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Estimating emissions from household organic waste collection and transportation: The case of Sydney and surrounding areas, Australia

Ben Madden*, Nick Florin, Steve Mohr, Damien Giurco

Institute for Sustainable Futures, University of Technology Sydney, Ultimo, NSW, Australia

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ABSTRACT

Australian waste related emissions are poorly characterised in National Greenhouse Accounts, with only landfill emissions directly attributed. Direct and indirect emissions however occur at all points along the waste management chain resulting from the consumption of energy and fuel during collection, transportation, and waste recovery activities. Without knowledge of waste-related emissions, it is difficult to evaluate the potential of different management pathways for achieving resource recovery and emission reduction objectives. Previous studies tend to utilise life cycle assessment (LCA) in examining waste transport emissions. Some studies have developed country-specific emissions factors for waste transportation based on LCA, however such factors have high variability owing to these models being dependent on widely varying local conditions. The aim of this study is to estimate emissions associated with kerbside organic waste collection from households and transportation in the Greater Sydney area in 2018–19. High-resolution road network and property-lot waste generation data was utilised in a GIS integrated route optimisation model. Our model considered transport of collection vehicles 'to' and 'from' transfer stations and kerbside collection areas across the 43 council areas, as well as transport of waste collected to reprocessing and landfill facilities. Greenhouse gas emissions for organic waste transport and collection were estimated at approximately 43,700 t CO_2-e, equal to approximately 2% of all road transport emissions in the study area. Kerbside collection was the largest contributor to overall transport emissions, accounting for approximately 89%. Average emissions intensity on a tonnes diverted from landfill basis was lowest for councils separating food waste out of the mixed waste stream at 45 kg CO_2-e/tonne, owing to the greater quantities of waste diverted via food collection and mixed waste recovery pathways. Average emissions intensity across all councils was 96 kg CO_2-e/tonne. Findings indicate that improved efficiency of bin-lift mechanisms, including increasing the intensity of bin-lifts per stop, as well as collection vehicle fuel efficiency and electrification, would have the greatest impact on reducing tra and collection emissions.

1. Introduction

Recent policy advancements in Australia have created an opportunity to align waste management and greenhouse gas (GHG) emission reduction objectives. Such policies include waste recovery targets (NSW EPA, 2014, 2020); a national target to halve food waste (Department of Agriculture, Water and the Environment, 2021); a circular economy decision making framework (NSW Government, 2019); and commitment to net-zero by 2050 (NSW Government, 2020). However, the contribution of waste management to overall emissions is poorly characterised in Australian greenhouse gas inventories, with only landfill emissions directly attributed (Department of Industry, Science, Energy and Resources, 2021a). Still, direct and indirect emissions occur at all points along the waste management chain, resulting from the consumption of energy and fuel during collection, transportation, and waste recovery. Without detailed understanding of these waste related emissions, it is difficult to evaluate the potential of waste management pathways for achieving resource recovery and emission reduction objectives.

Given the large transport distances between cities and regional centres in Australia, and also given the sprawling nature of Australian cities, emissions from road transport can be significant, contributing approximately 19% to overall national GHG emissions in 2020 (Department of Industry, Science, Energy and Resources, 2021a). The proportion of this owing to the collection and transportation of kerbside waste is however unknown. Studies in the literature tend to utilise life cycle assessment (LCA) for examining waste transport emissions. For example, the Organic Waste Research model—*ORWARE* (Sonesson,

* Corresponding author.
E-mail address: Benjamin.madden@uts.edu.au (B Madden).

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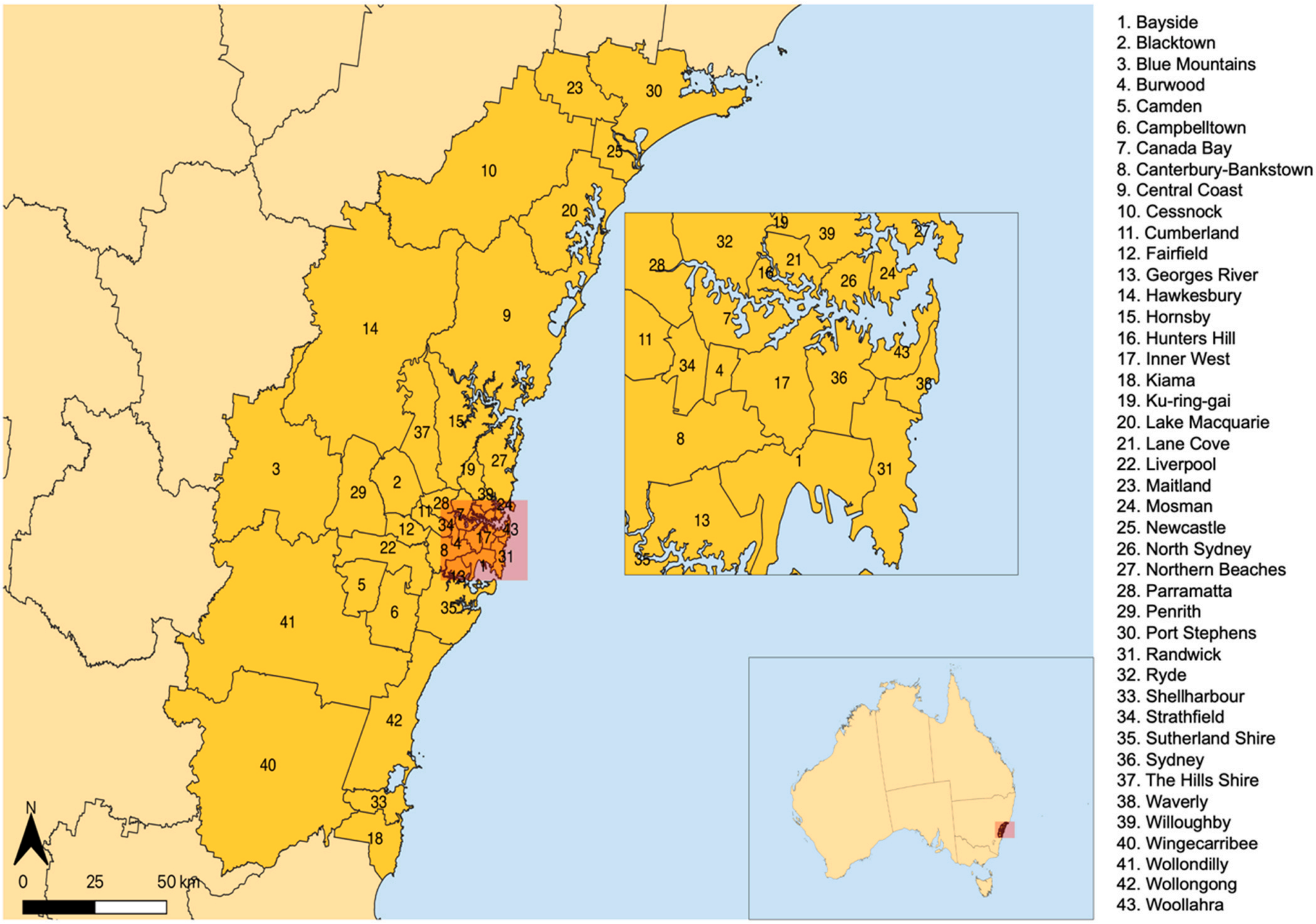

Fig. 1. Local government areas within the Greater Sydney Area in the Australian state of New South Wales.

2000) is a life cycle-based model for estimating the fuel requirements associated with organic waste collection, intended to be applicable to different jurisdictions and waste management systems. *ORWARE* considers the energy consumption of collection vehicles during haulage and travel between bins, however it utilises default parameters relevant to Swedish municipalities for which the model was originally developed, limiting its applicability to other jurisdictions, despite it being a commonly used model (Edwards et al., 2016). Other more recent studies have developed region-specific emissions intensity factors for kerbside waste collection based on LCA, including for Taipei City, Taiwan (Chen and Lin, 2008); Aarhus, Denmark (Larsen et al., 2009); Ontario, Canada (Nguyen and Wilson, 2010); and South Africa (Friedrich and Trois, 2013). Such factors however have high variability owing to these models being dependent on widely varying local conditions, with emissions factors between 3 and 40 kg CO_2-e per tonne of waste reported in the literature (Friedrich and Trois, 2013). Moreover, variability in emissions intensity can also occur within a region, with emissions from waste collection typically being greater in areas with low household density (Friedrich and Trois, 2013). This point is particularly relevant for Australian locales, given high levels of suburban sprawl and variation in household densities across cities. This makes applying emission intensity factors to estimate emissions from waste collection for a generic region, such as Australia, difficult.

A recent study by Edwards et al. (2016) sought to overcome the aforementioned limitations to estimate fuel requirements for separate organic waste collection for 19 local government areas across Australia. Waste collection vehicle activities in Edwards et al. (2016) were based on *ORWARE* to include travel to and from waste truck depots, and kerbside collection. They extended the modelling approach by also including energy consumption during the hydraulic lifting of bins during collection. Their model incorporated local spatial data in a geographical information system (GIS) to estimate location-specific parameters, for example, distance between stops. Despite these improvements, the model in Edwards et al. (2016) is still limited in that it did not consider transport along existing road networks, instead relying on straight-line Euclidean distances, and it applied simple local averages for distances between bins.

The aim of this study is to estimate emissions associated with the collection and transportation of household organic waste in the Greater Sydney and surrounding areas in New South Wales, Australia, for the 2018–19 financial year. A spatial model was developed utilising high spatial resolution waste generation and road network data to estimate the emissions associated with kerbside collection in addition to transportation to-and-from waste transfer stations, and to points of waste recovery and disposal. The focus of this study is kerbside organic waste derived from households, which made up approximately 46% of all kerbside waste collected in New South Wales in 2018–19 (NSW EPA, 2020b). Organic waste is collected via three different pathways across the study area: separate garden organic waste collection (GO) and separate food and garden organic waste collection (FOGO), both destined for organics recovery via composting; and mixed waste, typically destined for landfill, or for recovery at alternate waste treatment (AWT) facilities (i.e., mechanical biological treatment). There is a current preference for local government areas in NSW to move towards FOGO collection to manage household organic waste. Therefore, this study also aimed to compare the transport emissions intensity associated with each collection pathway, to identify the lowest-carbon collection system for household organic waste diversion.

The main contribution of this paper is in generating accurate and up-to-date emissions data and intensity factors for kerbside organic waste collection, useful in LCA comparative analyses of different waste collection systems. Findings can further inform decision making towards sustainable and low-carbon waste management, such as in comparing the emissions intensity of different recovery pathways with consideration to transportation, as well as in identifying facility locations minimising transportation (e.g., Karadimas et al., 2007; Comber et al., 2015); and informing technology selection such as fossil fuel alternatives for collection vehicles (e.g., Pastorello et al., 2011). The model developed has simple data requirements, making it readily applicable to other jurisdictions where spatial data on road networks and property lot boundaries are available.

2. Study area and scope of analysis

Fig. 1 shows the study area for this analysis. The study area included 43 local government areas (LGAs) across the Sydney Metropolitan Area, Greater Western Sydney, Central Coast & Hunter, and the Illawarra & Shoalhaven regions, which represent the major population centres of NSW. These regions have a combined population of approximately 6.3 million, and approximately 2.3 million households (Australian Bureau of Statistics, 2021). As such, the combined region is a significant source of household waste, generating approximately 2.2 million tonnes of waste across the dry recyclable, organics, and non-recyclable municipal waste fractions in 2018–19 (NSW EPA, 2020b).

Table 1 summarises LGA organic waste collection pathways employed across LGAs in the study area and included within scope of this analysis. GO and FOGO collections are mutually exclusive, however all LGAs in the study area collect mixed waste. Three LGAs did not have any separate organic collection services during the study time period, with the mixed waste fraction being the only form of organic waste collection for these LGAs.

