WHOLE ORCHARD RECYCLING (WOR)

Inclusion in the CDFA Healthy Soils Incentive Program

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Executive Summary

This report provides a scientific analysis, using mathematical modeling, of Whole Orchard Recycling (WOR) and its greenhouse gas reduction and carbon sequestration potential. WOR is a practice in which orchard trees are chipped and incorporated back into the soil. As an alternative to burning, it builds soil organic carbon and microbial biomass, which improves soil health, nutrient levels, structure and water retention. It has also been shown to boost tree growth and almond yields over time.

In order to assess WOR's effects on the greenhouse gas balance of orchard establishment and as a practice to be used in the CDFA Healthy Soils Incentive Program, the California Department of Food and Agriculture Office of Environmental Farming and Innovation (CDFA) and the California Air Resources Board (CARB) modeled soil carbon and almond tree growth using the Denitrification-Decomposition Model (DNDC). Validation of the model results were compared with scientific field experiment data records maintained over 9 years at the Kearney Agricultural Research and Extension Center (Kearny RECS) of the University of California Cooperative Extension (UCCE). The model provided conservative soil carbon predictions averaging 4.24 metric tons of carbon dioxide (CO_2) sequestration per hectare for 14 tons of dry wood chips per acre (the minimum expected woody biomass representing prune trees) and 8.16 tons per hectare for 30 tons of wood chips per acre (the average woody biomass in almond trees). Soil carbon sequestration in the Kearney RECS field trial data was estimated at 29 metric tons CO_2 by field data with 60 tons of wood chips and consistent with modeled results. Therefore, lower modelled results are supported as part of the WOR practice in the CDFA Healthy Soils Incentive Program to include not only almond trees, but all tree orchard crops grown for a minimum of 10 years in California.

WOR's effects on nitrous oxide emissions are uncertain but are being studied by a Healthy Soils Demonstration Project. The modelling results confirm that nitrous oxide effects, even if they offset some carbon sequestration, are very unlikely to outweigh greenhouse gas and carbon sequestration benefits. WOR has not been shown to transmit Prunus Replant disease, *Ganoderma* fungi or parasitic nematodes from removed orchards to the next planting.

Introduction

Healthy Soils Incentive Program management practices incentivized by the program have all been modeled and found to lead to reductions in greenhouse gas emissions. This report provides information on an agricultural management practice not currently included in the Healthy Soils Incentives Program. The report defines the management practice, provides a literature review of the scientific information currently available on the practice, models the practice's effects on greenhouse gas emissions, which are negative, and makes a case for the inclusion of the management practice into the Healthy Soils Incentive Program. The management practice reference in this report is WOR.

Whole orchard recycling is a practice which consists of the chipping of woody perennial crops at the end of their agronomic life cycle. Only fruit and nut trees are considered in this report. As new scientific field study information becomes available, either through the scientific community and results obtained in the Healthy Soils Demonstration Program or from federally funded initiatives, the new information will be used to further calibrate the models used to more accurately quantify the greenhouse gas and carbon sequestration benefits of the Healthy Soils Incentive Program management practices.

Definition

Whole Orchard Recycling (WOR) is a practice which consists of the chipping of woody perennial crops at the end of their agronomic life cycle. The wood chips are incorporated into the soil of the fields where the trees stood, which may be fallowed or continue agronomic production under minimum-tilled perennial crops.

Problem Statement

The closure of about half of the Central Valley's former biomass co-generation plants, along with the increased acreage of woody perennial crops and an increase in high-quality wood chips from forest thinning, have generally halted what was formerly an important use and disposal method for wood from removed orchards. This situation has led more growers to either burn removed orchards in the field, or simply stack them for unknown types of disposal in the future. Burning of orchard woody biomass in the field is subject to certain county restrictions, is expensive in the San Joaquin Valley, has direct adverse effects on human health, and increases emissions of particulate matter and atmospheric black carbon. Burning of woody biomass also releases nitrogen, sulfur, and phosphorus from woody biomass to the air instead of returning them to the local soil as plant nutrients. The remaining, largely alkaline nutrients in the ashes (e.g., Ca, K, Mg) usually remain undistributed in the agricultural field from which they came, promoting acidification of the original soil as well as lost fertility. Furthermore, carbon is emitted in burning which could otherwise serve to boost organic matter in soils, if the woody biomass material were incorporated back into the soil. Increasing organic matter would improve fertility, nutrient retention, soil structure, water retention, microbial biomass, and soil health in general, as well as likely bringing about long-term carbon sequestration in many Central Valley agricultural soils.

Other benefits of WOR include potential reductions in nitrate leaching from subsequent fertility management. There are also preliminary indications that WOR, instead of transmitting pathogens and vectors, ameliorates *Prunus* replant disease and other root diseases, by causing a shift in the soil microbiome, and particularly in nematode populations (e.g., free-living verses parasitic). WOR can also be combined with fumigation or Anaerobic Soil Disinfestation.

Existing Field Data

Whole Orchard Recycling as an on-site treatment for entire tree orchards has been researched primarily by Brent Holtz of the UCCE with various colleagues over the last 20 years. Their investigations found that WOR improved soil health (microbial biomass and various enzyme activities increased and was proportional with soil organic carbon (SOC) levels, hydraulic properties (water infiltration and soil water retention), soil structure (wet aggregate stability and bulk density; Jahanzad et al., 2019), and availability of micronutrients (Holtz et al., 2017)). In the study's fourth year, WOR soils contained more nitrate, calcium, manganese, iron, magnesium and boron than non-WOR soils, and in the fifth year, trees on experimental plots treated with WOR still had significantly higher leaf nitrogen content than non-WOR experimental plots.

Experimental field trial data for WOR includes a 9-year study at the Kearney UCCE RECS. The climate, soil, cropping system, wood characteristics, and management of the experiment were typical of almond orchards in the southern Central Valley (Holtz el al., 2017). In the 2017 study, 30 tons of dry wood chips were applied per acre, incorporated into a sandy loam, before establishment of a new almond orchard. Since the wood chips were applied onto half of the field area (planting rows) where subsequent soil tests were initiated, the trial effectively served as a test for 60-ton soil application. In the control treatment, the same quantity of wood chips was burned, and the ashes were redistributed following the same spatial field distribution pattern. There was no *Prunus* replant disease or significant pathogenic issues in either treatment. The results showed tree growth was somewhat slower under WOR in the first 2-3 years, but then increased such that the WOR trees consistently grew and yielded more compared to the burned wood treatment. Soil organic carbon was measured annually in the surface soil to the depth of 6 inches. The SOC fluctuated significantly, generally with wet and dry years. The overall trends, however, showed an increase of SOC in WOR. Figure 1 was published by Holtz et al. (2017).

A more comprehensive analysis was carried out in summer of 2017, after 9 years of WOR (Jahanzad et al., 2019). The soils were analyzed for soil carbon at three layers (0-30, 30-90 and 90-140 cm) under the tree rows. The results showed increases in SOC in the WOR treatment when virtually all of the mass in the original wood chips would have decomposed. The SOC gains were significant to 30 cm depth and similar proportional differences in SOC were suggested by data from lower depths. The study estimated that down to 140 cm depth, the WOR treatment soils contain at least 8 metric tons/ha of SOC more than burned wood treatment. Public presentations have been made of Figure 2 (Jahanzad et al., 2019).

WOR does not bring about carbon sequestration by simply depositing woody material that remains intact in the soil. Instead, WOR promotes the gradual migration of wood chip organic matter into an increased microbial biomass, from there creating more resistant soil organic matter; it increases microbial biomass connected with fungal populations, soil structure, and improved water retention (Jahanzad et al., 2019).

Eight other WOR experiments, including one Healthy Soils Demonstration Project, have recently been implemented in California; seven in the San Joaquin Valley, and one in the Sacramento Valley. However, given the long-term nature of WOR effects, complete data on soil carbon, soil health, and yield will not be available for several years to come. The Healthy Soils Demonstration Project will quantify nitrous oxide (N_2O) emissions under WOR, an important knowledge gap which will be compared to model projections for a short-term improvement of model simulations.

Figure 1: Percent organic carbon and percent soil organic matter over time under WOR (Grind) and Burned. Holtz et al. (2017).

