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Research article

Integrated tire wear buildup and rainfall-runoff model to simulate tire wear particles in stormwater

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A R T I C L E I N F O

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A B S T R A C T

This paper presents an approach to integrate tire wear buildup and rainfall-runoff models to simulate tire wear buildup on road surfaces and its subsequent transport in stormwater runoff events. To do so, a buildup model is presented based on vehicle kilometers traveled, vehicle type, vehicle speed, and road roughness within a watershed. This buildup model was integrated into an EPA SWMM model that simulated the runoff of tire wear particles in twelve watersheds in the San Francisco, CA bay area. Results demonstrate that tire wear particle buildup within the watersheds ranged between 0.4 and 0.51 (kg/km^2) per hour. Applied to the SWMM model, total event mean tire wear concentrations ranged between 0.5 and 67 μg/L. These concentrations were linearly correlated to depth-integrated samples collected at the outlet of each of the watersheds ($R^2 = 0.66$). The proposed modeling approach can ultimately be applied to create solutions to an emerging stormwater contaminant.

1. Introduction

Tire wear particles originate from the interaction of vehicle tires on pavements. They are estimated to be the largest sources of synthetic polymer-based material in the environment (Baensch-Baltruschat et al., 2020), with 1.3 million tons of tire wear generated on roads per year in Europe (Wagner et al., 2018). Stormwater is the main vector of tire wear particles reaching downstream water bodies. Tire wear particles on urban surfaces, such as roads and parking lots, are mobilized and transported during rainfall-runoff events, comprising 40%–85% of the total microplastics within urban stormwater (Järlskog et al., 2020; Werbowski et al., 2021). Tire wear particle concentrations have been found to decrease in streams the further the distance downstream of roadways (Knight et al., 2020), but even in estuaries subject to dilution from significant runoff and groundwater sources, tire wear particles comprise up to 17% of the microplastics (Leads and Weinstein, 2019). Therefore, they represent a significant microplastic pollutant source in urban water bodies.

The presence of tire wear particles in urban water bodies can pose a significant threat to aquatic health. Ingestion of tire wear particles by aquatic species can have direct physical effects, such as reduced food intake due to the accumulation of particles in the stomach (Baensch-Baltruschat et al., 2020). They can also have toxic chemical effects through leaching in the digestive tract, and it has been shown that the chronic toxicity levels for many aquatic species range between 10 and 3600 TWP/L (Wagner et al., 2018). In addition, they can have acutely toxic effects on aquatic biota. Tire wear particles have resulted in the mortality of adult coho salmon (>50%) due to the transformation of the chemicals N-phenyl-N′-(1,3-dimethylbutyl)-p- phenylenediamine (6-PPD) quinone from tire-derived leachate (McIntyre et al., 2021; Tian et al., 2021).

Despite the emerging importance of tire wear particles and their transport in stormwater, there are very few approaches for modeling the buildup and transport of tire wear particles in stormwater runoff. This is a major shortcoming as solutions to mitigating pollutants in stormwater runoff often rely on models that can simulate the buildup, transport, and removal in best management practices. Part of the reason for the lack of modeling approaches for tire wear in runoff is that models rely on empirical data for parameterization and calibration, yet there are no clear approaches to easily and effectively monitoring tire wear particles. Those approaches that do exist include determining the presence of TWP using chemical or elemental markers such as oleamide (Chae et al., 2021) and zinc (Klöckner et al., 2019), pyrolysis GC-MS (Rauert et al., 2021), identification of individual particles (L M Werbowski et al., 2021), or a combination of cross-validation techniques (Rosso et al., 2023); however, each is subject to analytical challenges (Rauert et al.,

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2021). Because of this, empirical data on TWP concentrations in stormwater runoff are lacking (Baensch-Baltruschat et al., 2020). Additionally, there is a lack of methods to simulate the buildup of tire wear particles on the surface of urban surfaces. Most stormwater models rely on a nonlinear buildup function based on dry days, land use type, and the specific pollutant; however, no such functions exist for tire wear particles. Those that do exist have broad assumptions in their buildup rates, such as 1 kg tread inhabitant^{-1} year^{-1} (Unice et al., 2019), that overlook the dynamics that contribute to tire wear like traffic, loading, or road roughness that vary across watersheds.

