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Near-term potential of organic waste management infrastructure for soil carbon sequestration in rangelands

A L Hall[1],[*] , **M D Potts**[2] and **W L Silver**[2]

1   Energy and Resources Group, UC Berkeley, Berkeley, CA, USA
2   Environmental Science, Policy and Management, UC Berkeley, Berkeley, CA, USA
*   Author to whom any correspondence should be addressed.

E-mail: anayahall@berkeley.edu

Abstract

Contemporary food and agricultural systems degrade soils, pollute natural resources, and contribute to greenhouse gas emissions. The waste output from these systems, however, can be repurposed as an agricultural input, reducing emissions associated with organics disposal while actively sequestering atmospheric carbon in soils—thus transitioning the sector from a carbon source to a carbon sink. This research estimates the near-term technical and economic potential of utilizing composted organic feedstocks as a soil amendment to mitigate climate change and improve long-term soil quality, in line with California's organics diversion policies, by connecting food scraps and organics residuals in California's municipal solid waste to existing infrastructure and working lands in the state. The multi-objective spatial optimization results indicate considerable carbon sequestration benefits in the range of -1.9 ± 0.5 MMT CO_2eq annually, by applying compost to 6 million hectares of California rangelands at a price of approximately \$200 per ton, presenting a cost-effective climate change mitigation strategy within proposed federal sequestration credits. Expanding composting capacity is predicted to increase the total amount of carbon sequestered while reducing the cost per ton and per hectare treated. This model aids decision makers in considering the technical, economic, and institutional potential of actively managing the State's organic materials in municipal waste streams for climate change mitigation.

1. Introduction

Building a just and sustainable food system entails reckoning with the waste that occurs throughout the food supply chain, and ensuring that edible food is directed to the 44 million Americans who suffer from food insecurity. Waste reduction policies, which attempt to prevent waste at the source of generation, are required to limit food scrap disposal in the US [1]. However, full adoption of prevention and recovery strategies will still yield significant quantities of inedible organic materials (e.g., trimmings, bones, cores) [2, 3].

Waste is created across the food system: on the farm, during processing and transport, in retail environments, and in homes and restaurants. A staggering 30 to 40 percent of the US food supply is unconsumed. Inefficiencies in market conditions, consumer behavior, and supply chain generate 40 million tonnes of food scraps annually with 75% destined for landfill, according to 2017 national estimates [4, 5]. Over half of this food waste occurs at the consumer household level [4]. Although rates of composting have been increasing in recent years, curbside collection programs only serve a fraction of US residences, limiting the ability of consumers to divert food and other organic residuals from landfills [5]. In landfills, the energy and nutrients remaining in organic municipal solid waste (MSW) is broken down by microorganisms in an anaerobic process that releases methane (CH_4), a potent greenhouse gas with 28 times the warming potential of carbon dioxide (CO_2), directly into the atmosphere. As a result, municipal landfills are the second largest source of anthropogenic CH_4 emissions in the US [6].

In California, the nation's most populated state, 6 million tonnes of food scraps and 9 million tonnes of other organic waste, including 3 million tonnes of yard trimmings, are sent to landfills annually [7]. Accordingly, the state's landfills contribute about 20% of the state's anthropogenic CH_4 emissions [8].

Recognizing the critical contribution of organic MSW to CH_4 and other short-lived climate pollutants, California passed SB 1383 into law in 2016 [9]. This law codified an ambitious goal of a statewide reduction in CH_4 emissions due to reliance on landfills and requires municipalities to reduce organic material disposal in landfills by 50 percent below 2014 levels by 2020 and 75 percent below 2014 levels by 2025. In addition, the law required recovery of edible food scraps for human consumption at 20 percent of 2014 levels. To reach this goal, an additional 14.5 million tonnes of organic material will need to be diverted from landfills by 2025 [10]. According to CalRecycle, the agency responsible for implementing the waste reduction legislation, the majority of this material is expected to be composted due to its low technological and capital requirements [11].

Composting is one of a suite of options to manage organic materials in waste streams. Disposal in landfills and anaerobic digestion (AD) are common alternatives. In a 2010 life-cycle assessment, the use of these three options for managing food scraps (with green waste as a bulking agent) were compared in terms of their total global warming potential (GWP) [12]. The authors found that AD was the most environmentally beneficial treatment option, driven by avoided electricity generation and soil carbon (C) sequestration from resulting digestate. Composting was the next best overall, again due to soil C storage from use as a soil amendment. Landfilling was the worst option, due largely to the rapid decay rate for food waste. This is consistent with more recent meta-analyses of life-cycle studies [13].

Composting is a biological conversion whereby organic feedstocks are transformed into a valuable soil amendment through controlled aerobic decomposition. Exothermic microbial activity, dependent on organic material for energy, reduces pathogens and recycles macro- and micronutrients in biomass, and converts feedstock into an organic rich product that has been valued as an agricultural input for millennia [14, 15].

In addition to preventing disposal-related emissions at municipal landfills, amendments of composted organic material to soil increases nutrient availability, water-holding capacity, and can sequester new C from the atmosphere [16–18]. Compost application is a best management practice (BMP) to reduce runoff and soil erosion, thanks to the minimal technology and maintenance requirements, relatively low cost, and high effectiveness of a single application [19, 20]. Amending soils with organic matter is a common management practice in cropping systems to increase net primary productivity and has been proposed on grazed grassland ecosystems as a strategy to enhance plant growth and belowground soil C storage [21, 22].

Soil C sequestration, as it occurs in natural ecosystems, is the increase in the net storage of C in soils and plants derived from atmospheric CO_2 and plant photosynthesis [23]. Compost decomposes much less quickly than fresh organic residues (mean residence time is typically several orders greater than un-composted organic matter) resulting in slower mineralization and the potential for longer-term storage of C in soils [24].

Recent work on C sequestration on semi-arid rangelands found that biosolid application improved chemical and biological soil health indices [25]. A single application of compost at low application rates resulted in lasting improvements of soil chemical properties, such as increased buffering capacity [26]. A study of compost amendments to rangelands across the state of California have found that a single application of 0.25 inches of finished compost can sequester on average 2.1 ± 1.0 Mg C per hectare per year [27]. Compost has also been shown to increase soil organic C in California croplands; winter cover crops resulted in greater increases in labile C [28].

In this paper, we evaluate the technical and economic potential of utilizing organic materials in MSW as a composted soil amendment on California's working lands. This analysis builds off of previous studies to provide a robust account of this proposed climate change abatement strategy by connecting technically-available raw MSW materials (referred to here as feedstocks) to existing composting capacity and suitable working rangelands across the state [29]. The results of this geospatial analysis provide near-term insights for long-term management of food scraps and agricultural systems in California.

Organic materials are high in water content, and thus expensive in terms of both monetary cost and vehicle emissions to transport long distances. Past studies of biomass inventories (biochar and digestate) in the state have recognized this critical constraint [30]. By accounting for infrastructure location and capacity, feedstock quantity and availability, suitable areas for land application, and transportation-related emissions, this study provides a rigorous assessment of the possible C sequestration impacts of applying compost as a soil amendment. This study develops a geospatial, multi-objective optimization model to simulate distribution of organic MSW feedstocks to compost processors and of finished compost to working lands, subject to physical and engineering constraints. The solved quantities resulting from the linear programming model are used to estimate the cost and performance of re-imagining the organic fraction of municipal waste streams as emissions sinks, rather than sources, and to assist decision makers in developing strategies to manage waste and promote soil health.

This study is the first to consider actual locations of compost facilities in a geospatial analysis to assess the near-term technical and economic potential of statewide repurposing of organic waste streams in grazed landscapes and calculate an abatement cost for compost application [13, 29, 31]. Building off Harrison *et al*, we consider the geographical and technical constraints of compost processors, which play a key role in the potential to repurpose organic MSW at scale. This work complements existing assessments to highlight near-term potential of the existing compost infrastructure. Further, the economic analysis will assist policy makers to compare costs and benefits associated with composting in California with other GHG mitigation strategies in the state. In the short-term, this study provides enhanced understanding of the present arrangement of organics management infrastructure and the use of composting for climate change mitigation. In the long term, the results may inform planning processes around organic waste management infrastructure including the need for source separation programs and expansion of the variety of types and locations of composting facilities across the state.

The goals of this analysis are three-fold: (1) evaluate the available stock of food scraps and green waste that could be composted given existing processing infrastructure in the State, (2) allocate feedstock to composters and finished compost to suitable grazing land with the competing objectives of minimizing net greenhouse gas emissions and minimizing overall cost, and (3) estimate the Pareto trade-off frontier to determine projected abatement cost (USD/tCO$_2$e) and performance (MMT CO$_2$e). These goals are achieved using a multi-objective optimization model to simultaneously consider two criteria—emissions and total cost—constrained by feedstock supply, processing capacity, and land availability in California.
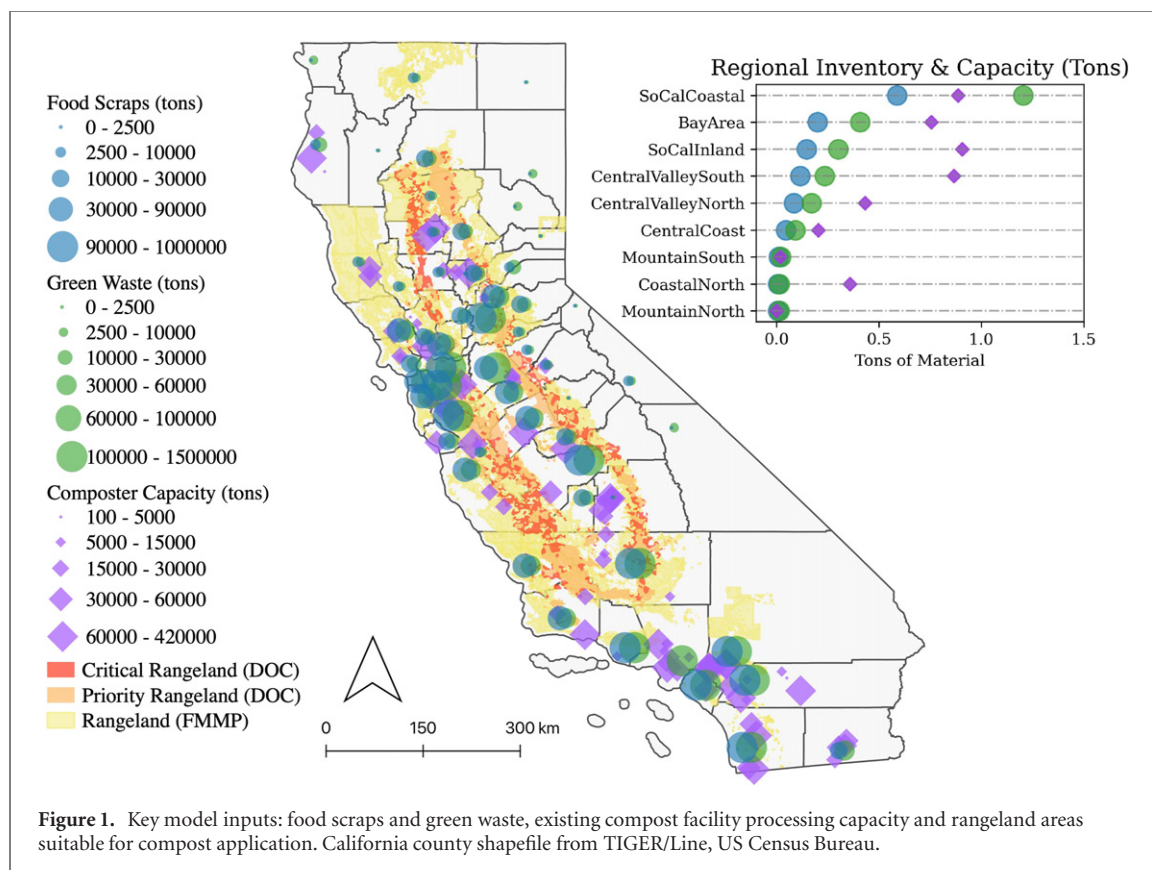
2. Methods and materials

