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Article

Quantifying the Farmland Application of Compost to Help Meet California’s Organic Waste Diversion Law

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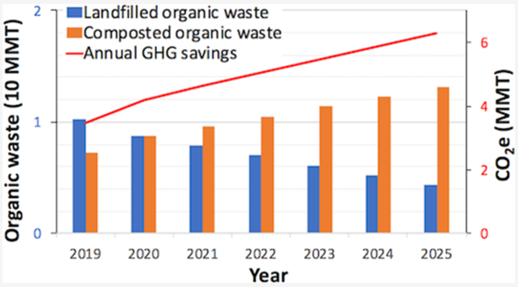
ABSTRACT: California’s landmark waste diversion law, SB 1383, mandates the diversion of 75% of organic waste entering landfills by 2025. Much of this organic waste will likely be composted and applied to farms. However, compost is expensive and energy intensive to transport, which limits the distance that compost can be shipped. Though the diversion of organic waste from landfills in California has the potential to significantly reduce methane emissions, it is unclear if enough farmland exists in close proximity to each city for the distribution of compost. To address this knowledge gap, we develop the Compost Allocation Network (CAN), a geospatial model that simulates the production and transport of waste for all California cities and farms across a range of scenarios for per capita waste production, compost application rate, and composting conversion rate. We applied this model to answer two questions: how much farmland can be applied with municipal compost and what percentage of the diverted organic waste can be used to supplement local farmland. The results suggest that a composting system that recycles nutrients between cities and local farms has the potential to play a major role in helping California meet SB 1383 while reducing state emissions by -6.3 ± 10.1 MMT CO_2e annually.



1. INTRODUCTION

Organic waste, approximately 50% of which is discarded food, accounts for about 41% of the total disposed material in the waste stream.[1] As buried organic waste undergoes anaerobic decomposition in landfills, methane, a greenhouse gas (GHG) with a global warming potential (GWP) 28 times greater than carbon dioxide, is emitted.[2] In California, 20% of methane emissions come from the disposal of organic waste.[3] However, if organic waste is diverted from landfills and composted, aerobic decomposition occurs and methane emissions are greatly reduced.[4]

In an effort to regulate the emission of short-lived climate pollutants such as methane, California Governor Jerry Brown signed into law SB 1383 in September of 2016. This law requires California to reduce organic waste disposal in landfills by 50 percent below 2014 levels by 2020 and 75 percent below 2014 levels by 2025.[5]

Much of the organic waste diverted from landfills as a result of this law will likely be composted, and this may increase the amount of organic waste that must be processed by the state’s composting industry and possibly applied to farmland. Compost contains more water and is less nutrient-dense per unit mass than mineral fertilizers, and this makes compost transportation expensive, which may limit shipping distances.[6] Though it may not be economically viable for growers to purchase compost that is transported over long distances, compost may be cost effective when distributed within local food systems where food is consumed within a few hundred kilometers of where it is produced.[7]

Local food systems offer socioeconomic benefits at the community scale and have the potential to meet much of the nation’s food demand, but some reports suggest that the environmental benefits of local food may be limited.[7−9] Currently, much of the food system relies on long-distance transportation, and so, food produced locally can offer GHG reductions by decreasing the distance that food must be transported.[10] However, transportation is estimated to account for just 11% of the total GHG emissions associated with food.[9] Therefore, even a significant reduction in food miles may have a relatively small impact on emissions compared to the total climate impact of food.

Because compost distribution is likely limited to local farms due to high transportation costs, the sustainability of local food systems can likely be strengthened by implementing nutrient cycling systems. We define nutrient cycling systems as systems that recycle nutrients in organic material by producing compost sourced from municipal organic waste. This compost is applied to farmland where compost nutrients can be taken up by plants. Then, nutrients will eventually be transported back to cities in food where the cycle begins again. This system

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results in a circular economy in which organic waste is converted into a useful product and reincorporated into the market at the end of each cycle.

Since nutrient cycling systems reduce the amount of organic waste that is landfilled, there is a net GHG saving due to the reduction of emissions associated with decomposition at the landfill.[11] In addition, applying compost to farmland has the added climate benefit of sequestering carbon in the soil.[12] While different soils likely respond differently to compost and the feedstock of the compost matters, compost has been widely shown to have multiple agricultural benefits as well. For example, compost can displace traditional mineral fertilizers, which have a fossil fuel-intensive production stage, can contaminate groundwater through the leaching of nitrate, and can increase soil N_2O emissions.[13,14] Additionally, the water-holding capacity of soil may be increased through the application of compost, which can allow farmers to use less water when irrigating their crops—a valuable soil property for California farmers as climate change will likely make the state more vulnerable to drought.[15,16]

While past studies have confirmed the environmental benefits of using compost as a soil amendment and the GHG reductions from diverting organic waste from landfills, the climate, agricultural, and economic impacts associated with the implementation of large-scale nutrient cycling systems between local farms and municipal organic waste remain unclear.[11−17] In particular, we are not aware of studies that demonstrate the feasibility of reusing organic waste streams from urban centers on the local farmland on a regional scale.