Despite these shortcomings, there have been efforts to develop approaches for modeling tire wear runoff, but they are limited to conceptual models or broad assumptions in rainfall-runoff dynamics. To that end, proposed conceptual models of how to model tire wear particles in stormwater runoff integrate data collection, vehicle emission models, and fate and transport models that can be applied for scenario-based assessments (Mian et al., 2022). Other empirical models predict coho salmon mortality based upon land use and land cover (Feist et al., 2011). For existing models that do simulate rainfall-runoff dynamics, they are based upon significant assumptions such as an annual 50% remobilization of tire wear (Baensch-Baltruschat et al., 2021) that do not consider the impact of rainfall-runoff dynamics.

The objective of this study is to integrate a model of tire wear buildup with a rainfall-runoff model to simulate the transport of tire wear particles in stormwater. To do so, we (1) calculate tire wear for road segments that included variables such as vehicle type, tire load, speed, and road roughness, and (2) integrate this buildup function into EPA SWMM to simulate the runoff of tire wear particles. We validate the event mean concentration against measured grab sample concentrations (particles/L) as outlined in Werbowski et al. (2021). In doing so, we present a potential approach to defining the pollutant buildup of tire wear particles on urban surfaces that can be integrated into rainfall-runoff models for simulating tire wear in stormwater runoff.

2. Methodology

2.1. Site description

This case study includes 12 watersheds within the California Bay Area, with areas ranging between 5.4 km^2 and 327 km^2 and containing a mix of urban land uses and road types (Fig. 1). These watersheds were selected because data were available on the concentration of tire wear particles during storm runoff from a previous study (Werbowski et al., 2021). In that study, depth-integrated samples were collected over a range of rainfall events (0.14–1.32 in) and tested for concentrations of fibers and black rubbery fragments that are likely from tire and road wear particles. Details on the data collection methodology and approaches can be found in Werbowski et al. (2021). These stormwater runoff concentrations were used to validate the outcomes of the model built and described in the following sections. For each watershed, a storm event was simulated that corresponds with the date at which the depth-integrated samples were collected, each on a different day. Details on the characteristics of storm events of each watershed during the sampling period can be found in Table SI-1.

2.2. Traffic and roadway data

Data on the roads, including their physical characteristics (geometry, roughness, classification, etc.) and traffic volume, were derived from each watershed. Road geometry data in shapefiles were retrieved from the U.S. Census Bureau Department of Commerce and contained local, arterial, and highways for each watershed. In addition, International Roughness Index (IRI) representing the roughness of the roads was obtained from the U.S. Department of Transportation Highway Performance Monitoring System (HPMS) dataset (US DOT, 2018). This dataset did not contain data for every road, as it focuses on major highways and arterial roads, but it did include coverage of these road types in every watershed with a median of 25% coverage (Table SI-2) and was therefore used as a representative IRI.

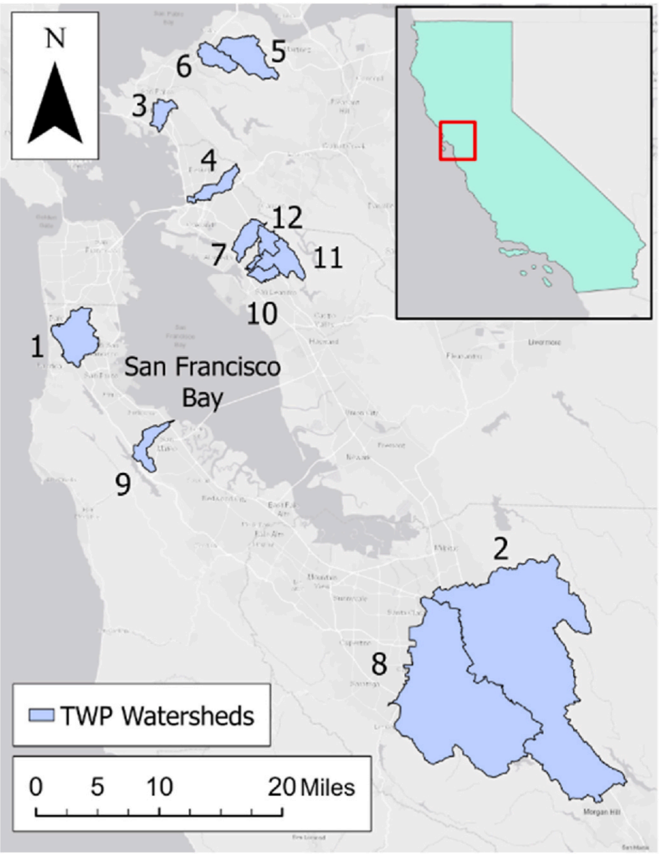

Fig. 1. Map of watersheds within the San Francisco Bay area.