The average composition of each organic collection pathway is summarised in Table 2. Contamination rates (i.e., non-organic materials) in GO and FOGO collection bins are low, at 2.8% and 2.2% respectively. This contamination is primarily made up of plastics, metals and in the case of FOGO, also non-compliant organic material such as meat (APC Waste Consultants, 2019; Rawtec, 2020, 2020b). Contamination in the municipal organic stream however has been raised as a concern for local organics recyclers (NSW EPA, 2018). This could indicate some underreporting of contamination in the available kerbside bin audit data, or that small levels of contamination have a significant impact on the quality of recovered organics. The average composition of the mixed waste stream varies depending on the level of separation via GO and FOGO collection, with the proportion of organic waste in mixed waste bins being highest in LGAs without separate collection of organics (61.3%). LGAs with FOGO collection have an average diversion rate for food waste of approximately 44% (Rawtec, 2020b), that is, 56% of all food waste generated in FOGO LGAs remains in the mixed waste bin. Analysis of the collection of the mixed waste stream has been included along with separate organic collection, as considering the high proportion of organic content in this stream, it is still a significant pathway for organic waste management.

From Table 2, the mixed waste bin is shown to be a significant source of organic waste, which is primarily destined for landfills within

Table 2
Average composition of organic waste collection pathways. Proportions shown are for the combined organic (i.e., food and garden waste) components only (APC Waste Consultants, 2019; Rawtec, 2020, 2020b).

Collection service	Organic waste composition of kerbside bin [%]	
	Mixed waste bin	Separately collected organics bin
FOGO collection	36.3%	97.8%
GO collection	51.0%	97.2%
No separate organic collection	61.3%	NA

and outside of the study area. 22 LGAs in the study area diverted quantities of mixed waste to AWT facilities for recovery of organic waste and other high-valued recyclable material (e.g., metals and rigid plastics) via mechanical biological treatment. Recently however, the NSW waste authority (NSW EPA) has restricted the use of recovered organic materials from AWT and mixed waste streams as a soil amendment product, owing to contaminants present in mixed waste organic outputs (NSW EPA, 2018). This limits the applicability of AWT as an organic waste management pathway in the future. Despite this, approximately 32% of mixed waste in the study area was diverted to AWTs in 2018–19, at a recovery rate of 41% (NSW EPA, 2020b). Fig. 2 shows waste collection service by LGA, including AWT diversion.

Waste is first destined for waste transfer stations and collection, where collection vehicles drop off waste collected on a collection route for aggregation before then being directed to recovery or landfill. AWT facilities, along with organic reprocessing (e.g., industrial-scale windrow composting) and landfills were the destinations of waste collected considered in scope for this analysis. Despite anaerobic digestion (AD) being a preferred recovery pathway for food waste given both bioenergy outputs and stabilised organic matter for soil improvement (Banks et al., 2018), anaerobic digestion is not currently deployed at municipal scale in the study area for household waste, with only small amounts of commercial food waste processed via AD in the study area. Recovery facilities generate residual wastes from their processes due to recovery inefficiencies and contamination, which is also then directed to landfills from these facilities. Fig. 3 shows the waste system boundary and scope of material flows along the waste management chain considered for this analysis. The figure also shows the sources of emissions considered in scope for the analysis, computed as carbon dioxide equivalent (tonnes CO_2-e).

Locations for waste infrastructure were based on data in the national *Waste Infrastructure Database - 2017* (Geoscience Australia, 2020), and in NSW LGA *Waste avoidance and resource recovery* data reports (NSW EPA, 2020b). Fig. 4 shows a map of infrastructure locations in scope for this analysis.

3. Methodology

Analyses of waste management systems using spatial data and geographical information systems (GIS) are common in the literature (Singh, 2019), and have been applied for: identifying optimal locations for landfills and other facilities (Eghtesadifard et al., 2020; Lin et al.,

Table 1
Summary of organic waste collection pathways in the study area. Total waste collected quantities includes non-organic waste collected (e.g., plastic, paper etc in mixed waste, and contamination in GO/FOGO).

Organic collection pathway	Number of LGAs with service	Typical frequency of collection	Total waste collected (incl. non-organics) [tonnes, 2018–19]
Separate GO collection	35	Fortnightly	363,436
Separate FOGO collection	5	Weekly	88,116
Mixed waste	43	Weekly (fortnightly for LGAs with FOGO)	1,298,301

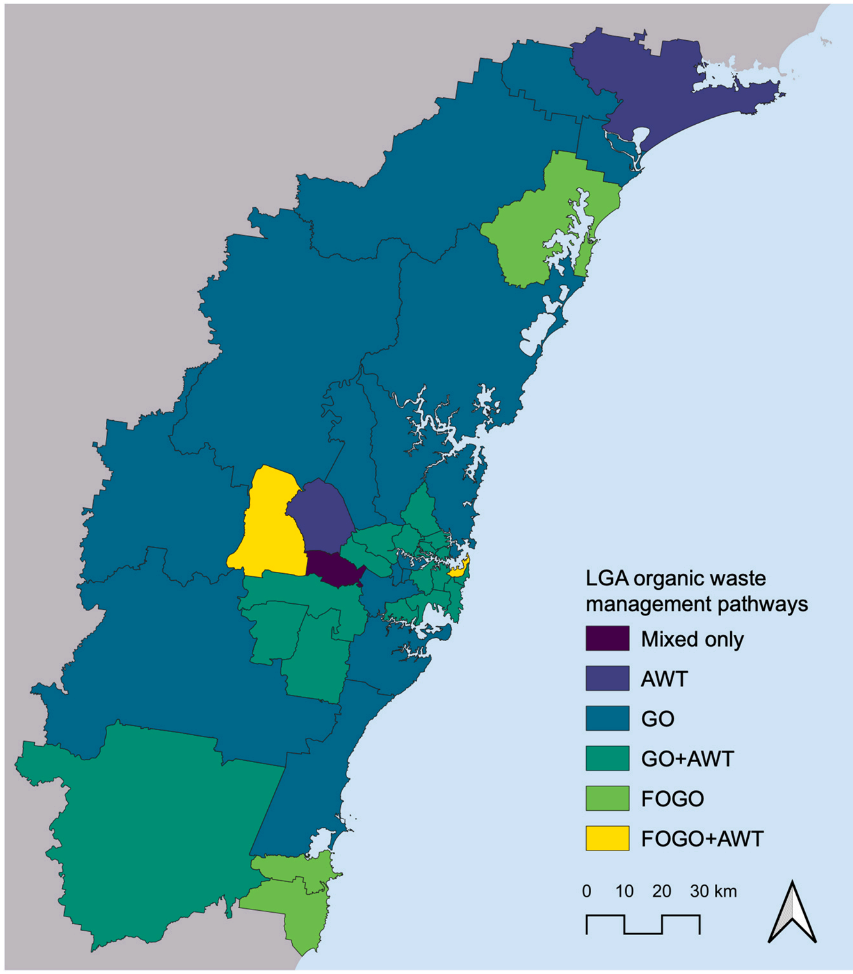

Fig. 2. Distribution of LGA organic waste management pathways in the study area.

2020; Aguilar et al., 2018; Yadav et al., 2018); service area planning (Hatamleh et al., 2020; Tanguy et al., 2017); and small-area estimation of waste generation (Liu et al., 2022; Madden et al., 2021; Yazdani et al., 2021; Kontokosta et al., 2018). Models utilising spatial data also have a diverse range of applications in the evaluation of waste transport flows. For example, Son (2014) applied a novel optimisation approach within a GIS-based environment to determine optimal collection routes for tricycle waste collection in Danang city, Viet Nam. Lella et al. (2017) utilised GIS to identify optimal collection routes for solid waste collection and disposal in a proposed smart city in India. Utilising road network data, the authors applied network analysis to identify the shortest routes between proposed transfer stations and collection points. Vu et al. (2019) applied predictive forecasting of weekly waste generation rates with GIS to analyse the impact of waste characteristics on collection route optimisation in the city of Austin, Texas, USA. The authors used network analysis applied using GIS to solve a vehicle routing problem (VRP)—a generalisation of the classic travelling salesman problem (TSP), whereby solutions were the shortest routes travelled by waste collection vehicles, with constraints such as maximum travel distance and maximum collection time applied. The basic concept of VRPs are to find least cost travel routes from a starting location to service a set of demand points, and then return to the starting location (Du and He, 2012; Hannan et al., 2018). Where vehicle capacity is considered, the problem becomes the capacitated vehicle routing problem, or CVRP, which has particular relevance for evaluating waste collection. Hannan et al. (2018) applied CVRP in the optimisation of waste collection routes to minimise drive time, drive cost, and environmental impacts, solved via particle swarm optimisation

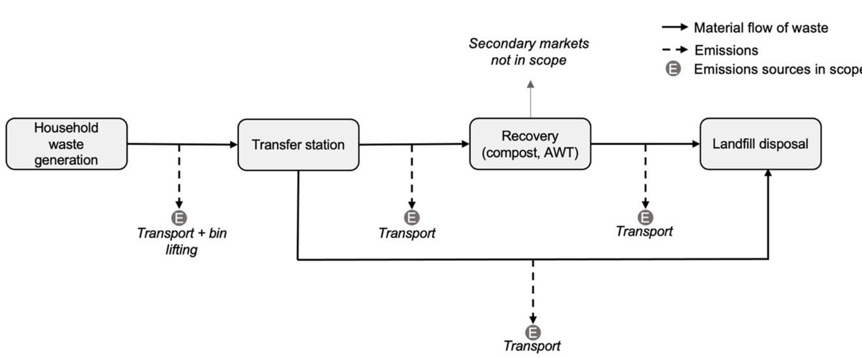

Fig. 3. Waste management system and sources of emissions in scope.

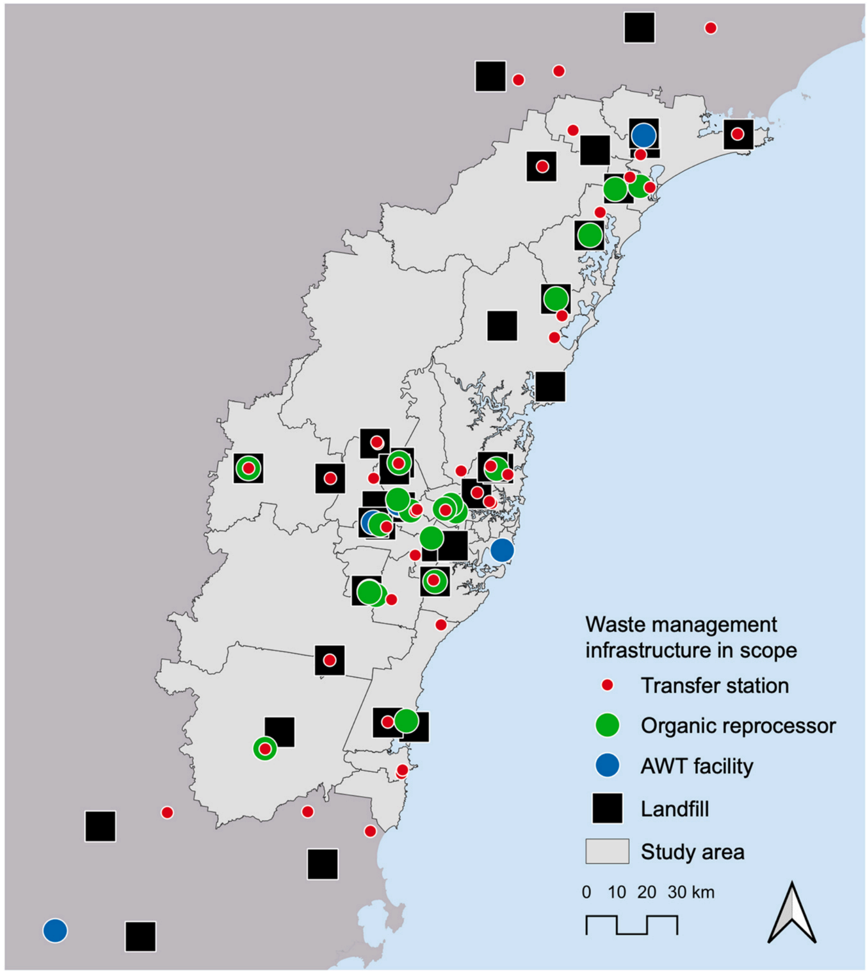

Fig. 4. Waste management infrastructure in the study area.