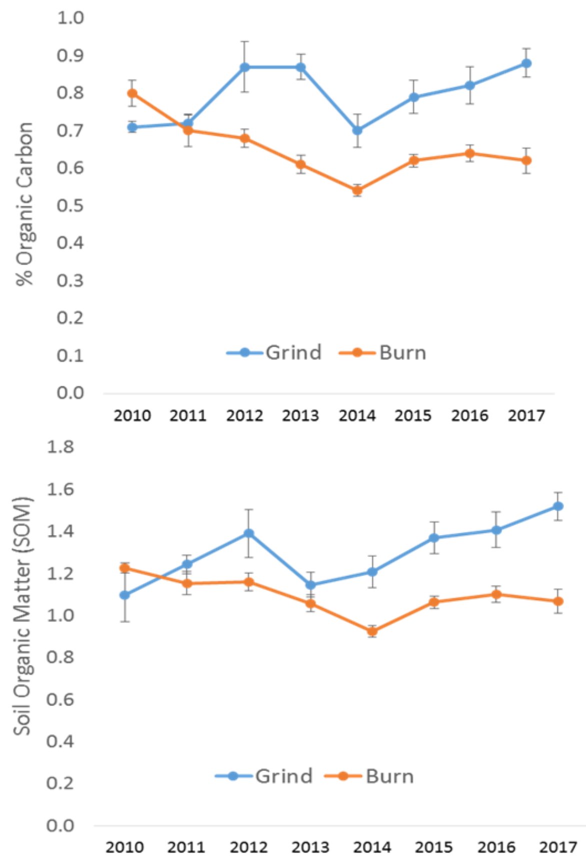
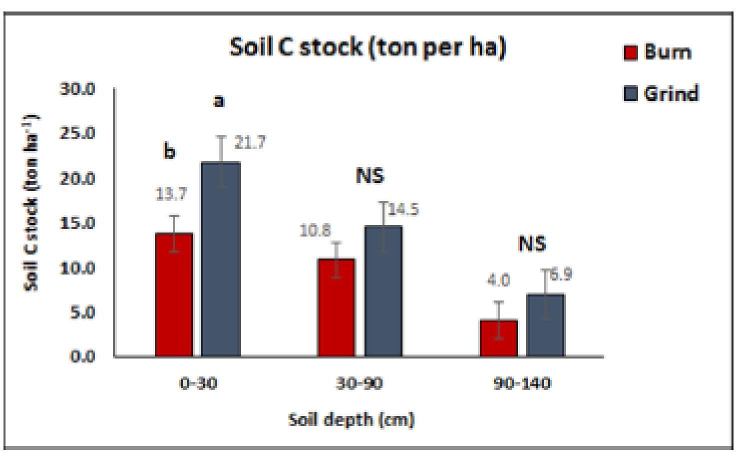


Figure 2. Soil Carbon Stock of "Burn" and "Grind," nine years after WOR (Jahanzad et al., 2019).



Model Description

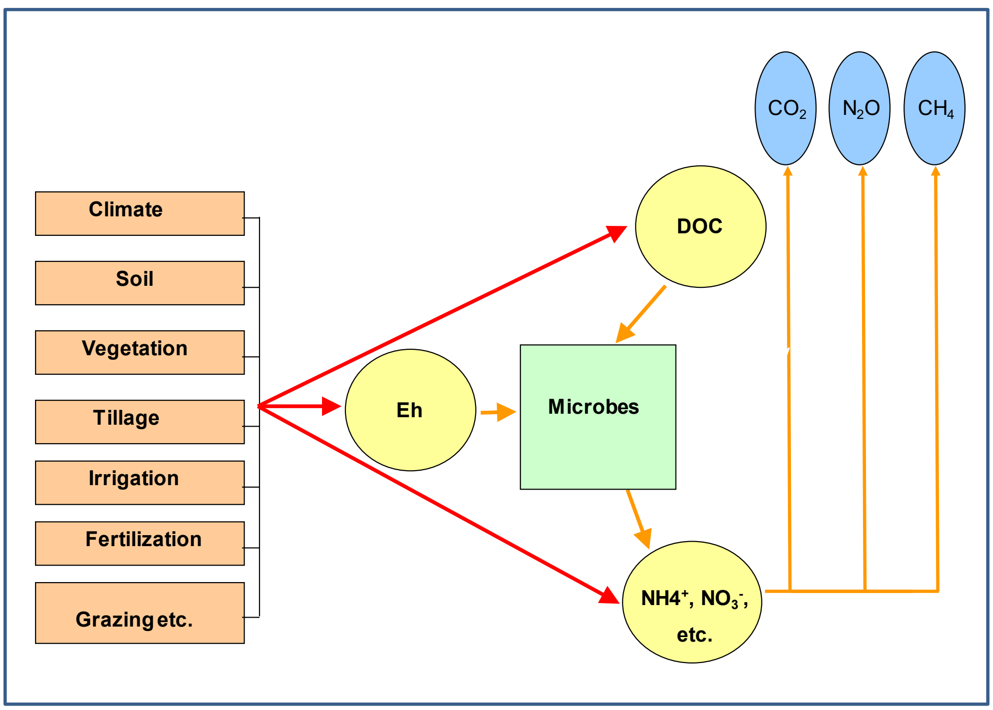
The Denitrification-Decomposition model (DNDC; Li et al., 1992; Li, 2000) is a process-based computer simulation model of carbon (C) and nitrogen (N) biogeochemistry and was developed for quantifying carbon sequestration and emissions of greenhouse gases in agroecosystems. The DNDC model consists of microbially-mediated biochemical processes commonly occurring in terrestrial soils. The processes simulated include decomposition, nitrification, denitrification, fermentation and methanogenesis. A full description of the DNDC scientific basis and processes, including all equations, is available at http://www.dndc.sr.unh.edu/.

DNDC simulates rates of different processes by tracking the activities of different groups of microbes, which are activated under various environmental conditions in response to temperature, moisture, pH, redox potential (Eh) and substrate concentration gradient in soil. Nitrification-induced N_2O production is modeled as first order of soil ammonium (NH_4^+) concentration under aerobic conditions. Denitrification-induced N_2O production is initiated once soil is saturated, which is assumed to lead to anaerobic conditions. Soil Eh is calculated with the Nernst equation at a daily time step following soil saturation and used to determine anaerobic microbial group activities under the given soil conditions. The anaerobic microbial group activity is then modeled using standard Michaelis-Menten type kinetics.

The hypotheses backing the DNDC simulations of soil greenhouse gas emissions include: a) CO_2, N_2O and methane (CH_4) are products of oxidation-reduction reactions through electron exchange between electron donors and acceptors that is mediated by microbes, b) the occurrence of the electron exchange is determined by the soil Eh as described by the Nernst Equation, a thermodynamic equation calculating Eh based on the concentrations of paired oxidative and reductive forms of dominant oxidants in the soil, c) when a suitable Eh is established, the corresponding functional groups of bacteria will grow to their full capacity within a short timeframe (hours or days) due to rapid regeneration and d) once the microbial capacity is established, the reaction rate will be primarily controlled by the concentrations of the relevant substrates as described by the Michaelis-Menten Equation. Within that framework, DNDC tracks important microbial activities for N_2O estimation from nitrate reduction under anaerobic conditions, primarily based on three drivers: Eh, dissolved organic carbon (DOC) as electron donors and oxidants as electron acceptors. In other parts of the soil, nitrification-induced N_2O production is integrated with ammonium (NH_4^+) and ammonia (NH_3) levels as the major drivers under aerobic conditions. Figure 3 provides an overview of DNDC and how climate, soil, vegetation and management practices influence Eh, DOC, substrate concentrations and greenhouse gas emissions.

Soil organic carbon resides in four major pools in the DNDC model: plant residue (e.g., litter), microbial biomass, humads (e.g., active humus) and passive humus. Each pool consists of two or three sub-pools with specific decomposition and recalcitrance rates. Daily decomposition rate for each sub-pool is regulated by the pool size, the specific decomposition rate, soil clay content, N availability, soil temperature, and soil moisture. When SOC in a pool decomposes, the decomposed carbon is partially lost as CO_2, with the rest allocated into other SOC pools. DOC is produced as an intermediate during decomposition and can be immediately consumed by soil microbes. During the processes of SOC decomposition, the decomposed organic nitrogen partially transfers to the next organic matter pool and is partially mineralized to NH_4^+. The free NH_4^+ concentration is in equilibrium with both the clay-adsorbed NH_4^+ and the dissolved NH_3. Volatilization of NH_3 to the atmosphere is controlled by NH_3 concentration in the soil's liquid phase and subject to soil environmental factors (e.g., temperature, moisture, and pH). When rainfall or irrigation occurs, NO_3^- leaches into deeper layers with the soil drainage flow. A simple kinetic scheme known as the "anaerobic balloon" predicts the soil aeration status by calculating oxygen and other oxidants' contents in the soil profile. Based on the predicted redox potential, the soil, discretized into 2-cm layers, is divided into aerobic and anaerobic pockets where nitrification and denitrification occur, respectively. The nitric oxide (NO) and N_2O gases produced in either nitrification or denitrification are subject to further transformation during their diffusion through the soil matrix.