To address this knowledge gap, we use a 75% reduction in the landfilling of organic waste mandated by SB 1383 as a framework for a geospatial simulation of a statewide composting system for California. We propose that, for a composting system to play a significant role in managing large quantities of diverted organic waste, there must be enough farmland in close proximity to cities. Otherwise, transportation expenses may prevent the compost from being cost effective for farmers. Therefore, we created the Compost Allocation Network (CAN) model to accomplish the following objectives: (1) Estimate the percentage of each city's municipal compost that can be transported and distributed to farmland existing within an economically feasible distance from each city. (2) Estimate the amount of farmland that can be amended with municipal compost. (3) Investigate the potential role that a statewide composting system could play in mitigating GHG emissions.

2. METHODS AND MATERIALS

Our analysis of the feasibility of a statewide nutrient cycling system in California consisted of three steps. First, we estimated the amount of compost that each city in California can generate if 75% of municipal organic waste is composted. Second, we determined the maximum distance that compost can be transported based on its life-cycle GWP and on economic factors. Third, we created the Compost Allocation Network (CAN) model to determine how much of each city's compost can be distributed to nearby farmland. The CAN script can be found at: https://github.com/Evanj80/OrganicCompostDistribution/blob/master/Distribution.m.

2.1. City Compost Production and Farmland Application Potential.

The potential compost generated if 75% of each city's organic waste is composted was approximated by first estimating the potential organic waste available to each city for composting (O) (eq 1). To determine this, the per capita generation of organic waste (W) was determined by dividing 20.7 MMT of organic waste (the CalRecycle estimate for the total amount of organic waste produced in California in 2014) by 38.6 million people (the population of California in 2014).[1,18] Next, the amount of organic waste produced by each city was calculated from W and from 2014 city population estimates (P).[18] In this analysis, we assume constant values of P and W from 2014 to 2025 as changes in these parameters will likely be small relative to other uncertainties in the model. In addition, organic waste generated from those living in unincorporated communities in California is not considered because these communities represent only 16% of California's population, and it is likely that many of these communities will be exempt from SB 1383 mandates.[5,18]

$$\mathrm{O} = \mathrm{W} \times \mathrm{P} \times 75\% \tag{1}$$

To account for the loss of mass that occurs during the conversion of organic waste to compost, O was scaled by a conversion factor (Cf) of 55%. This value is consistent with estimates of the ratio of the organic waste processed by California composting facilities to the amount of compost generated statewide.[19]

Finally, the farmland application potential (Lp) or the area of the farmland that each city could potentially amend with compost was determined by dividing the potential compost that each city could produce by an application rate (Ap) (eq 2). An Ap of 9 t/ha is the baseline value used in this analysis and is based on the California Department of Food and Agriculture's (CDFA) recommendations for supplementing both annual and tree crops with compost.[20]

$$\mathrm{LP} = \frac{\mathrm{O} \times \mathrm{Cf}}{\mathrm{Ap}} \tag{2}$$

For farmland, we assume that compost is being used as a soil amendment rather than as the main source of plant fertility due to municipal solid waste compost's low nitrogen (N) content (typically 1−2%) and slow mineralization of organic N.[21,22] While compost can be used as a source of fertility, large application rates are needed to meet the N demand of crops.[22] While some farmers opt to invest in using compost as their main source of N, this would likely be expensive, and so, it is unlikely that there would be widescale adoption of high rates of compost application by farmers across the state. At lower application rates, compost can be used to improve soil structure, increase organic matter, and reduce erosion in addition to providing some nutrients and sequestering carbon.[21−24]

2.2. Distance Thresholds.

2.2.1. Emissions Distance Threshold.

A life-cycle assessment (LCA) of compost production was conducted to determine the emission distance threshold, which we define as the maximum distance that compost can be transported from a city compost facility to the farmland while still offering GHG savings. Data for the total GWP of aerobic composting (A_c), which includes transportation, collection, processing, carbon sequestration, fertilizer, and peat displacement, were retrieved from Morris et al. because it is a recent meta-analysis of 28 LCAs of food waste management methods.[15] Morris et al. also provide an estimate for the GWP impact of landfilling organic waste (Wc), and this value was subtracted from the GWP of compost to account for the GHG savings associated with the diversion of organic waste from landfills for composting feedstock. Life-cycle GWP

