GHG Benefits of Trash Capture Projects

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Introduction

The primary purposes for proper management and disposal of roadside trash include direct aesthetic, social, and environmental benefits. Preservation of roadside landscapes in attractive, litter-free states contributes to the overall health and welfare of natural resources and communities. Direct environmental benefits include preservation of wildlife, ecosystems, and natural resources in healthy states. In keeping with Caltrans' response to California Water Boards Orders and for the protection of beneficial uses of aquatic and marine environments, Caltrans installs trash capture devices to prevent litter from entering drainage systems and being swept into waterways and oceans (California Water Boards, 2021, 2017a, 2017b; Southern California Coastal Water Research Project, 2021). **Figure 1.** Examples of trash capture devices for stormwater systems. Source: U.S. Environmental Protection Agency, 2020 illustrates four types of trash capture systems that can be installed on stormwater drainage systems.

In addition to the direct protection of aquatic and marine ecosystems, proper trash management and disposal can help reduce or avoid greenhouse gas (GHG) emissions. These GHG effects represent a value-added, secondary environmental benefit of trash capture projects and are the focus of this report. Costs of trash management are significant (Caltrans, 2020). Quantifying the secondary GHG benefits of trash capture projects would illuminate the cost-benefit analyses of these projects so that they consider the secondary, value-added GHG benefits in addition to the direct aesthetic and environmental benefits. GHGs are currently of interest in the state of California, as the state works towards a 2030 goal of reducing state-level GHG emissions by 40% below 1990 levels (as expressed in AB 32 and Executive Order B-30-15). One of Caltrans' six expressly stated strategic goals is to lead climate action (Caltrans, 2021).

Sonoma Technology, Inc. (STI) completed a literature review to develop an understanding and document how Caltrans may consider, characterize, and quantify the potential greenhouse gas (GHG) benefits of roadside Trash Capture projects. Proper management of roadside trash has the potential to affect GHG emissions by (1) avoiding direct emissions from trash breakdown; (2) reducing overall product lifecycle emissions through materials recovery and recycling; and (3) avoiding indirect effects from ecosystem disruptions that can tip the ecosystem's balance away from being a carbon sink and towards being a carbon source. This memorandum addresses all three possibilities, summarizes findings, presents illustrative quantitative analyses, and recommends next steps Caltrans may follow to extend this work. In the short term, emissions benefits from avoiding direct emissions and reducing product lifecycle emissions are likely to be quantifiable using currently available information. However, quantifying the indirect effects of ecosystem disruptions is currently an area of emerging research.

