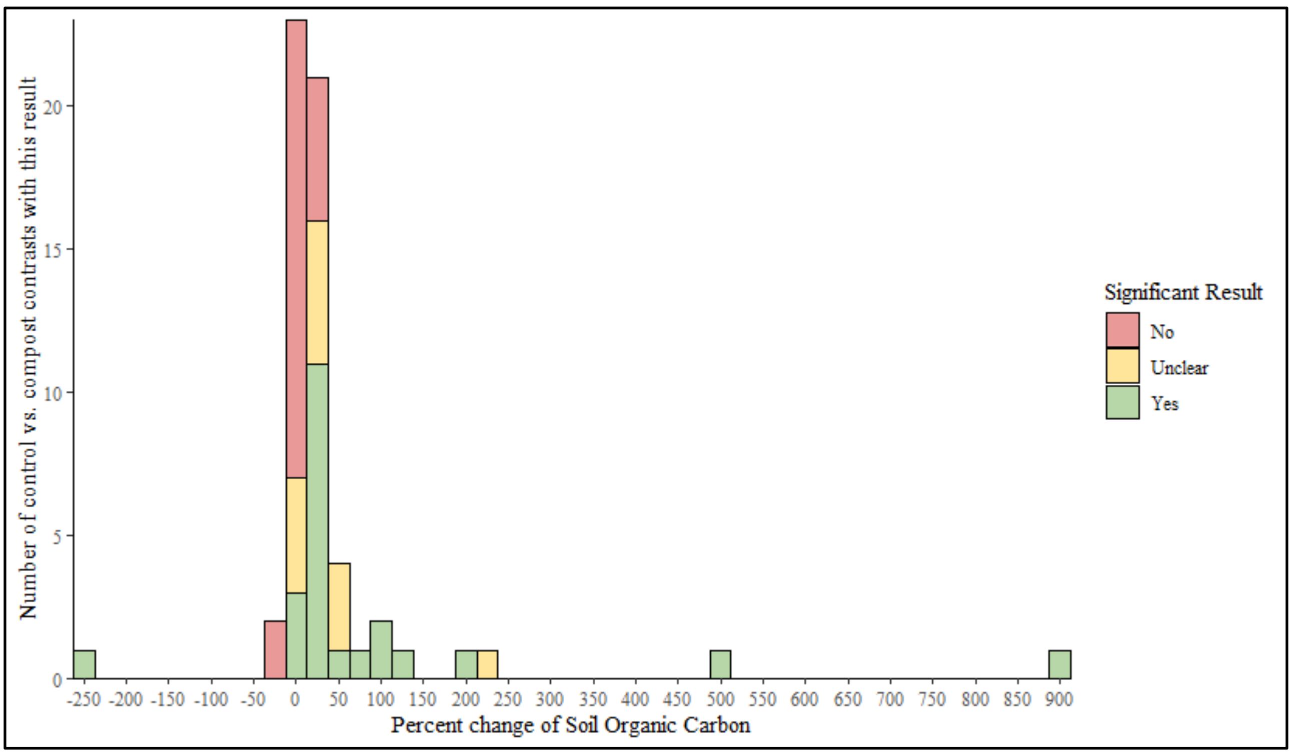

Figure 2. Number of control vs. compost contrasts with these results vs. percent change of SOC.

One major factor to consider is the use of cover crops as illustrated in *Figure 3.* This plot shows the mean percent change and confidence intervals of SOC for samples that were treated with compost only and compost with a cover crop. Treatments of only compost had a mean percent change in SOC, around 32%, and this is significantly positive since the confidence intervals do not overlap with 0. Treatments combining compost plus a cover crop had a mean increase of 113%, but the confidence interval for compost and cover crop is very large, and intersects with zero. Finally the pooled mean of all contrasts lies at 46%, with a confidence interval that does not overlap with zero, indicating that as is expected, compost application does indeed sequester carbon on average.