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Table 1. Parameter Values for Each of the 12 Scenarios Run Through the CAN Model

scenario name	distance (km)	landfill diversion rate (%)	application (t/ha)	per capita organic waste generation (t/person)	organic waste to compost mass conversion factor	explanation for varied parameter
135 km baseline	135	75	9.0	0.54	0.55	economic distance threshold
90 km baseline	90	75	9.0	0.54	0.55	33% shorter economic distance threshold
45 km baseline	45	75	9.0	0.54	0.55	66% shorter economic distance threshold
AppMax	135	75	22.4	0.54	0.55	maximum application rate recommended by CDFA (2016)
AppMin	135	75	4.5	0.54	0.55	minimum application rate recommended by CDFA (2016)
ConvMax	135	75	9.0	0.54	0.7	estimated upper bound for compost conversion
ConvMin	135	75	9.0	0.54	0.15	estimated minimum conversion factor (MB)
DivMax	135	100	9.0	0.54	0.55	diversion rate if all organic waste is diverted
DivMin	135	50	9.0	0.54	0.55	diversion rate if half of organic waste is diverted
WasteMax	135	75	9.0	0.73	0.55	35% increase in organic waste production
WasteMin	135	75	9.0	0.36	0.55	50% decrease in organic waste production

for the production and the use of the mineral fertilizer (Yf) was retrieved from industry values.[25] The GWP associated with the life cycle of compost and of the mineral fertilizer was calculated with respect to the amount needed annually to supplement one acre of farmland to account for the difference in application rates between compost (9 t/ha) and the mineral fertilizer (1.4 t/ha).[11,20]

To vary the transportation distance, we subtract the GWP associated with the transportation stage of the compost life cycle (Xc) from Ac as Xc assumes a fixed distance. We then make the total life-cycle GWP for both compost and the mineral fertilizer a function of distance from the production facility to farm (d) by adding the GWP per mile associated with the transportation of compost (Tc) and of the mineral fertilizer (Tf) multiplied by d. Both compost and the mineral fertilizer were assumed to be transported by large diesel trucks with a 24 ton capacity. Because compost is typically applied at greater rates than mineral fertilizer, more trucks are needed to supplement a given area with compost than with mineral fertilizer, and this results in Tc being greater than Tf. Therefore, while the GWP of mineral fertilizers is greater for short distances, net compost emissions approach net fertilizer emissions as the transportation distance from compost facility to farm increases until net emissions become equivalent at the emission distance threshold.

The emission distance threshold was determined by setting the net GWP of compost equal to the net GWP of the mineral fertilizer and solving for d (eq 3).

$$\mathrm{Ac} - \mathrm{Wc} - \mathrm{Xc} + (\mathrm{Tc} \times d) = \mathrm{Yf} + (\mathrm{Tf} \times d) \qquad (3)$$

2.2.2. Economic Distance Threshold. In our model, we assume that municipalities are responsible for the costs associated with building a compost facility, hauling organic waste to the facility, and producing compost. However, the compost produced by cities is sold to farmers at rates similar to private compost companies. The cost of transportation represents a significant portion of the total price that farmers pay for compost and increases with distance. Thus, there exists an economic distance threshold in which compost is no longer cost effective for farmers. We assume that the total price of a metric ton of compost, N, is composed of the cost per mile to transport compost, S, the price per metric ton of compost C, and the price per metric ton to apply compost B (eq 4).

$$N = (S \times d) + C + B \qquad (4)$$

We chose three California composting companies to interview, one each in southern, central, and northern California, to collect compost rates from geographically diverse areas. Interviewees were asked for their price per ton of compost, their compost transportation rates, average and maximum distances they ship compost, and the maximum net price farmers are likely to pay for a ton of shipped and applied compost. Data from the interviews were averaged to estimate values of S and C as well as typical transportation distances, d, while application costs were retrieved from the literature.[26]

2.3. Compost Allocation Network (CAN) Model.

2.3.1. Spatial Analysis. Spatial data for California farmland were retrieved from the California Department of Conservation Farmland Mapping and Monitoring Program's statewide 2014 dataset.[27] The categories from this data included in our analysis are prime farmland, farmland of statewide importance, unique farmland, farmland of local importance, and grazing land. The urban and built-up land and other land categories are not included. We included the grazing land in addition to the cropland because of the ecological, economic, and climate benefits of applying compost to these lands.[23,28] Spatial data for California incorporated city boundaries were obtained from CalFire's Fire and Resource Assessment Program's GIS dataset for incorporated cities.[29] We assume that each city's compost facility is located in the city center. While this is unlikely, this minimizes the error associated with choosing an arbitrary location for each city's facility.