Traffic data representative of the total kilometers traveled were derived to develop a model of tire-wear buildup on each road. To do so, we obtained traffic data for individual road segments using smartphone-based vehicle volume data (StreetLight, 2021). Using this data source, we determined the total kilometers traveled per day on each road segment within the case study watersheds. The estimated trip counts included all sampled bi-directional traffic sources, including cars, medium trucks, and heavy trucks, and their speeds. This data – total kilometers traveled per day within each watershed for different speed classifications – were then used to develop the tire wear buildup model described in the following section.

2.3. Tire wear buildup model

The implemented tire wear buildup model was proposed by Chatti and Zaabar (2012) as part of a study sponsored by the National Cooperative Highway Research Program (NCHRP). The NCHRP model combines mechanistic principles and field measurements to link road condition and tire wear. The model includes variables such as forces applied to the tire (normal, lateral, and circumferential forces), vehicle type (medium car, van, SUV, light truck, and articulated truck), and pavement roughness.

The collection of field measurements depended on the type of vehicle. For articulated trucks, the test track at the National Center for Asphalt Technology (NCAT) was trafficked with tractor-trailer assemblies traveling at 72 km/h for 18 h per day, 6 days a week, for 2 years. Data from NCAT included tire wear rate based on reduction of tread depth and road roughness and texture. For passenger cars, testing entailed driving for 4000 km on two roads with known texture and roughness. Tire wear was measured using a laser-based data acquisition system that captured the change in tread depth after completing the loops. The data collected and information from HDM-4 (Bennett and Greenwood, 2003) allowed the calibration of the tire wear model for other vehicle types. Because the data on traffic volume collected in Section 2.2 did not include vechicle type, in the model below we applied a conservative estimate that all cars were passenger cars, rather than assuming an unknown distribution of passenger, light truck, and heavy trucks.

The final model provides the total change in tread wear per tire (*TWT*) using the following equation:

$$TWT = C_{0tc} + C_{tcte} \times \frac{CFT^2 + LFT^2}{NFT} \tag{1}$$

where C_{0tc} and C_{tcte} are the tread rate constant and tread wear coefficient, respectively, and depend on the vehicle class. *CFT*, *LFT*, and *NFT* are the circumferential, lateral, and normal force on the tire, respectively, and are calculated as:

$$CFT = \frac{(1 + CTCON \times dFUEL) \times (Fa + Fr + Fg)}{NW} \tag{2}$$

$$LFT = \frac{Fc}{NW} \tag{3}$$

$$NFT = \frac{M \times g}{NW} \tag{4}$$

where *CTCON*: incremental change in tire wear related to congestion, *dFUEL*: incremental change of fuel consumption related to congestion, *NW*: number of wheels, *M*: vehicle mass, and *g*: gravity constant. In addition, *Fa*, *Fr*, *Fg*, and *Fc* are the aerodynamic, rolling resistance, gradient, and curvature forces, respectively. Of particular interest is the term *Fr* because it depends on the road's roughness and texture (Chatti and Zaabar, 2012). The equation to calculate *Fr* is:

$$Fr = CR2 \times \left[b11 \times Nw + CR1 \times \left(b12 \times M + b13 \times v^2\right)\right] \tag{5}$$

where *v* is the vehicle speed, and the rolling resistance parameters *b*11, *b*12, and *b*13 depend on the wheel diameter *Dw* as follows:

$$b11 = 37Dw \tag{6}$$

$$b12 = \frac{0.064}{Dw} \tag{7}$$

$$b13 = 0.012\frac{Nw}{Dw^2} \tag{8}$$

In addition, the rolling resistance surface factor *CR*2 is obtained from:

$$CR2 = Kcr2 \times (a0 + a1 \times Tdsp + a2 \times IRI + a3 \times DEF) \tag{9}$$

$$Tdsp = 1.02 \times MPD + 0.28 \tag{9b}$$

MPD, *IRI*, and *DEF* are variables that depend on road surface texture, pavement roughness, and pavement stiffness, respectively. *Kcr*2 is a calibration factor, while *a*0, *a*1, and *a*3 are model coefficients; their corresponding values are introduced in Table SI-6. The formulae to calculate the other forces – *Fa*, *Fg*, and *Fc* – are given in the SI document.

