



OPEN Mapping open dumps and waste dynamics in a subtropical ecoregion of Argentina

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The proliferation of plastic waste since the 20th century has exacerbated pollution problems despite technological advances in waste management. In Argentina, 35% of municipal solid waste is discarded in untreated open dumps, causing environmental and public health risks. This study focused on detecting and mapping open dumps in the most densely populated province, Tucumán, using satellite imagery and unmanned aerial vehicles (UAV). Specifically, for each dump we (1) described spatio-temporal dynamics, (2) analyzed topography and hydrology characteristics, and (3) quantified waste mass. We identified and mapped forty open dumps (range size: 0.05 to 3.79 hectare). Most dumps were located within an endorheic basin, at 5 km or less from urban centers. Many have increased in size over the last decade, especially larger dumps (> than 1 hectare). The hydrological analysis showed material movement from dumps to surrounding environments, mainly watercourses and crops. Total waste mass averaged 5.72 kilotons (kt) per dump (range: 0.06 to 38.45 kilotons, where 1 kt = 1000 tons). This exhaustive survey of open dumps highlights the urgent need for sustainable waste management practices to mitigate environmental and public health risks in Tucumán and other regions facing similar challenges.

Keywords Anthropocene, Unmanned aerial vehicle, Solid waste, Municipality, Watershed, Plastic pollution

Waste management has been a challenge for humanity since the beginning of sedentary life, regardless of the technological advancements achieved through time to address resource efficiency and circularity¹. The massive production of plastics that started in the 20th century and has accelerated since, has brought upon one of the biggest pollution problems that socio-ecological systems have ever seen². Argentina is not the exception. For example, only 65% of municipal solid waste arrive at sanitary landfills where leachates, greenhouse emissions, and proliferation of disease vectors are better controlled, while the remaining 35% of the argentinian population's waste ends up in open dumps and lacking basic preventive measures³. In many cases, open dumps include municipal solid waste (i.e. governmental) which is deposited without treatment or adequate management, causing public health and environmental problems^{4,5}. For instance, bad odors, pests, soil, and water contamination affect the quality of life of the people who live in the surroundings^{6,7}. In addition, the anaerobic decomposition of organic matter at open dumps generates greenhouse gases such as methane, contributing to climate change⁸.

To enhance waste management and reduce pollution, it is essential to detect and map open dumps. Efforts in detecting dumps are limited, probably because traditional methods to characterize land use, such as satellite image classifications, face technical challenges, especially if dumps are not spatially concentrated (i.e. if they are scattered), or if they are under dense vegetation or located in arid ecosystems⁹. In spite of limitations, satellite images such as the LANDSAT series^{10,11}, SPOT¹² and Sentinel-2^{13,14} have been used to rapidly detect waste accumulation in terrestrial environments⁹. Moreover, in order to map open dumps, the use of newer technologies such as unmanned aerial vehicles (UAV) has increased in recent years¹⁵. For instance, UAV have been used to train classifiers with the aim of detecting unknown dumps^{16–18}, to identify trash and litter types¹⁹, to estimate volumes of waste and recyclable materials^{20,21}, to plan cleanups²², and to develop pollution risk analyses²³. Though the occurrence of dumps in the world is pervasive, the use of remote sensors for locating and mapping these sites in contrast to sanitary landfills, is still limited.

As in other regions of the globe, the occurrence of dumps is common in Tucumán, a province that occupies 22,592 km² and is the most densely populated of Argentina. In this subtropical province, the most concerning

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situations regarding municipal solid waste management occur outside the metropolitan area, where more than 50 open dumps have been identified during field surveys by the environmental local administration²⁴. Temporal and spatial dynamics of open dumps in the province remain largely unexplored, such as their growth or decline patterns (i.e. when they become inactive and covered by vegetation), as well as the emergence of new ones. Additionally, solid waste transportation within and across landscapes, and its ultimate fate within endorheic systems or river basins remains unclear. This study aimed to comprehensively assess open dumps in Tucumán through the use of satellite imagery and UAV flights. For each dump, we: (1) analyzed spatial and temporal dynamics (area), (2) characterized topography (digital elevation and terrain models) and hydrology (watershed delineation, and flow direction), and (3) quantified waste mass (in kilotons). The results of this study will establish a baseline for future monitoring, and will serve as inputs for policy makers in order to mitigate plastic pollution associated with socio-ecological impacts.

