Estimating Carbon Emissions from Processing Building Debris in Gaza

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Estimating Carbon Emissions from Processing Building Debris in Gaza

Samer Abdelnour* and Nicholas Roy

University of Edinburgh Business School
* Email: samer.abdelnour@ed.ac.uk

Summary

- The debris from destroyed and damaged buildings is a material representation of the unprecedented human, infrastructural, and environmental devastation resulting from the bombardment of Gaza.
- Removing, transporting, and processing the immense quantity of building debris will have a significant impact on Gaza's physical infrastructure and environment, while also representing a considerable portion of military-related carbon emissions.
- We estimate the carbon emissions arising from transporting building debris to nearby disposal sites, and from crushing uncontaminated concrete rubble into finer aggregates for reuse in building blocks, roadway repair, and shoreline protection.
  - We use open-source spatial data to **identify the location of over 32 million tonnes of debris** resulting from destruction and damage to buildings across Gaza.
  - Based on estimates of truck capacity and fuel consumption, it may take over **12,471,211 kilometres driven** to completely clear the debris present from sites where buildings are destroyed or damaged, equivalent to over **311 times the Earth's circumference**, and generating over **37,002.13 tonnes of CO_2e.**
  - Accounting for the likelihood that trucks will return to most building sites to refill their debris loads, **the cumulative distance driven could effectively double**, reaching the equivalent of over **600 times the Earth's circumference** and generating around **55,513.95 tonnes of CO_2e.**
- Once the debris is transported to disposal sites, processing will require industrial-scale machinery and manpower, and the carbon emissions produced by crushing uncontaminated concrete rubble are highly sensitive to the type of crusher used.
  - If a fleet of **50 high-capacity industrial jaw crushers** are employed, processing 32 million tonnes of debris could take just over **5 months** if 80% of this debris is viable for crushing, and generate an additional **2,584.03 tonnes of CO_2e**.
  - With a fleet of **50 smaller crushers**—the primary type used in the wake of previous bombardments—it could take over **29 years** to process the same quantity of debris, resulting in an 8-fold rise of carbon emissions to **21,849.03 tonnes of CO_2e.**
- Although the exact location of disposal sites is still to be determined, some of the disposal site locations proposed by the UNEP will likely face large differences in the quantity of debris that surrounds them.

1. Introduction

Since October 2023, Palestinians in Gaza have been subjected to a campaign of bombardment by Israel that is unprecedented in terms of human, infrastructural, and environmental devastation. As of 15 August 2024, over 40,000 people in Gaza have reportedly been killed, including nearly 17,000 children.[1] When indirect deaths due to disease and malnutrition are considered, the total death toll is likely to be well over 186,000,[2] reflecting the widespread destruction of critical infrastructure. As of July 6th, approximately 63% of structures in Gaza were estimated to have been damaged or destroyed,[3] including hospitals, schools, universities, waste management systems, and public utilities.[4] This has resulted in the internal displacement of over 1.9 million people, or approximately 85% of Gaza's inhabitants.[5]

Several intergovernmental and human rights organizations have called for an immediate permanent ceasefire[6] and reconstruction of civilian infrastructure.[7] However, the unprecedented volume of debris generated by destroyed and damaged buildings raises significant challenges on the path towards reconstruction. According to the United Nations Institute for Training and Research (UNITAR), over 41,946,018 metric tonnes of debris still line the streets of Gaza—14 times more than the combined sum of debris from all other conflicts in Gaza since 2008.[8] For scale, this is equivalent in weight to around 8 Great Pyramids of Giza, concentrated in an area less than one-quarter the size of Greater London. Spread over the entire area of the Gaza Strip, each square meter would contain an estimated 114 kilograms of debris. Removing the debris may take years and cost as much as $700 million, likely leading to additional waves of displacements as structurally unsound buildings are demolished or repaired.[9]

The safe removal, transportation, and recycling of debris is complicated by the presence of the remains of victims as well as contamination from unexploded ordnances (UXOs), asbestos, and other hazardous substances. In its preliminary assessment released on 18 June 2024, the United Nations Environment Programme (UNEP) estimated that over 800,000 tons of debris were likely contaminated with asbestos, and would therefore have to be transported and processed separately as hazardous waste.[10] Although the exact quantity and location of UXOs in Gaza is still unknown, a representative from the United Nations Mine Action Service (UNMAS) stated that around 10% of ordnance may not detonate on impact.[11] The Mine Action Group (MAG), a UNMAS partner, also reported that over 25,000 tons of explosives had been dropped on Gaza between October 2023 and February 2024.[12] Based on these figures, it may be inferred that around 2,500 tons of ordnance—over 6 times the explosive power of the 2020 Beirut explosion[13]— remained buried in Gaza as of February alone.

Palestinians in Gaza responded to debris-related challenges in 2009, 2012, 2014, and 2021 through a combination of disaster and demolition waste management practices.[14] In 2021, debris removal began with on-site assessments of damaged buildings, UXO removal, and separation of hazardous waste from rubble. Debris was then transported to several processing sites, including the Juhr Al Deek landfill in northern Gaza, the primary disposal site for the United Nations Development Programme's (UNDP) contractor. At the landfill, hazardous waste was stored separately for recycling, treatment, or disposal. Uncontaminated rubble was sorted by material type, revealing a composition of 88% concrete, 8.6% non-concrete, and 3.4% reinforced concrete. Smaller concrete pieces were crushed on-site or sold to the private sector for reuse in building blocks and road pavement, while larger reinforced concrete foundations were transported to off-site for shoreline protection and land reclamation.[15] Of the 122,525 tons of rubble brought to Juhr Al Deek, 111,621 tons were reportedly crushed, indicating that recycling rubble could play an important role in reconstruction. Palestinians in Gaza have thus obtained materials typically difficult to procure because of Israel's blockade through recycling using local machinery and labour.

The 2021 post-bombing response illustrates steps needed for effective debris management. However, addressing the substantially greater volume of debris currently in Gaza—around 41.9 million tonnes compared to 335,658 tonnes in 2021[14]—will require significantly more resources, including disposal space, manpower, and industrial-grade machinery. The mobilization of these resources is essential, but may be associated with considerable economic and environmental implications. For instance, carbon emissions arise from the fuel consumption of heavy trucks and crushers, as well as from the carbon embodied in materials consumed throughout the debris management process, such as depreciating equipment and polythene sheets.