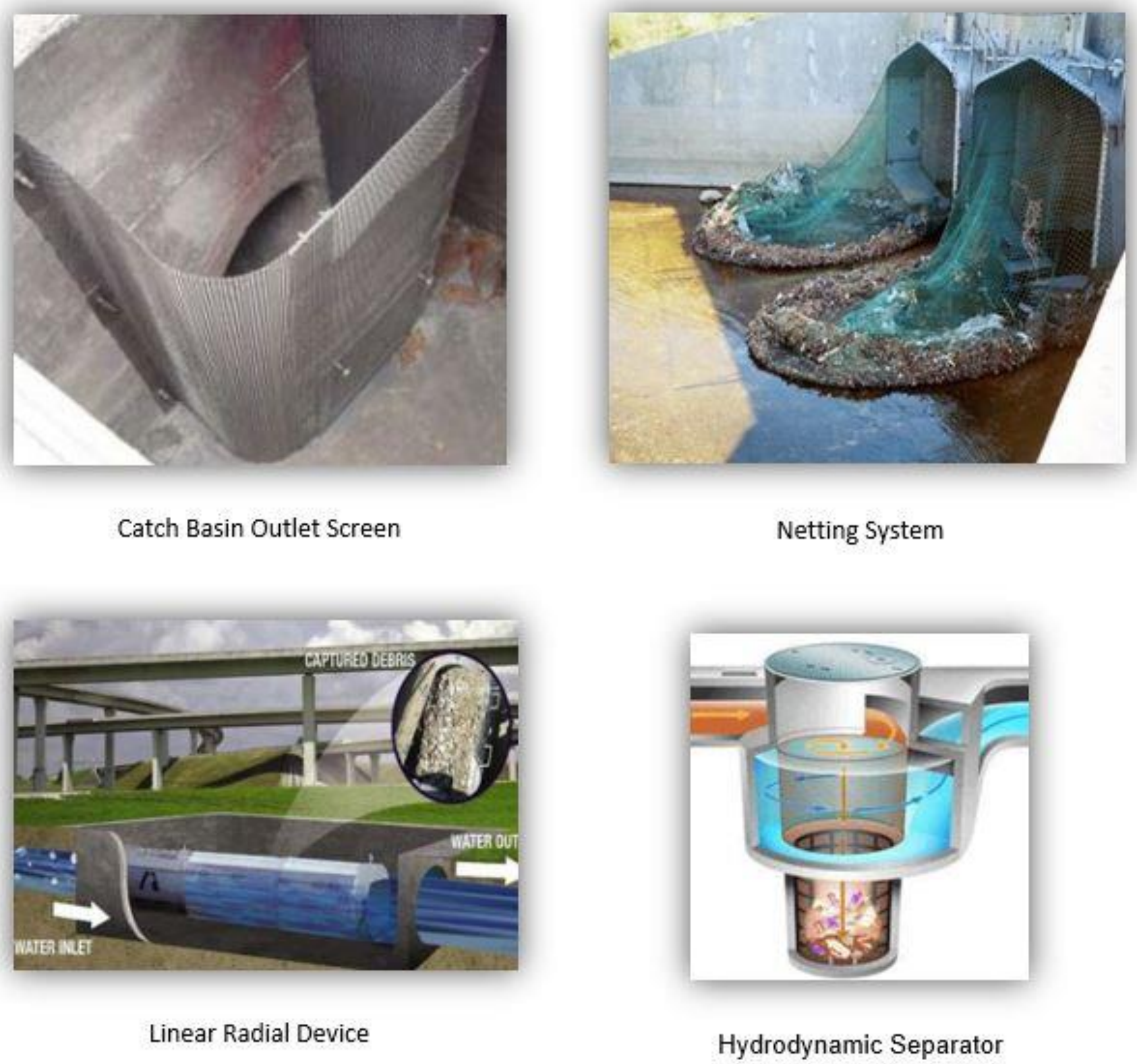

Figure 1. Examples of trash capture devices for stormwater systems.
Source: U.S. Environmental Protection Agency, 2020

General Principles of Greenhouse Gas Accounting

GHG emissions are generally tracked according to categories that have been defined by the Intergovernmental Panel on Climate Change (Eggleston et al., 2006; Calvo Buendia et al., 2019)—i.e., Scope 1, Scope 2, Scope 3, or Biogenic CO_2 (BC) emissions, defined as follows:

- Scope 1 — Direct emissions are generated by sources within Caltrans organizational boundaries and within the ownership or control of Caltrans. Some, but not all, emissions associated with management of roadside trash could be considered Scope 1 emissions for Caltrans. For example, the tailpipe emissions from Caltrans-owned vehicles, which may be deployed for trash management purposes, are part of Caltrans' Scope 1 GHG inventory.
- Scope 2 — A special category of indirect emissions includes emissions that occur at sources owned or controlled by entities other than Caltrans but result from activities located within Caltrans' organizational boundaries. Scope 2 emissions are associated exclusively with purchased or acquired electricity, steam, heating, or cooling. If Caltrans-owned *electric* vehicles are powered by utility-generated electricity, then the emissions from the electricity generation activities are part of Caltrans' Scope 2 GHG inventory.
- Scope 3 — Indirect emissions are related to Caltrans operations but are generated by sources outside Caltrans' financial or operational control. Emissions associated with roadside trash will almost certainly be considered part of Scope 3 GHG inventories. Scope 3 emissions include all indirect emissions not covered by the Scope 2 category. The "well-to-tank" component of the lifecycle emissions from production of gasoline or diesel fuels used by Caltrans-owned vehicles would be counted as part of Caltrans' Scope 3 GHG inventory.
- Biogenic CO_2 (BC) is directly emitted carbon dioxide (CO_2) from combustion or aerobic degradation of renewable biomass and is considered a part of the short-term carbon cycle. Similarly, biogenic CO_2 that arises as a part of the organization's value chain is categorized BC. For example, disposal by incineration and complete combustion of wastepaper products contributes to the BC component of GHG inventories.

