SOIL ORGANIC CARBON STUDY IN CALIFORNIA

FINAL TECHNICAL REPORT

Prepared for:

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1. EXECUTIVE SUMMARY

The ability to sequester soil carbon (C) in California is highly debated. The warm, arid nature of the Mediterranean climate, and reliance on tillage is generally thought to work against storing significant amounts of soil C. In general, soil C levels in California agricultural areas are lower compare to more temperate climates. The intensification of agriculture following the completion of various phases of the State Water Project has led to soil C gains from irrigation due to increases in net primary productivity compare to lands prior to agriculture development. Long-term decadal projects at the University of California-Davis show additional soil C gains can be achieved through agricultural practices such as winter cover cropping, manure additions, intercropping and any other practices that maintain annual soil cover with plants or crop residues to increase C inputs to soil. The decadal projects show a range of up to 2.25 US tons of soil C per acre per 10 years can be achieved through practices that have been demonstrated to promote soil C sequestration.

The SOC dynamics in California agriculture are mostly controlled by water and N availability. Water availability for irrigation is often limited, which in turn limits the amount of plant-derived C added to soils, and restricts adoption of cover cropping, used primarily to increase SOC. In addition, crop production in California is highly heterogeneous and market driven. Constant technological innovation and market pressures make long-term commitments to carbon-focused farming practices difficult to sustain. Some crops and cropping systems are unsuited to conservation practices, creating a barrier to their adoption. Measuring changes in SOC is difficult, and uncertainties are often associated with relationships between farming practices and SOC conservation or accumulation across regions, crops, and even farms. There is a general agreement that the effect of farming practices focused on increasing SOC is controlled by multiple interacting factors, including climate, soil type, crop species, and management.

Given the dynamic character of farming in California, it is a challenge to ensure the permanence of the C sequestered in soils. Added SOC can be emitted rapidly back to the atmosphere if conservation practices stop or economic or environmental conditions change. Therefore, quantification of soil C sequestration requires continuous monitoring of site-specific changes in SOC over time. Quantification is complex, challenging, and expensive. Currently, it is not feasible to easily verify sequestration rates that typically increase total SOC stocks by <1% on an annual basis. Innovative approaches integrating digital maps, modeling, the use of new sensors, remote sensing, and web-based interfaces are rapidly evolving and improve the ability to predict the effects of GHG reduction strategies and quantify results.

For soil C sequestration, current C market and protocols have been applied with difficulty and have low rates of adoption because of the high costs for certification of offsets and the low price paid for voluntary carbon credits, which farmers can usually obtain in limited quantity. GHG mitigation from soil C sequestration can be more efficiently achieved by integrating a large number of small annual increases in SOC obtained by numerous farmers over large areas while adequately accounting for uncertainty. Public policies can create alternative systems to the traditional C market for the C capture and storage of atmospheric C in agricultural soils as SOC. Financial incentives may motivate farmers to adopt or modify management practices to support SOC accumulation that otherwise would not be adopted. Policies should prioritize simplicity and lower costs over accuracy at a high spatial resolution, adjusting for uncertainty and risk.

Public policies can support additional C sequestration in agricultural soils. Barriers due to accurate quantification can be addressed by creating highly accurate, standardized, and widely available tools to quantify and verify annual SOC changes at the farm, region, and state scales. Policies could support soil C sequestration projects at a regional scale by creating large-scale SOC sequestration projects. Net annual SOC balances would not be determined by the outcome at a single site, but by net changes over a larger area, and reversal in one area can be compensated by net sequestration over the larger project area. Permanence can be addressed by using tools such as buffer pools, where part of the annual C sequestration is set aside so it can be used to repay forfeited credits from voluntary or involuntary project termination. Public policies can simplify permitting or other regulatory processes that may be barriers to GHG emission reduction projects. Payment amounts to farmers that are sufficient to incentivize conservation practices aiming to soil C sequestration and incorporate uncertainty and risk, can be developed

An example of a policy that supports innovation and is based on performance, accounting for risk and uncertainty, is California's Low-Carbon Fuel Standard (LCFS), which provides economic incentives to reduce transportation GHG emissions. Among other innovations in the transportation sector, this policy supports biofuel production, including renewable natural gas production on farms. The LCFS has been successful in promoting the development of transformative innovations, and it promotes industry rather than government mitigation of transportation GHG emissions. It provides a model for a SOC-focused program to support innovative changes in farming systems in California and elsewhere that currently have no viable pathways to adoption.

We believe the state's climate objectives would be advanced by policies and programs to support and account for modified or new farming practices that result in additional SOC sequestration. This is especially important since other state policies like the Sustainable Groundwater Management Act are projected to lead to the idling of large amounts of productive agricultural lands, which will cause SOM degradation and loss, setting back the state's carbon reduction goals.

2. INTRODUCTION

The use of soils for farming has a large effect on the global carbon cycle and on climate. Cultivated land covers 14% of the world's vegetated land surface (Ramankutty and Foley 1999; Field et al. 1998)., Approximately 60% of the areas farmed are estimated to display some level of degradation because of inappropriate land use and management (Bai et al. 2010). The conversion of native soils to cultivation has resulted in a significant loss of soil organic C (SOC) in many regions and resulted in an estimated total of 80 Pg[1] C lost globally since the beginning of the Industrial Revolution (DeFries et al., 1999; Zomer et al. 2017) . For example, 20–40% of SOC was reported to be lost over the first few decades of conversion to agriculture (Sanderman et al. 2017). Soil cultivation and degradation are estimated to emit approximately similar greenhouse gas (GHG) as fossil fuel combustion (Zomer et al., 2017). In the U.S., management of agricultural soils accounts for over half of the GHG emissions from the agriculture

[1] (Pg = petagram = 10^{15} g)

sector (US EPA 2022). Therefore, it is imperative that soil and crop management be considered as a potential GHG mitigation strategy.

Terrestrial ecosystems may offer one of the best opportunities to capture and store C from the atmosphere without high social costs (Sykes et al. 2020). Among the terrestrial ecosystem C pools, soil stores most C with approximately 1550 Pg as SOC and 750 Pg as soil inorganic C (Schlesinger 1986; Swift, 2001). The soil C pool is greater than the atmospheric and the terrestrial vegetation pools combined. Even in croplands, soils contain 2.6 times more C than the vegetation (Vine 2004). Therefore, increasing soil C through management of croplands represents a potential tool for mitigating the rise of atmospheric CO_2 levels (Swift, 2001).

Compared with natural soils, cultivation can lead to lowering SOC levels (Sykes et al. 2020) through (1) soil disturbances due to farming practices like tillage which can increase oxidation of organic matter, (2) reduced input of plant residues for some annual arable crops compared to native perennial vegetation and (3) soil erosion resulting in offsite removal. Nevertheless, in the last decades, studies have shown that the adoption of soil conservation practices (CP) has maintained and or reversed SOC loss in many agricultural regions (Paustian et al., 2019a). The 4 per mille initiative[2] launched at the UN Climate Change Conference in Paris (2015) established soils as a key GHG mitigation strategy. An average 0.4% annual global increase in soil C would offset most of the current annual increase in atmospheric CO_2 (15.8 $GtCO_2$ yr^{-1}), assuming that the current ocean and terrestrial C sinks remain intact and that increases become permanent. There is considerable debate about whether this level of soil C sequestration is possible, and whether agricultural soils should be the main target (Minasny et al. 2017; Van Groenigen et al. 2017, Jansen et al. 2022). Nevertheless, researchers need to determine more accurately the benefits and costs of sequestering C in soils, as well as to identify the most promising sequestration methods and their optimal implementation.

Soil C sequestration is considered permanent[3] if the C is maintained and not returned to the atmosphere over a short time (minimally one hundred years). In general, soil C sequestration occurs when C inputs, primarily from plant aboveground and below ground biomass, are larger than the C losses due to the activity of soil organisms; however, both processes are impacted by the intensity of agricultural management.

The soil organic matter (SOM), and thus SOC, is associated with many important processes in soils, including water infiltration, cation storage, nutrient cycling via microbial activity, and soil tilth (Mitchell et al. 1999). Therefore, additional benefits derive from C addition to soils, such as improved soil water retention, cation exchange capacity, increased plant and crop productivity, and potential benefits for ground and surface water quality. Thus, soil C sequestration represents a 'no regrets' strategy because it provides benefits in addition to climate change mitigation (Sykes et al. 2020).

The SOC pool is not an unlimited sink for C (Chenu et al. 2019). The level of SOC is determined through the interplay of inputs, decomposer activity and solid phase interactions, such as organo-mineral associations. Consequently, SOC increases are determined not only by C inputs but also by the initial levels in the SOC pool, and soils with low SOC are the primary target to accumulate new C. After practices to increase SOC stocks are applied over long periods (10-20 years), the SOC will find a new dynamic equilibrium and remain constant or even decline depending on a farmer's ability to maintain

[2] 4 per 1000 (0.4%)

[3] C sequestration is a flux of C from the atmosphere to the biosphere, whereas C storage is the C in the soil pool that is retained as part of the soil organic matter (SOM). C sequestration in soils is measurable as instantaneous flux density (mass of C per unit time per unit area) or as change in the soil C pool in time, i.e., an increase in SOC stocks of a given land unit over a certain depth and period of time.

inputs (Tiefenbacher et al. 2021). In some instances, adding organic matter (OM) to soils doesn't result in increased SOC storage, as fresh OM can promote the mineralization of "old" SOC in what is called priming effect (Fontaine et al., 2003).

Because of the common assumption that the top layer in the soil profile will be most affected by plant roots and agricultural management practices (Minasny et al. 2017), this layer is where most scientific studies focus, with only a few studies examining soil C dynamics below 40 cm depths. This overlooks much of the soil's capacity to sequester C, as soil below 30 cm contain between 30% and 75% of total soil C stocks, and it is the deep soil C that is inherently more resistant to decomposition (Tautges et al. 2019). Moreover, deeper layers are not subjected to the disturbance caused by tillage. Measuring SOC in the top 30 cm of soil can underestimate C sequestration or could result in grossly overestimated SOC gains when SOC increases in the top 30 cm are combined with effective cumulative losses over the 30–200 cm profile (Tautges et al. 2019).