(PSO). Akhtar et al. (2017) solved a CVRP using a backtracking search algorithm in the optimisation of fuel usage and GHG emissions from waste collection. Otoo et al. (2014) solved a CVRP using a cluster-first-route-second algorithm in a GIS for finding the lowest cost waste collection routes. Karadimas et al. (2007) also used GIS to solve a CVRP via genetic algorithm to identify cost savings through optimising waste collection routes. Indeed, the application of CVRP for evaluating waste collection is wide, and the choice of solution methodology is numerous. Mojtahedi et al. (2021) gives a comprehensive review of VRPs more generally including solution methodologies in the context of waste management. Despite the wide application of the VRP and its variants in waste management, it is noteworthy that case studies from the literature are generally at the city scale or smaller.

The approach developed for this study estimated emissions associated with the collection of kerbside GO, FOGO and mixed waste by solving a CVRP for the Greater Sydney and surrounding area—a combined area of approximately 20,000 km^2. The modelling approach developed utilised high spatial resolution household waste data derived in Madden et al. (2021), waste infrastructure data from Geoscience Australia (2020), and road network data from the NSW Digital Cadastral Database (Department of Finance, Services and Innovation, 2012), integrated with GIS. Our approach extends the work in Edwards et al. (2016) and Sonesson (2000) by utilising higher resolution data to estimate transport flows with greater resolution (for example, between bin distances); and by broadening the scope to also include emissions from transport to waste recovery facilities and landfills.

Fig. 5 gives an overview of the methodological approach. There were two key components of the model. The *waste collection and transport model* was used to estimate organic waste collection distances, achieved by solving a CVRP using a nearest neighbour search algorithm for waste collection services in each LGA in the study area. Furthermore, waste infrastructure data representing waste recovery facilities and landfills were also integrated with road network data to estimate the flows of waste between facility types as a simpler shortest-path problem, solved using Dijkstra's algorithm (Dijkstra, 1959)—a classic algorithm for finding shortest paths on a graph/network. Outputs from the *waste collection and transport model* were coupled with vehicle data from the literature in a *transport energy analysis* to estimate fuel

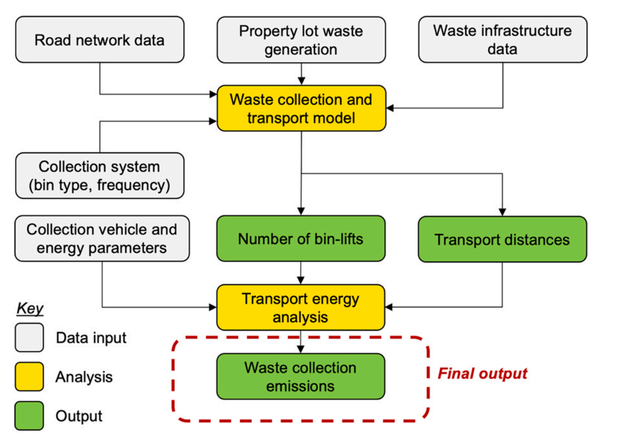

Fig. 5. Overview of the methodological approach for this study. The approach is applied for each local government area in the study are (Fig. 1).

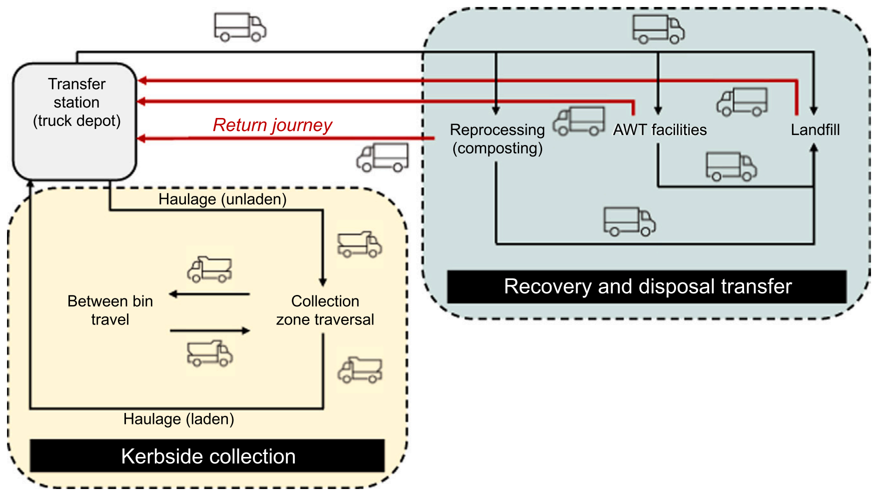

Fig. 6. High-level overview of the waste collection and transport model.

consumption and emissions from waste collection and transportation for each kerbside service across all 43 LGAs. The following sections describe our approach in further detail.

3.1. *Waste collection and transport model*

Fig. 6 gives an overview of the *waste collection and transport model*, showing the transport flows estimated for each LGA in the study area. Two high-level modes of transport were considered for each waste collection service: kerbside collection, which included the traversal of roads along a collection route (i.e., the collection zone) and the servicing of individual property lots within (i.e., the between bin travel); and recovery and disposal transfer, which included transport of aggregated waste from transfer stations to recovery facilities and landfills, and the transport of residual wastes from recovery facilities to landfills. Estimated travel distances for each LGA were multiplied by waste service collection frequency to calculate annual transport distances for the study timeframe.

3.1.1. *Estimating kerbside collection distances*

We estimated distances travelled for kerbside collection for each collection stream by solving a CVRP using the nearest neighbour search algorithm on road network data and property lot data derived from the NSW Digital Cadastre Data Base (Department of Finance, Services and Innovation, 2012) and Madden et al. (2021). The optimal collection routes in our model were treated as approximations of actual collection routes beginning and ending at transfer stations, where data on such routes are limited. We differentiated collection zone traversal and between bin travel distance as a simplification due to limitations in the road network data, which represents many multi-lane and multi-directional roads as single undirected line segments. Due to this, routing between individual property lots is not feasible, as kerbside bins located on opposite sides of a road may appear as adjacent, thus significantly underestimating the transport distance between them. Fig. 7 gives an overview of the collection zone traversal component, which is performed on an LGA-basis for each waste stream and transfer station servicing the LGA. Fig. 8 gives an overview of between bin travel, applied to all neighbourhood blocks within an LGA. Both components when summed give the overall kerbside collection distance. The estimation approach is explained in further detail in the following paragraphs.

Kerbside collection distances were estimated for each LGA separately. We first generated the set of neighbourhood ‘blocks’ for each LGA by merging contiguous property lots within an LGA together, bounded by adjacent roads on the road network. Each neighbourhood block consisted of at least one property lot occupied by a residential dwelling, with an expected amount of waste generated $w > 0$ per waste service collection interval. The number of bins to be collected within a block was equal to the number of dwellings, assuming that each dwelling within a property lot had exactly one bin per waste collection service.

Neighbourhood blocks within an LGA were assumed to be serviced by the nearest transfer station, which were also the assumed waste collection vehicle depot locations. As transfer stations are distributed across the study area, some LGAs were assumed to be serviced by multiple transfer stations. The CVRP for an LGA was then solved iteratively for each transfer station and corresponding set of neighbourhood blocks serviced.

First, $B_m = \{b_{m,i}\}$ is defined as the set of neighbourhood blocks in an LGA nearest to transfer station m, with $0 < w \le C$, where $C = 5$ tonnes was the assumed capacity of a collection vehicle, from Edwards et al. (2016). The estimation of kerbside collection for neighbourhood blocks with weekly waste generation greater than truck capacity (for example, where there are a large number of multi-unit dwellings) was simplified by assuming that collection vehicles travel directly to the neighbourhood block from the transfer station and back again via the shortest path. In these instances, distance travelled for collection was the length of this shortest path, multiplied by the number of collection vehicles required to service the neighbourhood block. This same approach was also applied where individual property lots had expected waste generated greater than C, for example, where large apartment complexes were located. Once transport distances were estimated for these property lots and neighbourhood blocks where $w > C$, they were removed from the following analysis to ensure collection from these locations were not counted twice.

For all other neighbourhood blocks with $0 < w \le C$, we estimated collection distance by solving a CVRP. The objective of the CVRP in our application was to find the optimal collection routes that minimise total travel distance between collection points and transfer station subject to constraints. The CVRP was defined on the undirected graph $G = (V, E)$, where $V = \{v_i\}$ is the vertex set representing locations visited by collection vehicles, and $E = \{(v_i, v_j): v_i, v_j \in V\}$ is the set of edges between vertices, representing the traversal of roads between locations. The initial vertex $i = 0$ represents transfer station m, where K waste collection vehicles begin and end their journeys. Vertices $i = 1, \ldots, n$ correspond to the neighbourhood blocks $b_{m,i}, \ldots, b_{m,n}$ where collection of bins takes place. A collection route is then a sequence of vertices $(v_i, v_{i+1}, \ldots, v_n)$, where v_i is adjacent to v_{i+1}, and travel distance over the whole route is minimised. The symmetrical matrix $D = [d_{i,j}]$ corresponds to the non-negative travel distance along each edge (v_i, v_j), computed as the shortest road travel distance between locations. This is computed as the shortest travel distance along roads between locations,

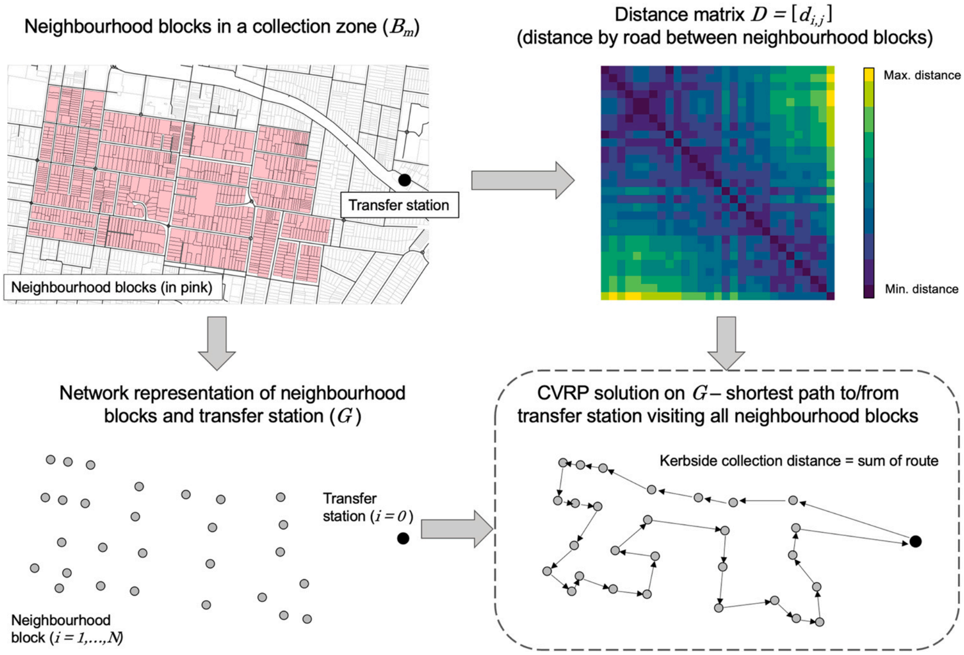

Fig. 7. Overview of the approach used for estimating collection zone traversal in the kerbside collection component of the waste collection and transport model.