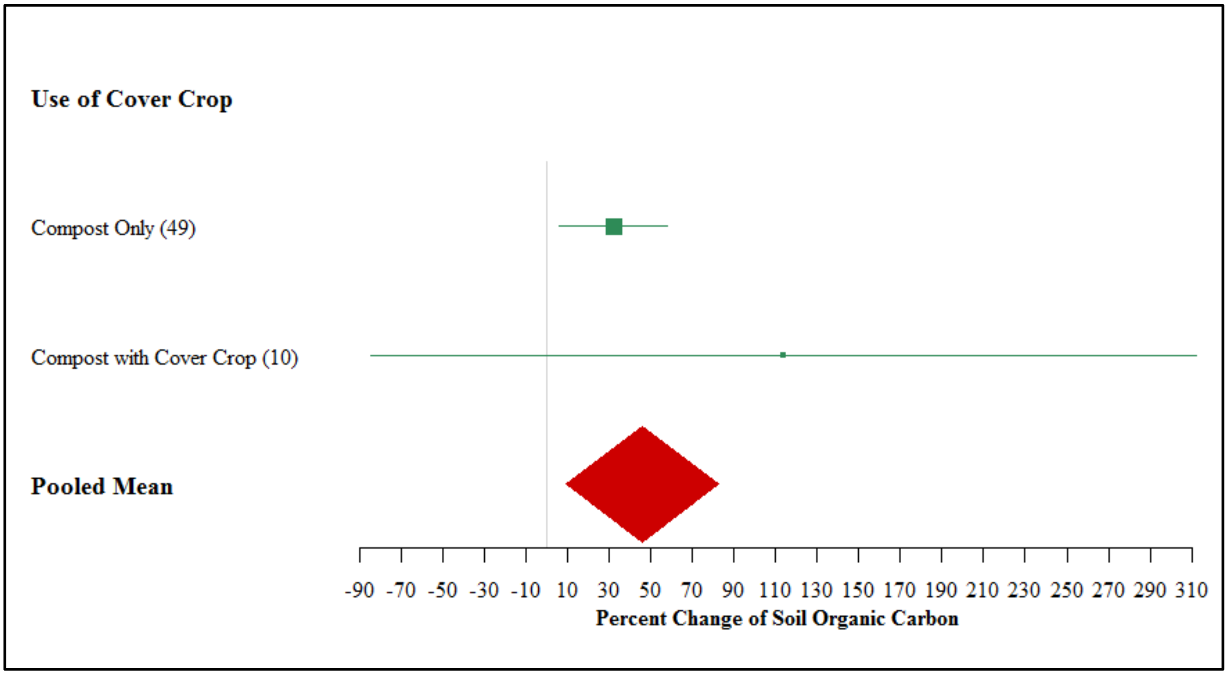

Figure 3. Comparison of percent changes of soil organic carbon with compost only vs. compost with cover crop. The number of contrasts for each type are indicated in parentheses next to the category.

We also examined the effect of compost type (*Figure 4*). This plot shows the mean percent change and confidence intervals of SOC for samples that were treated with different types of compost.. Treatments of manure had the highest mean percent change at approximately 163%, but only 8 contrasts used manure treatment, which is a very low amount when compared to mixed compost having 35 contrasts. This may explain the huge confidence interval for manure compost. Both mixed waste and municipal solid waste (MSW) & green waste (GW) had statistically significant results, with MSW and GW having a percent change higher than the pooled mean at 48%. Mixed compost had a slightly lower percent change than the mean at 20.35, but had a much lower confidence interval than MSW/GW. This could be due to the MSW/GW having only 11 contrasts, whereas mixed compost had 35 contrasts.