Carbon sequestration in agricultural soils must be considered holistically, integrating climate, crops, management practices, and the use of irrigation. Increases in SOC can be achieved by multiple approaches: for example, by increased allocation of C belowground, by enhancing biomass yields to increase input to soils, and by promoting soil microbial activity enhancing soil-plant interactions leading to more stable C fractions (Tiefenbacher et al. 2021). Also, the approach should integrate different GHGs, not focusing only on sequestration of atmospheric CO_2 but also including N_2O emissions generated from cropland soils, and, in general, including the relationships between C and the nitrogen (N) cycle. Dynamics of N and C are tightly coupled as SOC contains both N and C. To increase SOC by 1.1 GtC per year, about 100 million tons per year of N would need to be incorporated into the soils. This is equivalent to about 75% of the current global synthetic N fertilizer production (Paustian et al. 2019a; Van Groenigen et al. 2017). Moreover, many cropland soils currently lose a significant amount of added N (from fertilizer or manure) as gaseous losses and leached nitrate. Improved farming practices that could recover some of the excess and unutilized N and incorporate it into SOM would yield multiple environmental benefits. Lugato et al. (2018) argued that efforts to increase C storage in soils may result in the release of significant amounts of nitrous oxide (N_2O) into the atmosphere, an observation that is also supported by the fact that soils rich in C (for example, organic soils) tend to give rise to the highest N_2O emissions (Verhoeven et al. 2017). Adding animals to pasture for C additions to soil tends to increases methane (CH_4) emissions drastically, leading to a net GHG abatement that can be less than predicted solely on the basis of soil C storage (Baveye et al. 2020). When C is added to soil it can increase the release of CO_2 into the atmosphere through soil respiration. However, the C respired is a small part of the soil pool (Trumbore 2000).

Carbon enters the soil in the form of plant litter and root exudates which are consumed and metabolized by organisms. Greater retention of C has been hypothesized when soil organisms are more abundant, due to greater C conserved in biomass, gradual transformation to more recalcitrant forms of C, protection in smaller aggregate size fractions and through enhanced organo-mineral association. Fungi, in particular, produce compounds that are more degradation resistant and increase aggregate formation (Minoshima et al. 2007), though Throckmorton et al. (2013) found little difference in soil C processes across different microbial groups.

In a world with an increasing human population and a changing climate, agriculture needs to produce more on the same amount of land while becoming more resilient to extreme events such as droughts and floods. The term climate-smart agriculture was developed to indicate a set of strategies that can help increase resilience to climate change and, at the same time, decrease agriculture's GHG emissions that contribute to the problem (Steenwerth et al. 2014). Practices used to mitigate GHG emissions in addition to increasing soil C stocks include optimization of the use of synthetic fertilizer and chemical inputs, manufacturing low-carbon fertilizer/chemicals, reducing on-farm energy and fuel consumption, using crops to produce energy, and reducing CH_4 emissions from rice cultivation and livestock. However, not all the GHG emission reductions are equal. While avoidance of N_2O and CH4 emissions cannot be reversed in time, increases in SOC can be temporary. If the supportive crop management is not maintained, all of the added SOC can be released back into the atmosphere as CO_2. Still, increases in SOC is the most effective strategy to lower cropland GHG emissions. De Gryze et al. (2009) reported that SOC increase accounted for 70% to 90% of the GHG emission reduction resulting from conservative practices such as winter cover cropping and conservation tillage.

Detection of change in SOC in time is technically challenging because total stocks are large and change slowly by small amounts, so that monitoring for at least 5 years, but ideally for more than 10 years, is necessary to detect any change. In addition, SOC is characterized by pronounced spatial heterogeneity, and therefore a high number of soil observations is required to determine any change in SOC stocks (Smith 2004). In addition, estimations of SOC stocks are highly sensitive to accurate quantification of bulk density, a parameter needed to calculate the mass of C stored in the soil layers (Tiefenbacher et al. 2021). Depending on the method used to estimate bulk density, average SOC stocks ranged from 39 to 57 Mg C ha^{-1} in a study by Carey et al. (Carey et al. 2020). There is an inverse relationship between SOC and bulk density with depth and the effects can cancel out, making assessing SOC stock changes more difficult. This uncertainty affects the ability of farmers and others to monetize additional increases in SOC due to deliberate changes in farming practices.

3. CALIFORNIA'S AGRICULTURAL SOILS

The current state of SOC in California agriculture

The geographic extension, level of industrialization, and expertise of its agriculture make California a focal point for developing SOC sequestration strategies. California agriculture is unique due to its variety of perennial crops and high-value specialty crops. Two-thirds of the fruits and nuts and one-third of the vegetables in the United States are produced in California, even though California accounts for only 3% of the total cultivated land in the United States (CDFA 2022). Agriculture, including unirrigated rangelands, represents 22% of California's land. Perennial orchards (tree nuts, deciduous fruits, and citrus) and vineyards are planted on almost 30%, vegetable crops 10%, and cereal crops 20% (USDA-NASS 2022) of the approximately nine million acres of cultivated, largely irrigated agricultural land category.

The majority of crop acreage is cultivated using standard agronomic operations, including tillage and the use of fertilizers, pesticides, and irrigation. Thus, implementing conservation practices and optimizing inputs in California would provide an opportunity to reduce GHG emissions not only locally but globally (Suddick et al. 2010).

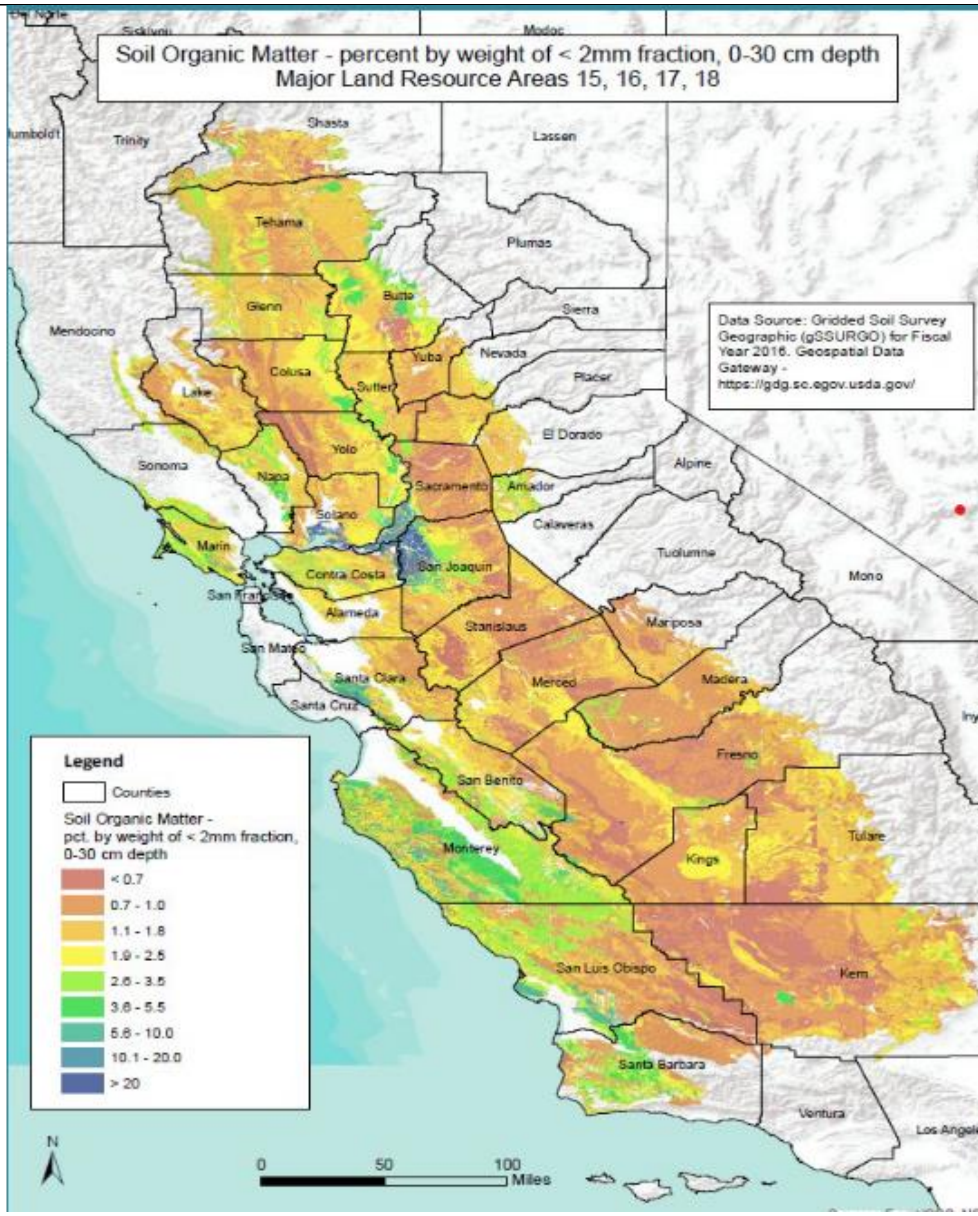

Figure 1: Rapid Carbon Assessment map (USDA NRCS 2016)

California soil stores 55% of its terrestrial C (Sleeter et al. 2019), and the C content of the state's soil is extremely variable. For example, Carey et al. (2020) monitored 45 rangelands to explore how SOC varies with geographic location, climate, vegetation, soil type, and topography within and across three regions of California. They found that rangelands in the Central Coast had greater soil C stocks than in the San Joaquin and Sacramento Valleys, where soils had similar levels of SOC. Soil C stocks ranged from 12–205 Mg ha^{-1} for 0–40 cm depth and varied sixfold within each region. Silver et al. (2018) found that SOC of California rangelands varied between 11 to 108 Mg C ha^{-1} (top 10 cm of soil profile).

California has large seasonally dry regions, where moisture limits plant productivity and the accumulation of C in soils (Abbas et al. 2020). In California, approximately 50% of the land area is part of a biome that experiences seasonal water deficits and 95% of the total cultivated land receives irrigation to overcome water limitations on crop productivity. The C stored in arid and semi-arid soils is generally low, but represents most of the C stored in these biomes (Wu et al. 2008). This explains why an estimated 75% of Mediterranean agroecosystems contain SOM lower than 2% (Tautges et al. 2019 and figure 1). In California, DeClerk and Singer (2003) measured agricultural SOC between 1.05% to 1.35%, while Mitchell et al. (1999) estimated it at 0.83%. Because the California water-limited agroecosystems tend to be low in SOC, they have the potential for sequestering additional C, but they are also particularly susceptible to rising temperatures and drought expected with climate change (Tautges et al. 2019). Increasing SOC could increase the adaptive capacity of these regions. Water deficits and high temperatures limit ecosystem productivity, and this affects the potential increase of SOC stocks compared with non-irrigated natural lands (Powlson et al. 2022). Water availability is one of the most important factors that determine SOC in croplands, and in arid regions it is largely dependent on public policies that build storage and conveyance infrastructure.