Figure 3. DNDC functional overview



Model Validation

The CDFA Office of Environmental Farming and Innovation, working in collaboration with the California Air Resources Board (CARB), have validated the performance of the DNDC soil nutrient cycling model using the WOR results from the Kearney RECS. The DNDC model was run on the soil and climate conditions gathered at the Kearney RECS on the WOR field trials (Holtz, 2018) and the parameters listed in Tables 1 and 2. The irrigation practice simulated was sprinkler irrigation as used in the field experimental trials. The UCCE crop coefficient values for almond (Kc) (Doll and Shackel, 2015) were applied with a corresponding nitrogen application regime to supply potential crop demand. The fertilizer regime reflects use of Urea Ammonium

Nitrate (UAN-32). Other parameters used are listed with their sources in Table 2. All values were established to reflect practical scenarios, representing averages across almond cultivars used in California:

Table 1. Fertilizer nitrogen (N) and phosphorus (P) Regime used in DNDC modeling

Date	Fertilizer	Year 1	Year 2	Year 3	Year 4	Year 5 and after
1-Mar	Urea-N	8	8	14	20	30
	Ammonium-N	4	4	7	10	15
	Nitrate-N	4	4	7	10	15
	Phosphate-P	1.5	3	4	4	5
15-Apr	Urea	9	9	14	24	34
	Ammonium	5	5	7	12	18
	Nitrate	5	5	7	12	18
	Phosphate	1.5	3	4	5	5
1-Jul	Urea	8	8	12	20	30
	Ammonium	4	4	6	10	15
	Nitrate	4	4	6	10	15
	Phosphate	1.5	3	4	5	5
1-Oct	Urea	4	4	6	10	15
	Ammonium	2	2	3	5	7.5
	Nitrate	2	2	3	5	7.5
	Phosphate	1	2	3	4	5
	Annual N	59	59	92	148	220
	Annual P	5.5	11	15	18	20

Table *2*: Parameters modified in DNDC and their sources

Parameter	Value	Source
Initial CO_2	385 ppm	Mauna Loa Observatory
CO_2 increase/year	2 ppm	Mauna Loa Observatory
Simulation Years	20 years	Expected lifespan for almond orchards
Soil parameters	Table 3	California Air Resources Board, by County
SOC Soil A depth	15 cm	Holtz et al., 2018
SOC Soil Decrease with Depth	"2.5"	Estimated using Jahanzad et al., 2019; dimensionless
Crop Maturity	10 years	Estimated (Kendall et al., 2015)
Kernel Biomass, kg/ha	2500	USDA NASS for 2018
Shell Biomass	2242	Kendall et al., 2015
Hull Biomass	4483	Kendall et al., 2015
Kernel % C	33%	Calculated from constituent nutrient analyses (USDA, 2019)
Shell % C	72%	Li et al., 2018
Hull % C Biomass	50%	Estimated from 85% fiber, cellulose and lignin (FAO, 2012)
Leaf % C	48%	Ma et al., 2018

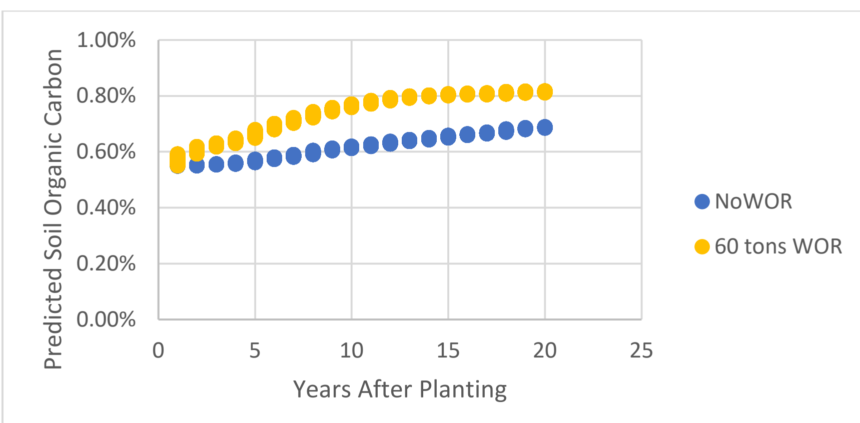
Shoot % C	48%	Ma et al., 2018
Root % C	47%	Ma et al., 2018
Grain Biomass Fraction	0.41	Calculated to obtain desired grain biomass as C
Leaf Biomass Fraction	0.1	Calculated. Assumed 2,000 kg/ha/year as a normal/high dry mass of leaves at harvest (Muhammad et al., 2015)
Shoot Biomass Fraction	0.27	Calculated. Assumed orchard adds 3,000 kg/year to attain carbon content of 60 metric tons/ha after 20 years (Holtz and Culumber, 2019)
Root Biomass Fraction	0.22	Few available data. Calculated following 1.25 shoot:root ratio (Heilmeier et al., 1997), similar to DNDC default value for almond
Grain Biomass as C, kg/ha	4681	Calculated from data above, combining hull, kernel and shell
Leaf Biomass as C	1142	Calculated by DNDC
Shoot Biomass as C	3082	Calculated by DNDC
Root Biomass as C	2512	Calculated by DNDC
Grain Biomass C/N ratio	21	Calculated. Verified by Muhammad et al. (2015) fruit nitrogen content of 2.3%
Leaf Biomass C/N ratio	32	Calculated. Verified by Muhammad et al. (2015) final leaf nitrogen content of 35 kg/ha
Shoot Biomass C/N ratio	140	Calculated. Verified by Muhammad et al. (2015) perennial organ N increase of 40 kg/ha
Root Biomass C/N ratio	140	Same as “shoot”
Grain Dry Matter, kg/ha	9059	Calculated from water demand
Leaf Dry Matter	2378	Calculated from water demand
Shoot Dry Matter	6442	Calculated from water demand
Root Dry Matter	5344	Calculated from water demand
Water Demand, g H_2O/g DM	400	Optimal high-yield water consumption of 1200 mm/biomasses as noted above; assume 25% water loss to leaching and soil evaporation
Planting Date	1-Jan	Compensates for the use of nursery transplants planted in spring
Harvest Date	31-Dec	Does not affect "perennial" crops in DNDC
Harvest Year	1	Anomalies have been seen with "20," so "1" is preferred
Residue left in field	0	Despite the "perennial" crop setting, with this parameter at "0," the model cycles leaf carbon and nitrogen, as well as some from stems, back into the soil’s reserves
Tillage Application	1, moldboard (20 cm)	Orchard establishment usually involves deep tillage, such as ripping
Tillage Date	4/15, Year 1	Estimated date of orchard planting
Manure Incorporation	15 cm	Minimum depth observed in the field.
Manure Type	Straw	Modeled because of its low nutrient content and high carbon to nitrogen ratio

Manure C/N	160	Holtz and Culumber (2019)
Manure amount	14000 kg C/ha	This value is close to the C in 14 U.S. short tons per acre of dry wood chips, which is a low-to-typical woody mass for a 10-year-old plum orchard. 60 tons was used for validation of model with Kearney RECS results.
Fertilization composition	Table 1	Reflects best practice with 4 applications of Urea Ammonium Nitrate at 220 kg N/ha
Fertilizer Injection Depth	15 cm	A mid-range depth of urea and itrate in drip-fertigated systems (Gärdenäs et al., 2005, p.; Wolff et al., 2017)
Irrigation Applications	2.5 cm each	An irrigation schedule was created to supply nearest California Irrigation Management Information System (CIMIS) ETo adjusted for UCCE monthly Almond Kc values (Doll and Shackel, 2015).
Irrigation Type	Sprinkler and Drip	Drip irrigation is more common and was used to model the Practice's future effects.
Cut Application	15-Sep	Harvested cut "grain" at a high fraction, 0.99

DNDC predicted overall SOC for 2017 as 0.73% for WOR, compared to 0.60% for a non-WOR simulation. This can be compared to the 2017 field results of 0.79% over 0.55% obtained in 2017 (Jahanzad et al., 2019) for the upper 15 cm or approximately 0.82% over 0.52% for the 0-30 cm depth (Jahanzad, 2019). The model predicts further increase of SOC through to the end of the orchard's assumed 20-year life span (Figure 4) but at a decreased rate compared to 0-10 years.

DNDC modeled kernel yields of about 1,930 average for the Kearney RECS field study, very close to the annual average of 1,917 measured in Kearney RECS field study (Holtz et al., 2018). The model's yields appear to have lower annual variance than the field results.

Figure 4. Simulated Carbon Stock of "Burn" and "Grind" soils over 20 years. DNDC modeled WOR effects on Soils carbon at Kearny RECS, upper 15 cm.



Overall, the modeled estimates are conservative and consistent with field trial research data collected at Kearney RECS. The model predicts increases in SOC with tree crop plantings. The model also predicts higher WOR SOC increases when a previous tree crop (as opposed to a field crop) had already been established and included in the simulation.

With the evidence discussed above, and available in similar published literature, it appears unlikely that the WOR practice will cause losses in tree growth and production. WOR's impacts on SOC should always be positive, leading to net carbon sequestration in carbon fractions resistant to decomposition. DNDC's predictions are conservative in large part because the modeling is restricted to the upper 50 cm of soil, while tree crops will generally have significant root systems below that depth. The 9-year analysis in Kearney RECS showed accumulation of SOC under WOR down to 140 cm depth and suggested that the benefits go even deeper.

Projection of WOR Effects by County and Region

Following DNDC validation as a predictor of SOC gains, the model was used to predict SOC gains and other greenhouse gas emissions in a geographically specific manner for California. This effort was critical to including WOR in Comet-Planner; the greenhouse gas quantification tool used in the Healthy Soils Incentive Program.