Theoretically, detrimental impacts on ecosystems could shift some carbon from the BC cycle into the Scope 3 category. For example, the presence of roadside trash could impact an ecosystem in a manner that shifts its carbon balance away from being a carbon sink and towards being a carbon source. In this scenario, the resultant net difference on GHG emissions is arguably anthropogenic and should be included in the Scope 3 component of an emission inventory.

Consistent with IPCC Protocols (Eggleston et al., 2006; Calvo Buendia et al., 2019), estimated emissions for different greenhouse gases are normalized to the global warming potential (GWP) for each pollutant and are reported in units of carbon dioxide equivalents (CO_2eq). We referenced the GWP values reported in the IPCC's Fourth Assessment Report (AR4) because these values are still in use by California Air Resources Board (CARB) as follows.

Variable	Definition	Value (per AR4)
GWP_{CO2}	GWP of carbon dioxide	1 unit of CO_2eq per unit of CO_2 (by definition)
GWP_{CH4}	GWP of methane	25 units of CO_2eq per unit of CH_4
GWP_{N2O}	GWP of nitrous oxide	298 metric ton CO_2eq/ton N_2O

The Nature of Roadside Trash

An understanding of the nature, quantity, and composition of roadside trash is necessary to effectively quantify potential GHG benefits from proper waste management. As shown in **Figure 2**, counted trash items across U.S. roadways are dominated by cigarette products (37.7%), paper (21.9%), and plastic (19.3%), followed by metal (5.8%), and glass (4.5%) (Schultz and Stein, 2009). This aggregate composition of roadside trash is consistent with the composition of trash collected from California waters. According to studies conducted by the California Coastal Commission and the Ocean Conservancy from 1989-2012, the top ten counted trash items, constituting approximately 90 % of collected items, from California beaches and waters included (1) cigarette butts; (2) paper and plastic bags; (3) food wrappers and containers; (4) caps and lids; (5) cups, plates, forks, knives, and spoons; (6) straws and stirrers (7) glass beverage bottles; (8) plastic beverage bottles; (9) beverage cans; and (10) building materials (California Water Boards, 2015). Similarly, a Litter Management Pilot Study conducted in the Los Angeles area by Caltrans (during 1998 through 2000) reported 11 material types of trash captured from freeway storm water (Lippner, et al., 2001). The weight, volume, and count of the collected trash are shown in **Table 1**. By count, the trash discharges were dominated by cigarette buts, plastics, and paper.

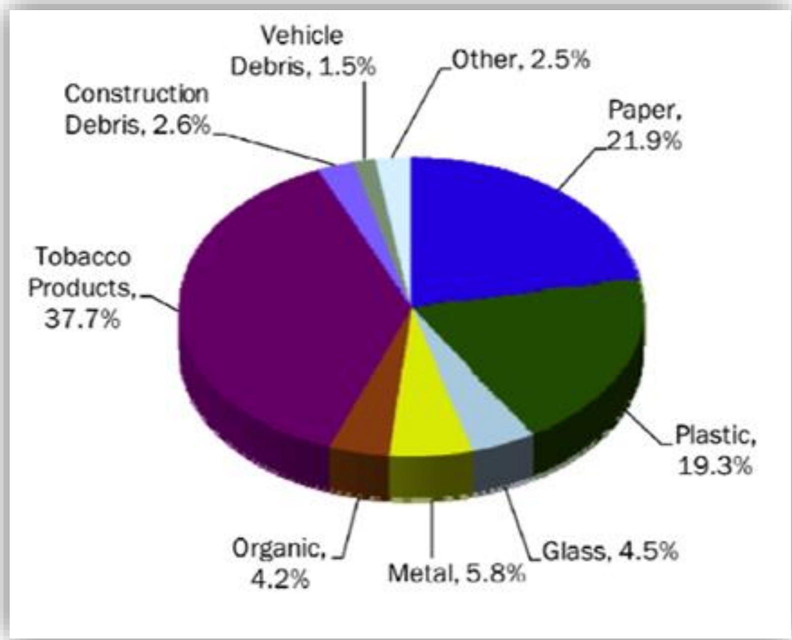

Figure 2. Composition of trash on U.S. roadways (by count of number of items). Source: Schultz and Stein, 2009