Soil C sequestration requires a combination of C inputs and nutrients [14]. To achieve quality compost with favorable C:N ratios for plants while limiting nitrous oxide (N$_2$O) emissions, a potent greenhouse gas, food scraps must be combined with other organic materials. Food scraps contribute substrate and nitrogen, with green waste acting as bulking agents and C sources [12].

Consistent with the goals of SB1383, this study focuses on the two largest components of organic MSW: food scraps and green waste. Food waste is defined in this study as otherwise edible organic materials disposed off throughout the food supply chain, including food scraps generated during food processing, retail, and in eating establishments and consumers' homes. Green waste is defined as landscape and yard trimmings, including grass clippings, leaves, branches, flower trimmings, hedge trimmings, and weeds. Food scraps and green waste were combined in this study to balance C:N ratios as composter inputs.

Although compost application may provide benefits for cropland and orchards, we focused on rangeland systems, which cover over 20 million hectares in California and frequently surround densely populated urban areas [32]. These ecosystems are the dominant vegetative cover type in California and represent an important sector of the state's agriculture economy [33]. Although composting effectively eliminates pathogens in organic materials some farmers and growers have citing food safety concerns about use of this material on their fields, expressing apprehension that compost amendments may result in bacterial contamination of their produce [34]. Further, application of composted organic material to rangelands can be performed using existing machinery, such as manure spreaders. Thus, rangeland landscapes offer a critical means to implement composting practices at scale in the near-term throughout California. The extensive nature of rangelands across the state as well as the potential for co-benefits for ranching operations suggests that the application of compost to rangelands will be limited by compost supply and geographic factors [35].

Gross and technical feedstock availability was determined by extent of generation rates and hauling networks, as well as strength of established markets for organic residuals (for example, diverting almond hulls or spent brewing grain for livestock feed). Food scraps and green waste disposal rates were estimated from county composition fractions from the 2014 CalRecycle disposal assessment [36]. We rely on data compiled by Breunig *et al*, which attempted to account for source-separation practices. Unfortunately there is little information available for the fraction of the population with access to curbside composting practices. As such, the available feedstocks used in this study represent the total recoverable organic material in MSW. Biomass resources are, by nature, distributed across the landscape. In the spatial analysis that follows, however, county-level estimates were allocated to the population-weighted centroid of each census tract polygon.

'Composters' are defined here as solid waste facilities holding an active compostable materials handling permit to compost organic material. There were 109 permitted compost facilities in California, accepting nearly 6 million tonnes of organic materials each year [37]. Composter data was collected from the CalRecycle solid waste inventory system (SWIS), which contains information on all permitted solid waste facilities in the State. This dataset contains information on facility size, location, activity category, permit type, and accepted feedstock. There were 109 operating composting or chipping and grinding facilities holding active composting permit facilities across 31 counties, predominantly concentrated in the Central Valley and south

Figure 1. Key model inputs: food scraps and green waste, existing compost facility processing capacity and rangeland areas suitable for compost application. California county shapefile from TIGER/Line, US Census Bureau.

coast, as shown in figure 1 below [37]. Mean composting capacity in this dataset was 50 000 tons per year. There were eight small (under 1000 tons per year) facilities, but most facilities were medium to large composters.

Rangeland data were acquired from the California Department of Conservation Farmland Monitoring and Mapping program [38]. Only those areas where vegetation and land characteristics, such as slope and accessibility, were suited to grazing of livestock as determined by a collaboration between the California Cattlemen's Association and UC Cooperative Extension. Soil C sequestration factors were determined by the California Air Resources Board (CARB) in their quantification of annual agricultural emissions for the Healthy Soils Program [39] and ranged from 3.347 (Sierra County) to 4.596 MTCO$_2$e/ac/year (Modoc County) [40]. These values were based on prior studies that show sequestration potential is variable and dependent on numerous factors including soil type, temperature and precipitation [41]. It is notable that these rates are considerably lower than published field studies (e.g. Ryals and Silver 2013, Ryals *et al* 2014, 2015, Silver *et al* 2018) and thus represent a conservative estimate [24, 27, 42, 43]. Given data availability and the general climatic similarity within counties, all rangeland sites in a given county were assumed to have the same sequestration factor.

The model objective was defined to address conflicting goals of minimizing greenhouse gas (GHG) emissions as measured by net GWP and overall project cost. This formulation allowed for the creation of a Pareto trade-off frontier to assess abatement cost (both per ton C and per hectare treated) using different weights for the two objectives. Net GHG emissions (kgCO$_2$e) was chosen as it is a significant environmental concern and provides commensurable evaluation over the complete chain from disposal to soil application.

2.1. Multi-objective optimization model

In order to model the efficient allocation of organic feedstocks from the point of generation to a processing facility and finally to the ultimate land-use destination, a multi-objective, linear programming model was constructed with the data sources given above and parameters derived from the literature (below). Rather than the single objectives of minimizing cost or optimizing for environmental impact, the model implemented in this study scalarizes multiple objectives into a single function through the parameter α. This multi-objective model allows for a weighted blend of two critical policy priorities and permits a Pareto analysis to understand the trade-off between cost and emissions reductions. Although the units of the objective function in this approach are less intuitively obvious than in a single objective model, use of a weighting parameter balances competing objectives to return possibilities along the Pareto frontier and is common in techno-economic studies [44, 45].

The optimization model was defined by a linear objective function and linear constraints. The key variables influencing the model are quantities of feedstock and compost to transport and apply, and the distances from

disposal site to processing nodes (D_{ij}) and from composter facility to land-use nodes (L_{jk}). The decision variables that the solver adjusts to find an optimal solution are the gross amounts of materials to distribute between nodes, denoted as f_{ij} and c_{jk} for feedstock and compost, respectively. The parameter variables included in the model were selected based on the organic recycling literature and expert interview.

Equation (1) below mathematically describes the objective function

$$\text{Objective}: \text{Min}((\alpha \cdot \text{Cost}) + ((1-\alpha) \cdot \text{GHG})) \tag{1}$$

where:

$$\text{Cost} = \underbrace{\sum_{i=1}^{n}\sum_{j=1}^{m} d \cdot D_{ij}f_{ij}}_{\text{collection cost}} + \underbrace{\sum_{j=1}^{m}\sum_{k=1}^{p} e \cdot L_{jk}c_{jk}}_{\text{hauling cost}} + \underbrace{\sum_{k=1}^{p} t \cdot A_k}_{\text{spreading cost}} \tag{2}$$

and

$$(\text{GHG}) = \underbrace{\sum_{i=1}^{n}\sum_{j=1}^{m} h \cdot f_{ij} \cdot D_{ij}}_{\text{collection emissions}} - \underbrace{\sum_{i=1}^{n}\sum_{j=1}^{m} l \cdot f_{ij}}_{\text{avoided landfill emissions}} + \underbrace{\sum_{i=1}^{n}\sum_{j=1}^{m} x \cdot f_{ij}}_{\text{composting emissions}}$$

$$+ \underbrace{\sum_{k=1}^{p}\sum_{j=1}^{m} h \cdot c_{jk} \cdot L_{jk}}_{\text{hauling emissions}} + \underbrace{\sum_{k=1}^{p} g \cdot c_{jk}}_{\text{spreading emissions}} - \underbrace{\sum_{k=1}^{p} q_i \cdot c_{jk}}_{\text{net sequestration potential}} . \tag{3}$$

Subject to:

Intake for each facility is sum of quantity from f_i for $i = 1, \ldots, n$:

$$I_j = \sum_{i=1}^{n} f_{ij}. \tag{4}$$

Output of each facility is equal to intake converted into compost:

$$O_j = u \cdot I_j. \tag{5}$$

Total compost applied on given land is the sum of the quantity of output from c_j for $j = 1, \ldots, m$:

$$A_k = \sum_{j=1}^{m} c_{jk} \tag{6}$$

where:
α = Pareto weighting parameter, between 0 and 1
f = quantity of feedstock from county i to facility j, $[n \times m]$
c = quantity of compost from facility j to rangeland k, $[m \times k]$
D = collection distance between county centroids and compost facilities, $[n \times m]$
L = Hauling distance between facilities and rangelands, $[m \times k]$
F_i = organic material generated in county i
C_j = maximum intake capacity of facility j
B_k = maximum amount of compost that can be applied to land k
X = minimum disposal quantity to divert from landfill (% of F_i)
and
q_i = sequestration rate in county
u = conversion factor of waste into compost
l = emission factor for waste left in county $\left(\frac{\text{kgCO}_2 e}{\text{ton}}\right)$
g = emission factor for applying compost via manure spreader $\left(\frac{\text{kgCO}_2 e}{\text{ton}}\right)$
h = transportation emission factor $\left(\frac{\text{kgCO}_2 e}{\text{ton km}}\right)$
y = emission factor for compost production $\left(\frac{\text{kgCO}_2 e}{\text{ton}}\right)$
d = cost to haul to facility from county $\left(\frac{\$}{\text{ton km}}\right)$
e = cost to haul away from facility to land $\left(\frac{\$}{\text{ton km}}\right)$
t = cost to apply compost to fields $\left(\frac{\$}{\text{ton}}\right)$.