Since such emissions occur during the clearing of debris from damaged and destroyed buildings, they fall outside the mandatory reporting categories under the current UN Framework Convention on Climate Change (UNFCCC).[16] However, under the Conflict and Environment Observatory's (CEOBS) military greenhouse gas (GHG) framework—proposed to address gaps in military GHG reporting—such emissions would be classified as 'Scope 3+' emissions. Other examples of Scope 3+ emissions under this framework include those arising from the combustion of fuels for military aviation and transport vehicles, the construction of military buildings and bases, military-derived waste management and disposal, fires impacting infrastructure and landscapes, movements of displaced populations, and the reconstruction of buildings destroyed by war.

The proposed CEOBS framework has been used to explore the climate impact of military activities and war. For example, emissions from fires, military vehicle fuel consumption, and materials needed to rebuild civilian infrastructure have been estimated in the context of the Ukraine war.[17] Similarly, the embodied carbon of reconstructing destroyed buildings, the construction of Hamas' tunnel network, and Israel's "Iron Wall', have been estimated in relation to Gaza.[18] In this report, we contribute to this growing literature by estimating the carbon footprint of transporting and processing debris from destroyed and damaged buildings in the Gaza Strip. Our findings underscore the often-overlooked climate impact of debris removal and processing, and highlights the challenges of quantifying military and war-related climate impacts when direct data collection is not possible.

2. Methodology

In this section, we provide a high-level overview of the procedure used to estimate carbon emissions from two key activities: transporting debris from destroyed buildings in Gaza to nearby disposal sites and crushing the rubble for reuse in future construction projects. More detailed descriptions are provided for steps involving data preparation or exogenous assumptions.

We start by constructing a spatial map of building debris across Gaza, which allows us to identify the locations of destroyed buildings and estimated quantities of debris at each destroyed building site. This spatial debris map draws from a variety of spatial datasets, which may differ slightly in their representation of building sites (e.g., as polygons vs. points) or in the exact location they assign to the site. To unify these datasets into a consistent map of debris across Gaza, we first obtain a map of the footprints—or surface areas represented as polygons—of buildings in Gaza from Microsoft's Global Building Footprints Dataset.[19] Collected from satellite imagery between 2014 and 2021, these building footprints identify each building's location and surface area prior to any destruction since October 2023 and serve as a common reference point for matching features from other spatial datasets.

Although the building footprints provide locations and surface areas, they do not identify which buildings have been destroyed or damaged thus far. For this, we obtained building damage classifications from UNOSAT's Building & Housing Unit Damage Assessment, which classifies damage at each building site (represented as a point) with labels such as "moderately damaged," "severely damaged," or "destroyed," based on satellite imagery.[3] We matched each building footprint to the single nearest damage classification point within a radius of 4 meters. If a footprint was within 4 meters of several damage classifications, it would inherit the highest level of damage—for example, a footprint near both "destroyed" and "moderately damaged" points was classified as destroyed. Footprints more than 4 meters from any damage classification point were assumed to be intact. The cut-off of 4 meters was chosen to allow a greater number of footprints to be matched with slightly misaligned damage classifications without overclassifying the number of destroyed or damaged buildings. Figure 1 illustrates the matching of damage classification points to building footprints around a street of Bureij, Deir al-Balah. Most footprints are matched to a single point they overlap, but some deviate by a few meters, and others contain several points of different damage classifications.

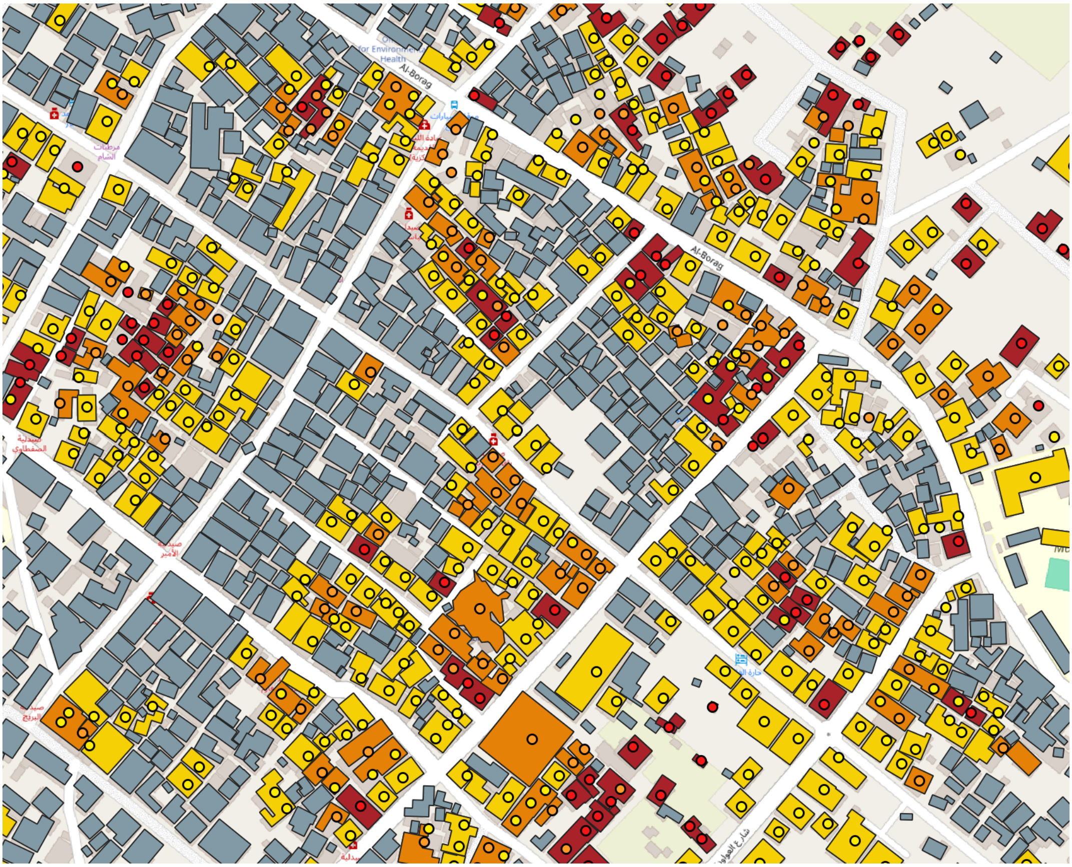

Figure 1. Matching building footprints to nearby damage classifications. Affected footprints (brightly coloured) inherit the highest damage classification of points within 4 meters: moderate damage (yellow), severe damage (orange), and destroyed (red). Footprints for which there are no points within 4 meters are assumed to be intact (grey).