Table 1. Distribution of trash components by mass, volume, and count. Source: Lippner et al., 2001

Component	Percentage of Total (%)		
	Mass	Volume	Count
Styrofoam	5	15	11
Plastic (moldable)	21	16	11
Plastic film	7	12	12
Paper	9	14	10
Wood	16	10	7
Cardboard/chipboard	10	11	4
Metal (foil and molded)	13	5	7
Glass	1	<0.5	1
Cloth	6	5	2
Cigarette butts	10	11	34
Other	2	1	1

Based on the definition of trash provided in the Caltrans Statewide Trash Implementation Plan (2019), the composition of roadside trash in this report is limited to the following materials:

1. Paper, e.g., paper packages (typically made of cellulose)
2. Plastic, which comprises mainly plastic bags (typically made of high-density polyethylene [HDPE]) and plastic bottles (typically made of polyethylene terephthalate [PET]), foam plates (polystyrene), and cigarette butts (filters of cigarette butts are typically made of cellulose acetate)
3. Metal, which is dominated by beverage cans (made of aluminum)
4. Glass, e.g., glass bottles.

As an indicative, semi-quantitative analysis, **Table 2** provides the weight (van Leeuwen, 2014; Qamar et al., 2020) and estimated carbon content of paper and plastic trash, as well as their potential carbon dioxide (CO_2) formation, assuming all the carbon content converts to CO_2 over a long period of degradation time. Paper bag wastes have the highest carbon content and the potential to produce the highest quantity of CO_2 (0.09 kg) when left in place to degrade. However, when landfilled, paper can undergo anaerobic biodegradation to potentially produce 0.033 kg of CH_4 (as shown in Table 2), which is equivalent to 0.825 kg CO_2eq (where global warming potential of CH_4 = 25). For the HDPE and PET plastics, their potential to degrade to produce CO_2 is relatively low, given that they require hundreds of years to degrade when left in place. When landfilled, the potential for HDPE and PET plastics to produce CH_4 becomes negligible since they are unlikely to undergo anaerobic biodegradation. As shown, quantification of CO_2 emissions from roadside trash is largely influenced by their management endpoints and degradation time.

The potential management choices for roadside trash include littering avoidance or active management approaches, including (1) capture or collect and divert to landfill, (2) capture or collect and divert to incinerator, and (3) capture or collect and divert to recovery/recycling. When trash is left in the environment or is disposed of in the landfill, its degradation timescale can vary from a year to hundreds of years based on its material composition and environmental conditions. Paper bags take a relatively brief period of time to degrade (2-5 months), followed by cigarette butts (1-5 years), plastic bags (20-100 years), plastic bottles (450 years), aluminum cans (80-250 years), and glass (1 million years) (Bell, 2020).

Table 2. Estimation of carbon content and potential CO_2 and CH_4 emissions from paper bag, plastic bag, plastic bottle, and cigarette butt.

Material	Weight (g)	Chemical formula	Molecular weight (g/mol)	Carbon ratio per material	Carbon content (moles)	CO_2 (kg)	CH_4 (kg)
Paper bag (cellulose)	55.2	$C_6H_{10}O_5$	162.14	6	2.043	0.090	0.033
Plastic bag (HDPE)	6	C_2H_4	28	2	0.429	0.019	0.007
Plastic bottle (PET)	26	$C_{12}H_{14}O_4$	222.24	12	1.404	0.062	0.022
Foam plate (polystyrene)	3.45	C_8H_8	104	8	0.265	0.012	0.004
Cigarette butt (cellulose acetate)	0.27	$C_{10}H_{16}O_8$	264.23	10	0.010	0.0004	0.0002

The nature of roadside trash can be better characterized for California-specific and Caltrans-specific conditions through aggregation of existing data from area-specific trash studies. Additional field studies may be required for areas in California with no roadside trash measurements. Further research can be conducted to study how the nature of trash is changing over time. Also, research into available trash endpoints in California may provide insights into feasibility and availability of recycling materials.