Methods

Selection of open dumps

We used a database generated by the Secretary of the Environment of Tucumán (SEMA) until 2013 which included the location of open dumps in the province (Fig. 1). This database served us as a starting point but needed to be improved as some open dump locations were not accurate, some had been closed, and some were even missing. In addition, we searched for new dumps to update the database. We visually scanned Google Earth images within a radius of up to 5 km around populated cities, and in the vicinity of watersheds, following the particular spatial (i.e., dendritic) patterns that dumps show. We confirmed the activity status of each dump (i.e., active or inactive) by inspecting it in updated 10 m -resolution Sentinel-2 satellite imagery in Google Earth Engine²⁵.

Survey of open dumps

Spatial and temporal survey using satellite imagery

Each time we identified a dump, we measured the current (i.e. spatial) and historical (i.e. temporal) area detectable from satellite images (Fig. 1). We utilized the historical collection of very high spatial resolution satellite images available in Google Earth Pro to monitor the dumps through time, recording changes in their area. We measured waste area delineating polygons around waste-dominated sites within the dumps (i.e., excluding vegetation cover). The total dump area was the sum of waste-dominated polygons.

Spatial survey using unmanned aerial vehicles (UAVs)

Collection of aerial images

For each dump, we established a sampling protocol that included desktop and field procedures. On the desktop we assigned an identifier number (ID) to each dump. Then, we generated the flight plan using DroneDeploy (version 2.119.0, <https://www.droneDeploy.com/>) (Fig. 1). The flight plan consisted of generating a polygon that followed the contour of the dump, using satellite imagery provided by Google Earth Engine. Each dump contour