found using Dijkstra's shortest path algorithm (Dijkstra, 1959) evaluated using the cadastral road network data. Cartesian coordinates of the transfer station and neighbourhood block centroids were mapped to positions on the road network by finding the nearest point on the road network perpendicular to v_i, using the method in Lu et al. (2018), implemented using the *points2network* function from the *shp2graph* library in the *R* statistical computing language. (see Supporting Information A for a summary of this method). The decision variables of the CVRP model are as follows (Eqs. 1 and 2):

$$X_{i,j,k} = \begin{Bmatrix} 1, \&\text{if vehicle} k \text{travels from location} i \text{to} j \\ 0, \&\text{otherwise} \end{Bmatrix} \tag{1}$$

$$Y_{i,k} = \begin{Bmatrix} 1, \&\text{if location} i \text{is visited by vehicle} k \\ 0, \&\text{otherwise} \end{Bmatrix} \tag{2}$$

The objective function of the CVRP is then to minimise the total travel distance of all waste collection vehicle routes visiting collection points to and from transfer stations as follows (Eq. 3):

$$\text{minimise} \quad Z = \sum_{i=0}^{n} \sum_{j=0}^{n} \sum_{k=1}^{K} d_{i,j} X_{i,j,k} \tag{3}$$

Subject to the following constraints:

- All waste collection vehicles begin their routes from transfer stations with no load
- Each location (neighbour hood block) with waste generation $0 < w \leq C$ is serviced by a single waste collection vehicle
- Collection vehicles must collect all waste generated at a location
- Collection vehicles visiting a location must also depart from that location
- Waste collected on a route must not exceed the truck capacity (5 tonnes)
- Collection vehicles must return to the transfer station after visiting the final collection point on a route
- Travel distance between two locations are the same in either direction

The above constraints are expressed mathematically in Supporting Information B. To solve the CVRP, we used the nearest neighbour algorithm—a greedy search algorithm that attempts to find the optimal solution by first selecting a random starting location $i \neq 0$, and building a route by adding locations nearest the randomised starting location, given the constraints in Eq. (4) to (11). The algorithm is performed over a large number of iterations (10,000) using the *R Statistical Computing* language (R Core Team, 2020), with overall route distance evaluated for each iteration. The optimal collection route is updated for instances resulting in a shorter overall route distance. The nearest neighbour

Fig. 8. Overview of the approach used for estimating the between-bin collection travel in the kerbside collection component of the waste collection and transport model.

algorithm has been used to solve VRPs previously in the literature for its simplicity and ease of implementation, especially for large-scale problems (Kulkarni et al., 2014; Du and He, 2012; Faccio et al., 2011).

Outputs from this process were the most optimal collection routes to and from a transfer station m, given as a sequence of vertices $(v_i, v_{i+1}, \ldots, v_n)$, with distance travelled given by the edge weight between vertices, i.e., $d(v_i, v_{i+1})$. This sequence was decomposed into unladen haulage (travel from the transfer station vertex to the first vertex of a collection route); laden haulage (travel from the last vertex of a collection route back to the transfer station); and collection zone traversal as the remaining vertices of the sequence. We then summed the distances for each component for all waste collection services and transfer stations that service the LGA to determine the total collection zone traversal and haulage distances for an LGA (Eq. 4):

$$Z_l^h = \sum_m \sum_x Z_{m,s}^h \tag{4}$$

Where $l \in L$ is an LGA in the study area, and $s \in S$ are the collection services active in the LGA, and h are the estimated transport components, i.e. $h \in \{unladen, traversal, laden\}$.

For the between bin travel distance, we found the point perpendicular to the nearest road segment for each property lot in a neighbourhood block, and then calculated the distance travelled along the adjacent road between these points, as visualised in Fig. 7. The method in Lu et al. (2018) implemented using the *R* library *shp2graph* (Lu et al., 2018) was employed, which maps points of interest (i.e., property lots) to the graph representing road vertices and road edges. We then summed these distances calculated for each neighbourhood block in an LGA to derive the total LGA between bin travel distance for a given waste service.

Final kerbside collection distance for an LGA on which carbon emissions were estimated was the combination of collection zone traversal and between bin travel distances (Eq. 5):

$$Z_l^{kerbside} = Z_l^{laden} + Z_l^{traversal} + Z_l^{between-bin} + Z_l^{laden} \tag{5}$$

3.1.2. Estimating recovery and disposal transfer distances

Distances travelled for recovery and disposal transfer were estimated by solving the simpler shortest-path problem on the road network data, and locations of waste infrastructure in Geoscience Australia (2020) using Dijkstra's algorithm. Dijkstra's algorithm performs by calculating the distance between a starting vertex on a graph, and all other vertices. The shortest path from the starting vertex to a destination vertex is then determined by finding the path that minimises the total length between the starting and destination vertices.

We calculated transport distances for five separate facility pairings: transfer station to composter; transfer station to AWT; transfer station to landfill; composter to landfill, and; AWT to landfill. Destination facilities were assigned to source facilities for each pairing based on proximity (e.g., the nearest composter to a transfer station). The exception to this was transfer station to AWT, where destination AWT facilities were assigned to transfer stations that service LGAs sending mixed waste to AWTs from the data (NSW EPA, 2020b). Road travel distance was calculated for each pairing from source location to destination location, mapped to the graph representing road vertices and road edges via the method in Lu et al. (2018), with the shortest path between facilities found using Dijkstra's algorithm (Eq. 6):

$$Z^{\tau} = \left(\sum_{i,j \in \tau} dist(i, j) \quad x_{i,j} \right) \times K_{i,j} \tag{6}$$

Where τ is the given facility pairing, $dist(i, j)$ is the length of edge (i, j) between facilities, and $x_{i,j}$ is the decision variable, taking a value of 1 if the edge (i, j) is on the shortest path. $K_{i,j}$ is the number of trucks required to transport aggregated waste between locations i and j, and is calculated from $q'_{i,j}/C_2$, where $q'_{i,j}$ is the total amount of waste to be transported from facility i to facility j during a collection service interval, and $C_2 = 15$ tonnes is the transport truck capacity. Compaction of aggregated waste material, and a larger truck size compared to waste collection, equivalent to a 3-axle, 22.5 tonne gross vehicle mass rigid truck (NSW Roads and Maritime Services, 2019) was assumed for C_2. We attributed distance between facility pairings to individual LGAs by calculating the proportion of waste transported between facilities that was derived from each LGA.

It was assumed that LGAs sending mixed waste to the Woodlawn AWT facility (located approximately 190 km outside the Sydney CBD) did so via rail, with waste first being transferred to the Clyde Transfer Station, located in the Parramatta LGA (Veolia, 2022). Distances between nearest transfer station to the Clyde Transfer Station were calculated as described as above. Distance travelled by rail was calculated between the Clyde Transfer Station and Woodlawn AWTs, assuming weekly transfer of AWT destined mixed waste.

3.2. Transport energy analysis

The *transport energy analysis* estimated the emissions from waste collection and transport, following the approach and parameters applied in Edwards et al. (2016), which was based on truck activity. These

Table 3
Parameters used for modelling fuel consumption of waste collection and transport vehicles. All parameter values taken from values derived in Edwards et al. (2016) unless where stated.

Parameter	Value [unit]	Description
Average time per bin-lift	8.27 [seconds]	Average time for collection vehicle to lift a bin using hydraulic lifting arm
Average speed - bin collection (urban)	7 [km/hr]	Average speed during bin collection (between bin travel) for urban LGAs
Average speed – bin collection (peri-urban)	9 [km/hr]	Average speed during bin collection for peri-urban LGAs
Average speed – haulage (urban)	35 [km/hr]	Average speed for laden/unladen haulage (collection zone traversal, and facility-to-facility transfer) for urban LGAs
Average speed – haulage (peri-urban)	40 [km/hr]	Average speed for laden/unladen haulage for peri-urban LGAs
Average speed – haulage (highway)	82 [km/hr]	Average speed for laden/unladen haulage along highways
CO_2-equivalent emissions from diesel	0.0027 [tonnes/L]	Average CO_2 equivalent emissions per litre of diesel fuel combusted (National Transport Commission, 2019)
Energy from diesel	39 [MJ/L]	Energy content of diesel fuel
Energy during bin lift	0.1 [MJ/s]	Amount of energy consumed by the hydraulic lift per bin lift
Energy during laden haul (urban/peri-urban)	0.176 [MJ/s]	Energy consumed whilst driving laden along roads urban/peri-urban LGAs
Energy during unladen haul (urban/peri-urban)	0.035 [MJ/s]	Energy consumed whilst driving unladen along roads urban/peri-urban LGAs
Energy during laden haul (highway)	0.450 [MJ/s]	Energy consumed whilst driving laden along highways
Energy during unladen haul (highway)	0.183 [MJ/s]	Energy consumed whilst driving unladen along highways
Energy during kerbside bin collection	0.176 [MJ/s]	Energy consumed whilst moving between bin collection locations (between bin travel)
Diesel consumption per kilometer (freight rail)	7.5 [L/km]	Diesel consumption per locomotive kilometre for desiel-electric freight locomatives. From TIC (2020)

Table 4
Summary of estimated annual distances travelled by waste collection and transport vehicles for the management of organic waste in the study area for 2018–19.

	Total distance travelled [km/year]	Distance travelled – GO waste [km/year]	Distance travelled – FOGO waste [km/year]	Distance travelled – Mixed waste [km/year]
Total kerbside collection	*14,028,217*	*3,428,644*	*892,603*	*9,706,971*
Collection zone haulage (unladen)	4,070,921	909,816	206,055	2,955,050
Collection zone traversal	1,736,337	471,109	143,288	1,121,940
Bin pickup	4,286,622	1,172,764	347,231	2,766,628
Collection zone haulage (laden)	3,934,338	874,956	196,029	2,863,353
Total recovery transfer (incl. return)	*2,393,477*	*521,116*	*201,815*	*1,670,546*
Transfer station to composters	722,930	521,116	201,815	0
Transfer station to AWTs (road)	1,645,504	0	0	1,645,504
Transfer station to AWTs (rail)	25,042	0	0	25,042
Total disposal transfer (incl. return)	*1,405,319*	*10,000*	*3440*	*1,391,878*
Transfer station to landfills	976,060	0	0	976,060
Composters to landfills	13,441	10,000	3440	0
AWTs to landfills	415,817	0	0	415,817
Total	*17,827,013*	*3,959,760*	*1,097,858*	*12,769,395*

activities were: i) unladen haulage from transfer station to the first collection point on a collection route; ii) 'stop-go' travel between bins; iii) bin-lifting (i.e., emptying of bins into truck receptacle via hydraulic lifting arm); iv) laden haulage back to the transfer station, and; v) laden haulage between facilities. Hydraulic lifting systems are standard practice for waste collection vehicles, which ensure worker safety and efficiency in loading waste into the vehicle receptacle. It was assumed that all collection vehicles employed utilised the same technology.