Modeling was County-specific for Central Valley counties that have almonds or walnuts. To account for some missing county specific climate data, the area outside the Central Valley was divided into four Regions, represented by the counties in them which have the highest tree crop production, with their characteristic irrigation conditions (in parentheses): North (Shasta, unirrigated after 4^{th} year); South (Ventura, irrigated); Coast (Sonoma, unirrigated); and Foothills & Sierra (averaged results from modeling Amador, Calaveras, El Dorado, Mariposa, and Tuolumne counties, irrigated). Although almond is not produced in all Californian counties, it was preferred as primary crop for the entire State since (1) almond was the model-validated crop, (2) simulations of other "regional" crops gave very similar results in soil carbon WOR benefits and (3) simulations of other tree crops suggested unverifiable, confounding differences in nitrous oxide (N_2O) emission predictions, due to the crops' different fertilization regimes.

For the projections, soil data were collected from USDA's Soil Survey Geographic Database (SSURGO) database (USDA, 2016c). Key soil data, including soil organic carbon content, clay content, pH and bulk density, were compiled. The SSURGO map units were overlaid with the regions of agricultural land use developed by the Land Use Surveys of the California Department of Water Resources (CDWR, 2014) and the area-weighted means of the four soil properties were calculated for each Valley county and used as representative soil values for DNDC simulation (Table 3).

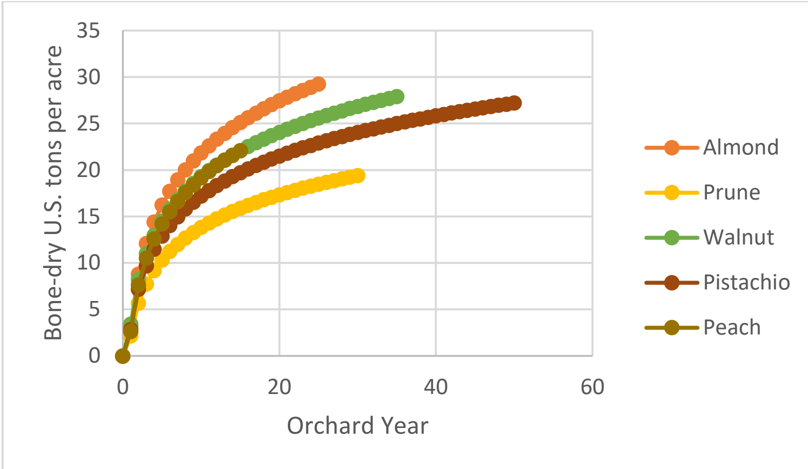
Table 3: Major soil property values used in the DNDC modeling

County	Average SOC *Kg C/Kg*	Average Clay *%*	Average pH	Average Density *g/cm³*
Amador	0.010	0.15	6.12	1.53
Butte	0.016	0.37	5.28	1.35
Calaveras	0.005	0.13	6.37	1.47
Colusa	0.011	0.30	6.60	1.44
El Dorado	0.012	0.17	6.05	1.38
Fresno	0.006	0.24	7.15	1.48
Glenn	0.009	0.30	6.27	1.45
Kern	0.003	0.19	7.33	1.52
Kings	0.006	0.18	7.57	1.52
Madera	0.005	0.13	6.61	1.55
Mariposa	0.015	0.19	6.00	1.45
Merced	0.006	0.20	6.82	1.52
Placer	0.007	0.15	6.04	1.53
Sacramento	0.006	0.22	6.18	1.53
San Joaquin	0.010	0.24	6.74	1.51
Shasta	0.014	0.22	6.11	1.41
Solano	0.009	0.35	6.53	1.46
Sonoma	0.012	0.23	5.74	1.44
Stanislaus	0.006	0.19	6.70	1.53
Sutter	0.009	0.33	6.76	1.44
Tehama	0.009	0.20	6.33	1.48
Tulare	0.007	0.20	7.21	1.50
Tuolumne	0.017	0.19	5.86	1.26
Ventura	0.012	0.22	6.90	1.47
Yolo	0.010	0.32	6.71	1.46
Yuba	0.008	0.22	6.30	1.48

Local climate data (not shown) were taken, if the record was complete for April 2008 - April 2018, from the California Irrigation Management Information System (CIMIS) weather stations at representative altitudes in each county. The major Central Valley counties for fruit and nut production had adequate CIMIS information. In counties where CIMIS data was not available, records for the same period were obtained from the Daymet database (daymet.ornl.gov). This data is also used by the California Air Resources Board in prior DNDC simulations of compost effects on soil organic matter for the Healthy Soils Incentives Program. Simulations repeated the 10-year records to reflect the second half of a 20-year orchard lifetime. This decision was based on the timeline of the validated orchard in Kearney RECS. Projections assumed drip irrigation (Deng *et al*., 2018); DNDC provided very similar results under drip and micro-sprinkler. Other model parameters were as listed in Table 2.

The final parameter to be determined for projections was the amount of wood chips to be incorporated into the soil as a result of the WOR incentives. Orchard woody biomass vary primarily by the species of tree and age (Figure 5) but are also affected by climatic, soil and management effects.

Figure 5. Biomass Accumulation as estimated for the top 5 tree crops of the San Joaquin Valley.



The variation in biomass accumulation by different tree crops led to the following challenges in establishing a single application rate to be adopted by the Healthy Soils Incentive Program for WOR; 1) prior estimation of an orchard's biomass is challenging to scientists (e.g., measuring truck bed diameters), 2) measurements on depth of wood chips would feasible after the even distribution on the ground, but on-site measuring for each field is not practically feasible and leads to methodological and data quality issues, 3) applicants may report their tree species and the Healthy Soils Program could assume that the orchard is at maturity for biomass purposes. This method could result in an over-estimation to carbon sequestration since the actual age of the trees are not known. Requesting actual age of the trees would lead to addition data collection and verification requirements, 4) using typical species growth curves like those below, applicants could inform the Healthy Soils Program of their orchards' species and age, and a reasonable estimation could be made using growth curves. However, at this time the CDFA has only found growth curves for 4-5 major tree crops grown in California. This could also be potentially disadvantageous to applicants with certain species and with older orchards, 5) an orchard biomass of 30 dry tons/acre could be assumed, in line with EPA emissions assumptions for orchard burning. This is a middle-to-low biomass for mature almond orchards, and low for mature walnuts, which are the tree crops likely to receive WOR treatments during the first years of the program. But it is an overestimation for fruit trees.

Given the challenges noted above, the need to be conservative in greenhouse gas estimations and maintaining consistency across different tree species, the CDFA Healthy Soils Incentive Program utilized a minimum-biomass and minimum-age methodology. In consideration that orchards are rarely removed before the age of ten years and generally attain about 70% of their mature biomass, a minimum-biomass age approach was feasible. The tree crop of least biomass at 10 years was used (prunes) to calculate the amount of wood chips added to the ground and for the calculation of a greenhouse gas emission factor. This methodology allowed for different tree crops to be considered and incentivized in the Healthy Soils Incentive Program WOR practice.

Using almond as its test crop, DNDC calculation are presented in Table 4. The WOR rates described for scientific purposes as "metric tons of carbon per hectare" are very close to the corresponding quantity of "U.S. tons of wood chips per acre" (e.g., 30 U.S. tons of dry wood chips per acre contain 30 metric tons of carbon per hectare).

Table 4. WOR application rates and carbon sequestration factors per county.

County	WOR Rate (mt-C/ha)[1]	C-Seq Factor	SOC (mt CO_2 /ha)	N_2O (mt CO_2/ha)	CH_4 (mt CO_2/ha)	Net WOR Impact (mt CO_2/ha)
Butte	14	7.3%	3.74	-2.07	0.16	1.84
	30	*6.8%*	*7.43*	*-4.61*	*0.34*	*3.15*
Colusa	14	10.6%	5.45	-3.39	0.31	2.37
	30	*9.8%*	*10.83*	*-9.82*	*0.64*	*1.66*
Fresno	14	7.2%	3.72	-1.35	0.13	2.50
	30	*6.9%*	*7.60*	*-2.71*	*0.48*	*5.37*
Glenn	14	10.9%	5.59	-3.27	0.27	2.59
	30	*6.9%*	*11.18*	*-6.73*	*0.56*	*5.01*
Kern	14	8.0%	4.13	-0.25	0.07	3.95
	30	*8.0%*	*8.77*	*-0.57*	*0.37*	*8.57*
Kings	14	8.1%	4.18	-0.25	0.28	4.21
	30	*7.8%*	*8.58*	*-0.58*	*0.84*	*8.84*
Madera	14	7.3%	3.74	-0.49	0.11	3.37
	30	*7.4%*	*8.14*	*-0.96*	*0.63*	*7.80*
Merced	14	7.7%	3.96	-0.84	0.22	3.33
	30	*6.9%*	*7.59*	*-1.74*	*0.65*	*6.50*
Placer	14	7.6%	3.88	-3.80	0.36	0.44
	30	*7.5%*	*8.28*	*-7.30*	*0.80*	*1.78*
Sacramento	14	6.9%	3.55	-1.89	0.23	1.89
	30	*6.5%*	*7.15*	*-3.84*	*0.66*	*3.97*
San Joaquin	14	7.5%	3.83	-1.23	0.27	2.87
	30	*7.0%*	*7.72*	*-2.51*	*0.55*	*5.75*
Shasta	14	10.2%	5.24	-3.67	0.33	1.89
	30	*9.5%*	*10.45*	*-7.14*	*0.67*	*3.97*
Solano	14	6.2%	3.16	-1.59	0.29	1.87
	30	*6.0%*	*6.62*	*-3.15*	*0.57*	*4.05*
Stanislaus	14	7.1%	3.64	-0.81	0.22	3.04
	30	*6.4%*	*7.05*	*-1.71*	*0.65*	*5.99*
Sutter	14	6.2%	3.20	-2.15	0.35	1.39
	30	*6.3%*	*6.89*	*-4.69*	*0.67*	*2.87*
Tehama	14	8.8%	4.54	-2.77	0.41	2.18
	30	*8.5%*	*9.31*	*-5.50*	*0.82*	*4.64*
Tulare	14	8.1%	4.18	-0.20	0.40	4.38