Table 1. Baseline parameter values, description, and source.

Variable	Description	Estimate	Unit	Source(s)
u	Conversion factor	0.58	%	[48]
l	Landfill emission factor	182.9	$\frac{\text{kgCO}_2e}{\text{ton}}$	[49]
h	Transportation emission factor	0.22	$\frac{\text{kgCO}_2}{\text{ton\_km}}$	[50]
y	Composting emission factor	6.67	$\frac{\text{kgCO}_2}{\text{ton}}$	[27]
g	Application emission factor	1.08	$\frac{\text{kgCO}_2}{\text{ton}}$	[51]
d	Collection cost (municipality to facility)	0.35	$\frac{\$}{\text{ton\_km}}$	[52]
e	Hauling cost (facility to land)	0.12	$\frac{\$}{\text{ton\_km}}$	[53, 54]
t	Rangeland application cost	3.4	$\frac{\$}{\text{ton}}$	[55–57]

The cost function contains three terms, following the flow of organic material from generation through processing to land application. The first term accounts for collection costs due to transportation of feedstocks from population-weighted county centroids to processing facilities. Cost is calculated based on the volume-kilometers that the quantity of organic material is moved. The following term represents hauling cost of finished compost from processing facilities to rangeland centroid. The final term represents the cost to apply the compost using industry standard machinery. The amount of compost that can be applied to a rangeland is based on polygon area and an assumed application rate of 4.7 dry tons per acre [41].

The GHG emission function also follows the flow of organic residuals from municipal centers through processing facilities and to final land application. The net estimated emissions accounts for avoided landfill emissions and expected soil C sequestration, which were subtracted from emission-generating activities of transport and processing.

Expert interviews suggested that compost tipping fees, which are the prices paid by generators to discharge organic materials at processing facilities, were designed to just cover operation and maintenance (O & M) costs (personal communication, 2019) [46, 47]. Tipping fees were highly variable between different operations and the actual figures were frequently obscured from the general public as a trade secret to protect contracting agreements [11]. Due to the lack of reliable data, both tipping fees and O & M costs elements were excluded from this analysis on the assumption that, on average, they balance each other out. Rather, the focus here is on the cost of moving organic materials and applying compost across the state's rangelands in order to estimate a baseline abatement cost. Waste generation rates in the near-term are assumed to be consistent with recent estimates.

The objective function is solved over 15 iterations of the α parameter at equal steps between 0 and 1 to construct a Pareto trade-off frontier. After the objective function is solved at each α level, the optimal values for the quantity of organic material to move between all model nodes are used to calculate the net environmental impact in terms of net GHG emissions (GWP), the total estimated cost (USD), and the area of land treated with compost (hectare). These in turn were used to calculate abatement cost in $\frac{\text{USD}}{\text{kgCO}_2e}$ and $\frac{\text{USD}}{\text{hectare}}$.

We used the open-source package, CVXPY to solve this optimization problem, which relies on the solvers ECOS, OSQP, and SCS. This package is used for a variety of mathematical programming problems, including linear programming, quadratic programming, and mixed integer linear programming among others. We relied on their linear programming solutions. The model is implemented in the Python programming language.

2.2. Parameters and emission factors

The global parameter values used in the model are listed in table 1. All emission factors are given in 100 years GWP. GWP was chosen as it provides commensurable evaluation of environmental impact across transportation, disposal, and soil application. Additional information on the source and evaluation of each key parameter used in the model is included in the supplementary information. Sequestration rate was not listed in table 1 as it varied by county, but the average value across the state is 4.4 MTCO$_2e$/acre/year [40]. Tonnage was evaluated for either feedstock or compost, depending on which material was being moved and managed (i.e., collection cost and landfill emission factors are based on tonnage of feedstock, while hauling cost and application emissions are based on tonnage of compost).

The sensitivity of the results to key parameters was evaluated using a parametric sensitivity analysis. Key parameters were selected based on previous research and expert judgement. Each key parameter was evaluated at 50% and 150% of the baseline value in order to consistently assess a range of input variables. For parameters where multiple values could be found in the literature, this range included both low and high estimates. The Pareto weight parameter was set to $\alpha = 0.75$ for sensitivity runs, representing a slight preference for minimizing cost over emissions to reflect a realistic policy priority.
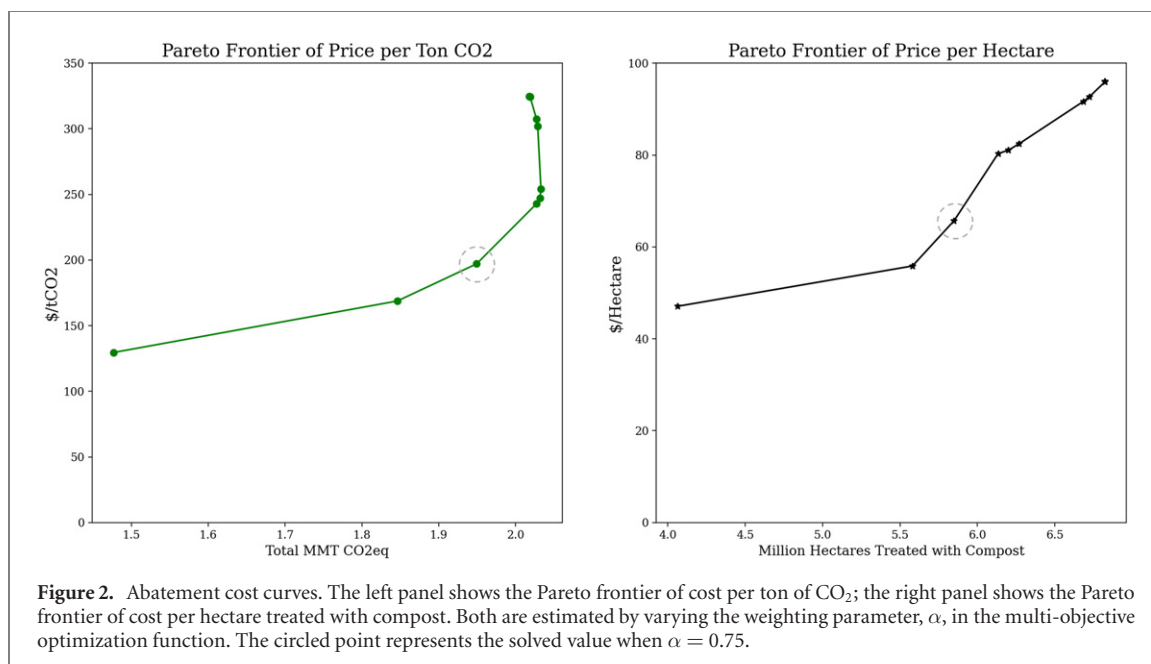
Figure 2. Abatement cost curves. The left panel shows the Pareto frontier of cost per ton of CO_2; the right panel shows the Pareto frontier of cost per hectare treated with compost. Both are estimated by varying the weighting parameter, α, in the multi-objective optimization function. The circled point represents the solved value when $\alpha = 0.75$.

3. Results

3.1. Pareto analysis and disposal scenarios

Mitigation potential is presented in millions of metric tons (MMT) and costs are presented in 2020 USD. The scenario results are plotted in figure 2 to present an estimated abatement cost cure. At the assumed current rate of organic material disposal, within existing infrastructure constraints, over 2 million tonnes of food scraps and green waste were moved to facilities to be processed into compost, resulting in a net greenhouse gas savings of 1.95 million metric tonnes of CO_2-equivalents, at a cost of 197.11 USD/ton ($\alpha = 0.75$) (figure 2). When only cost is considered by the model ($\alpha \approx 1$), the approximately 1.3 MMT CO_{2e} were mitigated at a cost of 123.09 USD/ton. When the model prioritized minimizing emissions only, over 2.0 MMT CO_{2e} were mitigated at a cost of 324.74 USD/ton. The highest mitigation (2.03 MMT CO_2e) was found when costs and emissions objectives were nearly balanced at $\alpha \approx 0.5$. At these weights, the price per ton of CO_2e was 254.19 USD.

As expected, the overall mitigation potential and abatement cost both increased with higher diversion rates as more waste was diverted from landfills and hauled to working lands (table 2). The abatement cost per ton of CO_2e also increased with increased diversion rates, as material had to be transported longer distances. The abatement cost curve echos this result showing an upward trend as annual mitigation potential increased leading to higher costs per ton (figure 2).

The amount of material applied to the State's rangelands decreased as the objective to minimize cost was prioritized over emissions (figure 3). Rangelands near the dense population areas of southern California and the Bay Area, as well as in the Southern San Joaquin Valley, received the most composted material. As cost was prioritized, these rangelands continued to receive compost applications, while rangelands in the north coast region receive less.

3.2. Parametric sensitivity results

Following the base model runs, an analysis was performed to evaluate the robustness of the model outputs to the specification of key parameters, including C sequestration rate, emission factors, and collection costs. Sensitivities were run using a combination food scraps and green waste as feedstock with the Pareto parameter α set to 0.75, as this value and the associated results represented a reasonably realistic balance of cost and emissions objectives to act as comparison (table 2).

As expected, varying the emission factors parameters was associated with altered overall mitigation potential. A low landfill emission factor reduced the abatement cost to 169 USD per ton CO_2e. This was due to the model having less incentive to move material out of landfills and on to rangelands, resulting in both reduced overall emissions mitigation and a greater reduction in total cost.