With each building's location, surface area, and damage classification (intact, moderately damaged, severely damaged, or destroyed), we require only the number of storeys to complete the spatial debris map. This is because the quantity of debris generated by the destruction of a building is closely related to its total living space, which is calculated by multiplying the number of storeys by its surface area. While similar to estimating debris by volume, this method accounts for the fact that buildings with fewer floors may generate less debris than shorter buildings with many compressed floors. Following UNEP's approach, we assume that each square meter of destroyed living space produces about one tonne of debris.[10] In the spatial debris map, the quantity of debris is calculated by multiplying the surface area of each footprint classified as "destroyed" by the number of storeys. For footprints classified as "severely damaged" or "moderately damaged", we replicate the same procedure, with the caveat that they likely produce a fraction of the debris generated by destroyed buildings. In the results section, we report the full emissions associated with each damage classification separately and provide a recommendation for how the figures may be aggregated.

Since the storey count for each destroyed or damaged building is not provided in the UNOSAT damage classifications or the Microsoft building footprints, we rely on other spatial datasets to obtain this information. We turned to a dataset in the Palestinian Central Bureau of Statistics' (PCBS) public spatial data repository, which represents buildings as points with attributes such as the number of storeys derived from the 2017 census.[20] However, some of our baseline footprints lacked nearby

PCBS points, and some PCBS points had missing values for the storey count attribute. To fill these gaps, we used 'Average of Net Building Height' (ANBH) from Copernicus' Global Human Settlement Building Height (GHS-BUILT-H) raster, which provides the average height, in meters, of built-up structures within a 100m x 100m grid across Gaza.[21] For footprints missing a storey count, we thus assigned the height of the ANBH grid in which they are located. The inherited height was then converted into an approximate storey count by assuming each storey is 3 meters tall and rounding to the nearest whole number. Overall, we found that about 55,000, or 19%, of the Microsoft building footprints lacked a corresponding PCBS building point nearby and thus required the ANBH raster to estimate their storey count. Figure 2 illustrates the matching of building footprints to nearby PCBS storey points around a street of Bureij, Deir al-Balah. Most footprints are matched to the single point they overlap, but some are matched to points located within 4 meters, and others are matched to multiple PCBS points they overlap. In the case when a footprint overlaps multiple PCBS points, it inherits the average number of storeys, rounded to the nearest whole number. Averages resulting in midpoint values (e.g., 0.5, 1.5, 2.5) are rounded down to prevent overestimating storey counts of buildings overlapping only two PCBS points.

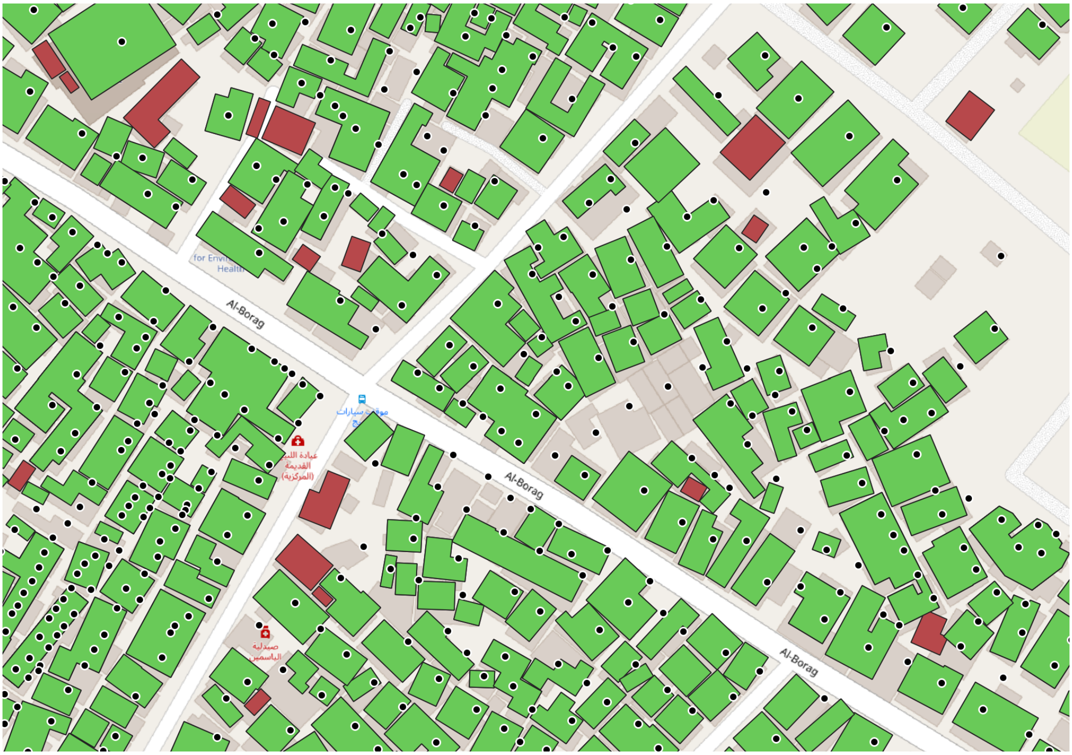

Figure 2. Matching building footprints (green if within 4 meters of a PCBS point; red otherwise) to nearby PCBS points containing storey count information (black).