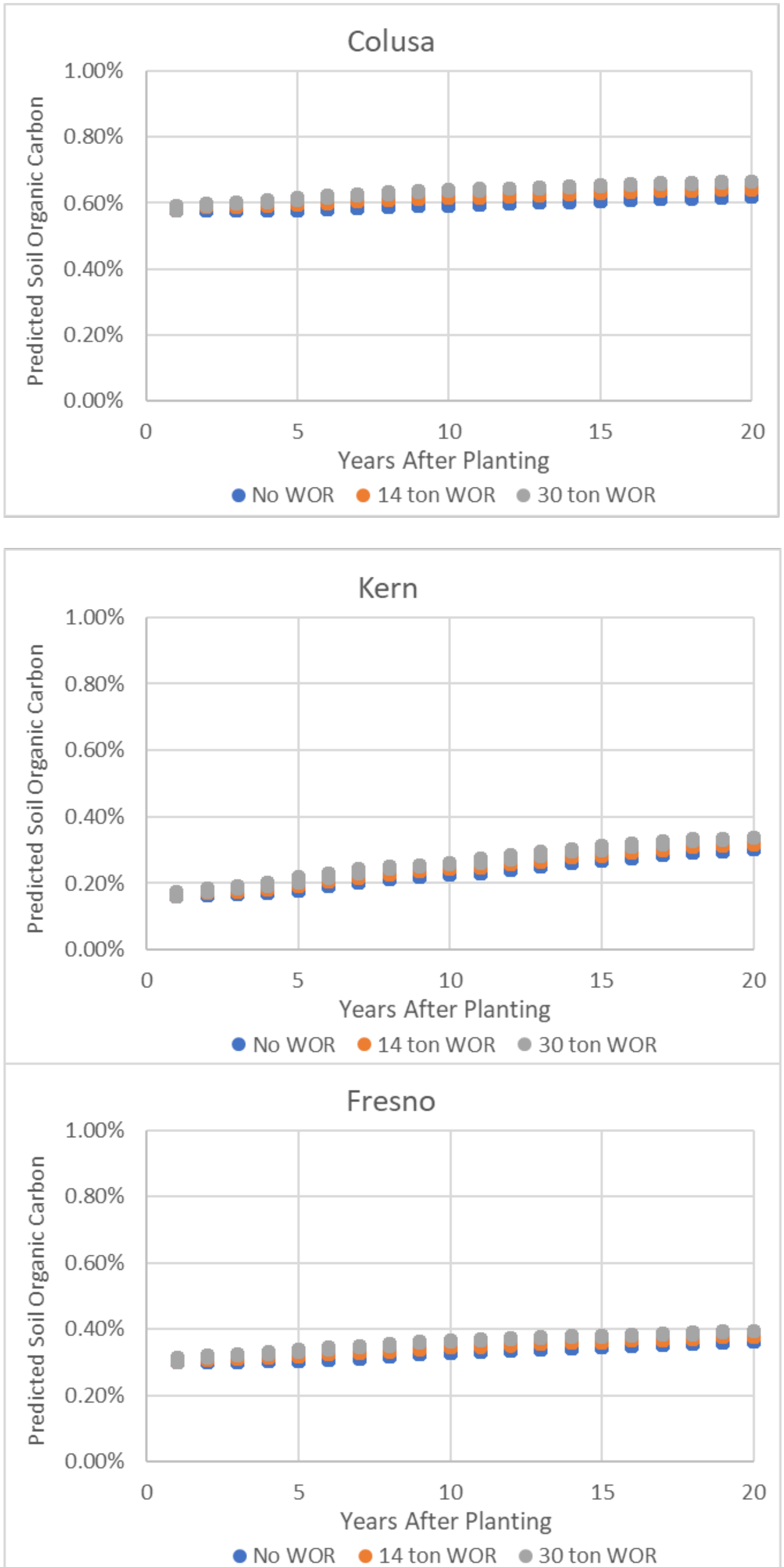
	30	*7.5%*	*8.30*	*-0.50*	*0.92*	*8.72*
Yolo	14	6.1%	3.13	-1.55	0.30	1.87
	30	*5.9%*	*6.44*	*-3.05*	*0.58*	*3.97*
Yuba	14	9.0%	4.59	-2.95	0.41	2.06
	30	*8.6%*	*9.48*	*-5.81*	*0.85*	*4.52*
Coast	14	10.7%	5.50	-4.07	0.33	1.76
(Sonoma)	*30*	*10.0%*	*11.05*	*-8.26*	*0.67*	*3.47*
South	14	6.8%	3.49	-1.78	0.31	2.02
(Ventura)	*30*	*6.5%*	*7.13*	*-3.10*	*0.62*	*4.65*
Foothills /	14	8.4%	4.30	-3.72	0.24	0.82
Sierra[2]	*30*	*8.3%*	*9.08*	*-7.15*	*0.55*	*2.48*
North	14	9.3%	4.76	-3.10	0.30	1.96
(Shasta)[3]	*30*	*8.8%*	*9.69*	*-6.22*	*0.61*	*4.08*

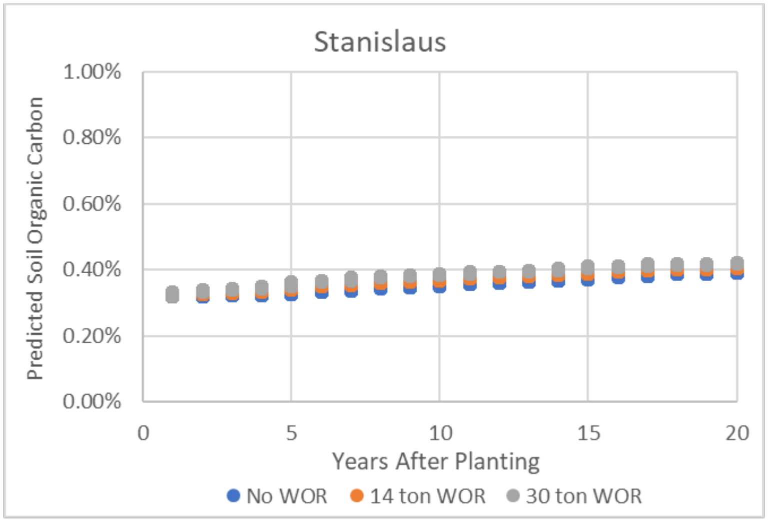
1. also equivalent to dry U.S. tons of chips per acre
2. Counties averaged were Amador, Calaveras, El Dorado, Mariposa, Tuolomne.
3. Shasta climate records were applied without irrigation following the 4th year, to reflect likely practice with fruit and nut crops in Northern counties surrounding Shasta.

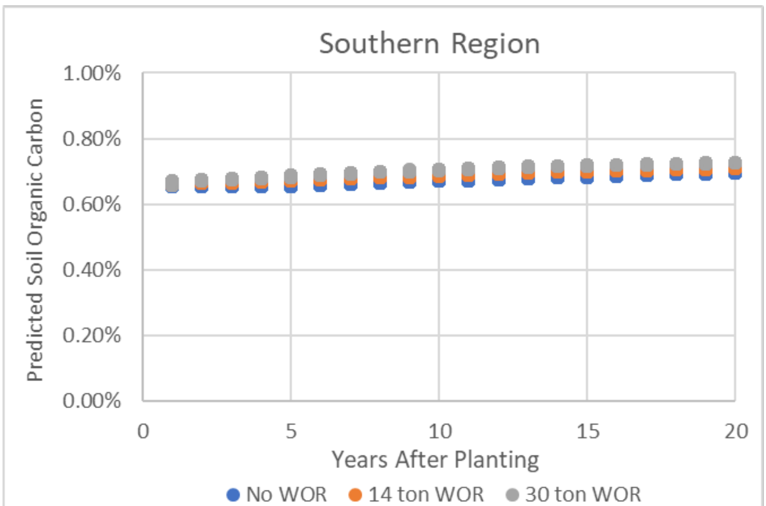
The DNDC simulations predict close-to-linear returns in carbon sequestration by WOR rate. The “percentage” of additional carbon sequestered from a given amount of chips does not vary strongly with the amount. Similar “percentage” results are seen in the model even up to 60 tons of dry chips per acre, a quantity sometimes seen in walnut orchards, especially in the Sacramento Valley. Mathematically, these model results imply that a single emission factor (EF) should be sufficient, on a per-County basis. The emission factor corresponding to 14 tons of wood chips per acre provides a conservative estimate for greenhouse gas reductions to be achieved across California. Emission factors for 30 tons of wood chips are provided as well. Modeled carbon sequestration ranged from 3.16 metric tons of CO_2 per hectare in Solano County to 5.59 in Glenn County. These ranges are caused by a range of factors, including climate, but are not closely correlated to soils’ prior carbon or clay contents.