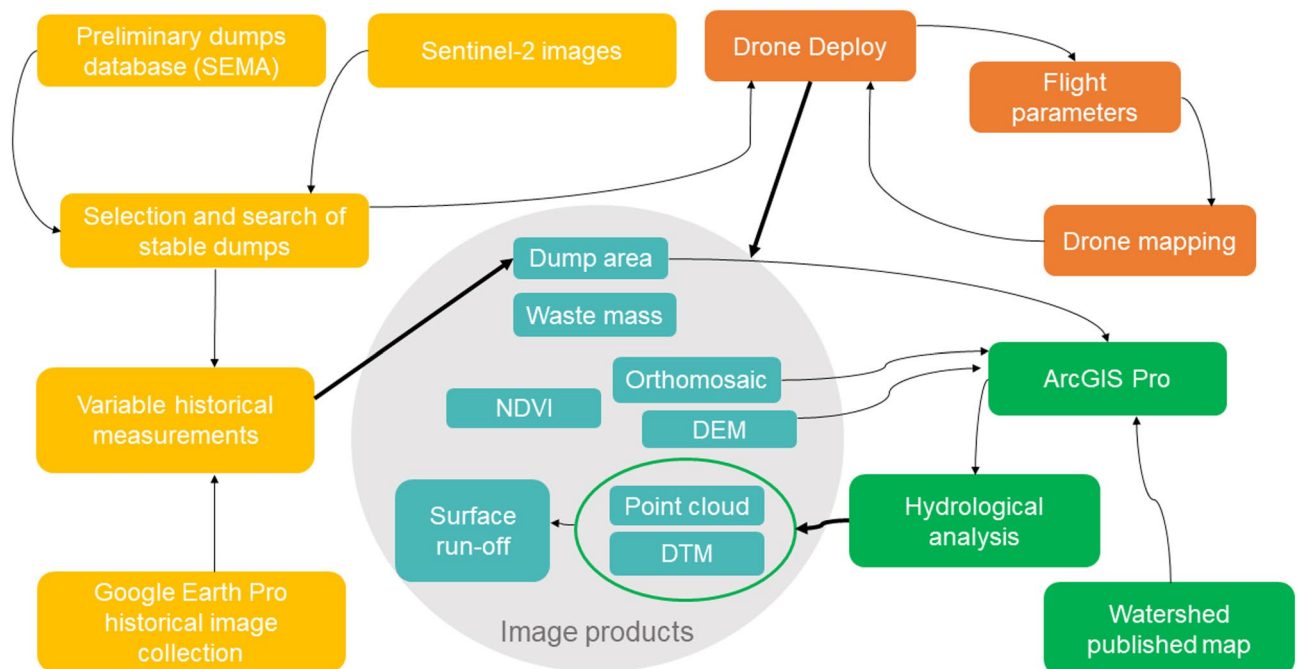


Fig. 1. Workflow of analyses detailing satellite image (yellow), unmanned aerial vehicle image (orange) and hydrological (green) analyses. The products were images that were used as intermediate steps in the analyses or were final products.

was set within a grid and this grid was used by the UAV as a guide to take aerial photographs at the lines' intersections, from different angles and observation points. This allowed the posterior generation of a three-dimensional image of each dump with minimum distortion. Finally, in the field we used a DJI Mavic 2 Pro UAV to take the photographs. These were taken at 75 m above the ground, which allowed an efficient balance between battery charge and image resolution.

Topography, hydrology, and waste mass analysis

To analyze the spatial dynamics of materials within each dump, we ran different analyses. First, we georeferenced a map of watersheds generated by the province²⁶ in order to consider watersheds at the scale of each dump. Then, we estimated the area of the dump and its topographic characteristics, using the high definition photogrammetrically orthorectified image generated by DroneDeploy as a template. We used the imagery taken by the UAV, the orthomosaic, and the digital elevation and terrain models (DEM and DTM) generated by DroneDeploy to perform a fluvial analysis. This fluvial analysis was performed in order to estimate the direction of surface run-off, which includes the direction of solid and liquid waste (including leachates) movement. For this step, we used the watershed delineation, and flow direction and accumulation tools in ArcGIS Pro version 3.0.2 (<https://www.esri.com/en-us/arcgis/products/arcgis-desktop/overview>). Finally, topographic products including slope, aspect, shading, and contours were generated. The point cloud from which topographic models were derived and used for this step was downloaded from DroneDeploy. Macro-scale SRTM 30 m data was downloaded through OpenTopography, to be compared with the hydrologic output of the drone-derived DTM. In order to automate the processing, a model was produced using ArcGIS Pro ModelBuilder.

To estimate total waste mass (kt, kilotons, where 1 kt = 1000 tons), and mass per unit area (kt ha⁻¹) at each dump we first used a theoretical distribution of materials based on published reports for this region (i.e., around 15% plastics, 3% glass, 50% organics, and others)^{3,27} (Table 1). Second, for each dump we assigned an average density to each material and used this value and the waste volume measured by the UAV to calculate waste mass as follows: Waste mass = Density * Volume. Third, to calculate mass per unit area (kt ha⁻¹) at each dump, we used the waste area measured by the UAV.

Results

We identified 40 open dumps in Tucumán, mostly located towards the south of the province, at a distance of no more than 5 km from urban centers and near watercourses (Table S1). In most open dumps no operation facilities existed at the site or in nearby localities. Instead, waste was subjected to burning and/or removal using excavator buckets by the local governments (municipality and communes). Although waste pickers (mostly men) collected recyclable materials (mainly plastic, metal, and cardboard) in many dumps (personal observations), this activity constituted a minor portion of the overall waste^{3,27}.

Three dumps (ID 21, 25, 40) were too small (i.e. <0.001 ha) to be detectable from the satellite images or to allow UAV flights, in two dumps (ID 23, 33) we encountered logistical challenges that prevented UAV data acquisition, and two dumps (ID 17, 36) were detected only once from the satellite image database. Five open dumps were out of use (ID 2, 6, 7, 31, and 33). Most dumps (35) were located in the upper basin of the Mar Chiquita system, draining into the Río Hondo dam either directly or through the Salí river (Fig. 2a). Downstream, the Salí turns into Dulce river which continues southward, contributing with more than 80% of the flow rate of Mar Chiquita lake. Only five of the open dumps were outside the Mar Chiquita system, emptying into the Santa María river to finally drain eastward into the Paraná plains of the Salado Paraná system (Fig. 2a, b)^{28,26}.