By integrating the building footprints, surface areas, and story counts, we can create a map estimating the debris generated by destroyed buildings, as illustrated in Figure 3. This allows us to calculate the number of truckloads or trips required by a typical transport truck to clear all the debris from a given building site. The number of full truckloads is calculated by dividing the total debris at each building site by the truck's maximum capacity and rounding down to the nearest whole number. We assume that each truck has a maximum carrying capacity of 19 tons or around 12 cubic meters. This is the same capacity assumed by the UNEP to estimate the total time it may take to remove all of the debris in Gaza—with a fleet of 105, 19-ton capacity trucks operating in 8-hour shifts for 30 days a month, it could take up to 15 years.[10]

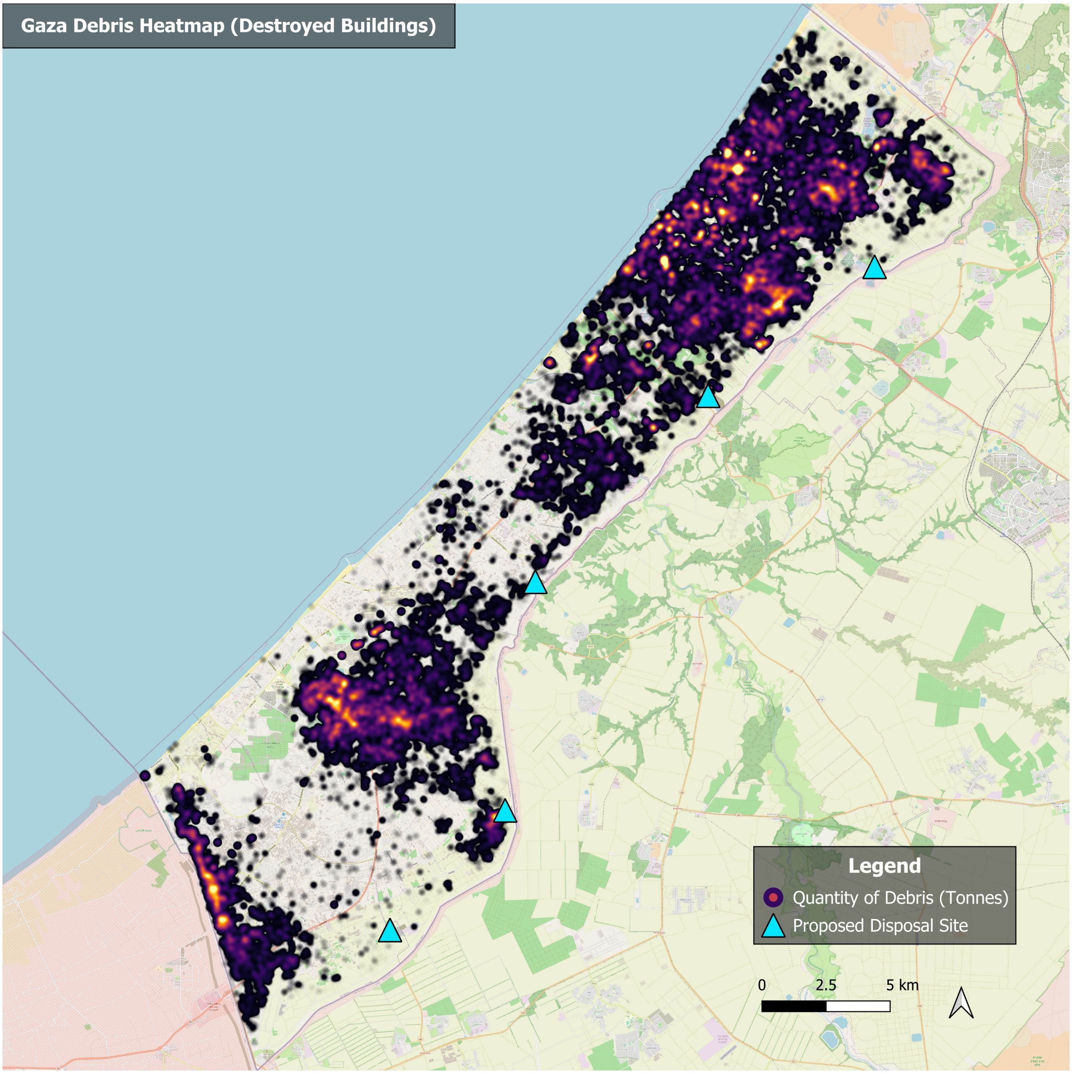

Figure 3. Heatmap of estimated debris (in tonnes) generated by destroyed buildings. Brighter areas indicate the presence of larger quantities of debris. Blue triangles indicate disposal sites proposed by the UNEP.[10]

In addition to the number of truckloads, the carbon emissions arising from debris transport also depend on the distance each truckload must travel from the destroyed building to the disposal site. Although there is still some uncertainty regarding the exact location and capacities of disposal sites, we adopt the disposal site locations proposed by the UNEP in its preliminary assessment, and assume trucks travel the shortest path, along Gaza's network of streets and roads, from each destroyed or damaged building to the nearest proposed disposal site. For simplicity, we assume that this road network will resemble Gaza's 2021 road network[22]; however, it is important to note that large-scale reconstruction of the road network will likely have to occur concurrently to the removal of debris.

As of 29 May 2024, UNOSAT estimated that approximately 33% of the road network in Gaza was moderately affected, 8% severely affected, and 24% destroyed.[23] Figure 4 highlights shortest paths that were calculated from 5 different destroyed buildings in Khan Younis to the nearest disposal sites. Since shortest paths must follow the topography of the roadways, this offers a more realistic distance metric than simply following a straight line to disposal sites.