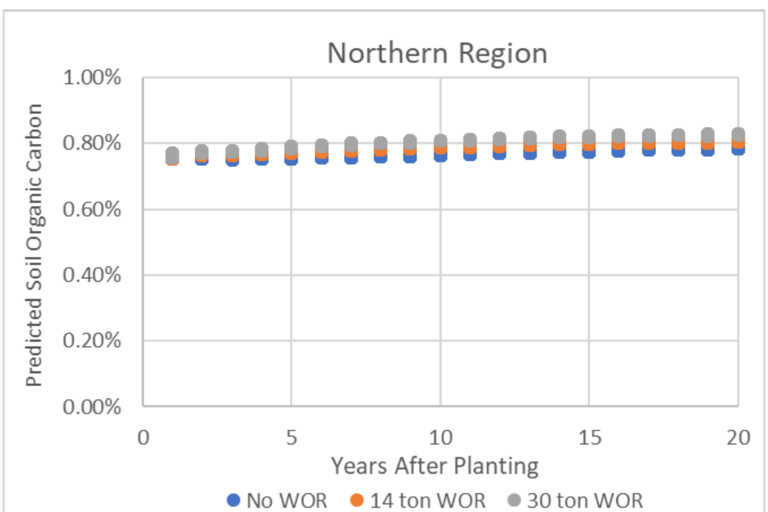
Provided below are time series of the accumulation of carbon over the modeled orchard’s lifespan in four Central Valley counties, and in the four Regions outside the Central Valley that will be used for the Quantification Methodology. The 4 counties were picked to describe a transect of the Valley north to south. Observing the vertical difference between points in the graphics, which show the practice’s effects, maximum soil carbon differences generally occur around year 10.

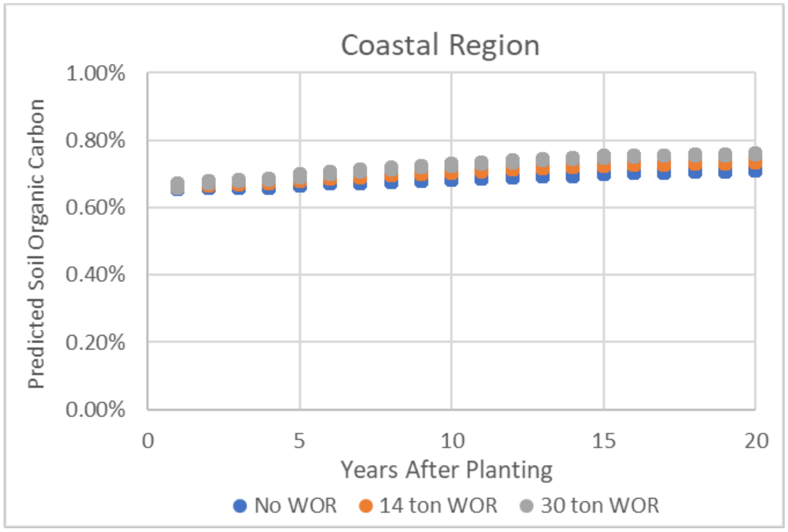
Figure 6. Whole Orchard Recycling predicted effects on Soil Organic Carbon in four counties and four regions

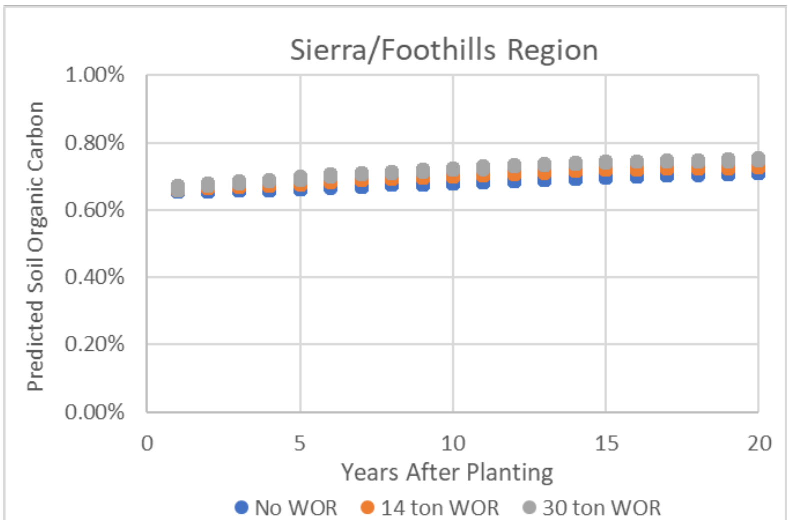



Stanislaus
Predicted Soil Organic Carbon
1.00%
0.80%
0.60%
0.40%
0.20%
0.00%
0
5
10
15
20
Years After Planting
No WOR
14 ton WOR
30 ton WOR


Southern Region
Predicted Soil Organic Carbon
1.00%
0.80%
0.60%
0.40%
0.20%
0.00%
0
5
10
15
20
Years After Planting
No WOR
14 ton WOR
30 ton WOR


Northern Region
Predicted Soil Organic Carbon
1.00%
0.80%
0.60%
0.40%
0.20%
0.00%
0
5
10
15
20
Years After Planting
No WOR
14 ton WOR
30 ton WOR





Nitrous Oxide and Methane Impacts

To establish accurate accounting of WOR's impacts on greenhouse gases, N_2O emissions were considered as well. DNDC modeling should reflect data in published reports for N_2O emissions. In Belridge, Kern County, emission factors averaged 0.23-0.35% of applied N (Schellenberg et al., 2012). In Arbuckle, Colusa County, the emission factors for N_2O were 0.26% (Alsina et al., 2013). Deng et al. (2018) reported a calculated emission factor of 0.42%. The model predictions in this report for Kern and Stanislaus Counties (Figure 7) are lower than the Deng et al. (2018) study. However, Fresno and many northern counties are above some of the published values.

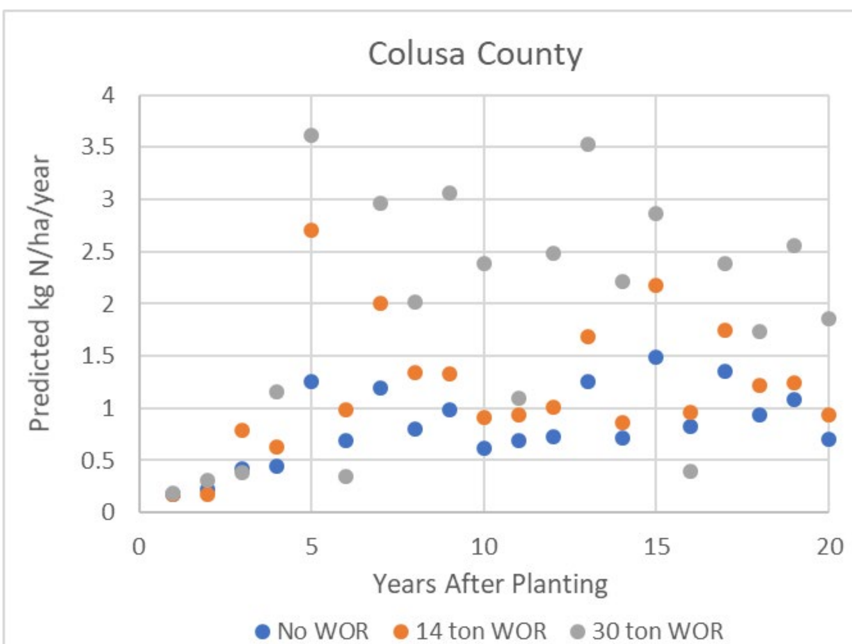
N_2O emissions in Figure 7 are sporadic, even on an annual basis, due to fluctuation in yields with different climate and patterns that affect yield and crop nitrogen uptake. In areas with important rainfall contributions to the crop's water needs, such as Colusa county, results are more scattered and variable. This is consistent with the variability seen in field results from similar sites with higher precipitation. The values reported in this report (Figure 7) show that the Northern and Coastal Regions have higher predicted N_2O emissions. These results may be overestimating the N_2O emissions because the trees were fertilized with the same amount of N in all simulations. The same trees were not capable of producing higher yields. Therefore, excess nitrogen remained in the soil in the simulations and resulted in producing additional N_2O.