Spatial and Temporal survey using satellite imagery

Open dumps differed in their spatial (i.e. current) and temporal (i.e. historical) dynamics, according to satellite images (Figs. 3 and 4). Thirty five dumps out of 40 were detectable through time (Table S1). We registered most dumps since 2011 (~ 13 years), with the exception of two dumps (ID 29: Villa Medina and ID 35: Tacanas), which were already present in 2002 and 2005, respectively (~ 22 years). Most recently, 14 dumps were recorded after 2016 (~ 8 years). Twenty three dumps were smaller than one hectare (ha) while 12 dumps reached 1 ha or were even larger during the period 2011–2022. Smaller dumps tended to be highly dynamic, but if we considered their area in the first and last date registered, 11 open dumps increased in size, nine decreased and three showed the same initial and final area (Figs. 3a and 4). Larger dumps were more stable and tended to grow even larger over time, i.e. nine showed an increase taking into account initial and final areas (Figs. 3b and 4).

Material	Percentage	Density (kg/m ³)
Glass	3%	2 500
Aluminum	3%	2 710
Cardboard	15%	0
Plastic (PET)	15%	689
Organics	50%	1 455
Other	14%	1 080
Sum	100%	1 017.9

Table 1. Percent and density averages of the materials commonly found in open dumps in Argentina based on published reports for this region^{3,27}.