Once *TWT* is obtained using road and vehicle conditions, it is multiplied by the number of wheels in a vehicle to find the tire wear of one vehicle. The resulting number is combined with traffic information to calculate the accumulation of tire wear in a given road segment over time.

2.4. EPA SWMM model

Input data into the EPA SWMM models were derived from GIS analyses of watershed characteristics, precipitation data from rain gages, and the associated buildup function (Fig. 2). Watersheds were delineated in ArcGIS using digital elevation model files of 30 m from the National Elevation Dataset and land cover and impervious data was derived from the 2019 National Land Cover Database (NLCD) 2019 dataset from the Multi-Resolution Land Characteristics (MRLC) Consortium. Using this information, watershed areas, slopes, travel times, and curve numbers were developed. In addition, curb lengths were derived from roadway data, as described in Section 2.2. Precipitation data for the twelve storm events were gathered from a rain gauge at the San Francisco Airport. Finally, the buildup model developed previously was used to parameterize the buildup coefficient for each storm event based on the time between the start of the runoff event and the previous antecedent event. A SWMM model was developed for each watershed that simulated the rainfall-runoff using the curve number method with single catchments for each watershed that drained to the outlet.

The washoff of pollutants was simulated based on buildup and washoff functions, and specific parameterizations of the model can be found in Table SI-3. Within SWMM, the governing equations for buildup are largely nonlinear functions of dry days based upon the pollutant and land use and are described as a mass per unit of watershed area or curb length. However, because the total buildup was computed from the previously described function, the buildup was set as an instantaneous mass of pollutants at the start of the event per unit of curb length. Washoff was established using an empirical model within SWMM known as the event mean concentration (EMC), where the loading rate varies in direct proportion to the runoff rate. The total loadings of tire wear particles were then assessed, and their relative magnitudes were compared against the concentrations measured by Werbowski et al. (2021).

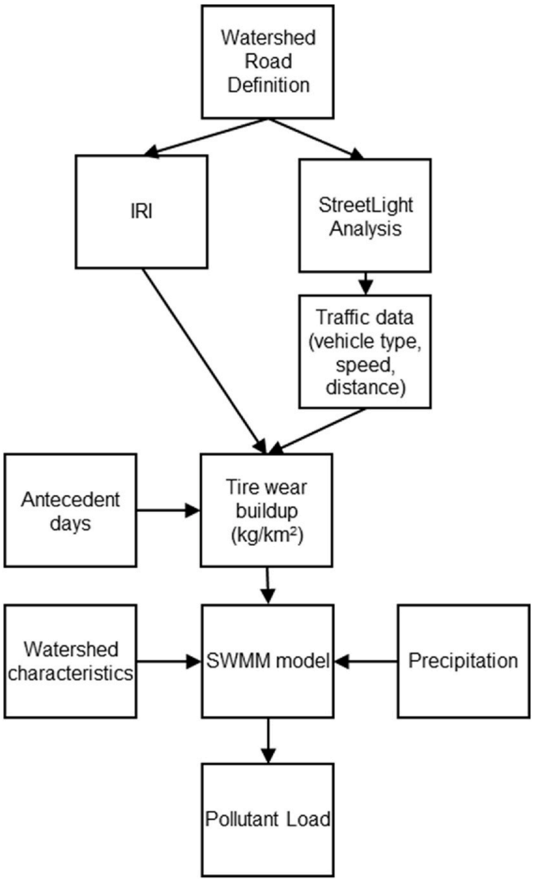

Fig. 2. Diagram of the modeling process.