Potential for Direct Emissions from Roadside Trash Materials

The direct GHG emissions from roadside trash materials are largely dependent on the waste management endpoints, which are defined briefly as follows.

(1) Avoid littering. Litter avoidance campaigns are admittedly expensive and produce limited success rates. However, when successful, litter avoidance is the most effective means of minimizing the climate impacts of roadside trash. Avoidance entirely negates GHG emissions that result from collection and transportation of roadside trash to waste management endpoints, optimizes the chances of successful materials recovery and recycling efforts, and eliminates indirect impacts from ecosystem perturbance.

(2) Collect wastes and divert to management endpoints—i.e., landfill, incinerator, or recovery/recycling facility. The collection process itself is a potential source of GHG emissions when vehicles or equipment are employed for the collection

efforts. Emissions from vehicle or equipment sources can be estimated on the basis of fuel consumed, electricity used, or emission factors.

a. Divert to landfill. Landfilled paper can slowly degrade anaerobically to form CH_4 and CO_2. However, a fraction of carbon remains stored in landfilled paper due to incomplete decomposition of paper by anaerobic bacteria (ICF International, 2016). Landfill-related emission factors for paper products obtained from EPA's Waste Reduction Model (WARM) are 0.4 to 1.49 $MTCO_2E$/ton landfill CH_4 and -0.82 to 1.22 $MTCO_2E$/ton net emissions (ICF International, 2016), where $MTCO_2E$ is a metric ton of CO_2eq. For glass, metals, and plastics, landfill-related emissions are those used for transporting the waste materials to the landfills, which the EPA WARM model estimates as 0.02 $MTCO_2E$/ton for each material (ICF International, 2016). Some landfills generate GHG benefits via landfill-gas-to-energy projects, which are a means of avoiding use of generated utility electricity.

b. Divert to incinerator. Incineration completely avoids methanogenesis from paper waste decomposition. In addition, incinerators typically operate as waste-to-energy project and produce GHG benefits by avoiding use of generated utility electricity.

c. Divert to materials recovery/recycling facility. Note that some landfills or incinerators recover high-value, separable materials (e.g., metals) and thus, partly fulfill this management endpoint. Potential for direct emissions from the materials is largely avoided. (Lifecycle effects are discussed elsewhere in this memorandum.)

Table 3 provides the total lifecycle CO_2 equivalences (a measure of GWP) and CO_2 emission factors of materials produced in America, as reported by Kissinger and Sussmann, et al. (2013). According to a report by Edwards and Fry (2006), the end-of-life GWP for a 55.2 g paper bag and an 8.27 g HDPE plastic bag are 0.8 and 0.2 kg CO_2 eq., respectively. The reported end-of-life GWP values for the paper and plastic bags included collection, landfill, and incineration. Alternatively, to quantify direct GHG emissions from waste materials, reliable CO_2 emission factors associated with manufacturing and transportation of materials are required. Direct GHG emission factors can then be calculated from the difference between the total lifecycle CO_2 emissions and CO_2 emissions associated with manufacturing and transportation of each material.

Table 3. CO_2 equivalence and CO_2 emissions of materials. Sources: Kissinger and Sussmann, et al., 2013; Edwards and Fry, 2006

Material	CO_2 equivalence (kg CO_2 eq./t)	CO_2 emission (kg CO_2/t)	End of life (kg CO_2 eq.)
Paper	520 - 3,140	1,410	0.8
Plastic (HDPE)	1,080 - 3,270	1,010 - 2,770	0.2
Plastic (PET)	1447	1072	N/A
Aluminum	7,100 - 10,700	7,940 - 12,000	N/A
Glass	N/A	585 – 1,250	N/A

Potential for Lifecycle Emissions Reductions from Materials Recovery and Recycling