In ArcMap, a table of city names and their corresponding farmland application potential (Lp) values was joined to the spatial data for cities. The Generate Near Table tool was then used to create a nearest neighbor table that, for each city, ranks all of the farms located within a city's distance threshold in order of proximity. In addition to the proximity rank, the

Table 2. CAN Model Results for 12 Scenarios

scenario name	farmland supplemented compost (ha)	farmland supplemented compost (%)	compost allocated (t)	compost allocated (%)	GHG reduction (MMT CO_2e)
135 km baseline	8.05×10^5	6.42	7.22×10^6	100.0	−6.3 ± 10.1
90 km baseline	8.05×10^5	6.42	7.21×10^6	99.9	−6.3 ± 10.1
45 km baseline	6.64×10^5	5.29	5.95×10^6	82.4	−5.2 ± 8.3
AppMax	3.22×10^5	2.57	7.22×10^6	100.0	−6.3 ± 10.1
AppMin	1.61×10^6	12.83	7.22×10^6	100.0	−6.3 ± 10.1
ConvMax	1.02×10^6	8.16	9.16×10^6	100.0	−8.0 ± 12.8
ConvMin	2.20×10^5	1.75	1.97×10^6	100.0	−1.7 ± 2.8
DivMax	1.07×10^6	8.54	9.62×10^6	100.0	−8.4 ± 13.5
DivMin	5.38×10^5	4.29	4.81×10^6	100.0	−4.2 ± 6.7
WasteMax	1.07×10^6	8.54	9.62×10^6	100.0	−8.4 ± 13.5
WasteMin	5.38×10^5	4.29	4.81×10^6	100.0	−4.2 ± 6.7

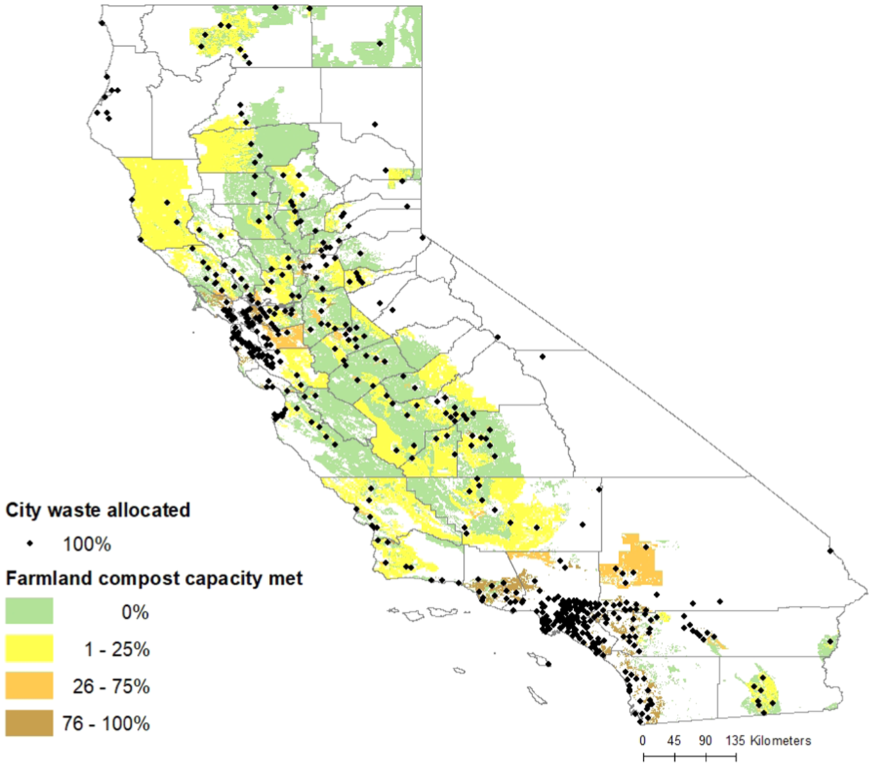

Figure 1. Percent of each city's diverted organic waste allocated to the farmland as compost and percent of each farmland's capacity for compost application (assuming recommended application rates) met under the 135 km baseline scenario. 7.22 MMT of compost or 100% of the diverted organic waste is distributed to the farmland in this scenario. Cities are mapped as the centroid of each city polygon..

nearest neighbor table includes the area of each farm and each city's Lp value.