Land use and management have a large effect on SOC. Cropland experiences the most intense continuous management. Estimates of the SOC in the state reported that forests have the highest stocks with 147 Mg C ha^{-1}, compared to 90 Mg C ha^{-1} in pasture, 70 Mg C ha^{-1} in croplands, and 28 Mg C ha^{-1} in drier, unmanaged rangelands. The highest C stocks density is in wetlands, but this land use has the most limited spatial representation, mostly in the San Joaquin and Sacramento Delta region and in a lesser amount in Modoc County (USDA NRCS 2016). Among perennial crops, large variability in SOC stocks was reported, with SOC stocks of 54 Mg C ha^{-1} for walnut orchards, 16 Mg C ha^{-1} for almonds, and 105 Mg C ha^{-1} for wine grapes (Suddick et al. 2013).

Land use change can cause a loss or increase in SOC. When 125 agricultural California soils surveyed in 1950 were surveyed again in 2000 to assess the change of quality of soil over time, De Clerk and Singer (2003) observed that their chemical quality did not decrease significantly over the previous 60 years, even if the increased clay percentages observed could be interpreted as a sign of accelerated erosion. They reported an average increase in SOC from 1.05% to 1.35% (DeClerck and Singer 2003). The increases observed occurred mostly in vineyards and pasture, much less in orchards, and there was no change in croplands.

In past decades, California has seen an increase in perennial agriculture and crop yields in general. For example, California's perennial farmland increased from 3,140,000 acres in 2012 to 3,640,000 acres in 2017, while areas in annual production decreased from 8,000,500 to 7,858,000. Kroodsma and Field (2006) estimated that yields of California's crops were an average of 20% higher in 2000 than in 1980, and 90% higher than in 1950. The increase in perennial crop acreage is linked to C sequestration because management of perennial crops disturbs soils less than management of annual crops, higher lignin content in woody residues is less readily decomposed, and perennials store C within the woody biomass of trees and vines. The increased yields over the past half-century resulted in higher biomass residues returning to soils which promoted C sequestration. Kroodsma and Field estimated that California's agricultural land between 1980 and 2000 sequestered 11.0 Tg C within soils and 3.5 Tg C in woody biomass, for a total of 14.5 Tg C statewide, mainly due to the conversion of land from annual to perennial crops.

However, even if land use change has the potential to increase California SOC stocks, climate change may have the opposite effect. A study by Sleeter et al. (2018), using models, predicted a 432 Tg C decline in C storage in California's terrestrial ecosystems and a 328.3 Tg C decline in soil pools between 2015 and 2100 as a result of the higher decomposition rate of SOC caused by the increase in temperature.

Factors controlling SOC in California cropland

There are numerous physical, chemical, and biological processes affecting the stabilization (and destabilization) of SOC. These processes are dependent upon climate, soil type, vegetation, and management practices, which in turn affect temperature, moisture, aeration, and aggregation. The potential to increase SOC is controlled by the same factors controlling its variability among the different regions of the state. Biotic and abiotic environment are extremely important for the persistence of SOM (Rasmussen et al. 2018; Devine, et al. 2022). Explanatory variables predictive of SOC storage are soil texture, soil water regime, soil C/N ratio, total SOC content, soil pH, climate, vegetation, and well as the land-use history of the sites. The biological activity in soils depends on all these other factors. Precipitation and soil parent material appear to exert an influence on soil C turnover and storage as strong as temperature (van der Voort et al. 2019)

In California, the potential to increase SOC varies in different areas. Cropping systems in the Sacramento Valley showed more potential to mitigate GHG emissions than those in the San Joaquin Valley because the warmer temperatures in the San Joaquin Valley increase decomposition of SOC compared with that of the Sacramento Valley (Carey et al. 2020).

The current understanding of soil organic C cycling divides SOC into different pools associated with specific mechanisms that affect its decomposition, such as mineral sorption, aggregation, and microbial access. (1) The free particulate fraction is the most microbially available and the least persistent of the fractions. (2) The aggregates of the particulate occluded fraction protect SOC from microbial access. (3) The mineral-associated organic matter is most protected from microbial decomposition and is therefore the C pool cycling more slowly (Heckman et al. 2022; Schweizer et al. 2021). Soil organic C dynamics are largely (?) determined by the pool most responsive to changes in inputs. The abundance and persistence of SOC are regulated in distinct ways, and thus C stock size and stock persistence shouldn't be confused.

Effective pathways to sequester C are management practices that encourage greater C stabilization and slower rates of soil organic C mineralization. For example, labile pools may accumulate SOC much faster but are also more prone to losses than stable pools. Management can aim to enhance physically protected SOC stocks independently from an increase in the total SOC stock. Soils storing almost 60% of their organic C in mineral fractions highlight the important role of mineral protection in regulating C stocks and C persistence (Heckman et al. 2022).

The storage and stabilization of soil C is controlled by complex interactions. For example, climate controls stock levels and temporal dynamics, SOM chemical composition controls adsorption to mineral surfaces and complexation with metals, vegetation controls quality and quantity of inputs; lithology controls soil characteristics; and fire and topography control production of biochar and erosive redistribution of soil C. All factors control microbial community structure and function. The variation in biotic and abiotic factors determining variation in SOC at regional scale also exist at scales much smaller than a single crop field, and thus spatial variation in SOC is very large. The main predictor of change in SOC is depth (Rasmussen et al. 2018). Most of the SOC is present typically in the top soil layers and decreases with depth, but decreased microbial energy and increased sorption capacity of soil minerals with depth cause deeper C to be more persistent (Ahrens et al. 2020). Also, SOC at depth represents the sum of weathering and transport processes over time.

Climate

Environmental influences on SOC change are affected by different temporal and spatial scales. Higher temperatures (with unchanged precipitation patterns) increase soil C turnover, which means that a higher proportion of the SOM is converted or mineralized. It is predicted that, due to climate change, California will have a substantial increase in temperature (Hayhoe et al. 2004). Thus, these changes are predicted to translate into a decrease in SOC stocks and increased water demands within the state, posing a challenge for future policy and land management in California (Suddick et al. 2010).

The increase in soil respiration (emissions of CO_2 fluxes mostly due to microbial activity) with temperature and the accumulation of SOC in low mean annual temperature regions show how warming causes SOC losses. Sensitivity to temperature is lower for dry climates and high temperatures (García-Palacios et al. 2021), and thus, in California, losses due to climate warming could be less than in colder, more humid climates. However, these drier areas have low SOC stocks to begin with, thus SOC losses can have more pronounced effects on ecosystems functionality and interactions with soil moisture, plant production and responses of the soil microbial community. Because Mediterranean agroecosystems tend to be undersaturated in SOC, increasing SOC could increase the adaptive capacity of these regions to climate change (Tautges et al. 2019).

Higher temperatures decrease SOC persistence in all fractions. Particulate C decreases more than mineral-associated C in response to warming. An increase in biological activity in response to temperature may actually promote SOC storage when plant and soil biota activity is enhanced by warming that promotes soil decomposition and will result in more microbial necromass interacting with mineral surfaces (Cotrufo et al., 2015). Soil moisture as a predictor of SOC storage is as important as temperature. The relationship between temperature and wetness with SOC varies by fraction and depth. Greater moisture availability can lead to increased C inputs as plant productivity increases. However, high moisture limits the decomposition processes as much as low humidity. Also, high moisture levels can lead to greater transport of C to deeper soil layers, where increased weathering and sorptive surface area lead to greater protection of C. In general, soil C persistence is higher in humid ecosystems than in dry ecosystems, and the response to moisture is stronger in the subsurface. In conclusion, not all SOC is equally vulnerable to global change. The most active (e.g., particulate) C pools may be more responsive because they are more sensitive to changes in inputs.

Topography

The relationship between topography and soil processes is relevant to determine the geographical distribution of SOC. Topography impacts the quality and quantity of SOC accumulation. Topographic features, such as slope, curvature, and catchment area control soil erosion, the process that redistributes soil across hillslopes affecting the amount and quality of SOC across the landscape. Erosion represents a widespread cause of soil loss, decreased soil productivity, soil hydrological properties, and SOC sequestration potential. Along the hillslope, SOC and nutrient content are typically lower and soil thickness is reduced compared to depositional positions, where SOC is accumulated and buried, resulting in greater SOC stocks and protection from further decomposition (Fissore et al. 2017). Soil erosion can greatly affect C stocks at a particular location, but at larger scales, erosion may not represent a loss process but rather a redistribution of soil C (Paustian et al., 2019a).

In Mediterranean and semiarid regions worldwide, including in California, climate change projections point to increased erosion in hillslopes because of more frequent extreme weather events and fires as a consequence of increased temperatures and decline in precipitation (IPCC, 2007). Erosion can lead to loss of SOC. Over 55 published studies were reviewed by Abdalla et al. (2020), and soil and SOC losses under different land use and crop types were assessed. Croplands had the highest SOC loss at 22.78 ± 2.22 g C m^{-2} $year^{-1,}$ while natural vegetation had 98% and 70% lower run-off and soil loss compared to croplands. Rainfall and slope were key drivers and correlated positively to soil erosion, while soil surface cover, SOC, and clay content had a negative effect. Orchards showed the highest soil losses (but lower SOC loss) among cultivated lands due to high soil disturbance by heavy machinery during tillage, land preparation, and harvesting operations. High soil erosion rates in orchards and vineyards also occur because they are more commonly located on hillsides. Soil cover by vegetation showed 70% and 39% lower soil losses than crop residue and manure cover, which demonstrated greater efficiency of vegetation in terms of preventing soil erosion.

Soil texture and mineralogy

Soil structure is the organization of both aggregates and the pore spaces surrounding them (Tisdall and Oades 1982) and it is dependent on the interaction between soil particles, soil microbial activity, and above- and belowground C inputs. The formation of a stable soil matrix decreases the accessibility of substrates to microorganisms and thereby reduces the decomposition of substrates. Rasmussen et al. (2018) quantified how variations in soil parent material and soil structure control the physical partitioning and stabilization of soil C. Particulate fractions were affected more than mineral-associated fractions by vegetation. Lower particulate C abundance in grasslands and croplands relative to forests and shrublands was likely due to the lack of slow-to-decompose woody litter inputs. The SOC mineral fraction is particularly important in water-limited systems that include deserts, grasslands, savannas, and shrublands, largely characterized by Aridisols, Mollisols, and Alfisols. Models predict slower SOM turnover and higher storage in more finely textured soils because they offer larger surface area to interact with SOC. However, SOM content may be more related to the amount of extractable metals (Rasmussen et al. 2018). Soil pH is a primary control in environmental microbiology. For example, microbial processes (including the breakdown of organic matter into CO_2) are slowed down in acidic conditions (Wiesmeier et al. 2019).