3. Results and discussion

3.1. Tire wear buildup

The tire wear buildup is determined using the model described in Section 2.3, the traffic data and speed (Table SI-4), and the pavement roughness (IRI in Table SI-3). The NCHRP model provides *TWT* for each speed range per vehicle, which, once multiplied by the number of vehicles, results in tire wear in kilograms per hour. Table 1 presents the tire wear for each location with the corresponding traffic and IRI. The data indicates that the most relevant factor affecting tire wear is the number of vehicles, as the location with the largest traffic provided the most tire wear. In addition, the relationship between the two variables was linear. For instance, location 3 has a traffic of 1.05 million vehicle-kilometers traveled (VKT) per day and tire wear of 2.59 kg/h; location 4 has approximately twice the traffic (2.03 million VKT per day) and twice the tire wear (5.30 kg/h). This relationship is only moderately affected by roughness, as can be seen by comparing locations 7 and 11, which have similar traffic (around 1.2 million VKT) and tire wear (approximately 3.1 kg/h), but IRI in location 11 is 67% higher than in location 7 (3.86 vs. 2.66 m/km). The similar tire wear among 7 and 11 is largely because the traffic data in this study is mainly at the low end of the speed range (Table SI-4), in which case the effect of IRI on tire wear is the lowest according to the NCHRP tire wear model.

3.2. Rainfall-runoff

Using the tire wear buildup, simulations were run for each storm event, and Fig. 3 illustrates the results from the loading. The tire wear particle concentrations from the model (x-axis) were found to be correlated ($R^2 = 0.66$) to the tire wear concentrations measured at the outlets (y-axis), with a statistically significant slope ($p = 0.001$) and normality of the residuals, indicating a linear relationship. While the units of the two axes and what they represent are slightly different, they both represent the relative magnitude of the TWP concentrations in stormwater runoff and provide context for validating the model. The y-axis of Fig. 3 represents the TWP concentration in particles per liter as derived from depth-integrated sampling at one point in time at the outlet during a stormwater event, while the x-axis represents the modeled concentration (μg/L) across the entire storm event. This relationship from the linear model implies a weight of about 4 μg per particle, which is close in magnitude to the average weight of microplastics in the environment of 12.5 μg per particle (Tamis et al., 2021). However, this latter number encompasses all microplastics, and limited data is available on the average mass per particle in stormwater runoff. Detailed outputs from the model can be found in Table SI-5.

3.3. Implications of results

This paper presents an approach to develop a buildup function for tire wear particles on roads within a watershed and then integrate that function into a rainfall-runoff model. The modeling approach was applied to twelve case study watersheds where tire wear buildup was estimated based on traffic data during antecedent dry days (kilometers traveled, vehicle type, and speed) and roadway characteristics. This estimation of tire wear buildup was then integrated into a rainfall-runoff simulation in EPA SWMM, with results demonstrating agreement with measured tire wear concentrations during storm events ($R^2 = 0.66$). These outcomes suggest that this approach may effectively simulate the buildup and washoff of tire wear particles within the urban environment.

Table 1
Tire wear kg/hr.

Location	Total Vehicle Kilometers Traveled (VKT) per day	IRI (m/km)	Tire Wear (kg/hr)
1	3,686,928	2.57	10.02
2	11,212,514	2.24	31.76
3	1,051,116	2.20	2.59
4	2,032,338	2.91	5.30
5	278,381	2.10	0.88
6	680,986	2.56	1.88
7	1,224,007	2.66	3.12
8	19,977,901	2.31	55.95
9	717,620	2.93	1.92
10	419,005	5.04	1.02
11	1,210,236	3.86	3.06
12	1,108,088	3.10	2.87

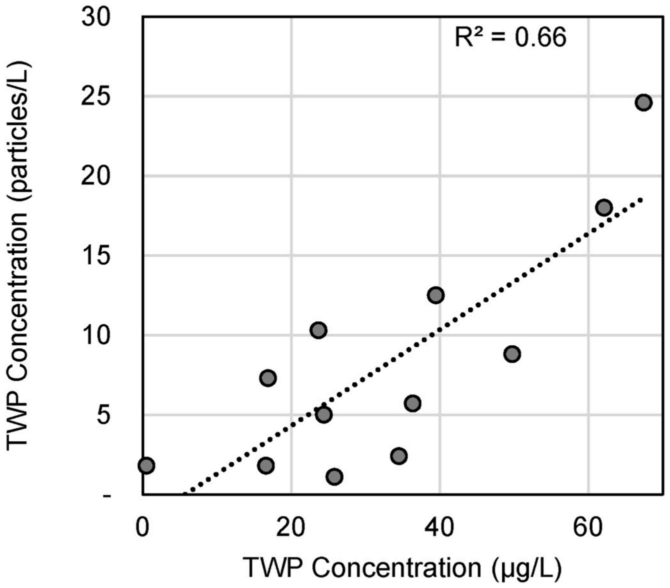

Fig. 3. Comparison of measured tire wear particle concentration from Werbowski et al. (2021) (y-axis) and the modeled tire wear concentration (x-axis).