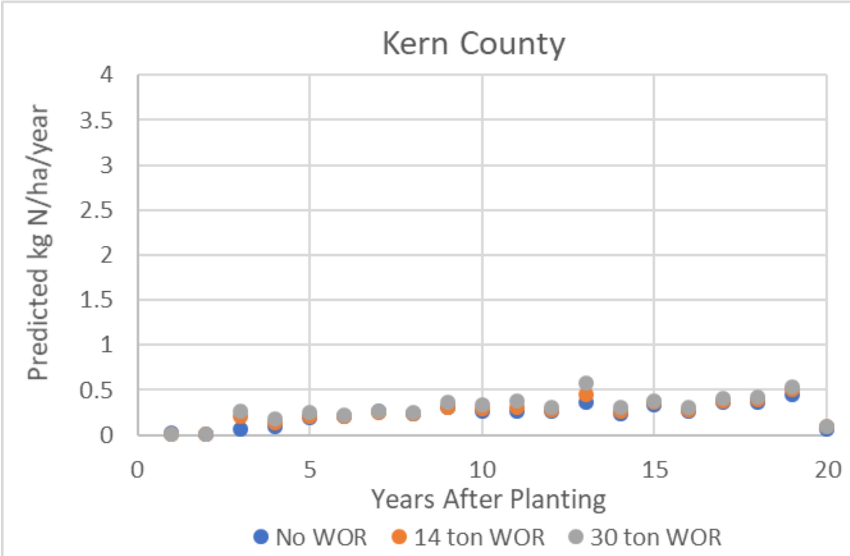
An important observation in Figure 7 is increased differences with WOR with years after planting or time. The pattern is caused by the nitrogen fertilization schedule, which reaches its maximum level in year 5, after which it is maintained (Table 1). The decomposition of high C:N wood chips may "immobilize", or absorb, some fertilizer nitrogen in the first years when it is decomposing and becoming microbial biomass which also may contribute to difference in WOR with years after planting or time. These effects can cause WOR to have low or even negative effects on N_2O emissions.

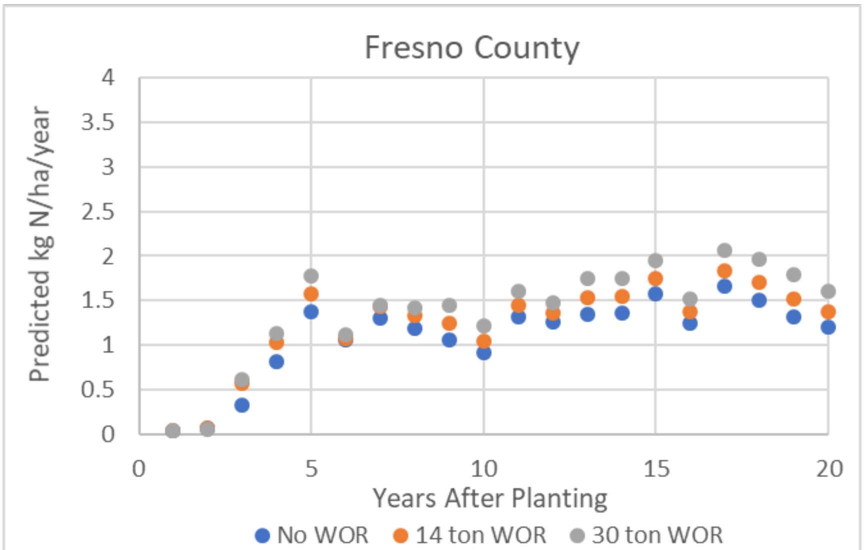
WOR's effects on CH_4 greenhouse gases were minor in DNDC simulations and provide more benefits in terms of reductions than emissions. There have not been measurements of CH_4 in the field trials.

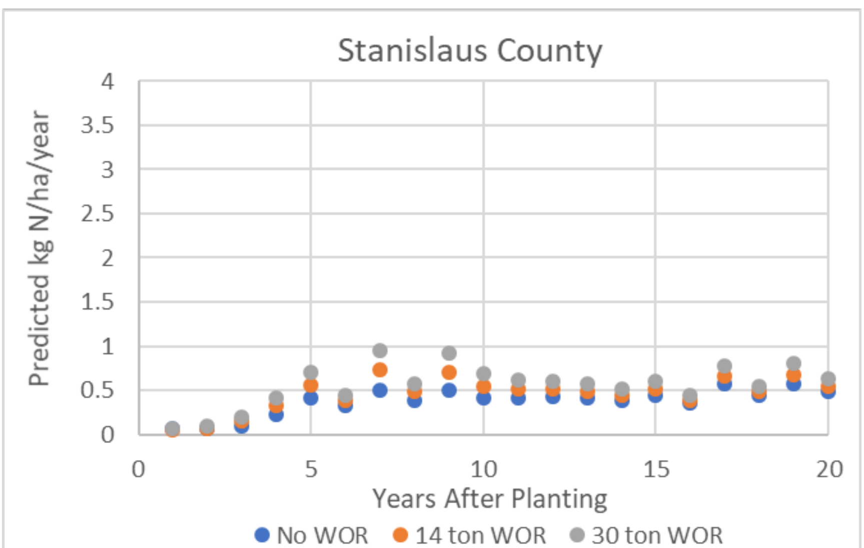
Considering the overall greenhouse gas balance of WOR, N_2O emission increases by the high margin seen in DNDC's Placer County 30-ton WOR simulations (reaching an 0.70% emission factor overall, which is higher than Californian field measurements in micro-irrigated systems). The cumulative emissions, in terms of CO_2 equivalents, are less than the SOC predicted by DNDC to be sequestered by WOR in that county. The quantification methodology for the Healthy Soils Incentive Program calculates net greenhouse gas emission reductions (CO_2 equivalents) which takes into account modeled increases in N_2O and CH_4 emissions consistent with the modelling.

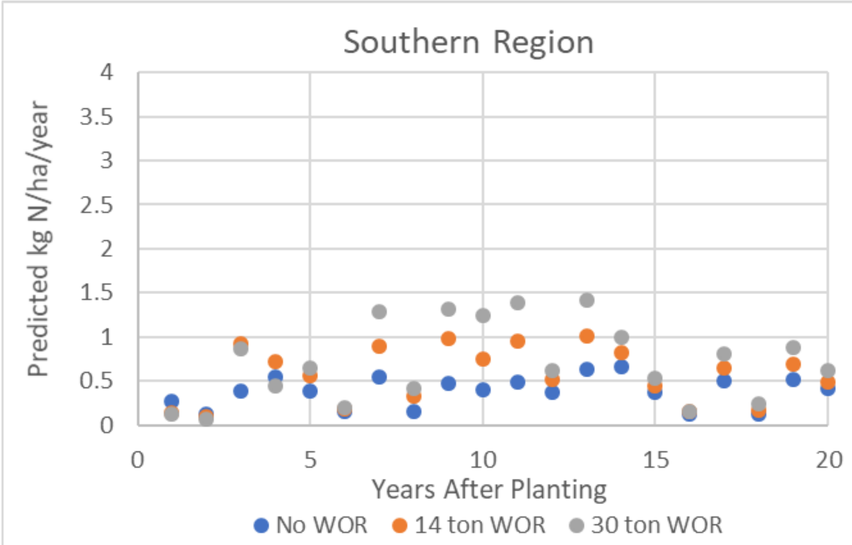
Figure 7. Whole Orchard Recycling predicted effects on N_2O emissions in four counties and four regions.