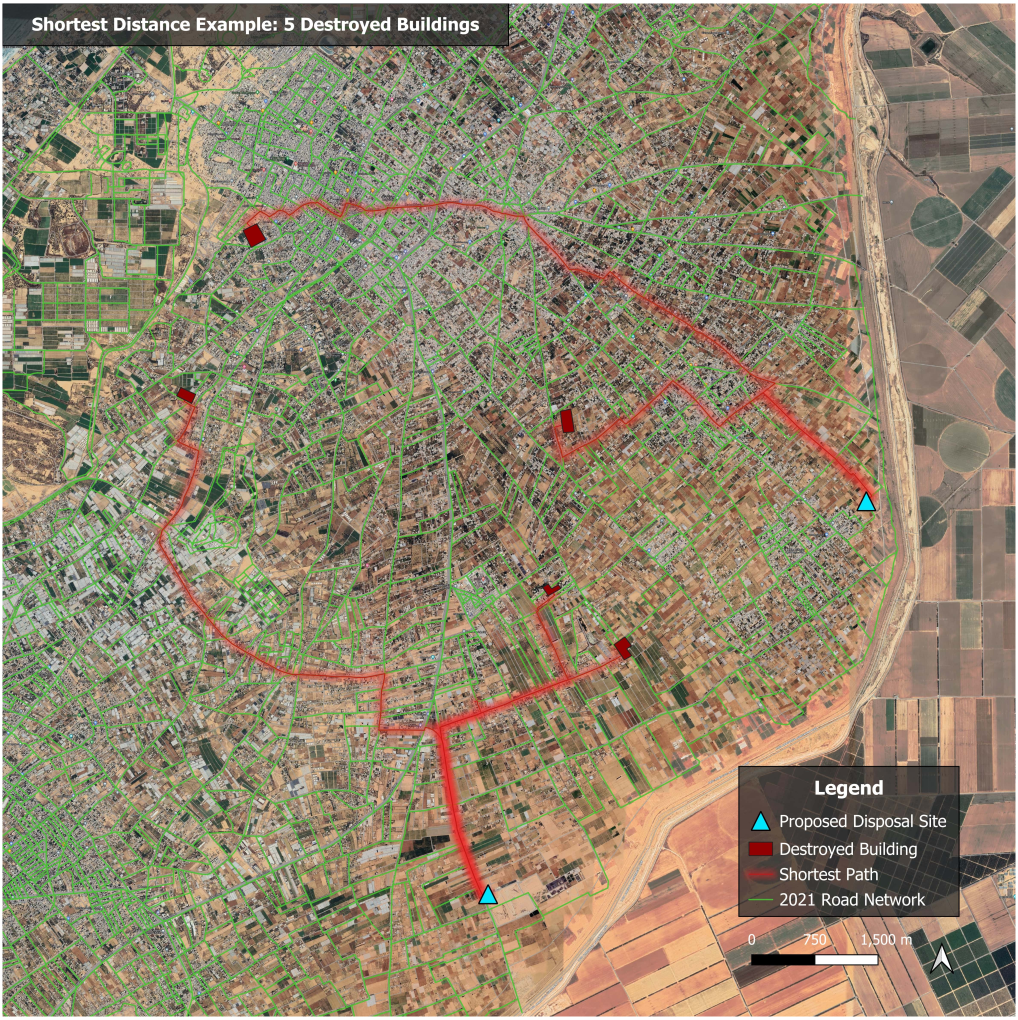

Figure 4. Shortest paths (red lines) from 5 destroyed buildings (dark red polygons, enlarged for visual emphasis) to nearest disposal sites (blue triangles) along Gaza's 2021 road network (green lines).

The total distance driven to clear all debris from a given destroyed or damaged building site can be estimated by multiplying the number of full truckloads by the shortest distance to the nearest disposal site. The cumulative distance driven by trucks to clear the debris across Gaza is obtained by summing the total distances from all destroyed or damaged building sites. When multiplied with an appropriate carbon emission factor, the cumulative distance yields the total carbon emissions (CO_2e) generated by the transportation of debris from buildings to disposal sites. The typical carbon emission factor for heavy transport trucks can vary significantly across vehicle model, road conditions, and geographical region, but likely ranges between 100-200g CO_2e / tonne-km. Climatiq estimates an emissions factor for medium- and heavy-duty freight trucks of 169.4g CO_2e / ton-mile, or around 116.1g CO_2e / tonne-km, based on the Environmental Protection Agency's (EPA) GHG Emission Factors Hub.[24] The International Council on Clean Transportation (ICCT) reports average emission factors for different truck types across the European Union, including 111.0g CO_2e / tonne-km for 6x2-axle regional delivery trucks, 197.2g for 4x2 regional delivery trucks, and up to 307.2g for 4x2 urban delivery trucks.[25] Given that most of the transportation of debris in Gaza will occur in urban areas and will likely require a minimum of 3 axles to handle a 19-ton debris load, we assume a carbon emission factor of 172.1g CO_2e / tonne-km, obtained by scaling up the 6x2-axle regional delivery factor to reflect the 1.55-fold increase of the 4x2-axle factor between regional and urban settings.

Since these carbon emission factors are normalized by carrying load, we must first multiply them by the assumed maximum capacity of the truck, before multiplying them by the cumulative transportation distance to obtain total carbon emissions. However, with a limited number of trucks available, trucks will likely need to return to a building site after each trip to the disposal site. In this case, the cumulative distance driven by all trucks could nearly double, but with a lower carbon emission factor for the unloaded return trip. The impact of load on the carbon intensity of a truck is still an ongoing topic of research, but one study found that overall emissions increased by 34% when the payload was similar in weight to the unloaded heavy-duty diesel truck.[26] Another found that carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_x), hydrocarbon (HC), and particulate matter (PM) emissions increased by 20.4%, 23.5%, 29.0%, 11.7%, and 9.4%, respectively, in fully loaded trucks compared to their unloaded counterparts.[27] Since carbon dioxide and nitrogen oxides are the two primary pollutants in diesel engines,[28] an increase of emissions of 20-34% from fully loading an empty truck would imply that emissions for unloaded trucks may be between 74-83% of their fully loaded counterparts. However, to ensure the estimate of return trip emissions remains conservative, we assume that the carbon emissions for unloaded trucks is only 50% of their loaded counterparts.