Recovery and recycling of waste materials can lead to substantial reductions in GHG emissions. The United States Environmental Protection Agency (USEPA) and CARB provide methods to estimate material-specific GHG emission benefits of recycling. USEPA uses the Waste Reduction Model (WARM) to calculate recycling emission factors based on the difference between emissions from manufacturing a short ton of recycled material and emissions from manufacturing a short ton of virgin material (ICF International, 2016). CARB uses the following equation to calculate recycling emission reduction factor (RERF) (California Air Resources Board, 2011):

$$RERF = ((MS_{virgin} – MS_{recycled}) + FCS – T_{remanufacure})*Ruse$$

Where:

RERF	=	Recycling emission reduction factor ($MTCO_2E$/ton)
MS_{virgin}	=	Emissions from virgin inputs for manufacturing the material ($MTCO_2E$/ton)
$MS_{recycled}$	=	Emissions from recycled inputs for manufacturing the material ($MTCO_2E$/ton)
FCS	=	Forest carbon sequestration ($MTCO_2E$/ton)
$T_{remanufacture}$	=	Transportation emissions associated with remanufacture destination ($MTCO_2E$/ton)
R_{use}	=	Recycling efficiency (fraction of material remanufactured from ton of recycled material)

Table 4 and Table 5 show the recycling efficiencies and RERFs values for aluminum, steel, metals, glass, plastics, and paper.

- Aluminum: As shown in Table 3, aluminum has higher recycling recovery efficiency (100%) than glass (90%) and plastics (90%). Similarly, aluminum has the highest RERFs among the recycled materials based on both USEPA (13.67 $MTCO_2E$/Ton) and CARB (12.9 $MTCO_2E$/Ton) methods (Table 4).

- Glass: The RERFs for glass based on USEPA and CARB methods are 0.28 and 0.2 $MTCO_2E$/Ton, respectively. Thus, glass has the least net GHG emission reductions among the recycled materials, which is approximately a factor of 5-6 less compared to aluminum (Table 4).

- Plastics: USEPA's estimated RERFs for HDPE plastics are 1.4 and 0.8 $MTCO_2E$/Ton, respectively, whereas CARB's estimated RERFs for PET plastics are 1.55 and 1.4 $MTCO_2E$/Ton, respectively.

Table 4. Recycling efficiencies of each material. Source: California Air Resources Board, 2011

Material	Recycling recovery efficiency (%) (a)	Recycling remanufacture efficiency (b)	Recycling efficiency (a x b)
Aluminum	100	0.93	0.93
Steel	100	0.98	0.98
Glass	90	0.98	0.88
HDPE	90	0.86	0.77
PET	90	0.86	0.77
Corrugated cardboard	100	0.93	0.93
Magazines/3rd class mail	95	0.71	0.67
Newspaper	95	0.94	0.89
Office Paper	91	0.66	0.6
Phonebooks	95	0.71	0.67

Table 5. Material-specific RERFs from CARB's method and USEPA's WARM model. Source: California Air Resources Board, 2011

Material	RERFs ($MTCO_2E$/Ton)	
	CARB's method	USEPA (WARM)
Aluminum	12.9	13.67
Steel	1.5	1.8
Glass	0.2	0.28
HDPE	0.8	1.4
PET	1.4	1.55
Corrugated cardboard	5	3.11
Magazines/3rd class mail	0.3	3.07
Newspaper	3.4	2.8
Office Paper	4.3	2.85
Telephone books	2.7	2.66
Dimensional lumber	0.21	2.46
Mixed Plastics	1.2	1.52

To quantify lifecycle GHG emissions reductions from roadside trash, the following data are required: (1) mass of materials; (2) recycling efficiencies (Table 2); and RERF data (Table 3). The total lifecycle GHG emissions reductions may be calculated as follows:

$$LGER = \sum_{i}^{n} mass_i \times Recycling\ efficiency_i \times RERF_i$$

Where:

LGER = lifecycle GHG emissions reductions
i = type of material
n = total number of materials
RERF = Recycling emission reduction factor