In previous lifecycle assessments landfill offsets were responsible for a large portion of the greenhouse gas savings associated with compost applications to rangelands [31]. To address this, we ran a no-landfill-offset scenario in which avoided landfill emissions were not included in the net emissions estimate. The results of this run still showed a positive greenhouse gas benefit, though much less material was moved under this scenario

Table 2. Parametric sensitivity values and results.

Variable	Description	Unit	Estimate	$\frac{USD}{kgCO_2e}$	MMT CO_2e	$\frac{USD}{ha}$
	Baseline	—	—	$197	1.9	$66
			Low: 94.4	$169	1.8	$56
ℓ	Landfill emissions	$\frac{kgCO_2e}{ton}$	High: 279.1	$245	2.0	$81
	No landfill avoidance		—	$90	0.5	$29
			Low: 9.8	$197	1.9	$66
y	Processing emissions	$\frac{kgCO_2e}{ton}$	High: 29.5	$200	2.0	$65
			Low: 0.3	$190	2.2	$69
h	Transportation emissions	$\frac{kgCO_2e}{ton\ km}$	High: 1.0	$204	1.8	$62
			Low: 0.2	$78	2.0	$23
d	Collection cost	$\frac{USD}{ton\ km}$	High: 1.0	$233	1.9	$77
			Low: 0.5	$184	2.0	$61
e	Hauling cost	$\frac{USD}{ton\ km}$	High: 1.6	$207	1.9	$69
			Low: 5.0	$197	1.9	$66
t	Application cost	$\frac{USD}{ton}$	High: 14.9	$193	1.9	$64
			Low: 50%	$185	1.9	$63
q_i	Sequestration factor	$\%$	High: 150%	$202	2.0	$68
			25%	$139	0.8	$42
			50%	$168	1.5	$54
	Disposal rate	$\frac{ton}{year}$	75%	$188	1.8	$60
			150%	$178	2.6	$58
			200%	$121	3.2	$55
	Capacity	$\frac{ton}{year}$	300%	$146	3.6	$45

and the abatement cost was considerably higher than baseline runs. This scenario run indicates the significant impact of model boundaries in anticipated benefits of developing compost soil amendments for climate change mitigation. Sequestration factors were also evaluated in the sensitivity analysis. Since these are county-specific, we ran one scenario in which each county estimate was 50% of the baseline value and one in which they were 150%. A higher sequestration rate increased the overall amount of CO_2e mitigated, but also increased the overall cost as more rangelands were treated with compost.

Base model runs assumed BMPs at composting facilities, which limit processing emissions, but may not represent actual facility operations. Higher processing emissions reduced mitigation potential below the baseline scenario and maintained roughly similar costs. Additional results of the sensitivity analysis suggest that transportation cost, particularly collection cost, were a strong driver of the quantity of organic material moved between nodes and overall abatement cost.

The model was also used to explore the impact of increasing facility capacity. Three scenarios were chosen in which permitted capacity at all existing processing facilities was increased by 150%, 200%, and 300%. Increasing capacity 300% across all existing facilities would meet requirement for additional organic material management as set out by SB1383, according to CalRecycle [10]. Each resulted in higher mitigation potential, as well as reductions in cost, highlighting the need for expansion of composting infrastructure in the State. At the highest capacity scenario, the cost per kg of CO_2e is reduced to $146\frac{USD}{kgCO_2e}$ while the total emission reduction increased to 3.6 MMT CO_2e. Additional figures showing the movement of materials under select sensitivity scenarios can be found in the appendix A.

4. Discussion

Compost applications to working lands can promote healthy, productive soils, sequestering new C from the atmosphere and restoring the agricultural resource that nourishes a national population. This study was designed to provide insight for policy makers and regulators working to implement ambitious climate change and organics diversion laws. Across both objectives evaluated in the multi-objective optimization model, it appears that utilizing municipally generated feedstocks can yield considerable C sequestration benefits and present a cost effective approach to climate change mitigation, costing approximately 200 USD per metric ton of CO_2e, which is in the range of some proposed sequestration credits [58]. Abatement cost increases with higher rates of disposal, as organic material must be hauled longer distances.

The map in figure 3 highlights the longer transport distances required in the southern part of the state to access available composting capacity, as well as to reach nearby landscapes for final use. The lack of composting infrastructure in northern counties of Modoc, Siskiyou, Shasta and Lassen highlight the difficulty of utilizing the municipal organic solid waste generated in these remote counties in existing composting facilities. This

Figure 3. Flow of feedstocks (purple) from county centers to compost facilities and of finished compost (blue) from facilities to rangelands (white polygons) across California under model optimization where $\alpha = 0.75$. Thicker lines indicate more volume.
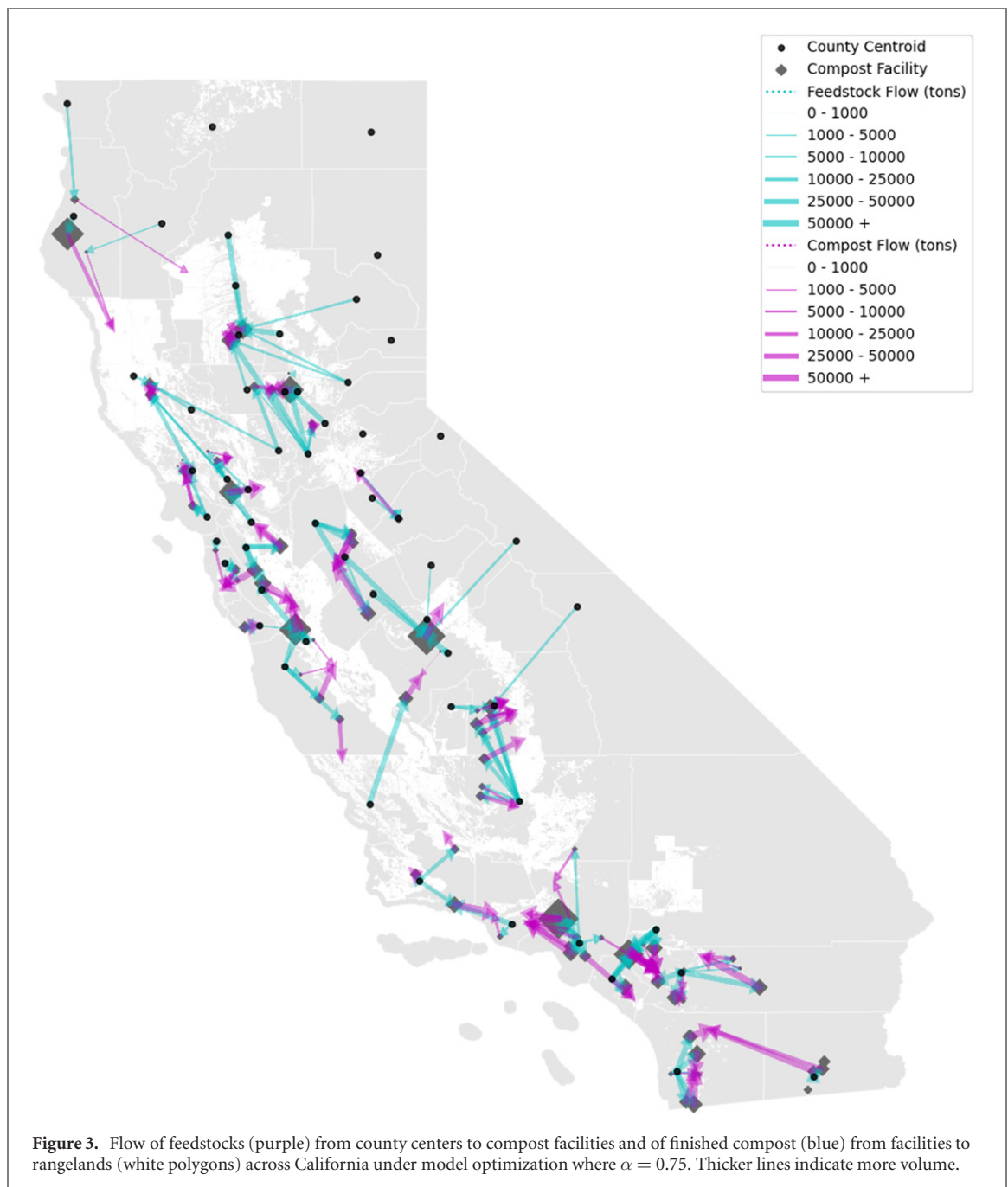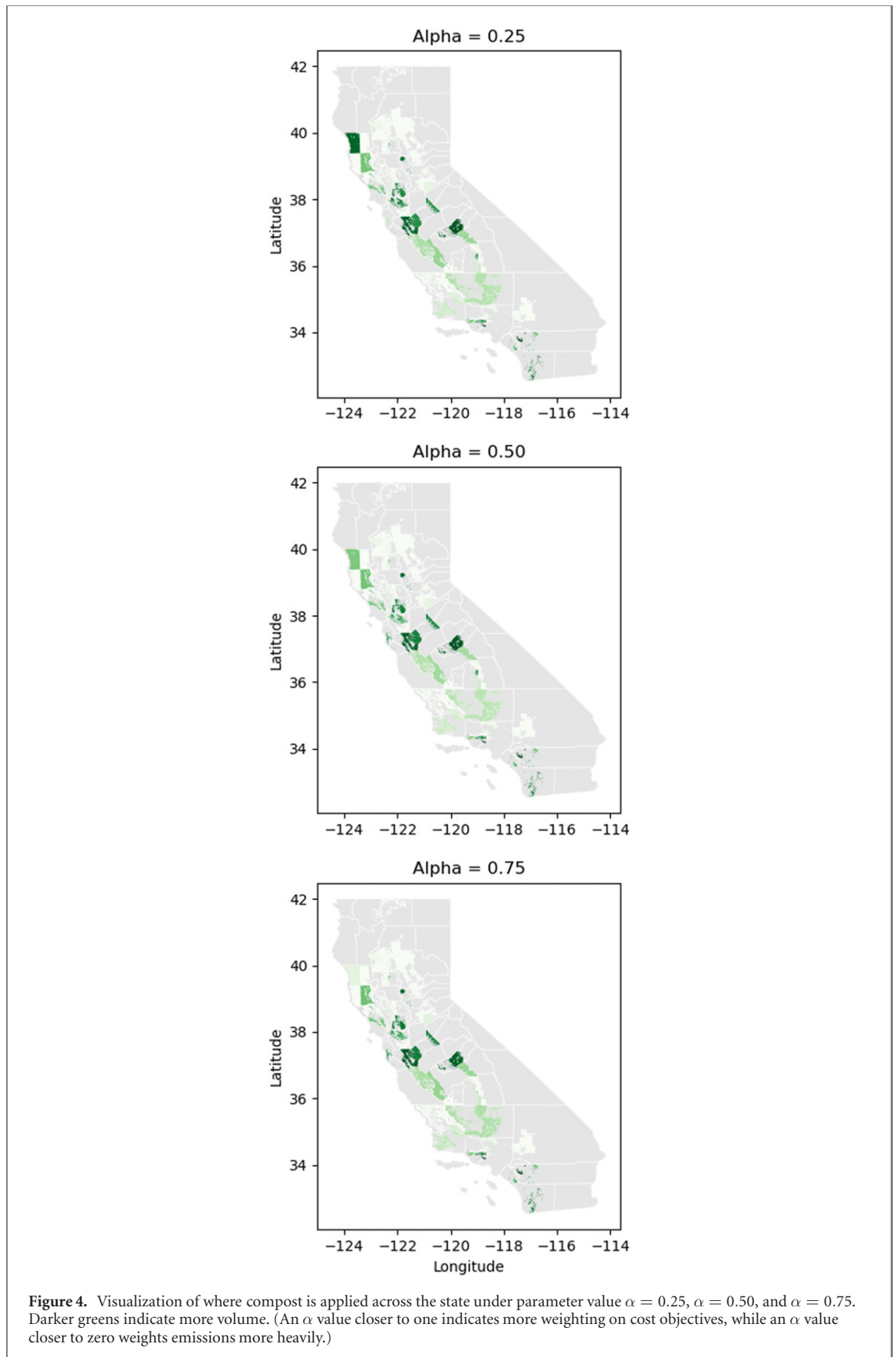
figure also highlights the regional movement of feedstock and finished compost. Across the state, feedstocks must travel further to reach compost facilities than compost must move to reach rangelands for soil application. For the most part, though, materials movement is limited to within-county or to nearby counties. The concentration of rangeland application in Southern California and the Bay Area, shown in figure 4, makes intuitive sense as these regions are nearest to existing processing infrastructure as well as municipal generation sources.