Land uses

Most cropland mineral soils have lost 30–50% of the C stocks in top soil layers (0–30 cm) compared to their undisturbed condition (Davidson and Ackerman 1993). Conversion of undisturbed soils to cropland is expected to increase with the need to convert marginal lands to address the increasing food demand of the growing world population (Bruinsma 2003). In the U.S, this phenomenon will occur again if water scarcity generates policies that reduce irrigated land area in California and the irrigated land supplied by the Ogallala Aquifer in the plains region declines (Hornbeck and Keskin 2014). The initial conversion of native soils to cropland released approximately 5 Pg C (Lal and Bruce 1999). In California, the growing population and the profitability of grapes (which can be grown on marginal land) is predominantly converting oak woodlands, but also some rangeland and abandoned agricultural land to agriculture (Suddick et al. 2010). On the other hand, C is sequestered when annual crops are converted to perennials and when land is converted to forestry. The annual amount of C sequestration from land conversion is highest when land is converted to forests because mature woods are able to sequester considerably greater C annually as biomass than soil does (Wang et al. 2021). A global synthesis by Conant et al. (2017) estimated that C stock increased 39% after conversion of annual cropland to permanent grassland vegetation, with an average rate of circa 0.9 t C $ha^{-1}y^{-1}$. In California, water availability defines the type of perennial vegetation that can be established. Production of woody perennials like nut and fruit trees and most vines are often possible only if land is irrigated. Thus, SOC levels are determined by interactions between water availability, plant photosynthetic capacity (Janzen et al. 2022) and land use (Powlson et al. 2022). As for many ecological processes, the rate of a process influenced by a number of factors is determined by the most limiting factor (Blackman, 1905). Thus, SOC accumulation rate is highly variable among different places and at different times.

Rangelands[4] cover nearly half the world's terrestrial surface and store up to 20% of the global soil organic C (Sanderson et al. 2020). In native rangeland ecosystems, the rate of detrital C inputs is a function of the vegetation type (e.g., annual vs. perennial, woody vs. herbaceous) and productivity, largely governed by climate but also nutrient availability (White et al. 2020). In California, water deficit has a large control on ecosystem productivity of biomes, including rangelands. This phenomenon favors plant species that allocate much of their energy to root biomass in search of water and nutrients. Thus, healthy rangeland and other well-managed grasslands soils are characterized by large organic C stocks (Paustian et al., 2019a). However, grassland soils in California as well as in the rest of the world are depleted in C due to intensive management (Bai, 2010). In California rangelands, climate is the strongest predictor of C sequestration. Past and current land use also affect SOC, indicating that there is a potential to rebuild SOC through management (Carey et al. 2020). Increasing soil organic matter content has considerable potential to increase resilience to drought and soil erosion by augmenting soil water holding capacity in addition to greater nutrient availability and improved nutrient retention (Silver et al. 2018). One of the most effective management practices to augment SOC in rangelands is the addition of livestock manure, and the practice could have wide use in California, considering the state is the largest producer of dairy cattle in the country (USDA ERS 2022). While this practice can result in significant soil C sequestration, the benefits of increased C storage may be partly or completely offset by the need to transport and spread the manure from its source to its use (Owen and Silver 2015). In the U.S. alone, rangelands comprise 31% of the total land area, and up to 18 Tg C y^{-1} could be sequestered by applying the reported rate of 0.02–0.44 Mg C ha^{-1} y^{-1}. Approximately 960,000 ha of U.S. rangelands were converted to other uses between 2007 and 2015 (USDA-NASS 2022). Avoiding the loss of rangelands offers a well-established approach to retaining soil C along with the other ecosystem services that rangelands provide.

Vegetable crops are a high-value, intensively managed systems in California. These are commonly grown in coastal areas or in winter in the Imperial and Central Valley where the relatively mild Mediterranean climate allows growers to produce multiple crops each growing season. The common management practices used (intense tillage, multiple crops annually, irrigation, and relatively high N fertilization rates) may exacerbate C losses from the soil. Furthermore, many leafy vegetables such as lettuce and spinach return relatively little, but rapidly decomposed post-harvest residue to the soil because of a low residue C:N ratio, tillage, and high moisture content. In the Salinas Valley region of California, a major center of U.S. vegetable production, vegetable crops under intensive vegetable production in sandy loam soils had microbial C approximately six times lower than annual grass pasture. Decades of cultivation have resulted in large SOC losses, and today urban yard waste compost is commonly applied to soils to counteract the loss of SOC (Brennan and Acosta-Martinez 2017).

[4] Rangelands refer to grasslands dominated by native species, often occur in drier environments, and management is limited to manipulate grazing intensity and duration. In contrast, pastures include non-native species, are often derived from other land covers, and support intensive and diverse management options (e.g., fertilization, irrigation, plant species introduction, as well as grazing management (Paustian et al. 2019a).

4. CROP CONSERVATION PRACTICES AND GHG EMISSIONS IN CALIFORNIA AND THE REST OF THE U.S.

While crop yields are generally higher in the United States (e.g., U.S. corn yield is 89% higher than the world average), the current farming system is energy and resource intensive on a per acre basis (Kwon et al. 2021). As a result, in the United States, the agricultural sector in 2020 was responsible for 628.6 Tg CO_2e emissions, mainly from livestock and fertilization (EPA, 2022). To account for all GHG sources and sinks directly and indirectly linked to agriculture, researchers and regulators have turned to life-cycle analysis (LCA) (Sieverding et al. 2020). For agriculture, crops are evaluated in terms of all activities related to the production of farm inputs, such as energy consumption, GHG emissions, and other environmental attributes. Importantly, LCA of the agricultural sector can also identify environmental hotspots to guide future GHG mitigation measures and set up priorities (Kwon et al. 2021). Proposed strategies to reduce GHG emissions related to farming are based on reducing energy use, substituting electricity used with renewable electricity generated on-farm, turning organic waste into biogas and biodiesel and finally, using conservation agricultural practices (CPs) (Wang et al, 2021). Conservation practices are agronomic practices aiming to provide climate change adaptation and mitigation by recovering SOC and are based on minimal soil disturbance, permanent soil cover, and crop rotation (Nicoloso and Rice 2021). Globally, CP are still not commonly used, as they are applied on only 12.5% of the total global agricultural cropland (Kassam et al. 2018). If these practices were implemented on 100% of the world croplands, the effect of increasing SOC stocks in the top 40 cm on average by 4 per mille per year would offset most of the current annual increase in atmospheric CO_2 (15.8 $GtCO_2$ y^{-1} ; Paustian et al., 2019a). However, in the U.S., this would only sequester about 5% of total U.S. emissions (Thompson et al. 2021). Also, these rates of SOC storage could be sustained for a limited time period, on the order of 2–3 decades before decreasing as soil C levels achieve a new equilibrium. In addition, recent studies have found that mitigating GHG emissions with C sequestration is not straightforward. Because the magnitude of the climate response to GHG emissions or removals is not symmetrical, a larger C sequestration is needed to compensate for a given C emission (Zickfeld et al. 2021).

Conservation practices are designed to sequester SOC in agriculture by adding C inputs or reducing C decomposition (Kwon et al. 2021). The C input can be increased by enhancing primary production (with mineral and organic fertilization and irrigation), by applying additional organic C (manure, compost, incorporation of crop residues, biochar, vermicompost or anaerobic digester bioproducts, or cover crops), by enriching subsoil organic C (deep-rooting crops), and by integrating woody biomass (agroforestry). Less SOC can be lost by reducing tillage. The CPs were designed to enhance the capacity of agricultural ecosystems to be net atmospheric CO_2 sinks.

Long-term field experiments, such as the Long-term Research on Agricultural Systems (LTRAS, now Century experiment) established in 1993 by researchers at UC Davis, the Sustainable Agriculture Farming Systems project (SAFS) conducted at UC Davis from 1989 through 2000, and the West Side Research and Extension Center (WSREC) were essential in assessing long term effect of agricultural management practices and specifically CP on agricultural SOC in California. These datasets were used to validate ecosystem-scale models such as DAYCENT (Grosso et al. 2010) or DNDC (Li 2007) that are used to scale results from local to state level, predict effects of changes in management practices, and estimate the mitigation potential of GHG emission in agriculture (Suddick et al. 2010). The DNDC model estimated that there are large differences in the C dynamics by crop and region (Li et al. 2014). The authors recognized that assessing the effects of CPs on GHG emissions requires further field monitoring and model validation. Furthermore, DAYCENT is not calibrated or validated for perennial cropping systems.

Synthesizing the effects of diverse CPs on SOC is not realistic. In addition to the range of soil types and climate of the experimental studies, there is variability even in the definition of the practices. For example, reduced tilling implies a range of operations made using different equipment, ranging from no tilling to mulching with crop residues. Different studies analyze soil C stocks over variable soil depths, experiments can last from one year to decades, and published data can be the result of field experiments or modeling exercises. The CPs can often overlap (for example, cover crops, rotations, and crop residue additions). Often CPs are used simultaneously with significant synergies and it is difficult to detangle the effects or alternated, paused, and combining over the years to mitigate trade-offs between the benefits and drawbacks of CPs (Jackson et al. 2004). Analysis of the interactions with other GHGs, pests and diseases, or economic impacts are commonly lacking.

We now review each of the main CP practices assessing their effect in California first, but also at the global scale, as more data are available and can fill gaps in knowledge at a local level. We limit our focus to the most recent publications, including reviews on the subject.