Potential for Indirect Ecosystem Effects

Carbon moves through the environment and ecosystems through biological, geological, and chemical processes that are interrelated. From the global scale to the micro-scale, carbon cycles may be in a balance, such that net inputs and outputs are equal, or out of balance, such that carbon reservoirs are being depleted or enriched. (**Figure 3** illustrates global-scale reservoirs and sinks as they were understood 30 years ago.) Biological processes are important factors that drive carbon fluxes between all reservoirs. CO_2, CH_4, and N_2O are biologically important species and critically important to the functioning of the biosphere. Photosynthetic organisms (also called primary producers, PPs) uptake CO_2 and sequester carbon in the biota—and release oxygen as a photosynthetic byproduct. Marine animals uptake CO_2, form calcium carbonates, and sequester the mineralized carbon in sediments or coral reefs. Biological respiration and decomposition processes re-release photosynthetically sequestered carbon to the atmosphere. Aerobic (oxygen-rich) ecologies favor respiration or decomposition processes that release carbon to the atmosphere as CO_2 in a short-term cycle that is generally considered a net neutral issue in the context of climate change. Anaerobic (oxygen-starved) ecologies favor respiration or decomposition processes that release carbon as CH_4—a much more potent GHG than CO_2—and may represent a net contribution to anthropogenic climate change if they have been accelerated or enhanced by anthropogenic influences.

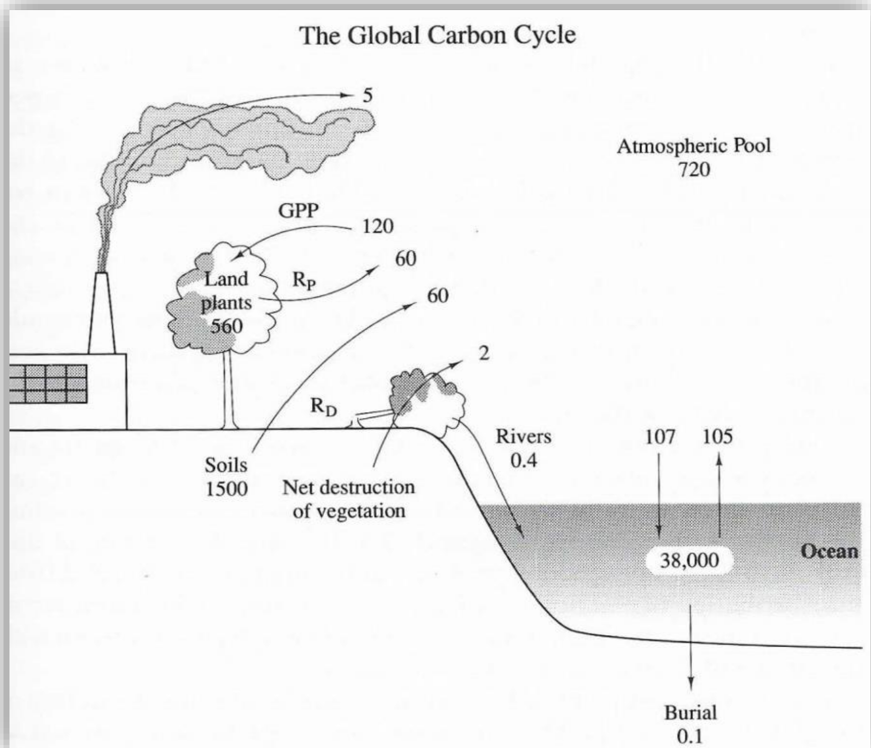

Figure 3. Representation of the major reservoirs and fluxes in the global carbon cycle. Source: Schlesinger, 1991, Chapter 11, page 309. Units of measure are expressed as 1015 g C (carbon reservoirs) or 1015 g C/yr (carbon fluxes).

Some ecosystems generally behave as carbon sinks relative to the atmosphere: healthy, old-growth forests; oligotrophic lakes; the arctic ocean. Others generally behave as carbon sources: diseased, fire-prone forests; eutrophic lakes; acidified tropical oceans. Anthropogenic and climate disruptions can perturb these systems and shift them into a different state; and roadside trash itself can be the cause of such ecosystem perturbations (Rillig et al., 2021; Galloway et al., 2017; Chen et al., 2020).

- In aquatic or marine environments, bulk accumulations of trash may act as physical barrier to vertical circulation of the water column and distribution/exchange of dissolved gases with aquatic or marine sediments. In addition, they may act as a physical barrier to light and restrict photosynthetic activity (Thushari and Senevirathna, 2020; Thevenon et al., 2014). Starved of dissolved oxygen (DO), the biota in the lower reaches of the water column or in the sediments tip towards an anaerobic state from an aerobic state.