In addition to the CO_2e generated by the transportation of debris, we also estimate the carbon emissions generated by processing debris once it has arrived in landfills. Particularly, we estimate the emissions associated with operating crushers to convert concrete rubble into finer aggregates for reuse in reconstruction. Although there is still some uncertainty regarding the exact proportion of rubble that is viable for crushing, we may be able to approximate it by deducting the quantity of contaminated debris from the total estimated with the spatial debris map, and then scaling the remaining amount by the proportion of rubble that was crushed after previous bombardments in Gaza. We assume that the proportion of debris contaminated by asbestos remains roughly equivalent to the proportion estimated by the UNEP in June 2024: 725,748 metric tonnes of asbestos-contaminated debris divided by their total estimate of 32,296,660 tonnes generated by destroyed buildings, or roughly 2.2% of total debris[10]. However, there are other forms of contamination besides asbestos which may require hazardous waste disposal, such as heavy metals, chemicals used in agricultural and industrial processes, and biohazardous materials. For a conservative estimate of crusher emissions, we therefore assume that potentially up to 10% of the total rubble generated could be designated as hazardous waste. We then assume that only 88% of the remaining uncontaminated rubble is composed of concrete elements which can be crushed. This proportion is roughly in line with the estimate that 88% of the total debris was composed of non-reinforced concrete elements at Juhr Al Deek in 2021,[14] as well as the UNDP's plan to crush 300,000 out of 340,000 tons ($\approx$ 88.2%) of removed rubble following the 2009 bombardment.[29] Together, these assumptions would imply that approximately 80% of total debris transported to the landfill sites may be viable for crushing.

Carbon emissions from operating crushers also depends on their type or model used at the disposal sites. In 2012, the International Labour Organization (ILO) reported that there were around 30-50 small crushers in Gaza, with a cost of around \$3,500 to \$4,000 per unit.[30] In 2010, they had reported that the average monthly aggregates produced by recycling rubble was approximately 38,000 tons.

Assuming 30 days of runtime each month, for 8 hours a day, the total crushing capacity would be around 158 tons per hour, or around 3.2 to 5.6 tons per hour for each crusher. Capacities of this magnitude would likely fall in the range of an 8" x 12" jaw crusher, which can process around 2 to 6 tons per hour.[31] Although similarly sized jaw crushers appear in a short 2010 documentary released by Al Jazeera on debris recycling in Gaza,[32] as well as in a photograph included in an Al Jazeera article about the 2021 recycling process,[33] there is indication that these were not the only type of crusher used. In the article detailing the 2021 debris management process,[14] a photograph of one of the crushing sites shows a mobile crushing unit of a significantly larger size. Reverse image search revealed that the model of the jaw crusher in this photograph is likely related to an Apollo OM Jaw Crusher model, which may have a maximum capacity of around 400 tonnes per hour according to the manufacturer.[34]

While it is difficult to estimate the exact proportion of smaller jaw crushers to larger mobile crushers in the fleet, it is likely that a substantial number of higher-capacity crushers are needed. With a fleet of only 50, 6-ton capacity crushers operating for 8 hours a day, 365 days a year, it could take over 38 years to process 41.9 million tonnes of debris if 80% of this debris is viable for crushing. However, with a fleet of 50, 400-tonne capacity crushers operating full-time, this figure drops down to just below 7 months. For simplicity in estimating emissions, we consider these two cases separately. In the first case, the fleet is assumed to be composed solely of smaller, 8" x 12" jaw crushers with an assumed capacity of 6 tons per hour. Fuel consumption varies by the engine that powers them but may range between 1[35] to 6[36] litres of petrol per hour. As a conservative estimate, we assume full-power processing of concrete consumes around 2 litres of petrol per hour. In the second case, the fleet is assumed to be composed solely of larger mobile jaw crushers with a capacity of 400 tonnes per hour and a fuel consumption of around 15 litres of diesel per hour.[37]

In both cases, we can estimate total emissions from operating the fleet by multiplying the total quantity of fuel consumed by the relevant carbon emission factors for diesel and petrol. According to the U.S. Energy Information Administration (EIA),[38] motor gasoline has a carbon dioxide emissions coefficient of 8.78 kg of CO_2 per litre, or roughly 2.32 kg of CO_2 per litre, whereas diesel has a slightly higher coefficient of 2.69 kg of CO_2 per litre. The estimate of carbon emissions from crushing follows by dividing the quantity of non-contaminated concrete rubble (assumed to be 80% of total debris), by the capacity of crushers employed in the fleet (6 tons per hour for smaller crushers or 400 tonnes per hour for larger crushers), and multiplying the result both an estimate of the fuel consumption (2 litres of petrol per hour / 15 litres per hour) and the relevant carbon emission factor (2.32 kg of CO_2 per litre / 2.69 kg of CO_2 per litre).

(a)

(b)

(c)

Figure 6. Equipment used for crushing concrete rubble in Gaza: (a) Mobile jaw crusher at Juhr Al Deek landfill in 2021.[14] (b) Related model used to approximate capacity and fuel consumption.[39] (c) Smaller jaw crusher used by Palestinians in Gaza in 2021.[33]

3. Results

In this section, we present the estimated emissions from the transporting and crushing the current quantity of debris in Gaza, along with key figures derived using the methodology outlined in the previous section.

We begin by discussing the average properties of buildings—such as surface area and number of stories—for each damage classification: moderate, severe, and destroyed. Table 1 shows that the number of moderately damaged and destroyed buildings greatly exceed the number of severely damaged buildings, likely due to the latter's high structural instability and potential for collapse. On average, destroyed buildings are slightly smaller in terms of both surface area and number of stories. However, this does not necessarily indicate that smaller buildings are targeted more frequently, but rather reflects a degree of selection bias: smaller buildings are more likely to be destroyed or severely damaged by a bomb blast of a given radius, because the degree of destruction is assessed as a percentage of the building structure affected. According to an UNOSAT report from 2014, buildings were identified as "destroyed" if 75-100% of the building structure was collapsed or destroyed; "severely damaged" if a 30-75% of the structure was destroyed; "moderately damaged" if 5-30% of the structure was damaged or destroyed.[40]

These percentages also have implications on how to aggregate the total quantity of debris across different damage classifications. In Table 1, we report the full debris quantities for each damage classification, as if all damaged buildings would eventually be destroyed, but the actual quantity of debris present in Gaza is likely a fraction of this figure for moderately and severely damaged buildings. We thus employ the percentages of UNOSAT's description of damage classifications as weightings and assume that destroyed buildings generate 100% of their unweighted debris; severely damaged buildings, 75% of their debris; and moderately damaged buildings, 30% of their debris. This yields a weighted sum of 32,020,134.26, tonnes of debris—approximately 76% the magnitude of UNITAR's estimate of 41,946,018 tonnes.[8] The discrepancy between these estimates likely arises from differences in calculation methodology and datasets employed. However, if the methodology behind the figure reported by UNITAR follows similarly to the one reported by UNEP,[10] then the figure may also include the debris generated by damaged and destroyed roads in Gaza, which we omit in our analysis. The UNEP report estimated that 3,600,000 tonnes out of the total estimate of 39,200,978—or roughly 9.2%—was generated by roads. If this proportion remains true, then our estimate of 32,020,134 tonnes of debris generated by buildings alone may imply an overall quantity of around 35.2 million tonnes of debris—slightly closer to UNITAR's preliminary estimates.