Table 1 California recent studies (>2005) of the effect of conservation practices on agricultural soil C sequestration

Practice	Soil depth	Study duration	Land use/cover	Change in SOC density	Method	Reference	Year of publication
	cm	years		kgC ha-1y-1			
Composting	100	1	Rangelands	2100	Field data	Silver	2017
Composting	200	19	Annual crops	1150	Review	Tautges	2019
Composting	30	8	Vegetables	1570	Review	White	2020
Composting	50	3	Rangelands	1000	Field data	Ryals	2014
Reduced tillage	Full profile	20	Crops	50-300	Modeling	Kroodsma	2006
Conversion to permanent vegetation	Full profile	20	Crops	330-470	Modeling	Kroodsma	2006
Cover crop	200	19	Annual crops	705	Review	Tautges	2019
Cover crop	0-30	8	Vegetables	400	Field data	White	2020
Irrigation	100	30/90	crops	274	Field data	Wu	2008

Tillage

Conventional tillage exposes some protected SOM to decomposing microorganisms. It also promotes soil erosion, reducing SOC stocks (Fissore et al. 2017). Reduced tillage (NT) usually implies a reduction of tillage depth and/or frequency (Tiefenbacher et al. 2021). Under NT, aggregation and aggregate stability is significantly enhanced, which is believed to be the main mechanism promoting increased C storage (Six and Paustian 2014). Within the United States, a decrease in standard tilling practices for planted cropland usage has occurred over the past 20 years (Claassen et al. 2018). Although the United States has the highest area under NT practice, NT farmland only covers 21% of all cropland (Abbas et al. 2020). In the Canadian prairies, NT enhanced soil health, increased soil water availability in near-surface layers, and allowed the introduction of new crops, including oilseeds and legumes (Lindwall and Sonntag 2010). Numerous studies are concentrated on colder temperate regions (Abbas et al. 2020; Grace and Robertson 2021). The NT practices are often controversially discussed as a climate mitigation option due to high uncertainties with outcomes. Effects can vary due to soil texture and climate (Ogle et al., 2019; Paustian et al., 2019a) and affect the vertical distribution of C, roots, water and temperature in the soil profile. Depending on site-specific conditions and interaction among these parameters, NT can result in increase, no differences, or losses in SOC, especially deeper in the profile (>30 cm) (Ogle et al. 2019) and interacts with the production of N_2O (Sandén et al. 2018). In some cases, NT can result in lower crop yields compared to conventional tillage practices because accumulation of both crop and cover crop residues can inhibit the early stages of crop growth (Soane et al. 2012; Sandén et al. 2018), which can result in the use of more herbicides (Chauhan et al. 2006). Even if the effects of NT on SOC are uncertain, consensus exists on the fact that NT promotes sustainability by reducing fossil fuel usage, labor, soil erosion, and water use (Mitchell et al. 2020; Suddick et al. 2010). When all GHG sources and sinks from farm operations, chemical inputs, soil C sequestration, and N_2O and CH_4 emissions were included per unit crop yield, NT systems had 71% lower GHG intensity than conventionally tilled systems (Sainju 2016).

Globally, NT practices have a carbon sequestration potential in the topsoil (0–30 cm) of circa 300 kg C ha^{-1} y^{-1} (Tiefenbacher et al. 2021). Overall, the C sequestration potential increased rapidly during the first ten years (+0.75 Mg C $ha^{-1}y^{-1}$), whereas after 15–20 years, a new equilibrium is reached. The most recent 2021 global meta-analysis by Nicoloso et al. re-examined the role of NT in promoting C sequestration throughout the soil profile (0–100 m) using 142 studies (no studies in California) with an average duration of 16 years. The review suggests NT has a greater potential for C sequestration than previously thought if N and C inputs limitations are overcome. Single-cropping systems lack the necessary C inputs to offset SOC losses in the soil profile, while double-cropping systems decrease soil N stocks constraining future C sequestration. The tight link of C with N regulates soil C sequestration, so agricultural practices that favored a positive N balance also favored SOC storage. When NT is associated with additional CPs (i.e., crop rotation, cover crops, rotations, use of organic amendments), the yield gap can be closed, and SOC stocks augment up to the levels of natural soils. Overall, NT soils had greater SOC and total N stocks than tilled soils, notably in the upper 15-cm soil layers and in warm climates, and C soil sequestration of 400 ± 100 kg ha^{-1} yr^{-1} (0-60 cm) (Nicoloso and Rice 2021).

Few studies have addressed NT within California, where adoption is still low (Bossange et al. 2016). This lack of research on NT effects on soil C sequestration is in part due to the heterogeneity of California agriculture and the challenges in adopting NT in irrigated systems, where often tillage maintains the furrows to convey irrigation water. In dry areas, including large parts of California, limits on water availability for irrigation can determine C inputs to soils. NT may leave crop residues on the soil surface, which will likely increase SOC mineralization (direct oxidation) without any effect on SOC (Unger et al., 1997). In a study on Mediterranean soils, NT practices increased SOC stocks (5–40 cm) by 7% compared to minimum tillage practices (Francaviglia et al. 2019). In California, studies indicate that using NT alone does not substantially increase soil C but can lead to sequestration of soil C when integrated with other CA practices (De Gryze et al., 2009; Veenstra et al., 2007). Various tradeoffs suggest that farmers could alternate between conventional and NT, with frequent additions of OM, to enhance several aspects of soil quality, and reduce disease and yield problems that can occur with continuous minimum tillage (Jackson et al. 2004).

In summary, NT practice will result in SOC storage in California in situations where there are no other limitations to productivity, such as water and N inputs, and if used in combination with additional management inputs.

Cover cropping

Cover cropping is a conservation practice that diversifies soil C inputs and has many benefits. Crop diversity can be increased on a temporal (crop rotation, catch crops) and spatial scale (several plant species at the same time, cover crop mixture). Cover crops (CC) generally are grown to protect soil from erosion and compaction, they may enhance N supply and diminish nutrient loss, suppress weed species through competition, and provide potential habitats for beneficial insect species. They improve soil quality and enhance soil C stocks by increasing plant biomass, soil nutrients, SOM levels, and biological activity (Suddick et al. 2010; Tiefenbacher et al. 2021). The CC are sown after the harvest of the main crop (such as cereals) or undersown in/with main crops. This creates a permanent plant cover and a longer C assimilation season (Chahal et al. 2020). However, CC cultivation is not always possible. It requires water, delays other field activities, may be an entry point for weeds if the CC grows slowly, inhibits the use of fields for commercial crops that might be grown during the same period, and costs money and energy to produce without generating any revenue.

Globally, the carbon sequestration potential of annual cultivation of CC reported by Tiefenbacher et al. (2021) amounted to circa 400 ± 140 kg C ha^{-1} y^{-1} (0–30 cm), and was 560 kg C ha^{-1} yr^{-1} in a 2020 meta-analysis of 131 studies across the globe by Jian et al. (2020). The quality and quantity of crop residues incorporated or remaining on the surface determine decomposition rates and C and N inputs into the soil. For instance, lignin found in cereals and woody plants results in slow decomposition. CC mixes ensure a combination of faster and slower decomposition, increasing soil microbial biomass and SOM. Overall, labile C fractions increase in surface soils (McClelland et al. 2021). Despite their C sequestration potential, N accumulated by N-fixing CC can cause N_2O emissions over decades (Lugato, et al. 2018). However, a meta-analysis by Basche et al.(2014) found no increase.

In California, CC has been practiced over the past several decades (Blake, 1991), for example, in the Californian grape industry. Between 2012 and 2017, CC use increased 50% on average nationwide, but only 3% in California (NRDC 2022). Different annual grass and legume species, cereal rye, and several cruciferous species are suitable CC in CA. Their management practices are less disruptive of soil than those used in annual crop systems (Kroodsma and Field 2006). In the higher rainfall regions of northern California, planting a winter CC can help to improve rain infiltration and enhance soil water storage (Suddick et al. 2010). However, successful integration of CC into agricultural production systems in arid and semiarid climate regions of California will only be feasible with careful consideration of water balance issues. Short-season CC can be integrated during the winter when evapotranspiration demand is typically low. Additional windows of opportunity for CC may exist following crops that are harvested during early or mid-summer. In order to provide long-term benefits of winter CC, all practices must be compatible both with the planting schedules of commodity crops and their management (Mitchell et al. 1999), conditions that are difficult to achieve. Farmers fallow croplands every other year to conserve soil moisture and stabilize grain yields, and inclusion of a fallow phase does not necessarily contribute to SOC losses (Tautges et al. 2019).

In California organic vegetable production systems, CC can reduce the number of cash crops produced and complicate management (Brennan and Acosta-Martinez 2017), which explains the infrequent use of CC reported (White et al. 2020). There are also cost considerations that affect grower decisions (Suddick et al. 2010).

Crop Rotation

In contrast to single cropping systems (monoculture with cereals or maize), diverse crop rotations with various main crops, perennial crops, forages, and cover crops yield distinctly higher SOC stocks (Poeplau and Don 2015). Beyond its beneficial effects on SOC stocks, a diverse crop rotation can also increase soil microbial diversity, soil aggregate stability, or even enhance organic C in the subsoil via deep-rooting crops (Kätterer et al. 2011). For this practice, as for the other CP practices, the effect predominates in the topsoil and declines with soil depth. Crop rotational systems can enhance the carbon sequestration potential of agricultural topsoils (0–30 cm) by circa 200 ± 100 kg C ha^{-1} y^{-1} when compared with single cropping systems (Tiefenbacher et al. 2021). Compared to high fallow frequency systems, intensifying and diversifying crop rotations can increase average annual C inputs, leading to higher SOC stocks.

Organic amendments

Compost and Manure

Organic amendments add new C to the soil and increase C sequestration by stimulating plant productivity. They also enhance soil quality which in turn provides a better habitat for beneficial soil fauna. For example, decomposers, such as earthworms, can be attributed to inputs of organic amendments. Earthworms can improve plant growth, stabilize soil organic matter, and contribute to the formation of stable soil aggregates (Lazcano et al. 2008). Similar to mineral fertilization, organic fertilization may stimulate SOC biodegradation and can increase soil pH, which in turn can enhance the solubility of soil organic matter (Tiefenbacher et al. 2021). Animal manure appears to improve soil structure and water holding capacity, but also rapidly degrades in soil, and the enhanced microbial activity may reduce the SOC stock (Shahbaz et al. 2018). The quality of composts can be nonhomogeneous, and they may contain toxic substances such as heavy metals and organic contaminants. Organic fertilization enhanced the C sequestration potential of Mediterranean soils by 23.5% (Francaviglia et al. 2019). The impact of farmyard manure on SOC in some cases halted after a decade, but in others continued for 50 years (Tiefenbacher et al. 2021).