2.3.2. CAN Model. The nearest neighbor table was then run through the CAN model to find La, the actual amount of farmland that each city is able to supplement with compost. The model begins by considering the first city listed in the nearest neighbor table. The nearest farm to this city is allocated compost. If the nearest farm no longer has available land for compost application, then the next nearest farm is considered until all of the city's Lp is allocated or until there are no longer any available farms within the city's maximum hauling radius. In the case of either of these scenarios, the model then considers the next city in the nearest neighbor table, and the process continues until all cities have been considered. After the model runs through all of the cities, a result table is produced, which reports La values for each city.

2.3.3. Sensitivity Analysis. We define Lp as a function of the compost application rate, organic waste to compost conversion factor, hauling radius from each city, organic waste diversion rate, and per capita organic waste generation. To account for variation in these parameters, a sensitivity analysis was performed by assigning minimum and maximum values for each input. In addition to the baseline scenario, 10 unique scenarios were produced and run through the CAN model (Table 1). The 90 km baseline and 45 km baseline scenarios were used to investigate the potential of cities to use shorter transportation distances for compost distribution while other scenarios vary inputs influencing compost production and application.

3. RESULTS

3.1. Distance Thresholds. From our compost LCA, we found that the maximum distance that compost can be

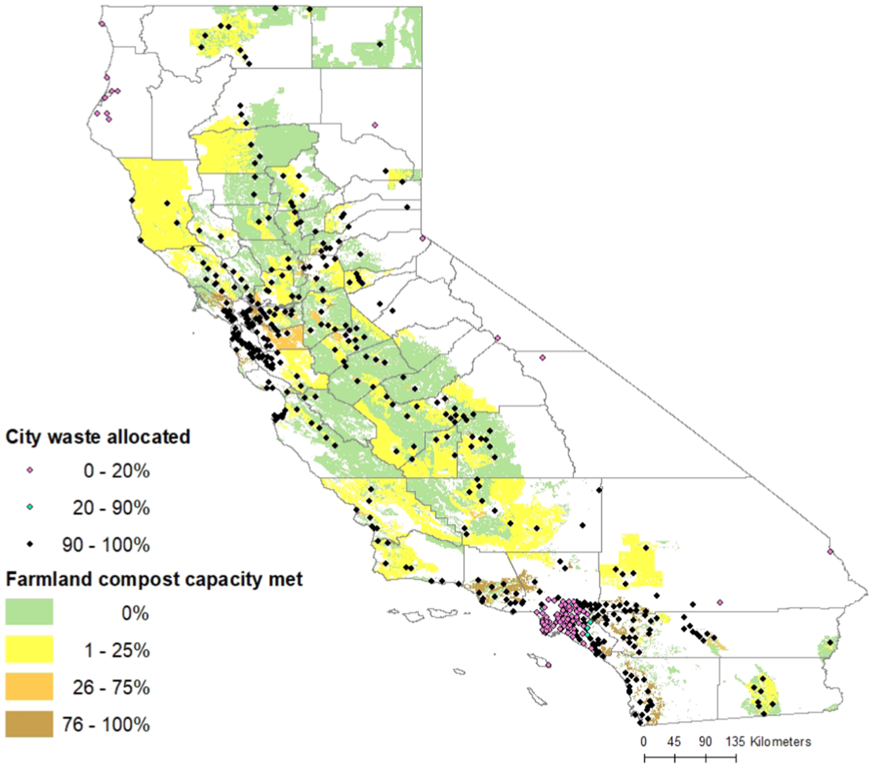

Figure 2. Percent of each city's diverted organic waste allocated to the farmland as compost and percent of each farmland's capacity for compost application (assuming recommended application rates) met under the 45 km baseline scenario. 5.95 MMT of compost or 82.4% of the diverted organic waste is distributed to the farmland in this scenario. Cities are mapped as the centroid of each city polygon..

transported while retaining emission savings relative to the mineral fertilizer to be very large at approximately 11 000 km. This is because the compost life cycle has large GHG savings from the diversion of organic waste from landfills, carbon sequestration, and peat and fertilizer displacement.[15] Furthermore, the GWP of compost was found to be negative for distances up to 8300 km. When assuming a high rate of methane capture at landfills, compost could be transported up to 7400 km without having a GWP greater than the mineral fertilizer.[30]

From interviews conducted with compost providers, it was estimated that farmers pay approximately \$32 per metric ton of compost and \$1.57 per kilometer to ship compost. Interviewees also suggested that farmers will generally spend no more than \$275 per metric ton of shipped compost. Additionally, compost costs approximately \$31 per metric ton to apply through mechanical spreading.[26] Therefore, we estimate that compost can be shipped no more than 135 km or it may no longer be cost effective for farmers.