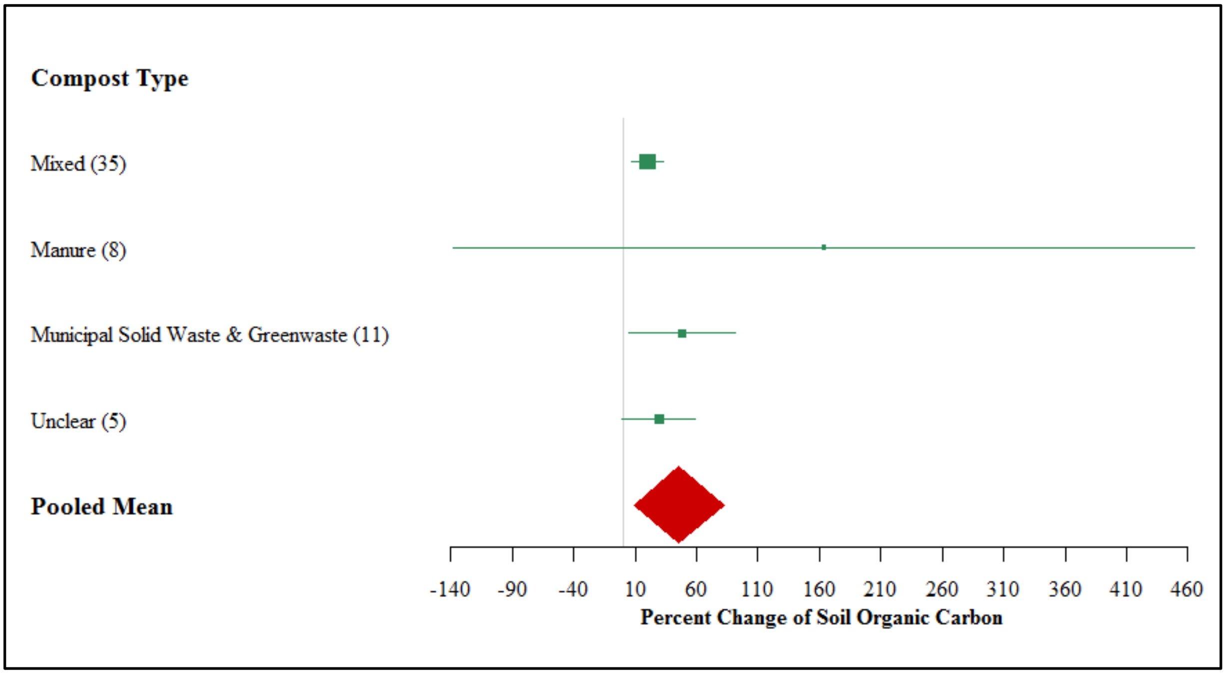

Figure 4. Comparison of percent change of soil organic carbon of mixed compost, municipal solid waste and green waste, and unclear compost type. The number of contrasts for each type are indicated in parentheses next to the category.

There were two weakly significant relationships that increased percent change of SOC: increased amount of compost application (Figure 5A) and increased years of compost application (Figure 5B). There were 11 measurements taken in m^3/ha and one in Mg N/ha that could not be compared to the Mg C/ha compost applications. This may provide evidence that soils receiving continuous, high levels of compost are likely to sequester more carbon. However, the trend seen in our data arises due to most of the compost application years in our studies being between 0.375 and 5 years, with less samples having compost applied up to 18 years. However, the range of compost application years in our studies falls mostly between 0.375 and 5 years, with a few samples having compost applied up to 18 years. Therefore, these regressions may rely too heavily on outliers to be a true representation of the relationship.