The replacement of synthetic fertilizers with compost has the potential to reduce GHG emissions. In a global meta-analysis of GHG emissions from organic and synthetic soil amendments, Charles et al. (Charles et al. 2017) found that compost had an N_2O emissions factor of 0.27% of total N applied, compared to 1.34% of total N applied in synthetic fertilizers. Emissions of N_2O were lower in organic systems fertilized with compost than in conventional systems with synthetic fertilizers, especially in Mediterranean croplands (Aguilera et al. 2013). Alluvione et al. (2010) observed a 49% reduction in N_2O and CO_2 emissions from soils following compost amendment compared to amendment with synthetic urea fertilizer and a substantial increase in soil C even in semiarid climates. The particular compost characteristics (e.g., C:N ratios) can be correlated with SOC sequestration potentials. Since it has already undergone partial decomposition, mature compost contributes relatively stabilized C to soil and increases the proportion of lignin in SOC, while CC contributes to the actively cycled SOC pools because residues decompose rapidly following incorporation due to their low C:N ratio (Tautges et al. 2019) Globally, the carbon sequestration potential was 290 ±130 kg C ha^{-1} y^{-1} for manure and 714 ± 404 kg C ha^{-1} y^{-1} for compost and varied with the application rate (Tiefenbacher et al. 2021;).

In California, a study of the microbiological activity from a 6-year study on vegetable crops in the central coast region that added large amounts of organic matter to the soil (>5 Mg dry material ha^{-1} annually) and frequent winter CC use provided strong evidence that compost had a great direct beneficial impact on SOC while the CC had a greater impact on the soil food web (Brennan and Acosta-Martinez 2017). A one-time application of compost in California rangelands resulted in greater soil C stocks in all the modeled soil C pools (Silver et al. 2018). The effect on SOC was dominated by an increase in the slow C pool and was due to both the direct addition of C as well as an indirect increase from enhanced plant productivity. The C sequestration achieved through applying compost to these California rangelands would avoid 15-20 million tons of CO_2e by 2030, accomplishing about half of the GHG reducing goal set by California.

However, organic fertilizers and amendments are not always available on site, and emissions caused by transportation over 100 km can exceed the C sequestration potential by 30% (Tiefenbacher et al. 2021). Importantly, the process of composting also emits GHG, though only represents 2.1% of total annual GHG emissions of the California agricultural sector and 0.18% of the total state emissions (Zhu-Barker et al., 2017).

Crop Residue

Besides enhancing SOC stocks, the incorporation of crop residues into agricultural soils improves soil structure, reduces bulk density, reduces evaporation, decreases erosion, and improves the water infiltration rate in soils (Mitchell et al. 1999). Generally, maize or perennial crops produce abundant residues, whereas root crops such as potatoes generate smaller amounts of residues (Tiefenbacher et al. 2021). Using residues for bioenergy production or animal feeding/bedding decreases crop residues returned back to soils. Moderate removal of crop residues for bioenergy (<50%) can still maintain or slightly increase soil C stock which emphasizes the importance of site-specific, sustainable residue management (Kwon et al. 2021). The residue's C: N ratio also influences SOC, and crop residues with a lower C: N ratio (e.g., soybean) promote microbial decomposition. Incorporating crop residues of varying amounts and types into soils yields an average carbon sequestration potential of 168 ± 67 kg C ha^{-1} y^{-1} (0-30 cm) (Tiefenbacher et al. 2021). In a meta-analysis of 39 publications involving long-term field experiments, residue incorporation enhanced SOC stocks by 7% (Lehtinen et al. 2014).

Biochar

Biochar is the product of thermally processing organic materials (plant-or animal based) at temperatures above 350 ^{o}C and under restricted oxygen supply ("pyrolysis"). Biochar also occurs in the soils of many fire-prone ecosystems, including grasslands and woodlands, and this pyrogenic C can make up as much as 35% of the SOC in these systems (Bird et al. 2015). Hence biochar/pyrogenic C is a natural constituent of many soils, and soil function is not generally impaired (and may be enhanced) with the addition of large quantities of biochar (100 t/ha or more). Most of the biochar mass is highly resistant to microbial decay, and biochar additions to soil can either stimulate or reduce the decomposition of existing SOM. Biochar impacts soil water holding capacity and soil moisture, changes pH and nutrient availability, and affects microbial community activity and composition (Paustian et al., 2019a). Finally, biochar additions can influence plant productivity and hence C inputs to soil. Biochar amendments may also decrease soil N_2O emissions, but because biochar production and transport cause GHG emissions, the actual mitigation attained depends on the full biochar life (Paustian et al., 2019a). The average carbon sequestration potential of biochar application is 1.6 ± 5.14 Mg C ha^{-1} y^{-1}. From an environmental point of view, biochar fertilization would be beneficial. However, currently, the monetary costs of biochar exceed its advantages (Tiefenbacher et al. 2021).

Irrigation

Irrigation can alter predominant soil-forming factors such as climate, vegetation, soil disturbance and topography (Jenny, 1941). With irrigation, effective precipitation is greatly increased, and sparse California shrublands or annual grasslands can be converted to fields of annual and perennial plants. During this process, the soil undergoes frequent tillage and compaction by heavy machinery, and land is leveled to promote efficient irrigation. Both losses and increases in SOC have been observed in lands after conversion to irrigated croplands (Wu 2008). The practice enhances plant growth and thus increases organic C inputs into agricultural soils, but the accelerated OM mineralization might reduce these benefits (Zhou et al. 2016). In a global meta-analysis, the carbon sequestration potential of irrigation amounted to -13 ± 78 kg C ha^{-1} y^{-1} as a synthesis of studies with contrasting results (Tiefenbacher et al. 2021). Also, the C costs of pumping water can exceed the increased SOC stock benefits. Furthermore, irrigation can boost denitrification and N_2O emissions from soils and may exacerbate nitrate leaching as well as the runoff of agrochemicals (e.g., herbicides, pesticides, and insecticides) Tiefenbacher et al. 2021).

<u>In California</u>, the SOC was significantly increased in the top layers of agricultural soils compared to that of native shrublands in the Imperial Valley after up to 90 years of irrigated farming. The fastest rate of SOC sequestration occurred in the 10 to 60 cm depths, where crop roots are denser than those of native shrubs (Wu 2008). A study comparing SOC in soils in irrigated vineyards and nut trees up to 100 cm in the profile found higher SOC in the lower depth in the irrigated lands compared to the adjacent natural ecosystems. At the same time, the conversion of natural ecosystems to irrigated crops resulted in loss of soil structure and increased soil bulk density, which affected SOC storage (Suddick et al. 2013).

Additional practices that can be used to increase SOC are crop cultivation for bioenergy production, development of deep root plants and perennial grain crops, application of inorganic C (Carbonate minerals, liming), rewetting of organic soils, and improved grazing management. Grazing management in rangeland is particularly significant in California due to the importance of this landscape. Almost all the ecosystem C in grazeland is in the slow-cycling soil pool, and thus most soil losses are due to management. Still, drought can decrease plant growth below the SOC decomposition rate, resulting in ecosystem C losses. The potential to increase soil C stocks in semiarid regions due to rangeland management is modest per unit area compared to avoiding conversion of native lands or restoring native perennials in formerly cultivated lands (Paustian et al., 2019a; Powlson et al. 2022)

5. POLICIES AFFECTING SOC SEQUESTRATION

The California Global Warming Solutions Act of 2006 (AB 32) set a statewide limit on GHG emissions and confirmed California's commitment to transition to a sustainable, clean energy economy. in 2016 California's governor raised its goal and committed to reduce GHG emissions by 40% below 1990 levels by 2030. To help reach this goal, California designed a market-focused solution (Niemeier and Rowan 2009). Markets can play a key role in mitigating the effects of climate change by allowing emissions reductions to occur with added flexibility and at a lower cost. Today's C market is organized into a regulatory compliance and a voluntary market. So far, agriculture has not been subject to C caps such as those in the EU Emissions Trading Scheme or in the California cap-and-trade program, largely because of challenges in quantifying GHG emission reduction through both measurement and modeling.

Soil C sequestration, beyond its climate mitigation potential, can be seen as an ecosystem service (ES). Systematic methodologies have been proposed and used to incorporate the role of ESs in life cycle assessment of agricultural products (Rugani et al. 2019). The simultaneous assessment of multiple ESs in the life cycle assessments estimates the potential for synergies and trade-offs among different environmental attributes. Also, assigning monetary values to ES and having "payments for ecosystem services" could incentivize sustainability in agriculture (Kwon et al. 2021; Farley and Costanza 2010). These methods, however, suffer from unavoidable subjectivity in defining the meaning of sustainability, what is included, and quantitative limits for compliance. California already supports extensive regulatory programs that seek to protect the environment. There are characterized by broad public participation and rely on expert testimony and research, and fulfill or exceed many of the functions required of sustainability assessments while preserving choice and sovereignty

There is consensus that increasing SOM improves most soil functions supporting crop production, but less consensus about the use of soil C sequestration as part of climate mitigation initiatives (Bradford et al. 2019). The lack of consensus is due to the variability in outcomes depending on local conditions (Devine, Steenwerth, and O'Geen 2022) and the difficulty in quantifying soil C sequestration and ensuring its long-term permanence.

Participation in the C market of agricultural soil C sequestration projects is currently on a voluntary basis, but adoption could occur at much higher rates if estimating GHG emissions from agricultural lands becomes technically and economically feasible. Currently, the transaction costs of measurement and certification of C credits are large relative to the amounts of C being valued.[5] Implementing a C credit system for agriculture requires a systematic method to accurately measure and account for agricultural GHG gas reductions based on sound measurements, reporting, and verification (MRV) system to track that claimed increases in soil C stocks are real. Much of the infrastructure for an effective MRV system for soil C sequestration could be assembled relatively quickly and with modest investments (Paustian et al., 2019b). Quantification tools would integrate ground-based experiments, monitoring, models, remote sensing, and farmer-based knowledge of management practices. Some of these uncertainties can be resolved by developing models that reflect the emerging understanding of the SOC system, that relatively simple molecules, which are otherwise readily consumed by microbes, persist in soil because of their physical location and chemical attraction to mineral surfaces. The development of these models will increase the ability to predict and quantify management effects on SOC in agriculture (Thompson et al. 2021).