3.2. Compost Allocation. For every scenario that allowed compost to be transported a maximum of 135 km, model results show that 100% of the municipal compost could be distributed to farms with annual GHG reductions ranging from −1.7 to −8.4 MMT CO_2e depending on the amount of compost produced in each scenario (Table 2, Figure 1). In the 90 km baseline scenario, there was sufficient farmland existing within 90 km of each city for 99.9% of compost to be distributed, and the expected GHG reduction was −6.3 ± 10.1 MMT CO_2e (Figure S1). Under the 45 km baseline scenario, 82.4% of municipal compost could be applied to the farmland, and GHG savings were reduced to −5.2 ± 8.3 MMT CO_2e because not all compost could be used (Figure 2). In this scenario, 83 of the 98 cities unable to allocate all of their compost to farmland were located in either Los Angeles or Orange county.

Compost production ranged from 1.97 MMT in the ConvMin scenario to 9.62 MMT in the WasteMax scenario, but the CAN model showed that all compost was able to be distributed to the farmland within 135 km of a city even at maximum waste production (Table 2). When dividing California into its Mountain, Central Valley, Bay Area, Southern California, and Coastal regions, compost production ranged by several orders of magnitude. Under the baseline scenario, the sparsely populated Mountain region of the state only produced 2.43×10^4 metric tons of compost, while Southern California produced 4.35×10^6 metric tons of compost (Table 3).

3.3. Farmland Supplemented with Compost. In the 135 km threshold under baseline conditions, our model predicts that 8.05×10^5 ha, or 6.42%, of California's approximately 12.5 million hectares of farmland can be applied compost annually at a rate of 9 t/ha (Figure 1). The 90 km baseline scenario showed similar results for the area of farmland amended; however, the 45 km baseline scenario showed a slight reduction as 6.64×10^5 ha or 5.29% of farmland was applied compost. The scenario with the least amount of farmland applied compost was the ConvMin scenario with 2.20×10^5 ha or 1.75% of farmland amended. The scenario that showed the greatest farmland application was the AppMin scenario, in which just 4.5 metric tons of compost are applied per hectare, with 1.61×10^6 ha or 12.83% of farmland supplemented with compost (Table 2).

Our regionalized results for the 135 km baseline scenario show that, for the most part, nearly all of the compost that was

Table 3. Regionalized 135 km Baseline Model Results

	mountain	coastal	central valley	bay area	southern
counties	Trinity, Siskiyou, Modoc, Lassen, Plumas, Sierra, Nevada, El Dorado, Amador, Calaveras, Alpine, Tuolumne, Mariposa, Mono, Inyo	Santa Barbara, San Luis Obispo, Monterey, San Benito, Santa Cruz, Mendocino, Lake, Humboldt, Del Norte	Kern, Tulare, Kings, Fresno, Madera, Merced, Stanislaus, San Joaquin, Sacramento, Yolo, Placer, Yuba, Sutter, Colusa, Glenn, Butte, Tehama, Shasta	Marin, Sonoma, Napa, Solano, Contra Costa, Alameda, Santa Clara, San Francisco, San Mateo	San Bernardino, Riverside, Imperial, San Diego, Orange, Los Angeles, Ventura
compost produced in region (t)	2.43×10^4	2.42×10^5	1.07×10^6	1.52×10^6	4.35×10^6
farmland applied w/compost in region (ha)	1.98×10^3	2.72×10^4	1.20×10^5	1.70×10^5	4.85×10^5
primary potential compost benefits	carbon sequestration, enhanced water-holding capacity	nutrient addition, enhanced water-holding capacity	nutrient addition, enhanced water-holding capacity	carbon sequestration	enhanced water-holding capacity, carbon sequestration

produced in a region was applied to farmland in that same region (Table 3). Only the Mountain region produced more compost than it applied to its farmland. Southern California's farmland received the most compost out of the five regions with 4.85×10^5 ha applied with compost followed by the Bay Area with 1.70×10^5 ha and the Central Valley with 1.20×10^5 ha. The Coastal and Mountain regions applied significantly less farmland with compost at 2.72×10^4 and 1.98×10^3 ha, respectively. Primary potential compost benefits are also presented in Table 3 and are based on climate and land use characteristics of each region. For example, Southern California is expected to experience a greater reduction in precipitation due to climate change so the enhanced water-holding capacity of soil will be especially important for this region while the Central Valley's great agricultural industry will benefit from nutrient addition.[16]