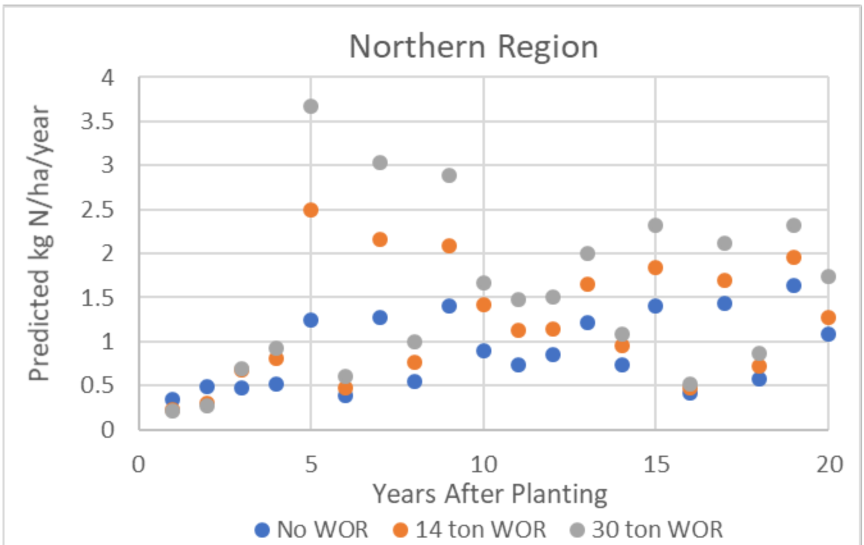


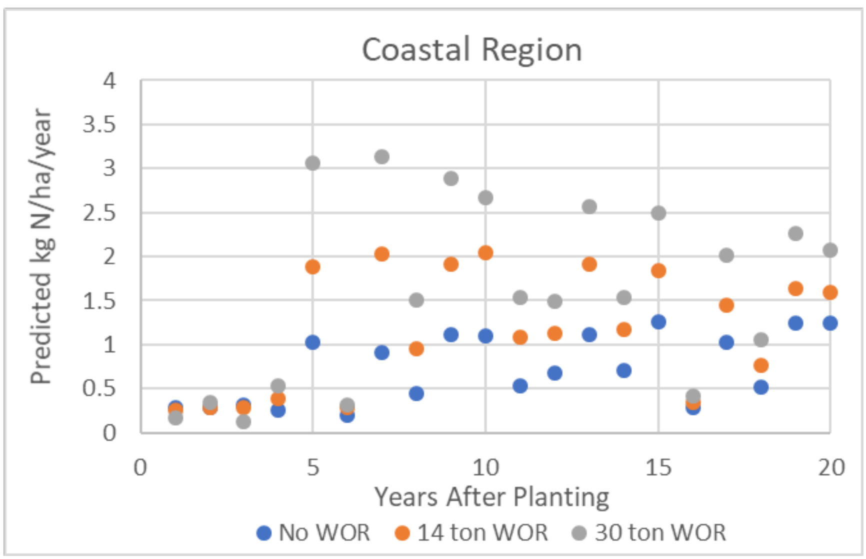

Kern County
Predicted kg N/ha/year
Years After Planting
No WOR
14 ton WOR
30 ton WOR

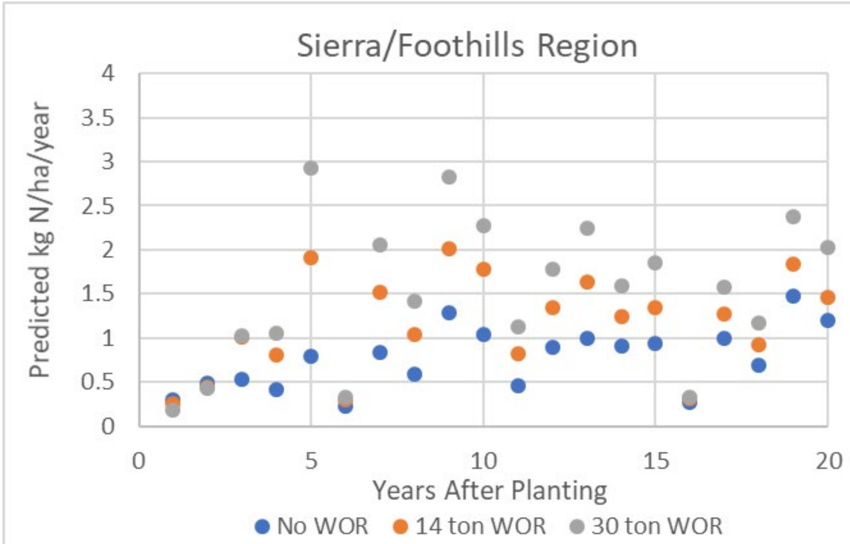

Fresno County
Predicted kg N/ha/year
Years After Planting
No WOR
14 ton WOR
30 ton WOR


Stanislaus County
Predicted kg N/ha/year
Years After Planting
No WOR
14 ton WOR
30 ton WOR


Southern Region
Predicted kg N/ha/year
0
0.5
1
1.5
2
2.5
3
3.5
4
0
5
10
15
20
Years After Planting
No WOR
14 ton WOR
30 ton WOR


Northern Region
Predicted kg N/ha/year
0
0.5
1
1.5
2
2.5
3
3.5
4
0
5
10
15
20
Years After Planting
No WOR
14 ton WOR
30 ton WOR


Coastal Region
Predicted kg N/ha/year
0
0.5
1
1.5
2
2.5
3
3.5
4
0
5
10
15
20
Years After Planting
No WOR
14 ton WOR
30 ton WOR



Co-Benefits

Research related to WOR has focused historically on mulching, which is an eligible separate management practice to WOR in the CDFA Healthy Soils Incentive Program. Mulching has increased soil organic matter in the literature in addition to providing several co-benefits. In British Columbia, an apple orchard had elevated SOC and higher water-holding capacity 7 years after shredded-paper mulch (Neilsen et al., 2003). The similar result was also observed in Washington State (TerAvest et al., 2011). Soil health also increases under wood chip mulching. TerAvest et al. (2011) found increased earthworms and root density with sugar maples (Green and Watson, 1989).

Tahboub et al. (2008) found, working with wood-chip incorporation in pecans in New Mexico, that the practice "significantly increased soil organic matter content and aggregate stability, particularly at the higher application rates and with repeated amendments." In Turkey, under a Mediterranean climate similar to California's, Yilmaz et al. (2017) found various soil health and structural benefits with vineyard pruning chip incorporation into a sandy soil. Barthes et al. (2010) have reviewed the similar use of "chipped ramial wood" (CRW), and found that "Broadly speaking, soil amendment with CRW has a positive effect on crop yield...CRW application increases soil organic matter content, stimulates soil biological activities, improves medium-term nutrient availability and - especially as mulch - soil hydro-physical properties (moisture, porosity, structure)."

WOR has a positive effect on Prunus Replant Disease (PRD) and *Phytophthora* root rot. PRD "has been associated with a complex of soilborne fungi, oomycetes, and bacteria left from the preceding crop" (Doll, 2009). Watson et al. (2017) wrote about the promise of mulching for addressing PRD: "composts and (bark chip mulch) show potential as alternatives to fumigation for suppression of PRD on sweet cherry, with promotion of beneficial rhizosphere microorganisms a possible contributing mechanism." Working in avocados in California, Downer et al. (2002) studied short and long-term effects of mulching on *Phytophthora* root rot and found that "Long-term effects include increases of soil mineral nutrients, soil aggregation and drainage, microbial activity, and cellulase enzyme activities. Biological control of

Phytophthora in mulched soil is partially regulated by cellulase enzyme activities". In general, a healthier soil is less subjected to opportunistic pathogens. Several other tree health issues are under field investigation, but there have been no recorded instances of promotion of plant diseases by WOR (see WOR website, "Tree Health").

Other potential environmental benefits of WOR may include mitigation of nitrate leaching given the decomposition dynamics of high C:N woody biomass and the expansion of tree root systems to capture and utilize available N. Salinity is also an increasing concern in Central Valley and coastal soils. In saline soils, organic mulches have improved tree health (Ansari et al., 2001; Sun et al., 1994). Buried straw, which is similar to WOR, show similar results to improved plant health for annual crops (Zhao et al., 2016).

Practice Requirements

A list of practice requirements is listed below based on analyzed data, modeling parameters and current field practices. These ensure that carbon sequestration benefits and greenhouse gas reductions are achieved by WOR as part of the CDFA Healthy Soils Incentive Program. The list of requirements was reviewed and moved as a recommendation to the Secretary of CDFA by the CDFA Environmental Farming Act Science Advisory Panel on January 16, 2020.

- WOR can only be incentivized in orchards whose trees are at least 10 years of age (DNDC modelled conditions, to ensure minimum biomass is reached for carbon sequestration).
- Following woodchip incorporation, land must be fallowed or replanted with trees within 3 years (consistent with the HSP grant term of 3 years and DNDC modelled conditions).
- Orchards must be chipped and incorporated in place on the field in which they were grown (for verification and DNDC modelled conditions).
- The WOR practice shall not be implemented in soils with Soil Organic Matter greater than 20% (DNDC modelled conditions).
- Chips must be evenly distributed throughout the orchard (consistent with DNDC modelled conditions). If a service provider is contracted, their commitment to spread the wood chips must be in the contract/invoice for verification purposes.
- Chips must be incorporated into the soil to at least 6 inches depth (DNDC modelled conditions).

Future Considerations

Research focused on the following topics would be beneficial to the WOR practice and further informing model input parameters and assumptions.

1. Combination of wood chips with other organic amendments, such as manure or compost, for WOR incorporation.
2. Combination of WOR with anaerobic soil disinfestation (ASD). Typically requires a readily decomposable carbon source such as rice husks or almond hulls, which is flooded, and often covered with plastic to stimulate the development of an anaerobic system. Wood chips are not likely to provide the right substrate for ASD, but interactions of WOR with ASD are being explored.
3. Development of a WOR Agricultural Offset Protocol.

4. WOR's effects on land that is converted back to annual crops, or otherwise tilled.
5. Applicability of WOR to non-tree crops such as vineyards.
7. Samples of WOR effects on nitrous oxide (N_2O) emissions at various points in the orchard's lifespan.
8. Measurement of nitrate leaching effects.

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Photo credits: Brent Holtz, UCCE

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