Table 1. Estimated Debris Quantities

Building Damage Classification	**Number of Buildings**	**Avg. Surface Area** (Sq. Meters)	**Avg. Storey Count**	**Avg. Quantity of Debris** (Tonnes)	**Avg. Quantity of Debris** (Tonnes)	**Qty. of Debris - Weighted**[a] (Tonnes)
Moderate Damage	50,217	205.14	2.42	568.29	27,247,640.76	8,174,292.23
Severe Damage	17,582	222.84	2.27	555.98	9,775,309.54	7,331,482.16
Destroyed	42,275	182.75	1.91	390.64	16,514,359.88	16,514,359.88
Total	**110,074**	-	-	-	**53,537,310.18**	**32,020,134.26**

[a] Weighted quantities represent the debris sum, scaled by damage classification: 30% for moderate damage, 75% for severe damage, and 100% for destroyed buildings.

Table 2 highlights the key factors in estimating the cumulative distance trucks travel when transporting debris from damaged or destroyed buildings to disposal sites proposed by the UNEP. With relatively equal average distances to the nearest disposal site, differences in cumulative distance depend largely on the quantity of debris present at building sites. For buildings classified as moderately and severely damaged, around 50% more full truck loads are required to clear the debris, on average, assuming that buildings of all damage classifications would eventually be demolished. However, if we assume that moderately damaged and severely damaged buildings generate less debris than destroyed buildings, the overall cumulative distance is lower. Adopting the same percentages as before, the weighted sum of 100% of the cumulative distance for destroyed buildings, 75% of the distance for buildings classified as severely damaged, and 30% for those classified as moderately damaged yields a cumulative distance of 12,471,211.55 kilometres. To contextualize this figure, the equatorial circumference of Earth is around 40,075.017 kilometres,[41] implying that the total distance driven by transport trucks to clear the current quantity of estimated debris in Gaza— assuming trucks travel only one-way with a full capacity to the nearest proposed disposal site— would wrap around Earth's equator 311.2 times. This does not account for the fact that trucks often must return to a building site with an empty load. In the case of destroyed buildings, which tend to be smaller in volume than moderately or severely destroyed ones, over 95% of buildings require more than one full truckload, indicating that the cumulative distance driven could effectively double to 620 times around the Earth's equator.

Table 2. Estimated Distances Driven

Building Damage Classification	**Avg. Distance to Nearest Disposal Site** (Kilometres)	**Avg. Number of Full Truckloads**	**Total Number of Full Truckloads**	**Total Number of Full Truckloads - Weighted**	**Total Distance**[b] **to Nearest Disposal Site** (Kilometres)	**Total Distance to Nearest Disposal Site - Weighted** (Kilometres)
Moderate Damage	6.72	30.99	1,556,317	466,895	10,899,442.72	3,269,832.82
Severe Damage	6.75	31.77	558,624	418,968	3,833,629.22	2,875,221.92
Destroyed	6.59	22.67	958,467	958,467	6,326,156.82	6,326,156.82
Total	-	-	**3,073,408**	**1,844,330**	**21,059,228.76**	**12,471,211.55**

[b] Total distances represent the sum of all distances to disposal sites, taking into account the total number of truckloads required to clear the debris from each destroyed or damaged building.

Table 3 summarizes the carbon emissions associated with the transportation of debris from damaged and destroyed buildings to nearest disposal sites (outbound), and the journey from disposal sites back to the same building site with an empty payload (inbound). It is important to note that the extent to which inbound trips contribute to total emissions is difficult to estimate for buildings requiring less than two full truckloads, but given that a significant majority of buildings—95% in the case of destroyed buildings—require more than two truckloads, we assume that each outbound trip is accompanied by an inbound trip of the same distance. Since the emissions of empty inbound trucks were estimated to be 50% of the emissions of full outbound trucks, the overall effect of including inbound trucks simply scales estimated outbound emissions up by 50%. As before, we can estimate the weighted sum of emissions using the percentages of the building structure affected for each damage classification, resulting in a weighted total of 37,002.13 tonnes of CO_2e. For reference, this is more twice the carbon emissions that would arise from combusting all of the marine and aviation-related fuel tanks on the Royal Navy's flagship aircraft carrier, *HMS Queen Elizabeth*.[42] While this figure is still relatively small on a country level—roughly on par with the annual emissions produced by the nearly 6,000 inhabitants of Saint Pierre and Miquelon[43]—it only represents the climate impact of a single component of a significantly larger reconstruction process: the transportation of debris from destroyed and damaged buildings to disposal sites.

Table 3. Estimated Transportation Emissions

Building Damage Classification	**Outbound Transport Emissions**[c] (Tonnes CO_2e)	**Outbound Transport Emissions - Weighted** (Tonnes CO_2e)	**Inbound Transport Emissions** (Tonnes CO_2e)	**Inbound Transport Emissions - Weighted** (Tonnes CO_2e)
Moderate Damage	32,338.69	9,701.61	16,178.74	4,853.62
Severe Damage	11,374.39	8,530.79	5,690.50	4,267.88
Destroyed	18,769.73	18,769.73	9,390.319	9,390.32
Total	**62,482.82**	**37,002.13**	**31,259.56**	**18,511.82**

[c] Outbound emissions refer to those generated during transport of debris to disposal sites, while inbound emissions cover the return trip with an empty truck.