4. DISCUSSION

4.1. Model Results in the Context of SB 1383. We estimate that California will need to process an additional 13 MMT of the diverted organic material annually to meet SB 1383s 75% diversion mandate. However, the state's composting industry has the capacity to process just 5.4 MMT of organic material per year.[19] While our study predicts that the state will not face significant compost distribution issues, California will need to substantially expand its organics infrastructure to process the additional diverted organic waste. The CAN model can be used as a tool to advise policymakers and local governments in determining the most suitable sites for new compost facilities in terms of their proximity to cities and farms; however, to locate the best sites for these facilities, additional research is needed that also considers the potential adverse impacts, such as air pollution from NH_3 and volatile organic compounds (VOC) produced during composting, that compost operations might have on surrounding communities.[11]

Additionally, our results indicate that compost can be distributed to farmland in all of the major regions of the state, and so, compost application can offer agricultural and environmental benefits to geographically and socioeconomically diverse areas across California. While our model predicts the most economically optimal farms (in terms of minimal transportation expenses) to apply municipal compost too, many of the farms chosen for compost allocation will not need to be applied compost the following year due to the multiyear soil health benefits of using compost as a soil amendment.[21−24] While the annual application of compost at high rates would be required if compost were to be used as the primary source of fertility, we assume that compost is used as a soil amendment and does not need to be applied annually because of its lasting beneficial effects. For example, Ryals and Silver found that a one-time application of compost to grazing lands led to a multiyear increase in NPP and soil moisture.[23] García-Gil et al.[24] also found that a single application of compost at low application rates resulted in lasting improvements of soil chemical properties, such as increased buffering capacity, 9 years after application. Additionally, Eghball et al. observed greater phosphorus, pH, NO_3^-, and electrical conductivity in soils applied with compost 4 years after the last application.[31]

Therefore, assuming that compost is not applied annually to farms, we can estimate the number of years it would take to apply compost to all 12.5 million hectares of farmland in California. We assume that all of the compost generated annually can be applied to farmland each year since all farmland exists in the economic distance threshold of 135 km from a city. We also assume that the diverted organic waste generated increases by 2% each year, similar to California's increase in disposed waste from 2012 to 2017 but scaled down to account for SB 1383s 20% food waste recovery program.[5,32] Based on these assumptions, we estimate that it would take 14 years to apply compost to all of California's farmland at recommended application rates.

A large-scale composting system in California could thus offer a unique opportunity to help restore the state's degraded agricultural soils. Increasing soil organic carbon (SOC) can be achieved through the application of organic matter amendments such as compost because while some of the applied organic carbon will be decomposed and return to the atmosphere as CO_2, a portion of the applied carbon can be protected from decomposition and, therefore, be sequestered in the soil for long periods of time.[33] However, the capacity of a soil to sequester carbon may vary with factors such as clay content, mineralogy, climate, and vegetation.[33]

While not included in our analysis, compost can also be applied to urban green spaces such as parks and gardens to reduce erosion, restore degraded soil, and increase productivity.[34] To estimate the amount of urban green spaces available for compost application in California, we used data from a report by The Trust for Public Land (2016) to get estimates of the percent of green space for 16 California cities.[35] From this sample, we found that the average percent of green space in a city was 13%, which is consistent with Wen et al.'s estimate of 10.5% for U.S. cities.[36] Assuming that 25−75% of this land is suitable for compost application and assuming similar application rates, we estimate that 6.3×10^5−1.9×10^6 metric tons of compost or 8−26% of the diverted organic waste could be applied to urban lands.

4.2. Potential for Increased Distance Thresholds. Our LCA suggests that the distance that compost can be shipped is not limited by transportation emissions as our emission distance threshold was 11 000 km and the length of California is approximately 1300 km.[27] Instead, we find compost transportation to be limited by cost. While our economic distance threshold is consistent with the maximum distance that the interviewed compost companies typically ship, it is possible that in some cases, compost may be shipped further. For example, larger, more profitable farms may be able to afford to ship compost longer distances. The economic distance threshold may also be expanded if financial incentives are offered to those that apply compost to their land as this would subsidize the net cost of compost. The California Department of Food and Agriculture's Healthy Soils Program is an existing example of such a program, and in 2018, it awarded over 7.6 million dollars to farms and demonstration projects involving compost production or application in California.[37] Our model predicts that it is economically feasible for unsubsidized municipal compost to be distributed throughout California because there is enough farmland existing in close proximity to cities. However, subsidies may be necessary for other states and regions with less farmland close to cities. We use the city of Arcata under the 90 km baseline scenario as an example of what it might take in subsidies to make compost cost effective in regions lacking enough farmland. There was not sufficient farmland within 90 km of Arcata for it to distribute all of its compost; however, if subsidies offsetting $31.50 per metric ton of compost were acquired, Arcata could ship its compost 20 km further, which would allow it to distribute all of its compost to farmland.