Results of the model output and sensitivity analyses show variable mitigation costs and benefits and, in all, highlight the need for additional facility expansion. Across the state, California counties generate over 15 million tonnes of food scraps and yard waste each year. The state's 6.5 million hectares of coastal and valley rangelands vastly outnumber the available organic material that could be land applied in a given year under reasonable application rates [38, 59]. Thus, a primary factor limiting the extension of compost applications to working lands is the lack of infrastructure to collect and process organic material.

Our results show a much smaller overall emissions reduction potential from statewide composting than Harrison *et al* [29] likely because that study was not limited to existing compost infrastructure and included

Figure 4. Visualization of where compost is applied across the state under parameter value $\alpha = 0.25$, $\alpha = 0.50$, and $\alpha = 0.75$. Darker greens indicate more volume. (An α value closer to one indicates more weighting on cost objectives, while an α value closer to zero weights emissions more heavily.)

fertilizer displacement[3]. Although the models are formulated differently, most parameter estimates, including those derived from interviews largely agree. Our results similarly highlight their conclusion of the need to extend infrastructure across the state.

If composting facility capacity was not a bottleneck, we would expect to see higher mitigation potential up to 8.5 MMT CO_2e. This simple estimate was derived by assuming that all organic feedstock generated within a county is composted and applied to rangelands locally, using that county's specific waste generation and net emissions estimate. Ignoring constraints on land availability within the county could increase this value by an additional 2.0 MMT CO_2e. These estimations ignore important transportation emissions, but highlight the potential upper limit of using composted organic MSW as a soil amendment for climate change mitigation.

Increasing compost infrastructure capacity in the state, on the one hand, can help reduce the transportation distance of material and extend the state's organic processing capacity. On the other hand, siting new compost facilities is difficult as they require large areas of undeveloped land because they can be a source of odor and air pollution, which can negatively impact vulnerable communities. New compost infrastructure development should be undertaken with careful consideration of the potential harm to local populations, especially the most vulnerable and those already suffering disproportionate environmental burdens. The results of this multi-objective model may inform waste management agencies on how best to utilize existing infrastructure and plan for new composting facilities in order to make organics material management for climate change mitigation more cost effective and environmentally impactful.

4.1. Limitations and future work

This assessment presents a model of an imagined food system scenario in which municipal organic waste becomes the primary feedstock of composters and rangeland application as the primary end-use. This assumption necessarily ignores existing demands of the compost market, as well as the limits of available feedstock collection.

Through evaluation of the literature and correspondence with ranchers and composters, we identify a few key challenges to the near-term potential of utilizing municipal food scraps and green waste to meet California's climate change mitigation policies. Surveys of the compost processing industry administered by CalRecycle indicate that most facility operators believe that end use markets for recovered organics are not a limitation for California's ambitious climate change mitigation goals. Many existing composting facilities have potential to increase the volume of materials they accept, but the requirement to apply for new or adjusted air district permits is often cited as a primary reason preventing them from accepting additional material [10].

Feedback from the CalRecycle surveys also suggest that the largest factor stimulating facility expansion is the availability of feedstock materials [10]. SB 1383 requires that city and county jurisdictions provide organics collection services to all residents and it is likely that new curbside composting contracts will promote facility growth. However, accessing available capacity may require increases in hauling distance, and therefore cost.

Siting new compost processing facilities, or expanding existing ones, has become increasingly challenging in California due to rigorous environmental protections around air and water quality. The State Water Resources Control Board is in the process of implementing a composting general order, which requires facility operators to submit a report of water discharge that is anticipated by the industry to have a significant financial impact on composters. The permitting process through local Air Quality Management District (AQMD) or Air Pollution Control District (APCD) is also often prohibitively costly for operators to undertake, restricting facility expansion [11].

Rapid expansion of small-scale community composting programs in schools, gardens, and parks across the state may offer a viable alternative to centralized, large-scale composting facilities. These facilities tend to utilize locally-generated organic feedstocks and distribute finished compost to community members or keep on site, in addition to potential co-benefits of promoting food security and providing local employment. Further if the total amount of feedstock and compost on-site at any one time does not exceed 100 cubic yards and 750 square feet, they can be exempt from permitting requirements [60]. Future research should evaluate the potential of small-scale facilities in advancing the policy goals of SB1383.

The waste generation estimates utilized in this study represent recoverable organic material in MSW. This fraction is not necessarily source-separated nor market-ready at this time. Although no single estimate could be found for the proportion of the population with access to curbside composting collection programs, CalRecycle acknowledges that few jurisdictions across the state have developed the collection infrastructure needed to deliver the quantities of organic materials that will be diverted under SB1383 [10]. Organics recycling program needs vary significantly across the state—food scraps will likely not be easily collected from all homes in different geographies. This work focused on the potentially recoverable food scraps and green waste material in MSW as this is the central push codified in SB1383. Future work may consider investigating existing collection

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[3] This study did not consider fertilizer offset because the focus was on grazed grasslands, which are typically not fertilized.

programs to suggest policies for facilitating organic material collection from residences or comparing MSW to alternative sources of food scraps (such as food processors).

SB 1383 proposed that the state recover 20% of edible food that would have gone to landfills for people to eat by 2025 [9]. The regulations to meet that goal focus primarily on supermarkets and other large food providers, rather than residents, with the surplus going food banks for distribution. Achieving this goal would help prevent food scraps from being produced in the first place and could reduce pressure on the compost industry to increase capacity. Future work could evaluate the impact of source reduction programs on waste generation rates and composting potential.

The results are also limited by a few key data gaps, uncertainties, and limitations. The realization of the C sequestration evaluated here will depend on costs of landfill diversion (tipping fees) and prices for land managers to acquire compost. Although management practices and physical conditions can vary substantially between composting facilities, a single emission factor for processing compost at solid waste facilities was used. Improved monitoring and data availability of composter facilities could also increase representation of the likely heterogeneity in processing emissions and affect the results.

A key limitation of this study is the uncertainty embedded in predicting land use emissions and C sequestration. Although we have tried to incorporate heterogeneity across the landscape through the use of county-level net emissions estimates, the capacity of a soil to sequester carbon may vary by soil minerology, vegetation type and climate [23]. Recent work has elucidated the difference in surface and subsurface soils C storage following compost application [61]. Advances in the field science underlying these estimates will greatly improve our understanding of the technical potential of using compost for C sequestration. Variability in fugitive gas releases from landfills may also impact the results presented here. Recent studies using real-time monitoring of CH_4 releases [62, 63] may improve the estimated effect of avoided landfill emissions on overall environmental impact.

This work focused exclusively on rangelands because of their scale, accessibility, and current management across California. However, compost has potentially significant economic and agroecological importance as a soil amendment for croplands and orchards. The methodology developed here may be used in future studies to explore the environmental and economic impact of compost as an alternative for fertilizer use on these landscapes in the state as well.

4.2. Broader impact

According to the U.N. Food and Agriculture Organization, approximately one-third of the global annual food supply is either lost or wasted, and ultimately, not consumed. In developing nations, food loss is often due to the lack of supply chain infrastructure and adequate storage technologies [64]. As industrialization and urbanization continue to grow across the globe, rates of food waste are expected to rise. At the same time grasslands make up over a quarter of global land surface, but over 50% are degraded with respect to C [65]. Compost made from municipally-generated organic feedstocks, in particular food scraps and green waste, can link organic resources from population centers with food producers in rural communities, offering an opportunity to minimize waste and improve soil health. The application of models such as the one presented here in other regions of the world may assist decision-makers in efforts to sustainably manage organic materials, promote food security and mitigate climate change.

Acknowledgements

Data availability statement

No new data were created or analysed in this study.

Appendix A

A.1. Parameter sources and details

The sequestration factor is derived from the California Department of Food and Agriculture's DNDC model and varies by county. Landfill emissions are from EPA's waste reduction model tool, which contains average emission factors for food scraps and green waste, among others [53]. Transportation emissions are from the

Figure 5. Distance histogram. The panels on the left show the frequency of distance between county of origin and compost facility. The panels on the right display the distance between compost facility and rangeland. The panels on the top include all pairwise distances of the nodes used in the study, while the panels on the bottom show only the nearest distance between county and facility (left), and facility and rangeland (right).