Table 4 displays the carbon emissions associated with the crushing of non-contaminated concrete rubble, assumed to be 80% of total debris, for two cases: the entire fleet is composed of either large 400-tonne capacity mobile jaw crushers or smaller, 6-ton (or equivalently 5.44-tonne capacity) jaw crushers. Despite motor gasoline having slightly lower carbon emission factor than diesel, the lower capacity of the smaller crushers relative to their fuel consumption resulted in significantly greater emissions. Aggregating the emissions of these cases with the UNOSAT weightings yields overall carbon emissions of 2,584.03 tonnes of CO_2e for a fleet of large crushers, and 21,849.03 tonnes of CO_2e for a fleet of small crushers. Both emissions are significantly lower than the overall emissions associated with transportation of debris; however, emissions can be greatly reduced by using more efficient, industrial-scale crushers during recycling.

Table 5 displays the quantities of debris arriving at each proposed disposal site, disaggregated by damage classification, in addition to the sites' approximate locations. This provides an overview not necessarily of the exact capacities and quantities that may arrive at the disposal sites, but of the quantities of debris which may be transported to each site, prior to the adjustment for contamination or crusher material suitability, if minimizing cumulative transportation distances along the road network was the only criterion used to allocate debris. It is important to note, as in previous tables,

Table 4. Estimated Crusher Emissions

Building Damage Classification	**Qty. of Debris Viable for Crushing**[d] (Tonnes)	**Large Crusher Emissions** (Tonnes CO_2e)	**Large Crusher Emissions - Weighted** (Tonnes CO_2e)	**Small Crusher Emissions** (Tonnes CO_2e)	**Small Crusher Emissions - Weighted** (Tonnes CO_2e)
Moderate Damage	21,798,112.61	2,199.00	659.70	18,592.51	5,577.75
Severe Damage	7,820,247.63	788.90	591.68	6,670.21	5,002.66
Destroyed	13,211,487.90	1,332.51	1,332.51	11,268.62	11,268.62
Total	**42,829,848.14**	**4,320.41**	**2,583.89**	**36,531.34**	**21,849.03**

[d] Assumes that 20% of total debris is contaminated by hazardous waste or composed of non-concrete and reinforced concrete elements, and therefore unsuitable for crushing.

that the quantities reported reflect the full volume of the building, even when the structure is moderately or severely damaged. To aggregate these quantities into a more realistic estimate of current debris in Gaza, we employ the UNOSAT percentages to produce weighted sums in the final column of Table 5. The weighted sums indicate that Disposal Site #2, corresponding to a newly proposed disposal site located at Khan Younis, may require the greatest capacity, if debris is routed in a way that minimizes distance travelled. If other allocations of debris are pursued, they will likely be associated with greater cumulative distances to transport debris from damaged and destroyed building to the disposal sites, and thus greater carbon emissions from transportation.

Table 5. Estimated Debris Quantities by Disposal Site

Disposal Site (Index)	**Approx. Location** (Latitude / Longitude)	**Qty. of Debris Nearest to Site: Moderate Damage** (Tonnes)	**Qty. of Debris Nearest to Site: Severe Damage** (Tonnes)	**Qty. of Debris Nearest to Site: Destroyed** (Tonnes)	**Total** (Tonnes)	**Total - Weighted** (Tonnes)
1	31.269393 / 34.321974	3,488,763.98	876,287.82	1,947,153.01	6,312,204.81	3,650,998.07
2	31.312357 / 34.368393	11,740,046.94	1,319,710.42	4,481,889.72	17,541,647.08	8,993,686.62
3	31.392757 / 34.379981	7,130,068.97	4,178,956.92	1,334,210.12	12,643,236.01	6,607,448.50
4	31.458955 / 34.450527	2,828,954.28	2,698,582.44	3,218,769.82	8,746,306.54	6,091,392.93
5	31.504582 / 34.518419	2,059,806.59	701,771.94	5,532,337.22	8,293,915.75	6,676,608.15
Total	-	**27,247,640.76**	**9,775,309.54**	**16,514,359.88**	**53,537,310.19**	**32,020,134.27**

4. Conclusion

In this report, we estimated carbon emissions associated with two phases of the reconstruction of Gaza: the transportation of debris to waste management sites and the crushing of concrete rubble for recycling. Our approach to transportation focused on estimating the total distance required to clear a significant portion of the debris in Gaza and calculating the resulting emissions using an approximate carbon emission factor. For crushing, we estimated total machine-hours required by both low- and high-capacity crushers to process uncontaminated concrete rubble and calculated the carbon emissions from the fuel combustion needed to power the machines. Although the resulting emissions are relatively low compared to those generated annually at international levels, they may still play a significant role in the overall emissions linked to the reconstruction of civilian infrastructure in Gaza. Given that these emissions would be concentrated within the small and densely populated area of the Gaza Strip, this also raises important questions about the potential health impacts of clearing such a large volume of debris. Further research is needed to assess the potential levels of dust, air pollutants, and noise generated by the daily movement of hundreds of trucks, and the impact this could have on both housed and displaced Palestinians in Gaza.

As the bombardment and destruction is ongoing, we recognize that some of these findings can change rapidly considering new data and assumptions. We sought to present our methodology in sufficient detail so that other researchers could potentially follow its underlying logic and adjust components as necessary.[1] Although this report narrowly focuses on the climate impact of only two phases of a much larger reconstruction process, we hope that some of the methods and datasets discussed may be relevant for addressing other gaps in military-related emissions in Gaza and elsewhere. For instance, spatially aggregating building footprints and other properties—such as storey count and building function from OpenStreetMap labels—may enable researchers to estimate the total carbon embodied in reconstructed buildings with higher fidelity than assuming a prototypical building structure and extrapolating by the number of destroyed structures. Emissions from the delivery of humanitarian aid and supplies may be quantifiable in a similar manner as the transportation of debris: by calculating the shortest distances to distribution points along intact roadways, and estimating emissions associated with the delivery trucks' combustion of fuel. We urge researchers to continue identifying and addressing gaps in military-related emissions to develop a more comprehensive understanding the impacts the unprecedented bombardment of Gaza has had on people, infrastructure, and environment. Finally, we feel it important to reaffirm that some losses are simply unquantifiable, particularly the loss of human lives and health, the destruction of historical sites and cultural heritage, and the irreversible damage to the natural environment.

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Notes

[1] For the project's QGIS folder, including the spatial datasets used in the estimation, please see: https://github.com/NetworkGestalt/Gaza-Debris-Emissions

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