Currently, only 7% of the farmers have actively engaged in discussions about storing C, and just 1% have actually entered into a contract to sequester C, even if demand for C offsets is expanding (Thompson et al. 2021). Challenges for farmers include the requirement of additionality (i.e., whether offsets represent a GHG benefit that would not have occurred in the absence of payment) and permanence (i.e., the risk that sequestered C will be emitted back when offset projects end). Since soil C sequestration is potentially impermanent (Ritter and Treakle 2020), farmers need to commit to specific crop/management plans and to monitoring for decades. In the United States, the major programs enrolling farmers in soil C sequestration programs are currently using 1- to 20-year contracts (Ecosystem Market Information 2022). Current prices are too low to provide incentives for widespread participation,

[5] https://www.nationalacademies.org/event/06-06-2022/accelerating-decarbonization-in-the-united-states-technology-policy-and-societal-dimensions-the-science-and-practice-of-agricultural-soil-carbon-offsets-webinar

and producers most frequently identified the payment level offered as the reason they are not participating in soil C markets (Thompson et al. 2021). The other frequently identified impediment to participation in C markets among the farmers is the legal liability associated with contract termination that would require the producer to pay back C offsets previously sold. Farms cannot guarantee that they will remain in business for extended periods in an uncertain future, so tools to account for project termination should be considered. Additionality requirements for most C offsets or credits require that only adoption of new practices or implementing practices on new acres qualify for C sequestration programs. Producers who have been previously implementing practices such as no-till and cover crops are ineligible to receive payments for C sequestration on land where those practices have been in place. There are also questions about whether producers who receive public funds to adopt conservation practices are also eligible to sell the resulting C offsets on the C market. Finally, monitoring SOC stock changes requires sampling every field in the program for actual soil C sequestration. This results in high certification costs for C credits. For this reason, current soil C programs rely on a combination of soil sampling and modeling to measure C sequestration. Available soil C programs almost unanimously bear the costs of testing, meaning the farmer does not have to worry about paying for soil C verification. But these reduce the amount of money farmers can expect for credits. There have also been questions about the government's role in legitimizing and bringing oversight to soil C markets. The recent U.S. Senate Bill S.1251, "Growing Climate Solutions Act of 2021" seeks to provide a framework that assists farmers participating in C markets by providing reliable information and establishing a series of standards for certification for C offsets.

Uncertainties associated with the quantification of SOC changes and effects of CP differ among regions. Crop production in California is very heterogeneous, market-responsive, and dynamic. Constant technological innovation and market pressures make long-term commitments to carbon-focused farming practices difficult to sustain. However, in other geographic regions, such as the Canadian and US prairies and the midwestern US, cropping systems are more stable and conditions are less heterogeneous. In those regions current ability to predict and quantify SOC increases with long-term commitments from farmers have greater viability.

The EPA GHG inventory includes conservation practices in the calculation of the annual GHG emissions of the U.S. It also promotes NT practices on cropland and improved grazing management practices on grassland as opportunities to reduce GHG emissions in the Land-Use Change and Forestry Sector (US EPA 2022). Priority should be given to increasing farmers' accessibility to the C markets that have lower verification costs and improved ability and accessibility of SOC monitoring technologies. Currently, none of these compliance programs allow row-crop agriculture as a source of C offsets. An overview of the current initiatives focused on California, but also for and outside the US follows.

Inset markets

Insetting represents an initiative taken by a company to combat emissions within its own supply chain. There are currently several examples of C insetting where companies have directly targeted the agricultural segments of their supply chains for opportunities to sequester C through the implementation of what are called regenerative practices. Examples of inset markets include initiatives by Nestlé and Bayer, as well as the efforts of the Field to Market Alliance (Thompson et al. 2021).

Healthy Soils Programs

The California Healthy Soils Program is part of a collaboration of state agencies and departments to promote the development of healthy soils on California's farmlands and ranchlands. The program provides financial assistance for the implementation of CP that improves soil health, sequesters C, and reduces GHG emissions. Practices incentivized are cover cropping, reduced tillage, mulching, compost application, conservation plantings, reduced fertilization, and use of nitrification inhibitors (CDFA-OEFI 2022)

Sustainable Agricultural Lands Conservation

The California Sustainable Agricultural Lands Conservation (SALC) Program utilizes Cap-and-Trade proceeds to protect agricultural lands on the outskirts of cities and near residential neighborhoods from conversion to non-agricultural uses. Protecting farmland from development avoids increased emissions associated with land-use change and provides an opportunity to capture C in soils. SALC's mission is to support California's need for agricultural conservation, economic growth, and sustainable development. In 2022, the program reports it enlisted 90,000 acres in 18 counties (CSGC, 2022).

CV Salts

The California CV-SALTS program investigates salt and nitrate water quality challenges in the California Central Valley and develops and recommends policies and actions to improve quality and efficiency in water use. The program includes representatives from growers, dairies, industries, local communities, government agencies, environmental and community organizations, and the Central Valley Regional Water Quality Control Board (CV-SALTS, 2022).

Certification protocols

Carbon by Indigo is a large-scale agricultural C program using protocols approved through two global C registries: the Climate Action Reserve and Verra. The credits issued by this program are registry-certified to be real, additional, permanent, independently verified, uniquely claimed, and with co-benefits. Techniques such as reduced tillage, N efficiency, and cover cropping are incentivized. Today, Carbon by Indigo represents over 3.3 million participating acres.

Nori's (2021) vision is to cut down on project verification costs by working with a third-party C quantification tool and allowing for the sale of additional ecosystem services. The "currency" used is one tonne of CO_2 sequestered for at least 10 years.

Truterra's TruCarbon program (2021) streamlines the path to agricultural C and ecosystem services markets. It incentivizes stacking many positive environmental outcomes of on-farm conservation practices, such as water quality and quantity**.** Enrollment in the Soil and Water Outcomes Fund will open in late March 2022.

The non-profit Ecosystem Services Market Consortium (2021) works to compensate farmers and ranchers who improve the environment through agricultural practices. Much of their work centers around the development of accurate and cost-effective ways to measure changes in soil health, as well as water quality and quantity. Techniques focus on sequestering and reducing GHG emissions as well as reducing farm and ranch runoff.

Low Carbon Fuel Standard (LCFS)

California's Low-Carbon Fuel Standard (LCFS) provides incentives to biofuel producers to reduce GHG emissions at biofuel conversion facilities. The LCFS applies a life-cycle C intensity analysis that captures all GHGs emitted per unit of fuel, including fuel extraction, cultivation, land-use conversion, processing, transport, and fuel use. The amount of C (by weight) emitted per unit of energy consumed for a given transportation fuel is defined as its C intensity ($gCO_{2eq}\ MJ^{-1}$). The C intensity includes the "direct" effects of producing and using the fuel, as well as the "indirect" effects that are primarily associated with crop-based biofuels. The program promotes the development of transformative innovations, reduction in transportation emissions, and industry rather than government mitigation of fuel GHG emissions (Steenwerth et al. 2014).

Challenges to LCFS implementation include the determination of an appropriate energy-related GHG target, the development of a robust life-cycle assessment methodology, and the construction of a transparent compliance system. The average credit price was $187 per credit for the calendar year 2021, and increased annually in prior years as set by the market (CARB, 2022). Other jurisdictions are joining California, including the Pacific Coast Collaborative, a regional agreement between California, Oregon, Washington, and British Columbia to strategically align policies to reduce GHG and promote clean energy. These states have existing LCFS programs in place or are considering a program (Washington). Canada and Brazil are also noticing California's success and developing LCFS-like performance standards for transportation fuels.

Agriculture-related C sequestration protocols are not part of the LCFS. Currently, the program does not extend incentives to biofuel feedstock producers due to the technical and economic difficulties in monitoring and verifying field-level GHG emissions. The inclusion of soil carbon credits associated with biofuel feedstock production would add complexity to LCA estimates of indirect changes due to feedstock use. However, studies that applied life cycle analysis to evaluate the sustainability of biofuel production have shown that farming activities contribute significantly to the GHG emissions of all biofuels derived from farmed crops. Incentivizing additional shifts to SOC conservation practices would further reduce the life-cycle GHG emissions of biofuels (Kwon et al. 2021). If SOC accumulated by using CPs in soils from which biomass is derived can be reliably quantified, the LCFS could support the adoption of such CPs, potentially having large-scale positive effects on farm management in California and elsewhere. This would be especially true as other states adopt the performance based approach to GHG reductions in fuels inherent in the LCFS.

Conservation Reserve Program (CRP)

The Conservation Reserve Program (CRP) pays U.S. farmers to retire marginal and highly erodible croplands. Signed into law in 1985, CRP is one of the largest voluntary private-lands conservation programs in the United States. It was originally intended to primarily control soil erosion and potentially stabilize commodity prices by taking marginal lands out of production. The program has evolved over the years, providing many conservation and economic benefits. Peak cumulative enrollment reported in 2012 was 35 million acres. In 2022, 22.1 million acres were enrolled, with 4.6 million acres into CRP signups in 2021 (USDA-CRP, 2022). Congress sets the levels of acres eligible for enrollment. The EPA National GHG inventory report credits CRP land as a key contributor to agricultural soil C sinks in the U.S. (US EPA, 2022).

Environmental Quality Incentives Program (EQIP) and the National Water Quality Initiative (NWQI)

Currently, the USDA Natural Resource Conservation Service is running the Environmental Quality Incentives Program (EQIP) and the National Water Quality Initiative (NWQI) programs to provide technical and financial assistance to farmers to plan and implement conservation and management practices. However, these programs focus on a fixed level of incentives regardless of their absolute impacts on the environment.

Incentive policies outside the US

In Australia, Carbon Farmers of Australia (CFA) has just launched the world's first Soil Carbon Industry Group. Under Australia's 'Emissions Reduction Fund,' there are currently contracts in place to supply over 3 million tonnes of soil C sequestration over the next 10 years.

In Canada, the province of Alberta started its own C offset program in 2007. In the voluntary market space, Canadian agriculture recently gained access to the Canada Grassland Protocol on Climate Action Reserve's voluntary market registry and the Improved Agricultural Land Management Methodology overseen by the Verified Carbon Standard program. The Federal Greenhouse Gas Offset System is currently developing an Enhanced Soil Organic Carbon protocol (Canada.ca 2022).

Currently, Europe does not have any targeted policy tools to significantly incentivize the increase and protection of carbon sinks for land managers (EU 2022). However, the EU Parliament recently held a plenary vote on the EU-wide Climate Law in 2021 that moved the jurisdiction closer to a soil carbon credit market. In addition, the European Parliament's Agriculture Committee has proposed a soil carbon sequestration scheme. The Commission has already promoted carbon farming in its recommendations (EU 2022).

6. QUANTIFICATION PROTOCOLS AND METHODOLOGIES

Traditionally, methods to quantify SOC stocks and SOC stock changes are based on soil surveys. Recently, soil SOC datasets have been aggregated and integrated with topography, climate, and other geographical information and extrapolated in space and time in Digital Soil Mapping (DSM) using models, statistical analysis, and remote sensing. The DSM offers a powerful tool for modeling the spatial distribution of SOC content. Generally, to develop DSM, soil C observations along with relevant covariates are collected in a database. The database is used to quantify empirical relationships between SOC and covariates, and the relationships are used to calibrate a spatial prediction function. From this, interpolation and/or extrapolation of the SOC prediction across the entire area of interest is performed, followed by validation using existing or independent observations (Feeney et al. 2022). Remote sensing can improve modeling of SOC (T. Zhou et al. 2021) and may point to priority areas where SOC is likely to decline or accumulate (Venter et al. 2021).