- Microplastics and associated biofilms may be directly toxic to photosynthetic organisms, which can (1) interfere with biotic carbon fixation rates in the natural environment, and (2) act as another mechanism that reduces DO concentrations in the water column and tips conditions towards an anaerobic state.

- Decomposition of wastes (paper waste, for example) under anaerobic conditions tends to release CH_4 to the atmosphere. Excessive loadings of nutrients (as anthropogenic wastes) to ecosystems can even contribute to tipping an ecosystem towards an anaerobic state from an aerobic state.

- As a secondary effect, anaerobic ecosystems tend to be more acidic (with lower pH) than aerobic and/or photosynthetically active systems. Acidification of aquatic or marine environments contributes to the dissolution of calcium carbonate sediments or coral reefs (Enochs et al., 2019) and results in releases of previously sequestered carbon as CO_2. Also, low pH can inhibit the types of organisms that mineralize calcium carbonates over time, eliminating this important carbon sink.

Research into the effects of trash on nutrient and carbon cycling in aquatic, marine, and soil ecosystems is a developing field of study. The scopes, mechanisms, and scales of these issues are areas of active academic research, but they are identified as areas in which sensible trash management choices can produce indirect GHG emissions benefits. However, not enough information is available for us to readily quantify the secondary effects of roadside trash in California on ecological sources and sinks of GHG.

Conclusions and Recommended Next Steps for Caltrans

As the outcomes of our literature review, we reached the following conclusions and recommendations for Caltrans' next steps to potentially quantifying the GHG benefits from trash capture projects.

Conclusions/next steps related to direct emissions.

- The magnitude of direct GHG emissions from roadside trash materials are highly dependent on waste management endpoints. Choices about trash management approaches affect the likelihood of material recovery and energy savings. However, limited data are available to quantify direct GHG emissions from roadside trash.
- To better estimate direct GHG emissions, further studies, including field measurements, are recommended to properly characterize and quantify roadside trash on Caltrans rights-of-way. Additionally, better GHG emission factors for common types of trash material would be useful.

Conclusions/next steps related to lifecycle emissions.

- A method for calculating lifecycle GHG emissions reductions from recycled materials was suggested based on CARB and USEPA's WARM recycling emission factors. To quantify GHG benefits of trash capture projects, GHG emissions related to collection, incineration, and landfilling need to be accounted.
- Therefore, further literature review needs to be conducted to compile credible emission factors associated with the end-of-life cycles of trash materials. The end-of-life emission factors combined with the weight of materials will form the basis for developing comprehensive methodologies for estimating GHG benefits of roadside trash capture projects.

Conclusions/next steps related to indirect ecosystem effects.

- Indirect effects of trash on nutrient and carbon cycling in aquatic, marine, and soil ecosystems has been identified as an area through which sensible trash management choices can produce indirect GHG emissions benefits. However, not enough information yet exists for Caltrans to readily quantify secondary effects of roadside trash in California on ecological sources and sinks of GHG.
- Caltrans could extend the literature review and consult with experts in this field to understand more about in-progress research, upcoming publications, gray or white literature resources, and expert opinion. Combined with a greater understanding of the nature of California's roadside trash, and a selection of hypothetical ecological scenarios, Caltrans could undertake semiquantitative analyses and at least bound the upper and lower ranges of scale for the potential benefits.

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15. Abstract

This memorandum presents the potential GHG benefits of roadside trash capture projects. First, this memorandum provides literature review on (1) the nature and endpoints of roadside trash, (2) the direct GHG emissions from trash materials, and (3) the indirect effects of trash on aquatic and soil ecosystems. Second, the memorandum provides suggested approach and data for estimating lifecycle GHG emissions reductions from recycled trash materials. Last, the memorandum suggests next steps Caltrans may pursue to potentially quantify the GHG benefits from trash capture projects.

16. Key Words Roadside trash; trash capture; aquatic ecosystem; GHG emissions; lifecycle GHG emission factors	17. Distribution Statement	18. No. of pages 16

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