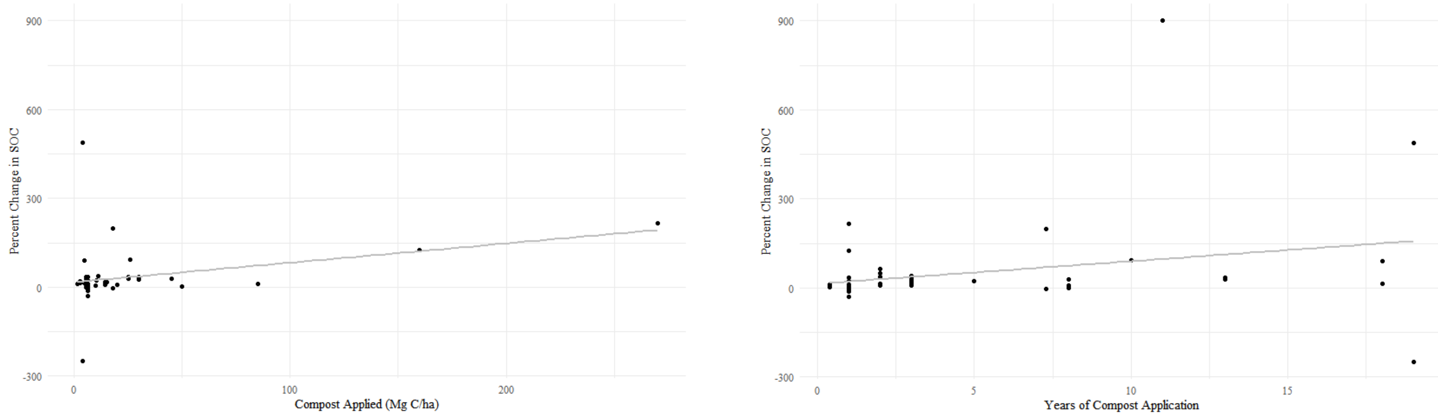

Figure 5. Effects on percent change. **A** shows the effect of different compost application amounts (Mg C/ha) on percent change in soil organic carbon (%change in SOC = 17.3954 + 0.6513(compost applied); adj. r2 = 0.08276; p = 0.02808). **B** shows the relationship between years of compost application and percent change in SOC. (%change in SOC = 13.900 + 7.556(years of compost); adj. r2 = 0.05461; p = 0.04149)

Findings Regarding Compost Use as a Carbon Sequestration Tactic

The results indicate that compost application does in fact sequester carbon, as SOC increases SOC by 46% on average. Although this may not seem like a profound change, it may be critical for Mediterranean soils. These soils have limited water availability and increased risk in desertification, factors which could dramatically decrease or even deplete the SOC content (IPCC, 2018). Additionally, many Mediterranean lands have already lost a considerable amount of SOC as a result of improper land management and intensive agricultural activity, such as tilling (Favoino et al., 2008). For example, in Southern Europe, 75% of the total area analyzed had low (below 3.4%) or very low (below 1.7%) soil organic matter content (Favoino et al., 2008).

Although our results are promising when looking solely at the average percent change of SOC, there still lies high uncertainty on the upper and lower bounds. These values make it difficult to decipher the true potential of rendering economic incentives for carbon sequestration due to compost. The average initial amount of carbon was 13.1 Mg/ha, so if there on the high end of a 900% increase in SOC on one hectare of agricultural land, the farmer could receive 1862.82 AUD/ha, when using the australian carbon trading system (Clean Energy Regulator, 2019). Under the California carbon market, this same change would equate to $2095.083/ha (CARB and MELCC, 2020). In contrast, a 250% *decrease* in SOC would simply mean that the practice is contributing to rather than mitigating atmospheric CO2 and would thus not be eligible for incentives.

Could Compost Amendments Qualify for Carbon Credits?

This high variability in results is likely due to the lack of uniformity in methodology and analysis across the studies, which is unsurprising as almost all were not aimed at studying carbon farming, but to study overall soil quality improvements. In order to effectively look at compost's potential of sequestering carbon from a climate perspective in order to adequately incite economic assistance, we propose the need for standardized protocol in carbon farming investigations. Such investigations are evidently necessary before any policy recommendations can be made, especially since we only identified 21 relevant studies.

We suggest that the protocol for future studies should include guidelines on location, duration, sampling sizes, and sampling depths. We have deemed in-situ field experiments to be most suitable, rather than models, greenhouse experiments, or incubation studies since these are not sufficiently indicative of what will actually happen on the farm and rangelands of Mediterranean climate zones. To assess how effective compost is at facilitating the sequestration of carbon over the long-term, studies of only a few years long are not enough to really show the full effect: we thus suggest a minimum duration of 5 years. For each field experiment, we recommend implementing both a control plot and an amended plot with a minimum of 5 distinct replicates for each. Under the recommendation of the 4 per 1000 Initiative, a maximum sampling depth should be set to 40cm (4 per 1000 Initiative, 2018). Lastly, we recommend increased investment in manure-based compost studies, as composted manure indicated the highest potential increase in SOC, but with the largest confidence interval. Another option could be further investigation of municipal / green waste, which indicated positive percent changes in SOC with statistical significance, but still had a relatively large confidence interval (though smaller than that of composted manure). Since we wish such investigations to help formulate policy recommendations and economic incentives, the type of compost must be taken into consideration as it evidently influences the potential increase of SOC.

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