CARB Emission Factor Database. This dataset contains emissions for Solid Waste Collection Vehicles, which are classified as heavy–heavy-duty vehicles, for a range of years and speeds. The transportation fleet is assumed to be made up of 70% diesel and 30% natural gas, based on the relative proportions of vehicle-miles-travelled in 2015 [50]. The emission factor for machinery used to spread compost is from the ECOINVENT database using the value for manure spreaders [51]. All CO_2-equivalents use the GWP values for 100 years time horizon from the IPCC 5th Assessment Report [20].

Costs associated with collection and transporting organic materials from counties to facilities are based on another feasibility analysis performed on compost infrastructure by the Washington DC Department of Public Works [52]. This estimate was proportionally increased to account for higher fuel costs in California and validated by industry experts in the State. The cost of hauling finished compost from facilities to rangelands relies on EPA estimates from waste management reports and consultations with franchise haulers working with the Marin Carbon Project [55]. The cost of spreading compost in California is based on personal conversation with land managers and the Organic Materials Review Institute. The value used is the highest estimate provided, ignoring potential savings from economies of scale, which may reduce costs if the practice was implemented extensively (figure 5).

A.2. Spatial optimization: constraints

As noted in the manuscript, this study builds on previous biomass inventory assessments and compost allocation models by leveraging the geographical and technical constraints of compost processors, which play a key role in the potential to repurpose organic MSW at scale [29, 30]. The results of the economic analysis are intended to assist policy makers compare costs and benefits associated with composting in California with other GHG mitigation strategies in the state (table 3).

In addition to those listed in the main manuscript, our spatial optimization model is subject to the following constraints: intake quantity of each facility (I_j) was calculated as the sum of the proportion of waste material from each contributing county (equation (1)); total compost applied in each rangeland (A_k) was

Table 3. Model variables and units.

Variable	Description	Unit
α	Pareto weighting parameter (between 0 and 100)	%
f_{ij}	Quantity of feedstock from county i to facility j	ton
c_{jk}	Quantity of compost from facility j to rangeland k	ton
D_{ij}	Collection distance between county and facility	km
L_{jk}	Hauling distance between facility to rangeland	km
F_i	Total organic material generated in county i	ton
C_j	Maximum intake capacity of facility j	ton
B_k	Maximum amount of compost that can be land applied to rangeland k	ton
X	Minimum disposal quantity to divert from landfill	%

Alpha	MMT CO2e	Cost (Million USD)	Hectares Treated	Price ($/tCO2e)	Price ($/hectare)
0.000	2.01	655.34	6.82E+06	324.74	96.03
0.071	2.02	655.34	6.82E+06	324.74	96.03
0.143	2.02	655.11	6.82E+06	324.49	95.99
0.214	2.02	655.11	6.82E+06	324.49	95.99
0.250	2.02	654.63	6.82E+06	324.23	95.93
0.286	2.02	648.40	6.80E+06	320.87	95.29
0.357	2.03	623.01	6.72E+06	307.31	92.67
0.429	2.03	612.82	6.68E+06	302.06	91.68
0.500	2.03	516.76	6.27E+06	254.19	82.44
0.571	2.03	502.53	6.20E+06	247.33	81.05
0.643	2.03	499.80	6.18E+06	246.12	80.84
0.714	1.96	400.15	5.89E+06	203.88	67.96
0.750	1.95	384.24	5.85E+06	197.12	65.69
0.786	1.91	351.63	5.75E+06	184.07	61.20
0.857	1.73	260.93	5.21E+06	150.54	50.06
0.929	1.31	160.80	3.56E+06	123.09	45.16

Figure 6. Detailed Pareto results. This table presents a more detailed breakdown of the results presented in figure 2.

likewise calculated as the sum of the proportion of output from each contributing facility (equation (2)).

In order to model realistic system behavior, a number of necessary constraints are imposed on the optimization model based on biomass supply, processing capacity and land availability. In particular, the intake quantity of any given facility (I_j) cannot exceed the maximum capacity of that facility (F_j). Similarly, the amount of compost applied to rangeland (A_k) in any county cannot exceed the suitable area available for soil amendments (B_k).

Over all facilities, f_{ij} must sum to less than or equal to the organic fraction of MSW available for all generating counties, and over all rangelands, c_{jk} and must sum to less than or equal the total capacity of a processing facility (equations (6) and (7)). The quantities of feedstock and compost distributed (f_{ij} and c_{jk}) must be positive (equations (8) and (9)). Further, the output of any facility must be equal to the intake of that facility multiplied by a conversion factor, u, representing the volume loss from waste to finished compost (equation (10))

$$I_j \leqslant F_j \tag{7}$$

$$A_k \leqslant B_k \tag{8}$$

$$\sum_{j=1}^{m} f_{ij} \leqslant F_i \tag{9}$$

$$\sum_{k=1}^{p} c_{jk} \leqslant C_j \tag{10}$$

Figure 7. Collection cost sensitivity flow. Movement of feedstocks (purple) from county centers to compost facilities and of finished compost (blue) from facilities to rangelands (white polygons) across California under model optimization where collection cost is 50% of the BAU parameter. As above, thicker lines indicate more volume. Under this scenario, counties noticeably send organic feedstocks further to compost facilities.
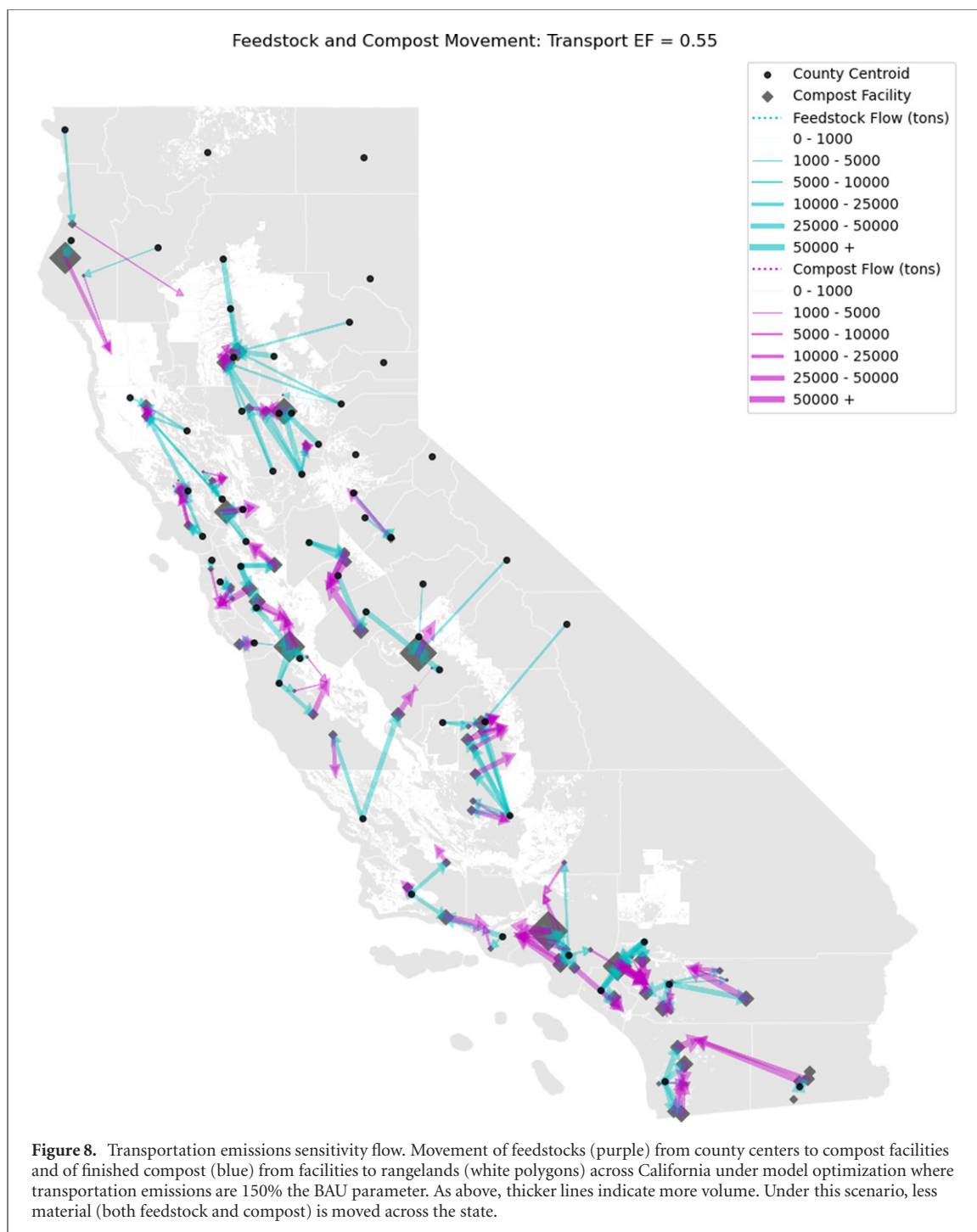
$$0 \leqslant f \tag{11}$$

$$0 \leqslant c \tag{12}$$

$$\sum_{j=1}^{m} f_{ij} \geqslant X_i. \tag{13}$$

Facility capacity and throughput, which are included in the SWIS data set, are necessary constraints in this model. However, the SWIS dataset allows for a variety of units to be reported for these key components. For example, some facilities report capacity in tons per day, while others report in cubic yards per year, with many other permutations in between. Facility reports capacity in terms of weight, it refers to wet weight of incoming material, while volume-based measures refer to finished product [47]. To ensure commensurability across facilities, a function was built to harmonize weight and volume metrics, assuming that mixed organic material loses on average 60% of its volume during the composting process, though differences in feedstock