To that end, integrating the proposed buildup function into existing stormwater quality models provides a straightforward and attainable way to model tire wear particles in stormwater runoff. The buildup function depends on variables that can be obtained across an entire watershed through smartphone-derived traffic estimates, including vehicles kilometers traveled, vehicle type, and speed, as well as physical road characteristics, such as road roughness and length. This approach enables the tailoring of a buildup function to actual traffic data and does not limit the buildup to an empirical function based upon antecedent dry days only, such as in the case of other pollutants (Charbeneau and Barrett, 1998) or simplified traffic surrogates, such as population (Unice et al., 2019). Because of this, the proposed model can be used to study the influence of traffic on tire wear particle generation, including roadway improvements and roughness, traffic volume changes, or vehicle types, on the hydrologic transport of tire wear particles.

While the results of this study suggest that the modeling approach presented may be an effective way of modeling the buildup and washoff of tire wear particles, there are limitations. Pollutant concentrations were collected at the watershed outlets, but there were no discharge measurements. Consequently, the flow rates from the hydrologic models are uncalibrated. However, by developing models using the same process for twelve separate watersheds and comparing the relative loadings to the measured concentrations, we provided a generalized assessment of the applicability of the models to measured data. In addition, the validation of the model is limited to data collected at the stormwater outlet. Therefore, the degree to which uncertainties are associated with the buildup of pollutants, washoff functions, or their hydraulic transport is unclear. In addition, the buildup function is able to consider vehicle type, but this was not available in the traffic data in this study; therefore, the conservative assumption that all cars are passenger cars likely underestimates the total tire wear. Future work that can accurately define a distribution of vehicle types on a given road could improve the validity of the model. Furthermore, tire wear is dependent upon the brand and type of tire. Hence, further research defining the rates of tire wear associated with various tire brands and types (all terrain, seasonal, passenger, etc.) will help to improve estimations of tire wear buildup on roadways. Finally, the buildup function relies on IRI data, which, while widely collected by the State Department of Transportations, may not be readily available for all roadways.

There is therefore a need for future work that can develop a better mechanistic understanding of tire wear buildup and its transport in stormwater. Future work could further evaluate the accuracy of the proposed buildup function through empirical studies on the rate at which tire wear buildup occurs as a function of the proposed or other variables. There is limited empirical data on the impact of traffic, loading, and road roughness on the generation of tire wear particles. Those that do exist have focused on the aerial dispersion of tire wear particles within a laboratory environment and found that tire speed, loading, and friction largely control tire-wear particle generation suspended in air (Kim and Lee, 2018; Park et al., 2018). However, further lab studies that validate the generation of these particles on the surface and their physical characteristics would be a valuable contribution. Finally, empirical field studies that collect more data throughout the watershed, including buildup rates, washoff concentrations, and flow rates, would provide a valuable validation of the proposed approach.

4. Conclusion

This paper presents a method to model the buildup of tire wear particles on urban roadways that can be integrated directly into a stormwater runoff model. Results indicate that this approach may be an effective way to estimate the buildup of tire wear particles based on road roughness and traffic volume and speed data. This approach could be applied to estimate the total loading of tire wear particles from urban watersheds to design effective treatment systems. Future work on validating the buildup rate and characteristics of washoff is needed to improve the proposed approach. Ultimately, the ability to effectively model a critical and emerging contaminant in stormwater runoff can help to enhance our ability to mitigate its impacts on human and environmental health.

Credit author statement

Matthew Dupasquier: Writing – original draft, Formal analysis, Investigation, Data Curation, Software; **Jaime Hernandez**: Conceptualization, Methodology, Supervision, Writing – Review & Editing, Funding acquisition; **Alondra Gonzolez**: Formal analysis, Investigation, Data Curation, Software**; Cesar Aguirre**: Formal analysis, Investigation, Data curation, Software; **Walter McDonald**: Conceptualization, Methodology, Supervision, Writing – Review & Editing, Funding acquisition.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2023.118958.

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