4.3. Opportunities to Reduce Uncertainties. While we assume that all of California's farmland is available for compost application, this is unlikely to be the case. For example, compost application may not be possible on farmland with steep slopes. It is also possible that farmers may be unwilling to invest in compost application. An analysis of suitable farms for compost application in terms of accessibility would improve estimates of statewide compost distribution.

The annual amount of organic waste generated in California assumed to be constant in our analysis, may also change over time. From 2012 to 2017, California experienced a 20% increase in the amount of disposed waste driven primarily by a growing population and economy.[32] An increasing amount of waste in the waste stream could result in more compost generated annually than predicted by our study as California moves toward its waste diversion goals, and this may make compost allocation to local farms more challenging.

It is also possible for per capita organic waste disposal to decrease as curbside organic waste services are implemented by cities to meet SB 1383. For example, residents, who would be tasked with separating their household organic waste, may become more cognizant of their disposal rates and seek to reduce their waste. SB 1383 also requires that 20% of edible food that would otherwise be landfilled be recovered and used to feed the hungry.[5] Achieving this goal could further decrease the amount of organic waste that would have to be processed by composting facilities and distributed to farms.

Uncertainties also exist regarding the total amount of GHG reduction that a statewide composting system could result in California. Our estimate of an annual -6.3 ± 10.1 MMT CO_2e reduction considers the emissions from the collection, transport, and processing of compost while subtracting GHG savings associated with carbon storage, fertilizer displacement, peat displacement, and avoided landfill emissions.[15] This estimate is based on an average savings of -0.48 ± 0.77 kg CO_2e per kg of diverted organic waste composted from Morris et al.'s harmonized meta-analysis of food waste LCA studies.[15] This saving was averaged from values ranging from −1.37 to 0.17 kg CO_2e per kg of organic waste composted.[15] The GWP associated with composting diverted organic waste could vary with composting conditions, methane capture at the landfill, and carbon sequestration potential.[15] Due to regional differences in these factors, the GWP of composting in California may be different from other locations, and it will also likely vary within the state. In addition, N_2O emissions may decrease following compost application compared to soil fertilized only with the inorganic fertilizer due to increased SOC and reduced N from the inorganic fertilizer.[38] On the other hand, GHG savings from carbon sequestration may decrease over time in soils that become saturated with carbon with repeated organic matter application from compost.[39,40] While we present an initial estimate of GHG savings from SB 1383 in this study, further investigation of the climate benefits of this policy is needed that accounts for California specific conditions and regional variation within the state.

4.4. Global Implications of the CAN Model. Due to methane's large GWP, governments can make significant strides toward meeting their climate goals by implementing policy, like California's SB 1383, that targets landfill methane emissions through the diversion of organic waste.[2] Other climate change mitigation goals, such as France's initiative to increase global SOC stocks by 0.4%, can benefit from strategic regional management and application of organic waste streams as this can lead to widespread carbon sequestration.[41] Unlike California, regions with limited farmland in close proximity to cities may have less success in implementing this strategy. The CAN model can play a key role in helping governments quantify the potential of large-scale nutrient cycling systems by predicting the amount of compost that can be allocated to farmland, the area of farmland that can be supplied compost, and the amount of GHG reductions associated with the system. Policymakers can also use the CAN model to predict which farmers may be the most willing to apply compost to their land because the model minimizes the hauling distance from cities to farms, and so, compost can be provided to the farmer at a lower cost. The model can also be expanded to include urban green spaces for compost application and alternative management strategies such as anaerobic digestion to determine the potential of systems that offer multiple management pathways.[33,34]

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.9b05377.

> Maps of CAN model results for other scenarios and multiyear allocation model; City's diverted organic waste allocated to the farmland as compost and percent of each farmland's capacity for compost application met under the 90 km baseline scenario, AppMax scenario, ConvMax scenario, ConvMin scenario (PDF)

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Notes

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