Figure 8. Transportation emissions sensitivity flow. Movement of feedstocks (purple) from county centers to compost facilities and of finished compost (blue) from facilities to rangelands (white polygons) across California under model optimization where transportation emissions are 150% the BAU parameter. As above, thicker lines indicate more volume. Under this scenario, less material (both feedstock and compost) is moved across the state.
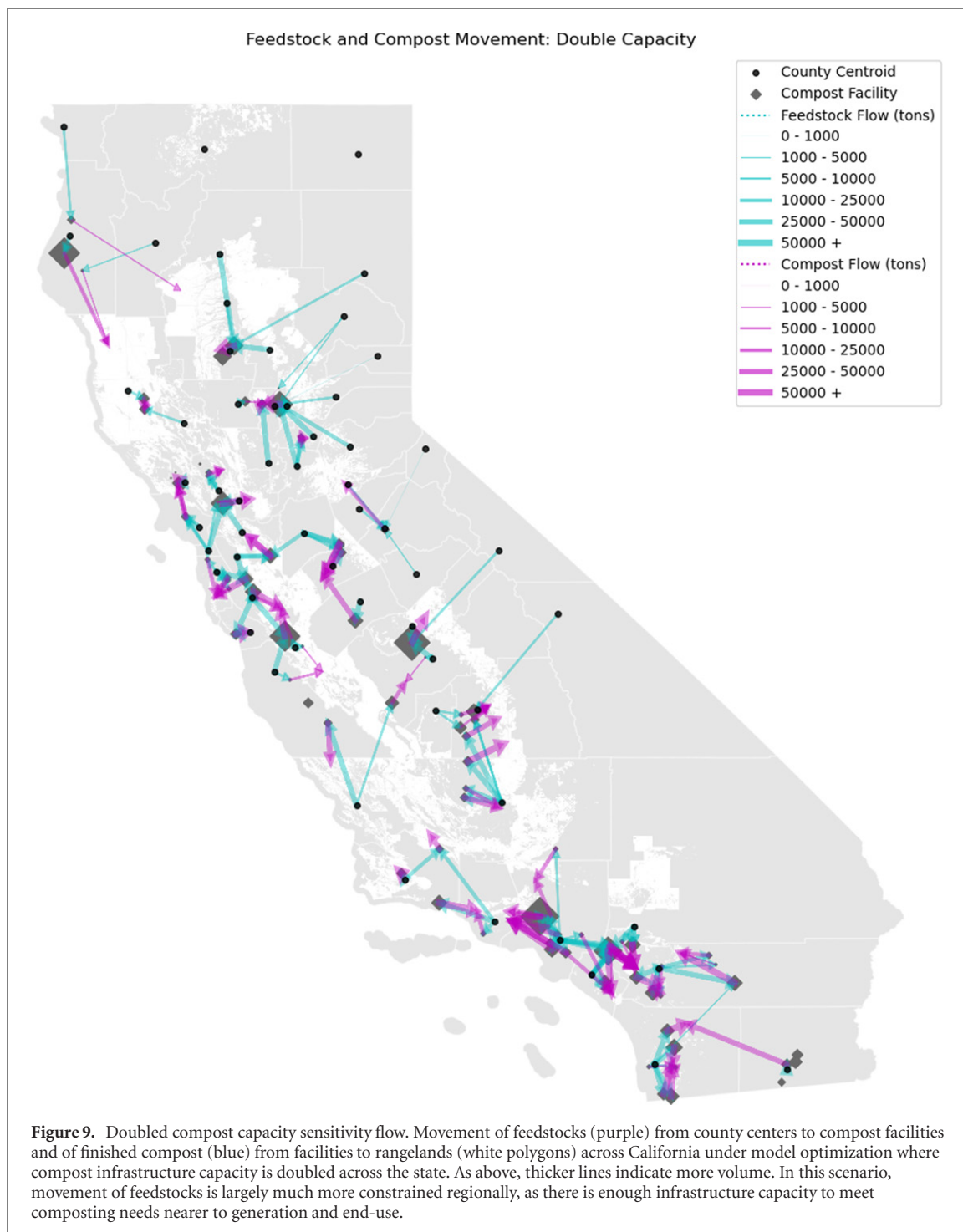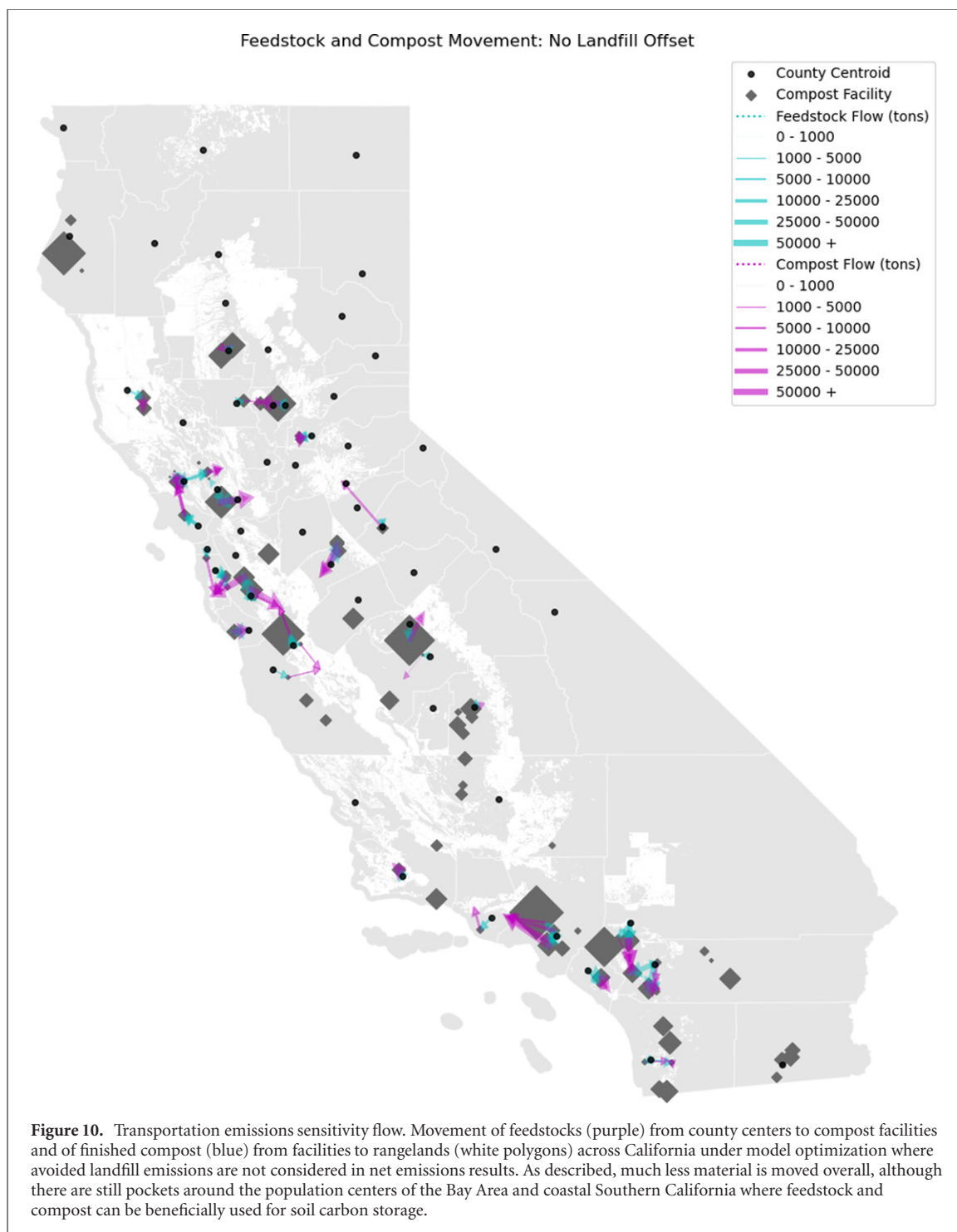
characteristics may vary this volumetric loss with values ranging from 42.1% to 81.5% [48]. Compost density was assumed to be 0.467 tonnes per cubic yard in accordance with CalRecycle conversion standards [66]. The impact of each of these key parameters are evaluated further in the sensitivity analysis.

Capacity and throughput metrics were each normalized to a per-year basis. In a few cases, no time dimension was listed for the capacity value of a facility. In this situation, the analyst's best judgement was used to infer the time-unit based on the reported throughput value and previous reports submitted to CalRecycle. Once clean, facility information was converted into a spatial dataset in Python based on the reported coordinates. A random sample was cross-checked in Google Earth to 'ground-truth' reported acreage and facility location.

A.3. Additional results

Below are additional results from the Pareto optimization and the sensitivity analysis described in the main manuscript (figures 6–10).

Figure 9. Doubled compost capacity sensitivity flow. Movement of feedstocks (purple) from county centers to compost facilities and of finished compost (blue) from facilities to rangelands (white polygons) across California under model optimization where compost infrastructure capacity is doubled across the state. As above, thicker lines indicate more volume. In this scenario, movement of feedstocks is largely much more constrained regionally, as there is enough infrastructure capacity to meet composting needs nearer to generation and end-use.

Figure 10. Transportation emissions sensitivity flow. Movement of feedstocks (purple) from county centers to compost facilities and of finished compost (blue) from facilities to rangelands (white polygons) across California under model optimization where avoided landfill emissions are not considered in net emissions results. As described, much less material is moved overall, although there are still pockets around the population centers of the Bay Area and coastal Southern California where feedstock and compost can be beneficially used for soil carbon storage.

ORCID iDs

A L Hall ⓘ https://orcid.org/0000-0002-6200-2883
M D Potts ⓘ https://orcid.org/0000-0001-7442-3944

References

[1] Thyberg K L, Tonjes D J and Gurevitch J 2015 Quantification of food waste disposal in the United States: a meta-analysis *Environ. Sci. Technol.* **49** 13946–53
[2] Conrad Z 2020 Daily cost of consumer food wasted, inedible, and consumed in the United States, 2001−2016 *Nutr. J.* **19** 1−9
[3] Moreno L C, Tran T and Potts M D 2020 Consider a broccoli stalk: how the concept of edibility influences quantification of household food waste *J. Environ. Manage.* **256** 109977
[4] Buzby J C, Farah-Wells H and Hyman J 2014 *The estimated amount, value, and calories of postharvest food losses at the retail and consumer levels in the United States* United States Department of Agriculture, Economic Research Service p 164262

[5]   Advancing sustainable materials management: 2017 fact sheet https://epa.gov/sites/production/files/2019-11/documents/2017_facts_and_figures_fact_sheet_final.pdf (accessed 20 April 2019).