Table 3 lists the parameters used in the model. Estimated distances (km) for a given activity were divided by the corresponding truck speed (km/h) for that activity (based on LGA classification as metropolitan/metropolitan-fringe, or regional in NSW OLG (2020)), and multiplied by the energy intensity (MJ/s) to calculate energy requirements in megajoules. From this, diesel fuel consumption (L) and associoated emissions (t CO_2-e) were estimated, based on average CO_2-e emissions for diesel combustion by rigid trucks in National Transport Commission (2019). Fuel type was consistent with data in (Australian Bureau of Statistics, 2020) showing 99.8% of the Australian truck fleet consuming diesel fuel in the study period. Proportion of highway travel for haulage and transport between facilities was determined from the cadastral road data (Department of Finance, Services and Innovation, 2012). For energy requirements and fuel consumption for bin-lifts, it was assumed that the number of bins per property lot at a collection point was equal to the number of dwellings in that property lot.

Estimated fuel consumption for facility-to-facility haulage of aggregated waste was calculated for each LGA, based on the proportion of waste derived from an LGA. To illustrate, if 10% of waste at a transfer station was derived from LGA1, then 10% of the fuel consumption associated with facility-to-facility haulage was associated with that LGA. For rail transfer of AWT destined waste, a standard diesel-electric locomotive operating at 5000 horsepower was assumed, based on the Australian Transport Assessment and Planning Guidelines (TIC, 2020).

3.3. Model validation

A sensitivity analysis was performed to test the robustness of emissions estimates given variation in key model variables. Variables chosen for evaluation were the selection of kerbside collection routes, given the stochastic nature of the nearest neighbour solution algorithm; waste transport truck capacity, where the actual size of transport trucks was unknown; and waste generation rates.

To test the sensitivity of emissions on kerbside collection routes, we performed 10,000 iterations of the CVRP solution algorithm for 3 LGAs selected from each LGA category from NSW Office of Local Government (2020) (i.e., metropolitan, metropolitan-fringe, and regional). The average coefficients of variation (CV) for each LGA category were computed, and used to estimate CVs on kerbside emissions for each LGA in the study area. This was done due to the large computation times necessary to perform iterations of the CVRP solution algorithm for a single LGA.

To test sensitivity of emissions on transport truck sizes, we estimated overall emissions based on candidate truck sizes in NSW RMS (2019) and Strandgard et al. (2021), assuming either 2-axle rigid, 3-axle rigid (the nominal transport truck size), and semi-trailer, at assumed load weights of 10, 15, 26 tonnes respectively.

To test sensitivity of emissions on variations in waste generation, we performed the model with waste generation rates perturbed by $\pm$ 20%, and compared against baseline estimates. Sensitivity of overall emissions given percentage-variation in kerbside collection routes, transport truck sizes and waste generation, were then evaluated by comparing the percentage change in emissions, after Acevado (2013).

A further unknown in our model was the assignment of landfill locations to transfer stations and recovery distances based on proximity. It is possible that some jurisdictions and transfer/recovery facilities may have agreements with particular landfill sites, and that capacity limits at landfills may lead to non-proximal landfill sites being the destination of disposed waste. To explore this uncertainty on the model results, the disposal transfer distance component waste computed, based on randomly assigned landfill facilities in a simulation with 1000 iterations. Landfills locations were selected randomly from a weighed sample, with landfills in closer proximity to transfer stations and recovery facilities more likely to be selected.

To evaluate the accuracy of modelled outputs with respect to waste transportation, model outputs were compared against data from the literature. This included for example, comparison against waste transport distances per litre of fuel consumption in Agar et al. (2007) and Larsen et al. (2009); litres of fuel consumed per tonne of waste transported in Nguyen and Wilson (2010), Quintili & Castellani (2020), and Jaunich et al. (2016); and emissions intensity per tonne of waste collected from LCA studies summarised in Friedrich and Trois (2013).

4. Results and discussion

4.1. Kerbside collection and facility-to-facility distances travelled, and fuel consumed

Table 4 summarises overall distances travelled by waste collection and transport vehicles in the study area for each waste stream (used to estimate transport emissions reported in Section 3.2). Fig. 9 shows the breakdown of collection and transport distances by component, and by

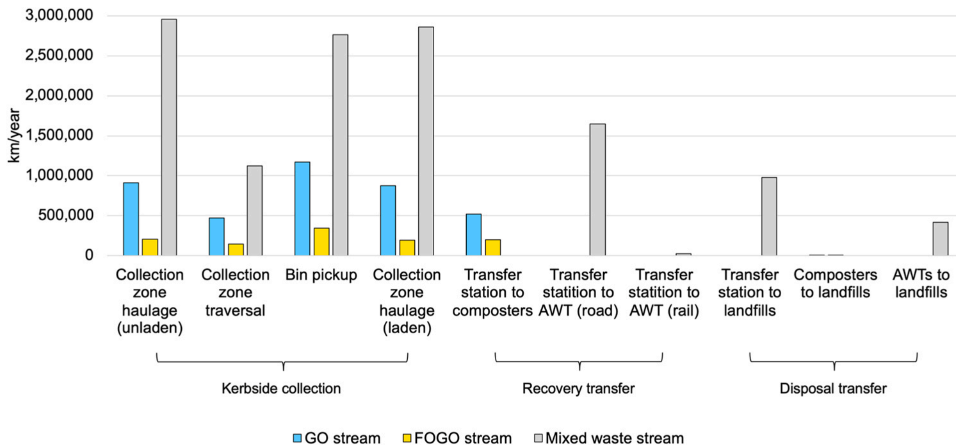

Fig. 9. Breakdown of waste collection and transport distance by waste stream, and waste component.

waste stream. Overall, approximately 18 million kilometres were travelled for the management of organic wastes in the study area in 2018–19 by road and rail, equivalent to approximately 694 times around the Earth. Distance travelled by rail were small, at approximately 25,000 km, or 0.1% of total distances travelled in 2018–19. The average distance travelled per LGA ranged between 208,000 km/year to 1.3 million km/year, with a mean distance of approximately 370,000 km/year travelled. Supporting Information C gives a breakdown of average distances travelled by LGAs. The overall intensity of transport per tonne of waste generated across the streams considered was 10.17 km/tonne. The mixed waste stream had the highest transport requirements, accounting for 72% of total mileage. FOGO waste had the lowest transport requirements at 6.2% of total mileage, expected given that FOGO waste collection accounts for only 4.9% of total waste collections. Intensity of transport was highest for the FOGO waste stream, at 12.7 km/tonne, reflecting the large distances travelled for collection, and the relatively small quantities of FOGO waste collected. The mixed waste stream had the lowest intensity at 9.8 km/tonne, which illustrates the efficient location-allocation of mixed waste management facilities, with landfills, AWT facilities and transfer stations located within close proximity with eachother. The exception to this is the Woodlawn AWT facility, however transfer of mixed waste via rail is much more efficient compared to road freight on a tonnes-kilometer basis (5.2 tonnes-kilometer for road compared to 0.26 tonnes-kilometer for rail).

Kerbside collection contributed the most to overall distances travelled by waste management vehicles, accounting for approximately 79% of total mileage. There was a large variance on LGA kerbside collection mileages, ranging from approximately 68,000 km/year to 570,000 km/year. Such variance is expected, given LGA sizes range from approximately 6 km^2 to 2800 km^2, and number of households per LGA ranging between 16,000 and 97,000. Larger LGAs typically saw greater kerbside collection distances than smaller LGAs, however this effect was most evident in metropolitan LGAs, where LGA size is smaller compared to regional LGAs. Larger, more regional LGAs with less urban development (for example Wingecarribee, Blue Mountains), are characterised by large proportions of national parks and primary produce land, with most residential dwellings located in smaller, less distributed parts of these LGAs. Indeed, the total number of dwellings was a stronger indicator of total kerbside collection distance, with distance increasing by approximately 5 km for every occupied household in an LGA. Average kerbside collection distance per dwelling ranged from between approximately 3 km/dwelling to 10 km/dwelling. Dwelling density and dwelling type, and their impact on transport emissions are discussed further in the following section.

A total number of 409,970 waste collection vehicle trips were required to service all households in the study area for 2018–19. Mixed waste collection required the greatest number of truck trips at 288,938, which is expected given that all LGAs in the study area have mixed waste collection services. FOGO waste collection had the fewest number of vehicle trips in 2018–19, at 19,864, with only 5 LGAs having FOGO collection services. GO collection required 101,168 trips.

Of the kerbside collection travel components summarised in Table 4, bin pickup was responsible for the greatest mileage. Table 5 shows the average between-bin distances for LGAs by regional classification from NSW OLG (2020). The average between-bin distance for all LGAs was approximately 44 m, with the metropolitan LGA average being approximately 30 m. Metropolitan-fringe and regional LGAs had similar between-bin distances of approximately 62 m and 64 m respectively. Between bin distances are not reported in Edwards et al. (2016), despite the authors noting that this variable is crucial for modelling fuel consumption for waste collection. Edwards et al. (2016) does however refer to between bin distances of 20–110 m used in other studies for urban locales.

Total recovery transfer distances were approximately 2.4 million km/year, including 25,000 km via rail. LGA variance was also high for this component, with average mileage ranging from 5000 km/year to 136,000 km/year. This can mostly be attributed to AWT transfer. Notably, AWT transfer intensity on a km/t basis was significantly greater than compost transfer, at an average of 5.2 km/tonne compared to 1.6 km/tonne.

Landfill disposal transfer made the smallest contribution to overall distances, at approximately 1.4 million km/year. LGA variance on disposal transfer was relatively small, between 6400 km/year and 72,000 km/year. Landfills were generally located in proximity to transfer stations and recovery stations, whereas recovery facilities were more dispersed across the study area. This is indicated by the average transport intensity for disposal of 1.3 km/tonnes, with a range of between 0.4—2.3 km/tonne.

Table 6 shows estimated fuel consumption for waste collection and transport. Supporting Information D gives a breakdown on LGA average fuel consumption. Overall, approximately 16,300,000 litres of diesel fuel was consumed in 2018–19 for organic waste collection and transportation, with approximately 25,000 litres consumed via rail transport. This is compared to a combined 661 million litres of diesel fuel

Table 5
Estimated average distance between collection points (i.e., bins) by LGA classification from NSW OLG (2020).

	Average distance between collection points [m] (St.dev.)
All LGAs	43.88 (32.23)
Metropolitan LGAs	30.17 (6.85)
Metropolitan-fringe LGAs	61.58 (35.59)
Regional LGAs	64.25 (12.73)

Table 6
Estimated annual diesel fuel consumption by waste collection and transport vehicles for the management of organic waste in the study area for 2018–19.

	Total annual diesel fuel consumption [L/yr]	Average fuel per tonne managed [L/t]	Average fuel per distance travelled [L/km]
Total kerbside collection	*14,429,470*	*8.23*	*1.03*
Collection zone haulage (unladen)	361,777	0.21	0.09
Collection zone traversal	705,220	0.40	0.41
Bin pickup	11,739,066	6.69	2.74
Collection zone haulage (laden)	1,623,408	0.93	0.41
Total recovery transfer (incl. return)	*1,178,288*	*0.77*	*0.32*
Transfer station to composters	352,012	0.39	0.24
Transfer station to AWTs (road)	801,234	1.26	0.24
Transfer station to AWTs (rail)	25,042	1.96	7.50
Total disposal transfer (incl. return)	*684,282*	*0.31*	*0.24*
Transfer station to landfills	475,266	0.28	0.24
Composters to landfills	6545	0.46	0.24
AWTs to landfills	202,471	0.41	0.24
Total	*16,292,040*	*8.86*	*0.87*

consumption for rigid, articulated, and non-freight carrying trucks in NSW for the 2018–19 period (ABS, 2020). Kerbside collection was responsible for approximately 88.6% of all fuel consumed and therefore is a significant contributor to emissions, and also had the highest fuel intensities, at 8.23 L/tonne waste managed, and 1.03 L/km travelled. Recovery transfer to AWT facilities (via road) also had high fuel intensity on a fuel consumed per tonne of waste managed basis compared to recovery transfer to compost facilities. Bin pickup was the most fuel intensive component of kerbside collection, which included both stop-and-go travel at low speeds between collection points, and the lifting of bins into the vehicle receptacle using a hydraulic lifting arm. Stop-and-go travel accounted for approximately 85% of bin pick up emissions (approximately 9,980,000 L), with hydraulic lifting accounting for the remaining 15% (1,760,000 L). Average kerbside collection fuel intensity was highest for FOGO waste collection, at approximately 13 L/tonne collected, compared to 10.4 L/tonne for GO waste collection, and 7.3 L/t for mixed waste collection. While average fuel intensity is highest for FOGO collection, there are only 5 LGAs that have this service, including 3 LGAs classified as regional. As such, fuel intensity for FOGO collection is impacted by other factors, including LGA size as regional LGAs are larger, and have greater between bin distances (see Table 5). Overall fuel intensity for organic waste managed in the study area was 8.86 litres per tonne, and 0.87 litres per kilometre travelled. These metrics are compared with validation data from the literature in Section 4.