There are several innovations facilitating the quantification of SOC in croplands. First, scientists have proposed protocols for establishing a soil monitoring network built on standardized SOC determination to quantify current and future soil C stocks in cropping systems. For example, a protocol has been proposed as a method to be used for a nationwide soil monitoring network in the United States and in western Canada for long-term monitoring of soil C on farms (Suddick et al. 2013). The protocol includes georeferenced locations of sampling (up to 1 meter deep) to allow precise resampling over time in order to minimize the impact of small-scale spatial variability.

The FAO Global Soil Organic Carbon Map was developed by a consultative and participatory process involving 110 countries (FAO. 2022). The project provides users with useful information to monitor the soil condition, identify degraded areas, set restoration targets, explore SOC sequestration potentials, and make evidence-based decisions to mitigate and adapt to a changing climate. The USDA Natural Resources Conservation Service (Soil Science Division) provides soil maps for Google SoilWeb products that can be used to access USDA-NCSS detailed soil survey data (SSURGO) for most of the United States. The agency also initiated the Rapid Carbon Assessment (RaCA) in 2010 in order to develop estimates on the amount of and distribution of C stocks in U.S. soils under various land covers and, to the extent possible, under differing agricultural management.

Several online companies now offer help for SOC field determination and accessibility of the C market. Some use satellite data to build C land estimates of C credits economic values at the parcel level (Carbon LandEstimates, LandGate). Some offer innovative sensors and mapping (Soiloptix and gamma radiation-based sensors) of high-resolution top soil property layers. It is possible to download cell phone apps to easily determine SOC (QuickCarbon).

The GHG inventory tool COMET-Farm developed by the USDA provides whole farm and ranch C and GHG accounting system (USDA-NRCS 2022). This tool guides the user by describing current farm and ranch management practices and examines alternative future management scenarios. Once complete, a report may be generated comparing the C changes and GHG emissions between current management practices and future scenarios. The tool utilizes the biochemical process CENTURY model (NREL, 2022). To derive expected emissions for dominant fertilization and rotation practices, soil types, and US climate regimes, the COMET-FARM tool adjusts these results using emission factors generated through meta-analysis of empirical studies. The tool has free access on the internet and provides a means for non-GHG specialists (farmers, consultants, government entities, etc.) to estimate farm-scale GHG emissions and to explore alternative management and land-use strategies. Users of COMET specify a history of agricultural management practices on one or more parcels of land. The results are presented as ten-year averages of soil C sequestration or emissions with associated statistical uncertainty values. The tool 'COMET-Mondial' is under current development in collaboration with international scientists through joint funding from EU, Brazil, Australia, and US sources to extend COMET-FARM platform to other countries.

Quick Carbon is a tool developed by the Yale School of forestry in collaboration with developers, open-tech advocates, researchers, and on-the-ground organizations to create an accessible measurement system that empowers individuals to generate reliable soil C data for ecological understanding, decision making, and markets (QC, 2022). The program developed an affordable, pocket-sized device to measure soil C using the reflectance of soils in the visible and infrared spectra. The open-source spectrometer can be used in tandem with a data collection app on the Android platform. The tools would allow users to streamline the data collection process in the field and generate usable C stock estimates for a variety of possible applications.

An alternative method to measure annual soil C sequestration is to measure the ecosystem net exchange of C over the year. The net flux is the balance between respiratory losses of plant and soil and plant photosynthetic uptake and thus represents the C that is stored in the ecosystem. The net ecosystem exchange can be measured with different techniques, mostly by eddy covariance (Baldocchi 2014). The technique monitors CO_2 and CH_4 exchanges at the ecosystem scale and continuously through the duration of a typical C project. However, current prices for equipment are high, and the technique is complex to use.

Current protocols and soil C programs often differ in quantification methods, field sampling protocols, use of models, verification of credits, and permanence requirements. Standardization and transparency of methods and verification criteria is critical to ensure accuracy and efficacy of mitigation efforts. In 2001, The International Organization for Standardization (ISO) developed and published ISO 23400, guidelines for the determination of organic C and N stocks and their variations in mineral soils at field scale.

Agriculture soil C sequestration is not included in the California compliance market. The main international organization, the UNFCCC Clean Development Mechanism, also doesn't have an agriculture protocol that includes conservation practices. However, it has a tool to quantify SOC and SOC changes. All quantitative methodologies inside and outside the U.S. are based on the IPCC guidelines (IPCC 2006). The guidelines were developed based on scientific consensus, but their primary aim was supporting GHG inventories of countries, and quantification on a different scale, such as the boundary of a C project, can be inadequate at times. Methodologies for the C market can vary among different sectors and adopting organizations. However, in general, registries include accountability of risks of reversal for C sequestration. The mechanism typically proposed is the creation of buffer pools, so that part of the C credits obtained by a project are set aside and can be bought back in case the project terminates voluntarily or involuntarily before the end of the crediting period. In North America, there are three offset registries: the Climate Action Reserve (CAR), the American Carbon Registry (ACR), and Verra. These three registries offer the voluntary program along with the California compliance program and generally utilize their own protocols and methodologies. Currently, they include more than 100 established methodologies employing best practices based on the ISO 14064 standard for quantifying, monitoring, reporting, and verifying GHG emissions and reductions.

The existing ACR methodologies are for Biochar, Compost Additions to Grazed Grasslands, and reduced use of N fertilizer on agricultural crops. Most of the soil C protocols are now inactive because of changes in standards or the need to update additionality and monitoring methods. The registry Verra adopted the Soil Carbon Quantification Methodology, the Agricultural Land Management (ALM), and the Improved Agricultural Land Management (IALM) Methodologies. The more recent IALM methodology allows for quantifying SOC stock change and N_2O and CH_4 fluxes associated with a range of activities such as improved water, residue, and livestock management, as well as reduced tillage and fertilizer use. The approach combines SOC measurements to set baseline SOC stocks and modeling to estimate the SOC stock changes. However, the IALM and the Soil Carbon Quantification Methodology are currently under revision or on hold from March 2022.

CAR is developing a biochar methodology, and a Soil Enrichment Protocol was adopted in September 2020. The required permanence of C is 100 years. Monitoring and reporting for a project continue even after the end of the project's crediting period. Committing to less than 100 years is possible but results in a lower payment than the standard 100-year approach.

Outside the U.S., an Austrian program called Ökoregion Kaindorf financed by the EU pays farmers for soil SOC addition independently from permanence.

It is important to notice that, within aggregated projects, potential soil C losses on individual farms (whether temporary or permanent) can be balanced by gains on other participating farms during the same monitoring period, so that the whole project net balance is still a C sink. Developing tools and maps at a regional scale would be easier for public organizations with strong scientific and technological capacity. The permitting process may be a barrier to GHG emission reduction projects. For example, at least nine federal regulations and seven state regulations will potentially influence C sequestration projects (Vine 2004). Also

7. IMPLEMENTATION and RECOMMENDATIONS

California has a high potential to sequester C in soils given that its current C stocks in agricultural soils are low compare to other temperate regions. This is partially a result of agronomic practices used in California in the last decades, which caused high soil disturbance and grew mostly crops (food crops and forage) that return minimal C residues to soils. However, the primary cause of the low C stock levels in California's agricultural soils is climatic. The high temperature promotes SOC decomposition and the high demand of N and irrigation limit the increase in plant biomass that can result in C additions to soils.

Increasing SOC stocks in croplands requires continuous additions of new C to soils. This can be accomplished by using conservation practices such as rotations, cover crops, or different organic soil amendments. Conservation practices can be used in combination. When combined, they showed synergistic effects and more significant SOC responses. However, some of these practices are not easily adopted in many common horticultural crops in California. Finally, adding organic matter to soils has multiple recognized benefits, including increasing the resilience of crops to climate change by increasing soil health.

It is challenging to quantify and generalize the effects of conservation practices on soil C sequestration because the SOC interacts in unique ways with climate, vegetation, microbiome, soil type, and additional management practices. The most straightforward way to assess the efficacy of conservation practices to sequester C in soils is to timely monitor the SOC changes onsite. Estimates are also complicated by the difficulty of detecting small annual changes in SOC stocks in soils with much larger and heterogeneous C backgrounds. A different and complementary approach is the ability to model the complex interactions among all factors determining the specific SOC response.

Currently, the application of the carbon market is often excessively complex and costly for farmers. The need to ensure that the newly sequestered C in soils will not be emitted back to the atmosphere by stopping current practices (permanence) is a significant barrier. It is difficult for farmers to commit agronomic measures for decades and still be responsive to often rapidly changing agronomic and regulatory changes. The existing soil C methodologies are thus rarely adopted by farmers.

New technologies and tools are under development. Digitalized maps, freely available tools, new sensors, integration of field data with modeling and remote sensing, and a new understanding of SOC dynamics are providing increasingly easier ways to quantify the SOC stock changes needed to certify soil C sequestration offsets. The permanence requirement can be addressed by creating buffer pools, where part of the emission reduction is set aside and can pay back credits in case conservation practices are stopped or by other discounting methods. These will free farmers from 100-year commitments.

Public agencies can prioritize crops and geographic areas that would ensure the best results and create large-scale projects where local soil C losses will be compensated. They have technical skills to quantify and verify accurately regional SOC changes and can standardize mechanisms and principles for sequestration programs.

The following are additional factors to consider:

- Reductions in irrigation and increased fallowing would result in large losses of SOC from agricultural soils in California.

- Documenting SOC changes in a heterogeneous agricultural landscape like California's, with a diversity of soils, temperature gradients, and large range of crops, is more complicated than in other regions with simpler, more stable cropping patterns. Perennial California commodities like tree nuts and grapes may provide a sufficiently large basis and consistency of management for evaluating landscape-scale changes in SOC.

- SOC accumulation is a function of C inputs from crop residue amounts and the addition of manures and composts. In California, crop residue accumulation may not be sufficient, and only the addition of composts can greatly influence increases in SOC because of long growing seasons and conditions that support SOC oxidation.

- Cumulatively, crop, climate, and soil conditions in California, combined with the expense and uncertainty of measurement and certification of SOC, do not support the use of the traditional carbon market credit system. Since agriculture is dynamic and changes over time, a shorter-term credit system and prioritizing simplicity and lower costs may be more appropriate. Alternative incentive programs to the traditional C market, such as the current LCFS programs, can be developed.

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