[6]   Desai M and Camobreco V 2019 *Inventory of US greenhouse gas emissions and sinks: 1990–2017* Environmental Protection Agency Technical Report No. 430-R-19-001 (Environmental Protection Agency)

[7]   Food scraps management https://calrecycle.ca.gov/organics/food (accessed 13 November 2020).

[8]   Organic materials management https://calrecycle.ca.gov/organics (accessed 27 September 2020).

[9]   SB-1383 short-lived climate pollutants: methane emissions: dairy and livestock: organic waste: landfills http://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201520160SB1383 (accessed 14 October 2020).

[10] Cotton Matthew 2019 *SB 1383 infrastructure and market analysis report DRRR-2019-1652* CalRecycle

[11] Reul-Chen C and Abbs A 2018 Composting in California—addressing air quality permitting and regulatory issues for expanding infrastructure California Air Pollution Control Officers Association California Air Resources Board, and CalRecycle Discussion Paper http://californiacompostcoalition.org/wp-content/uploads/2018/11/FINALC1-1.pdf (accessed 13 April 2019).

[12] Levis J W and Barlaz M A 2011 What is the most environmentally beneficial way to treat commercial food waste? *Environ. Sci. Technol.* **45** 7438–44

[13] Morris J, Brown S, Cotton M and Matthews H S 2017 Life-cycle assessment harmonization and soil science ranking results on food-waste management methods *Environ. Sci. Technol.* **51** 5360–7

[14] Lal R 2014 Societal value of soil carbon *J. Soil Water Conserv.* **69** 186A–92A

[15] Hargreaves J, Adl M and Warman P 2008 A review of the use of composted municipal solid waste in agriculture *Agric. Ecosyst. Environ.* **123** 1–14

[16] Lal R 2016 Soil health and carbon management *Food Energy Secur.* **5** 212–22

[17] Diacono M and Montemurro F 2011 Long-term effects of organic amendments on soil fertility *Sustain. Agric.* **2** 761–86

[18] Shiralipour A, McConnell D B and Smith W H 1992 Uses and benefits of MSW compost: a review and an assessment *Biomass Bioenergy* **3** 267–79

[19] Leonard B 2003 *Solid Waste Management and Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks* (DIANE Publishing)

[20] Pachauri R K *et al* Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)* (SwitzerlandGeneva) p 151 https://epic.awi.de/id/eprint/37530/

[21] Lal R 2004 Soil carbon sequestration impacts on global climate change and food security *Science* **304** 1623–7

[22] Smith P *et al* 2008 Greenhouse gas mitigation in agriculture *Phil. Trans. R. Soc.* B **363** 789–813

[23] Lal R 2018 Digging deeper: a holistic perspective of factors affecting soil organic carbon sequestration in agroecosystems *Global Change Biol.* **24** 3285–301

[24] Ryals R, Hartman M D, Parton W J, DeLonge M S and Silver W L 2015 Long-term climate change mitigation potential with organic matter management on grasslands *Ecol. Appl.* **25** 531–45

[25] Buchanan C M and Ippolito J A 2021 Long-term biosolids applications to overgrazed rangelands improve soil health *Agronomy* **11** 1339

[26] Garcia-Gil J, Ceppi S, Velasco M, Polo A and Senesi N 2004 Long-term effects of amendment with municipal solid waste compost on the elemental and acidic functional group composition and pH-buffer capacity of soil humic acids *Geoderma* **121** 135–42

[27] Silver W L, Vergara S E and Mayer A 2018 *Carbon Sequestration and Greenhouse Gas Mitigation Potential of Composting and Soil Amendments on California's Rangelands* (California Natural Resources Agency) p 62

[28] White K E, Brennan E B, Cavigelli M A and Smith R F 2020 Winter cover crops increase readily decomposable soil carbon, but compost drives total soil carbon during eight years of intensive, organic vegetable production in California *PLoS One* **15** e0228677

[29] Harrison B P, Chopra E, Ryals R and Campbell J E 2020 Quantifying the Farmland application of compost to help meet California's organic waste diversion law *Environ. Sci. Technol.* **54** 4545–53

[30] Breunig H.M., Amirebrahimi J., Smith S. and Scown C.D. 2019 Role of digestate and biochar in carbon-negative bioenergy *Environ. Sci. Technol.* **5** 12989–12998

[31] DeLonge M S, Ryals R and Silver W L 2013 A lifecycle model to evaluate carbon sequestration potential and greenhouse gas dynamics of managed grasslands *Ecosystems* **16** 962–79

[32] Petrova S, Martin N, Brown S and Kadyszewski J 2006 *Carbon supply from changes in management of forests, range, and agricultural lands of California: forest fuel reduction. winrock international for the California energy commission, pier energy-related environmental research Technical Report CEC-500-2006-093-AD* California Energy Commission

[33] Messer C 2018 *California Agricultural Statistics Review Agricultural Statistical Overview* California Department of Food and Agriculture

[34] Khalsa S D S and Brown P H 2017 Grower analysis of organic matter amendments in California orchards *J. Environ. Qual.* **46** 649–58

[35] Gravuer K, Gennet S and Throop H L 2019 Organic amendment additions to rangelands: a meta-analysis of multiple ecosystem outcomes *Global Change Biol.* **25** 1152–70

[36] Breunig H M, Jin L, Robinson A and Scown C D 2017 Bioenergy potential from food waste in California *Environ. Sci. Technol.* **51** 1120–8

[37] CA Department of Conservation Solid waste inventory system (swis) facility site/search https://2.calrecycle.ca.gov/SolidWaste/Site/Search (accessed 20 April 2019).

[38] CA Department of Conservation Farmland mapping & monitoring program https://conservation.ca.gov/dlrp/fmmp (accessed 20 April 2019).

[39] California Air Resources Board 2021 Quantification methodology: California department of food and agriculture healthy soils program http://.arb.ca.gov/sites/default/files/auction-proceeds/cdfa_hsp_finalqm_2021may20.pdf

[40] Li C 2017 *Quantification of greenhouse gas emissions for compost application in California croplands* California Air Resources Board

[41] Li C 2000 Modeling trace gas emissions from agricultural ecosystem *Methane Emissions from Major Rice Ecosystems in Asia,* ed R Wassmann, R.S. Lantin and HU. Neue (Berlin: Springer) pp 259–76

[42] Ryals R and Silver W L 2013 Effects of organic matter amendments on net primary productivity and greenhouse gas emissions in annual grasslands *Ecol. Appl.* **23** 46–59

[43] Ryals R, Kaiser M, Torn M S, Berhe A A and Silver W L 2014 Impacts of organic matter amendments on carbon and nitrogen dynamics in grassland soils *Soil Biol. Biochem.* **68** 52–61

[44] Minciardi R, Paolucci M, Robba M and Sacile R 2008 Multi-objective optimization of solid waste flows: environmentally sustainable strategies for municipalities *Waste Manage.* **28** 2202–12

[45] Cui Y, Geng Z, Zhu Q and Han Y 2017 Review: multi-objective optimization methods and application in energy saving *Energy* **125** 681–704

[46] Cotton M 2019 *Personal Communication with Integrated Waste Management*

[47] Edgar N 2019 *Personal Communication with California Compost Coalition*

[48] Breitenbeck G A and Schellinger D 2004 Calculating the reduction in material mass and volume during composting *Compost Sci. Util.* **12** 365–71

[49] Waste reduction model (WARM) https://epa.gov/warm/basic-information-about-waste-reduction-model-warm

[50] O'Connor K 2019 *California Air Resources Board Mobile Source Emission Inventory—EMFAC2017 Web Database* https://arb.ca.gov/emfac/2017/https://arb.ca.gov/emfac/2017/https://arb.ca.gov/emfac/2017/ (Accessed 16 October 2020)

[51] Wernet G, Bauer C, Steubing B, Reinhard J, Moreno-Ruiz E and Weidema B 2016 The ecoinvent database version 3 (part i): overview and methodology *Int. J. Life Cycle Assessment* **21** 1218–30

[52] Frey Jim 2017 *District of Columbia Compost Feasibility Study* District of Columbia Department of Public Works

[53] Office of Solid Waste 2002 *Waste Transfer Stations: A Manual for Decision-MakingEPA530-R-02-002* Environmental Protection Agency

[54] Scolari N 2019 *Personal Communication*

[55] Poncia A 2019 *Personal Communication with Poncia Fertilizers*

[56] Lunny K 2019 *Personal Communication with Lunny Paving and Grading*

[57] Creque J 2019 *Personal Communication with Carbon Cycle Institute*

[58] Jones A and Sherlock M 2020 *The tax credit for carbon sequestration (section 45q)* Congressional Research Service Report

[59] Byrd K B, Flint L E, Alvarez P, Casey C F, Sleeter B M, Soulard C E, Flint A L and Sohl T L 2015 Integrated climate and land use change scenarios for California rangeland ecosystem services: wildlife habitat, soil carbon, and water supply *Landscape Ecol.* **30** 729–50

[60] California Assembly 1994 *California Code of RegulationsTitle 14. §18100–18105.11*

[61] Tautges N E, Chiartas J L, Gaudin A C, O'Geen A T, Herrera I and Scow K M 2019 Deep soil inventories reveal that impacts of cover crops and compost on soil carbon sequestration differ in surface and subsurface soils *Global Change Biol.* **25** 3753–66

[62] Cusworth D H, Duren R M, Thorpe A K, Tseng E, Thompson D, Guha A, Newman S, Foster K T and Miller C E 2020 Using remote sensing to detect, validate, and quantify methane emissions from California solid waste operations *Environ. Res. Lett.* **15** 054012

[63] Duren R M *et al* 2019 California's methane super-emitters *Nature* **575** 180–4

[64] Xue L, Liu G, Parfitt J, Liu X, Van Herpen E, Stenmarck Å, O'Connor C, Östergren K and Cheng S 2017 Missing food, missing data? A critical review of global food losses and food waste data *Environ. Sci. Technol.* **51** 6618–33

[65] Bai Z G, Dent D L, Olsson L and Schaepman M E 2008 Proxy global assessment of land degradation *Soil Use Manage.* **24** 223–34

[66] Cotton Matthew 2010 *Third Assessment of California's Compost- and Mulch-Producing Infrastructure—Management Practices and Market Conditions Contractor's ReportDRRR-2010-007* CalRecycle