Table 7
Annual estimated emissions and emissions intensity for organic waste kerbside collection, and recovery and disposal transfer in the study area by waste stream for 2018–19.

Total annual emissions	Overall GHG emissions [tCO_2-e]	GO waste GHG emissions [tCO_2-e]	FOGO waste GHG emissions [tCO_2-e]	Mixed waste GHG emissions [tCO_2-e]
Total kerbside collection	*38,671*	*10,271*	*2997*	*25,403*
Collection zone haulage (unladen)	970	214	47	708
Collection zone traversal	1890	513	156	1221
Bin pickup	31,461	8578	2579	20,303
Collection zone haulage (laden)	4351	965	215	3170
Total recovery transfer (incl. return)	*3158*	*680*	*263*	*2214*
Transfer station to composters	943	680	263	0
Transfer station to AWTs (road)	2147	0	0	2147
Transfer station to AWTs (rail)	67	0	0	67
Total disposal transfer (incl. return)	*1834*	*13*	*4*	*1816*
Transfer station to landfills	1274	0	0	1274
Composters to landfills	18	13	4	0
AWTs to landfills	543	0	0	543
Total	*43,663*	*10,964*	*3265*	*29,434*
Average emissions per tonne of waste	**Overall GHG emissions [$kgCO_2$-e/t]**	**GO waste GHG emissions [$kgCO_2$-e/t]**	**FOGO waste GHG emissions [$kgCO_2$-e/t]**	**Mixed waste GHG emissions [$kgCO_2$-e/t]**
Total kerbside collection	*22.05*	*27.82*	*34.71*	*19.57*
Collection zone haulage (unladen)	0.55	0.58	0.55	0.55
Collection zone traversal	1.08	1.39	1.81	0.94
Bin pickup	17.94	23.24	29.87	15.64
Collection zone haulage (laden)	2.48	2.62	2.49	2.44
Total recovery transfer (incl. return)	*3.65*	*1.87*	*2.99*	*5.37*
Transfer station to composters	2.09	1.87	2.99	0.00
Transfer station to AWTs (road)	6.78	0.00	0.00	6.78
Transfer station to AWTs (rail)	0.70	0.00	0.00	0.70
Total disposal transfer (incl. return)	*1.68*	*2.70*	*2.03*	*1.67*
Transfer station to landfills	1.16	0.00	0.00	1.51
Composters to landfills	0.02	2.70	2.03	0.00
AWTs to landfills	0.50	0.00	0.00	2.21
Total (tonnes generated basis)	*24.90*	*29.70*	*37.81*	*22.67*
Total (tonnes managed basis)	*11.76*	*14.87*	*18.48*	*10.52*

4.2. Organic waste collection and transport emissions, and emissions intensities by activity

Table 7 shows overall waste collection and transport emissions, and average emissions intensity per tonne for each waste stream. Emissions intensity is calculated on a per-tonne waste generated basis, and on a per-tonne waste managed basis, that is, the amount of waste collected or transported for each component. Overall, approximately 43,700 tonnes of CO_2-equivalent emissions were emitted across the study area for 2018–19 through kerbside collection and organic waste transportation. Overall emissions intensity in 2018–19 was 24.9 kgCO_2-e per tonne of waste generated, and 11.8 kgCO_2-e per tonne weighted by quantities managed for each component. The overall impact of waste collection and transport emissions on state-wide emissions was small. In 2018–19, approximately 136,570,000 tonnes of CO_2-e emissions were reported for NSW across all economic sectors (Department of Industry, Science, Energy and Resources, 2021b). The overall contribution of waste related transport emissions from the study area was therefore less than 0.01%. Road transport emissions for medium-duty trucks was reported as approximately 2,356,000 tonnes CO_2-e, with waste related transport in the study area contributing approximately 2% to these emissions.

Management of the mixed waste stream was responsible for approximately 67% of all emissions—expected given the large quantities of mixed waste generated compared to the other streams (approximately 1.3-million tonnes compared to combined 451,000 tonnes for GO and FOGO). Kerbside collection across all waste streams was the activity with the greatest impact on emissions, responsible for approximately 89% of all emissions. This proportion was highest for GO and FOGO waste streams, where kerbside collection was responsible for 94% and 92% of emissions respectively.

The mixed waste stream had the highest proportion of recovery and disposal transfer contributing to overall emissions, at 8% and 6% respectively. Compared to GO and FOGO recovery, mixed waste recovery transfer was more emissions intensive on a per tonnes transported, given the smaller waste quantities and greater distances travelled from transfer stations to AWT facilities, compared to composters. The proportion attributed to disposal transfer is also higher for mixed waste, given that a fraction of mixed waste is diverted to landfill from transfer stations after collection. FOGO was the waste stream with the highest average emissions intensity, expected given the high fuel intensity of kerbside collection of FOGO waste (Section 3.1). Recovery transfer emissions intensity is also higher for FOGO compared to GO. This indicates for those LGAs where FOGO is collected, FOGO waste is transported over greater distances to recovery compared to GO. Although this difference in intensity in small, it is likely a regional effect, where 3 out of 5 LGAs with FOGO services are located outside the metropolitan area, where there are fewer recovery facilities located in proximity to transfer stations. Recovery transfer intensity was significantly higher for mixed waste, due quantities of mixed waste for recovery transported to a fewer number of AWT locations distributed through the study area.

Considering that kerbside collection emissions are responsible for the majority of waste management related transport emissions, emissions intensity of kerbside collection is further examined in Fig. 10. The figure also compares LGA size, and the proportion of dwellings that are multi-units (MUDs) with kerbside collection emissions intensity. A positive correlation was observed between kerbside collection emissions intensity and LGA size, with large LGAs generally located regionally or on the metropolitan-fringe, therefore having greater distances to travel to service properties. A negative correlation was found between the proportion of MUDs and kerbside fuel intensity, which is expected given that average between-bin distances and stop-and-go travel are reduced when servicing MUDs on account of there being several bins located on a single property lot. Dispersal of collection points is therefore an important factor when considering total mileage and fuel intensity, and thus GHG emissions, for kerbside collection services. While population and dwelling density are the important drivers of dispersal of collection points, and driven by urban planning policies and regulations, improving GHG intensity for GO and FOGO collection services could also theoretically be achieved through the deployment of community collection hubs, or other similar systems whereby household organic waste is collected at more centralised locations. Examples of this in the study area include a trial of centralised 'compost huts' servicing between 40 and 60 households, conducted by Inner West Council in 2017, where participating households could drop-off food scraps at council-managed public drop-off locations for on-site composting (Inner West Council, 2018). Another example was the 9-week trial of 'compost hubs' in Blue Mountains City Council also in 2017, which connected households that do not compost with households that do, in an effort to reduce food waste in the mixed waste bin (Blue Mountains City Council, 2022). Both trials saw reductions in food waste in the mixed waste bin for participating households over the trial period, however reduction in fuel requirements for collection were not objectives of either trial. Nevertheless, centralised collection systems have been shown to reduce fuel requirements of collection due to shorter distances being travelled by collection vehicles for the collection of plastic waste for recycling (Kerdlap et al., 2020). In the context of organic waste, centralised collection locations could limit collection truck requirements, however would be likely be practical in locations with high density, where collection hubs could be placed in efficient locations limiting the need for vehicle transport. Such systems would also likely only be practical for small amounts of garden waste and food waste due to space limitations, making urban locations ideal candidates. Such a collection system however would place more of the burden of waste management onto waste generators and the general public, which could lead to perverse outcomes including poorer diversion of organic wastes to recycling.

4.3. Comparison of emissions intensities between organic waste management pathways

Fig. 11 compares average kerbside collection and transport emissions across LGAs classified by organic waste management pathways employed. Data presented in this figure is different to data in Table 7, which presents emissions by management of each waste stream individually. Kerbside collection intensity was lowest for the single LGA that collected mixed waste as the only pathway for organic collection, which was disposed directly to landfill. This is anticipated, given that only a single bin per-household is collected. For this LGA (Fairfield, located in Sydney's south-west), food waste is collected entirely in the mixed waste stream, with garden waste collected through council drop-offs at waste depots. Only 10 tonnes of garden was reported collected for this LGA in the time period via drop offs. Note that drop-offs are not considered in scope of our analysis.

For the remaining LGAs, those employing AWT, both on its own as the only pathway for organic waste management, and in combination with separate organic waste collection, had the lowest kerbside collection intensities. For the AWT only LGAs, low kerbside emissions are expected given, as noted above, that no separate organic bins are collected on a weekly or fortnightly basis. For GO + AWT and FOGO + AWT LGAs, these LGAs are located in denser areas, with average population densities of 3639 and 2687 persons/km^2 respectively, compared to the LGA average of 2347 persons/km^2. Population (and dwelling) densities have been shown earlier to negatively correlate with fuel intensity and thus emissions intensity of kerbside collection.

Recovery transfer emissions intensity was highest for GO + AWT and FOGO + AWT LGAs. This is anticipated, given that additional transport flows are required compared to GO and FOGO only management.

Table 8 compares transport emission intensities on a per tonne diverted from landfill basis, and total organics recovered across the organic waste management pathways employed, as a way to compare organic waste management performance across the LGA types

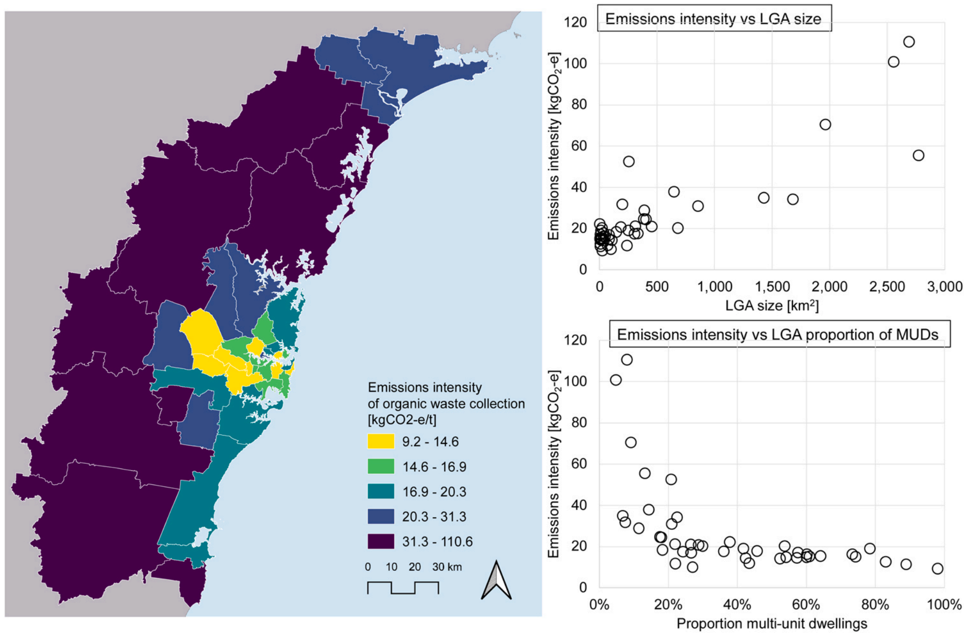

Fig. 10. Spatial distribution of kerbside collection GHG emissions intensity, and correlations between LGA size and proportion of multi-unit dwellings in LGAs.

observed. Data in Table 8 shows a correlation between increased levels of food separation and lower emissions intensity, with councils separating food waste through FOGO having the highest recovery rates, and lowest emissions intensity per tonne diverted. However, given the small number of LGAs for each pathway, variation (reported as standard deviation) in estimated emissions intensities is high. On average, emissions intensities were 96.26 $kgCO_2$-e per tonne of organic waste diverted. Note that these emissions intensity values do not include emissions generated from landfill disposal, nor do they consider emissions generated through recovery activities.

LGAs with FOGO collection had the highest recovery rates, and lowest emissions intensities of the LGA organic waste management pathways. LGAs with FOGO as the only organic recovery pathway had an average organic waste recovery rate of 68%, and emissions intensity of 73.83 $kgCO_2$-e per tonne diverted. With the addition of diversion of mixed waste to AWT (FOGO + AWT), average recovery rates increased to 77%, and average emissions intensity improved to 45.35 $kgCO_2$-e per tonne diverted. This indicates that while FOGO alone is an efficient collection stream for diverting food waste from landfill, there still remains a significant proportion of food waste in the mixed waste stream that can be managed via AWT. While the increase in collection and transport emissions intensity is significant for LGAs adopting AWT along with FOGO, this does not take into account emissions from the AWT recovery process itself, which due to the mechanical nature of AWT separation, would likely be higher than direct emissions from composting of FOGO.

LGAs with GO as the only organic recovery pathway had the lowest average recovery rate at 49% (excluding LGAs with no separate collection of organics or AWT diversion only), and highest average emissions intensity at 124.64 $kgCO_2$-e per tonne diverted. Fig. 12 shows the spatial distribution of LGA emissions intensity by tonnes diverted across the study area. Many GO only LGAs were located regionally or on the metropolitan fringe, where kerbside collection distances and fuel consumption were significant. GO only LGAs with emissions intensity below the average for this pathway were located within the Sydney metropolitan area, where kerbside collection fuel intensity was lower, on account of higher dwelling density, and closer proximity of organic recovery facilities. With the addition of AWT diversion (GO + AWT), average recovery rate increases to 63%, and average emissions intensity improves to 80.25 $kgCO_2$-e per tonne diverted. While an improvement over GO only, the addition of AWT diversion does not improve efficiency to the levels seen with FOGO collection. This indicates that FOGO is the most efficient pathway for food and garden waste diversion in the study area. Based on this analysis, councils would likely be better off transitioning from GO to FOGO as a first step towards improved organic waste management under lower carbon emission policies, assuming composting is the recovery pathway for organic waste.

Comparison of the different management pathways employed across

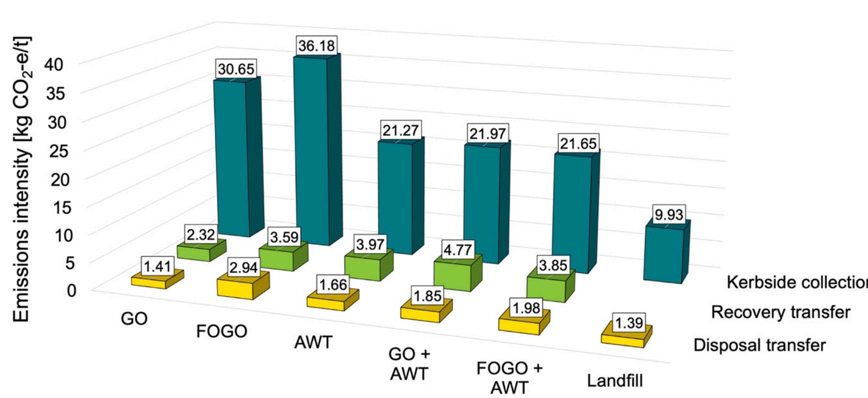

Fig. 11. Comparison of average emissions intensities of kerbside collection, recovery transfer and disposal transfer for LGAs classified by organic waste management pathways employed.

Table 8
Comparison of total organic waste generation and recovery, with average collection and transport emissions intensity per tonne of organic waste diverted for LGAs classified by organic waste management pathway for 2018–19.

	Total organics generated, 2018–19 [tonnes]	Total organics recovered, 2018–19 [tonnes]	Average recovery rate [-]	Average emissions intensity per tonne diverted [kgCO_2-e/t] (St.dev)
Mixed waste only LGAs (*n = 1*)	30,640	10	< 1%	NA
GO only LGAs (*n = 17*)	458,867	226,344	49%	124.64 (98.91)
FOGO only LGAs (*n = 3*)	69,473	47,147	68%	73.83 (24.31)
AWT only LGAs (*n = 2*)	58,813	34,494	59%	83.73 (33.57)
GO + AWT LGAs (*n = 18*)	357,676	227,091	63%	80.25 (66.57)
FOGO + AWT LGAs (*n = 2*)	60,319	46,353	77%	45.35 (2.55)
All LGAs (*n = 43*)	1,035,788	581,428	56%	96.26 (78.6)

the study area however is problematic, given the small sample sizes for each pathway as indicated in Table 8. For a fairer comparison, a simple scenario analysis was performed. For this, 3 LGA areas were selected, representing metropolitan, metropolitan-fringe, and regional LGAs: Burwood, Hornsby, and Lake Macquarie respectively. For the scenario analysis, 6 scenarios were analysed, assuming all 3 LGAs employed no separate organic pathway; GO only; FOGO only; AWT only; GO + AWT; and FOGO + AWT. Quantities of FOGO for Burwood and Hornsby were estimated assuming diversion from the mixed waste stream with a constant proportion of food waste in the FOGO bin of approximately 11% (Rawtec, 2020b). With FOGO employed, mixed waste was assumed to be collected at fortnightly instead of weekly intervals. Quantities of mixed waste diverted to AWT was estimated based on the average proportion of mixed waste sent to AWT across the study area. Estimated emissions for this scenario analysis by organic pathway and emissions component, as well as emissions per tonne managed and diverted are summarised in Table 9.

Findings from this scenario analysis were typically consistent with overall findings presented in Table 8. Lower emission intensities and higher recovery rates were observed as more of the organic waste stream was diverted from landfill to recovery. On an emission intensity per tonne of waste managed basis, GO pathways had higher emissions intensity than FOGO, by approximately 3%. This result indicates that both reduced volume and less frequent collection of mixed waste has an impact on gross collection and transport emissions, albeit the impact is small. Similar to Table 8, the addition of AWT to GO and FOGO

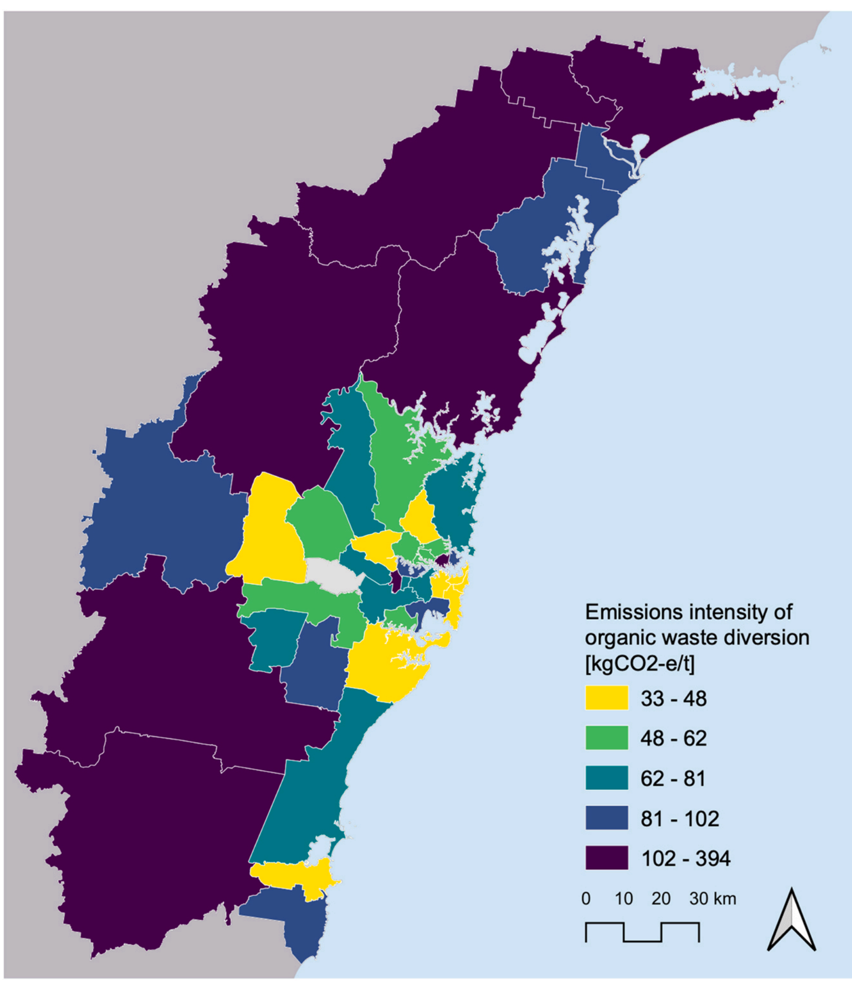

Fig. 12. Spatial distribution of emissions intensity per tonne of organic waste diverted in the study area for 2018–19.

Table 9
Results of scenario analysis exploring emissions for different LGA organic waste management pathways.

LGA scenario	Kerbside collection emissions [tCO_2e]	Recovery transfer emissions [tCO_2e]	Disposal transfer emissions [tCO_2e]	Overall emissions [tCO_2e]	Emissions per tonne waste managed [$kgCO_2e/t$]	Emission per tonne waste diverted [$kgCO_2e/t$]
No organics	2299	0	421	2720	21.43	NA
GO only	3350	132	261	3743	29.50	75.22
FOGO only	3255	150	240	3644	28.72	64.90
AWT only	2299	469	145	2913	22.95	94.42
GO + AWT	3350	403	93	3846	30.31	56.23
FOGO + AWT	3255	395	86	3736	29.44	51.04

management resulted in reductions in emissions intensity.

Results here indicate that improvements to organics recovery and emissions intensity could be achieved through increasing diversion of household food waste into the FOGO stream, through improved household communication and better disposal practices. This may have the effect of reducing the proportion of food waste in the mixed stream, and thereby making diversion to AWT redundant as a pathway for organic waste recovery. This is particularly relevant given recent decisions limiting the application of AWT derived organic products for soil improvement (NSW EPA, 2018).

5. Model validation and limitations

Fig. 13 compares sensitivity of overall transport emission to variation in kerbside collection distances, transport vehicle load capacities, and waste generation. Variation in kerbside collection distances as a result of stochastic uncertainty in outputs from the CVRP solution algorithm was relatively small, ranging from between approximately ± 1%. This suggests that the solution algorithm converges on an optimal solution for each LGA that is roughly equivalent to a minimum distance that must be traversed in the LGA to service all properties. While the nearest neighbour search algorithm can be trapped in local optima, the large number of iterations performed for the CVRP solution gives some confidence that this is unlikely. Performing the CVRP on an even larger number of iterations as performed for this study, or utilising alternative solution approaches that appear in the literature including genetic algorithms, or swarm optimisation, may result in an improved solution. However these approaches were considered impractical for this study owing to the significant additional computational resources required for such a large study area analysed.

Bin pickup was the most significant component of kerbside collection as indicated in Table 7, however emissions from this component were not impacted by the CVRP solution. The mean sensitivity ratio of kerbside collection distance was approximately 0.88%/%, implying for a 1% change in kerbside collection distance, total emissions change by 0.88%. This sensitivity analysis performed for kerbside collection distances was simplified by estimating average variation in route selection by LGA classification—necessary due to the long computation times required for the CVRP solution algorithm. Despite this limitation, Fig. 13 shows a linear relationship between %-change in kerbside collection route distance and variation in overall emissions, implying that even with a larger variation in these distance for example ± 10%, the impact on overall emissions would be in the range of ± 8.8%.

Variation in total waste generation (± 20%) had a relatively small impact on overall transport emissions, with an approximate variation of between − 0.6% and 2.5% in emissions. Results of the sensitivity to transport emissions to variation in waste generation are summarised in Table 10. Variation in recovery transfer and disposal transfer emissions were approximately equal to the variation in waste generation, however these components were only responsible for approximately 11% of overall emissions (see Table 7). The kerbside collection component exhibited different sensitivities, with both variation in waste generation above and below baseline levels leading to increases in emissions. Lower quantities of waste generated led an increase in kerbside collection emissions of 1.2%. With reduced LGA waste generation, fewer collection routes were required, however the average distance of these routes were longer than baseline in order to meet the constraints of the CVRP approach (i.e., collection trucks aim for approximately 5 tonnes of waste collected per route). The sensitivity analysis showed that a 20% reduction in waste generation across the LGAs resulted in a 1.5%

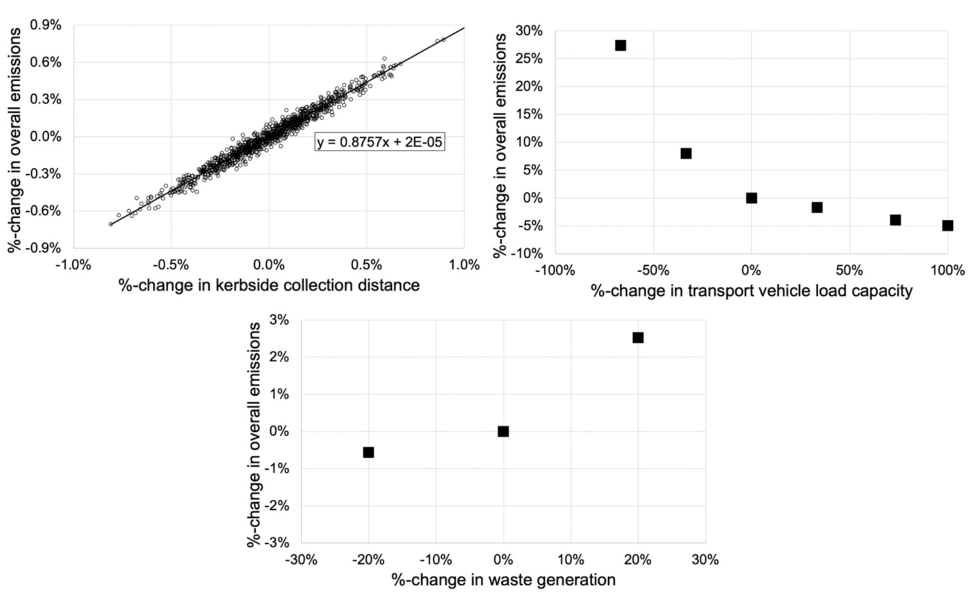

Fig. 13. Sensitivity plots for change in kerbside collection distance, and change in transport vehicle load capacity.

Table 10
Summary of sensitivity of emissions to variation in LGA waste generation. Values in the table are compared to baseline.

Variation in waste generation (% change)	Variation in kerbside collection emissions (% change)	Variation in recovery transfer emissions (% change)	Variation in disposal transfer emissions (% change)	Variation in overall transport emissions (% change)
+ 20%	+ 1.0%	+ 19.8%	+ 20.1%	+ 2.5%
-20%	+ 1.2%	-20.1%	-20.2%	-0.6%

increase in collection zone traversal distance, and a 22% increase in the average route length compared to baseline. For variation in waste generation above baseline, emissions compared to baseline were also higher, but only by approximately 1%. Total collection zone traversal distance increased by approximately 0.2%, and the average length per collection route decreased by approximately 1.4%. This implies that the CVRP estimation approach performs as expected with variation in waste generation across the LGAs, and gives confidence in the approach utilised.

Variation in transport truck sizes was found to be the more sensitive variable compared to variation in kerbside collection distances and waste generation. Small truck sizes (moving from the nominal value of 15 tonnes to 10 tonnes) lead to an average increase in emissions of approximately 8%. Larger truck sizes (moving from 15 tonnes to 26 tonnes) lead to an average decrease in emissions of 4%. The relationship between change in transport vehicle size and change in overall emissions is not linear as indicated in the figure. This suggests that transport truck sizes greater than 26 tonnes would have a reduced impact on overall emissions. Truck sizes smaller than 10 tonnes would have a greater impact on overall emissions, however this would imply little difference between waste collection vehicles and trucks used for transporting waste.

A further unknown in our model was the assignment of landfill locations to transfer stations and recovery distances based on proximity. To evaluate sensitivity on emissions, 3 candidate LGAs were selected (Burwood, Hornsby, Lake Macquarie) representing metropolitan, metro-fringe and regional LGA classifications. A simulation was performed whereby landfills were allocated to transfer stations and recovery facilities randomly over 1000 iterations. Landfill locations were randomly selected from a weighted sample, whereby random selection of landfills at large distances from transfer stations and recovery facilities was less likely. Results of this showed that disposal transfer distances could vary by up to 85% higher than baseline distances. The impact of this variation on overall transport emissions however was small, at approximately 4%.

The sensitivity analysis performed highlights some limitations in our model. Transport vehicles are a significant unknown in our model, with little data on the fleet of vehicles used for transporting aggregated waste quantities available. A comprehensive account of waste vehicles in operation in the study area would be required to further calibrate our model to give more certainty around overall transport emissions. While sensitivity of kerbside collection route selection is relatively small, calibration data including actual waste collection route data, or information on LGA waste collection zones would improve our model and give more confidence that our CVRP solutions are sensible and reflect actual waste collection routes in the study area. Sensitivity on landfill selection was small, and how likely non-proximal landfills are likely to be selected for disposal from transfer stations and recovery facilities is unknown. Data on specific landfills to which waste is destined by jurisdiction and recovery facility would improve accuracy of the results.

A further limitation of our model is in the treatment of apartment complexes in the estimation of kerbside collection distances. While data is available on the estimated distribution of dwelling types at the property lot level, data is limited on the bin systems for multi-unit dwelling types. The model presented here assumes that most apartment style buildings have bin collection systems similar to detached dwelling types, and have their bins collected on the same route as detached dwellings. This is not strictly true, especially for larger apartment complexes, which are more likely to have separate waste collection agreements with the local waste management authorities, and different bin collection systems. These buildings therefore may not be managed via the same kerbside system that detached dwellings and smaller apartment buildings are serviced by. However data on the management of large apartment complexes on an LGA level for the study area is limited, and is problematic to obtain given privacy issues, and contractual agreements between apartment buildings, local council, and

Table 11
Comparison of mean value performance metrics from this study, compared with data from literature sources.

Performance metric	Mean value ± uncertainty from this study	Value range in the literature	Literature reference
Emissions per tonne collected [kgCO_2-e/t]	22.1 ± 1.0	3.7 – 40.3	Friedrich and Trois (2013)
		48.8	Chen and Lin (2008)
		19.5–32.3	Larsen et al. (2009)
		27.8 ± 2.0	Nguyen and Wilson (2010)
Fuel economy of vehicles during collection [km/L]	1.12 ± 0.05	0.6 – 1.4	Jaunich et al. (2016)
		0.46 – 1.34	Agar et al. (2007)
Litres of fuel per tonne waste collected [L/t]	8.2 ± 0.4	1.4 – 10.1	Larsen et al. (2009)
		10.1 ± 0.7	Nguyen and Wilson (2010)
		7.1 – 10.6	Quintili and Castellani (2020)
Litres of fuel per tonne diverted (FOGO) [L/t]	13.2 ± 0.7	~17 ± 5	Edwards et al. (2016)

waste management service providers. It seems plausible however that regardless of the waste collection arrangement, waste collection vehicle travel between apartment complexes and transfer station, and hydraulic bin lifting requirements would be on the same scale as what is estimated here. Further analysis on apartment complex bin systems, and how individual LGAs manage apartment dwelling wastes would help to improve the certainty of model estimates, however was outside the scope of this work.

Despite these limitations, an analysis of calculated performance metrics from data generated from our model compared with literature data, gives confidence that our estimates are reasonable. Table 11 summarises this analysis. Literature cited in the table refer to studies performed across jurisdictions in a number of different countries, including South Africa, Taiwan, Denmark, Canada and the USA. Performance metrics compared to literature values were calculated from overall study area level estimates for emissions intensity of waste collected; and fuel economy of waste collection in terms of litres per kilometre travelled, and litres per tonne of waste collected. In general, performance metrics calculated from our model fall within, or close to, the ranges found in the literature, giving confidence that estimates from our model are realistic compared to other studies. This analysis also illustrates that emissions intensity and fuel intensity for waste collection in the study area are similar to values reported in the literature globally.

6. Conclusion

This study developed a spatial model for the estimation of emissions associated with kerbside collection and transportation of household organic wastes in the Greater Sydney and surrounding areas for 2018–19. The model developed was used to estimate waste related transport emissions of approximately 43,700 tonnes of CO_2-e for the management of kerbside organic waste.

Kerbside collection, specifically the between-bin travel and lifting of bins to waste vehicle receptacles, was found to be the most emissions intensive activity completed during organic waste collection and transportation. Findings from the study indicate that kerbside collection emissions are lower for more population dense areas—suggesting that collection emissions might be reduced by moving towards more centralised waste collection models, where greater quantities of waste are collected per collection point. The practicalities of such collection systems however were not assessed in this work. The separation of food waste from mixed waste via the co-collection of garden and food waste, with additional diversion of mixed waste to AWT facilities, was found to be the most efficient collection model in the study area, in terms of tonnes of organic waste diverted, and lowest emissions intensity. Collection of food and garden organic waste should be prioritised for LGAs in the future in support of emission reduction strategies, given recent restrictions on the application of AWT recovered products applied to land. Findings from this study also indicate that organic waste collection and transport emissions do not contribute significantly to state-wide transport emissions.

The model presented here has value in assessing the environmental impacts of waste collection and management for waste streams in the study area. Further work could incorporate this study's findings into a more comprehensive analysis of emissions over the entire waste management chain, including net emissions from the recovery of organic wastes, and emissions from landfill disposal. Moreover, results presented could be parameterised in order to estimate transport emissions from key variables, including population density, road network complexitiy, waste generation rates, and waste collection systems employed. The model presented could also be utilise to explore aspects of the waste management logistics chain, including more efficient routing to reduce labour costs, and also fuel costs—important when considering future scenarios exploring the electrification of the waste vehicle fleet. Future studies could also utilise the methodology developed for estimating emissions for collection and transport of non-organic materials including dry-recyclables to obtain a more complete estimation of waste-related emissions for the municipal waste stream in the study area.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.clwas.2022.100013.

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