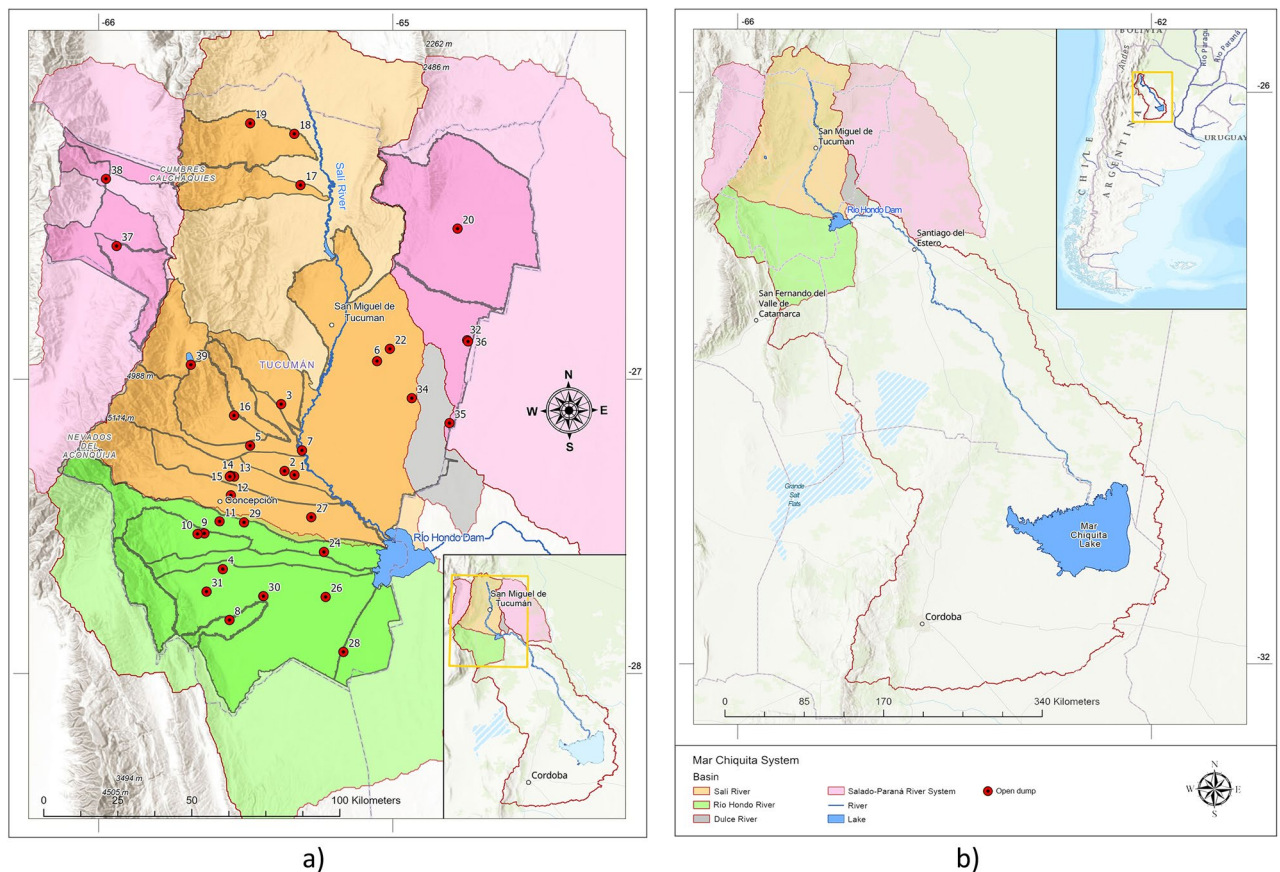


Fig. 2. (a) Map showing open dumps surveyed in Tucumán, Argentina; different colors refer to different basins. Numbers are the identifier (ID) of each dump (see **Table S1**); (b) Open dumps were found mainly within the Salí-Río Hondo-Dulce river basin, which empties into the Mar Chiquita lake, in the province of Córdoba. Open dumps shown here are those that were detected using satellite images. Maps were created using hydrographic layers freely obtained from the National Geographic Institute of Argentina. (<https://www.ign.gob.ar/NuestrasActividades/InformacionGeoespacial/CapasSIG>) and ArcGIS Pro version 3.0.2 (<https://www.esri.com/en-us/arcgis/products/arcgis-desktop/overview>).

Spatial survey using unmanned aerial vehicles

Aerial images

Open dumps measured, on average, 1.01 ha although variability was high (range: 0.05 ha to 3.79 ha) (Fig. 5, Table S1). Famaillá (ID 3), Alberdi (ID 4) and Concepción (ID 12) were the largest dumps, covering more than 3 ha each (Fig. 5a). On average, dumps had a waste mass of 5.72 kilotons (kt); the dump with the highest mass were Concepción (38.45 kt) and El Mollar (ID 39, 35.29 kt), while the lowest mass was registered in Paso Santa Ana (ID 10, 0.06 ktn) and in Tacanas (ID 35, 0.08 kt) (Fig. 5b). Regarding mass per unit area, the average was 4.88 kt ha⁻¹; the dump with the highest mass per unit area was El Mollar (ID 39, 39.21 kt ha⁻¹), and the lowest mass per unit area was Graneros (ID 30, 0.21 kt ha⁻¹) (Fig. 5b).

Topography, hydrology, and waste mass analysis

At the scale of each dump (local scale) we found diverse situations regarding surface run-off and the potential movement of waste from the open dump to the surrounding environment. Many open dumps were located near watercourses draining most of the material to them directly (i.e. ID 1, Simoca 1) (Fig. 6). In some cases, although open dumps were next to watercourses they drained mainly in the opposite direction ending in crop fields and natural vegetation (i.e. ID 3, Famaillá). Still, other open dumps were not contiguous to watercourses, and they were immersed in an agricultural matrix draining in all directions (i.e. ID 4, Alberdi) (Fig. 6). In fact, more than half (51%) of the dumps were located on the banks of rivers, or near streams and channels (Figure S1, Table S1), many (23%) were adjacent to crops (Figure S1) and some (17%) were, both, adjacent to watercourses and crops. 9% of the dumps were surrounded by natural vegetation only. Eventually, other land uses were registered near some open dumps, such as urban areas or roads (Table S1).

Discussion

We reported one of the most exhaustive surveys of open dumps in Argentina using satellite imagery, and flying unmanned aerial vehicles at each dump to map superficial run-off. We detected and described 40 open dumps

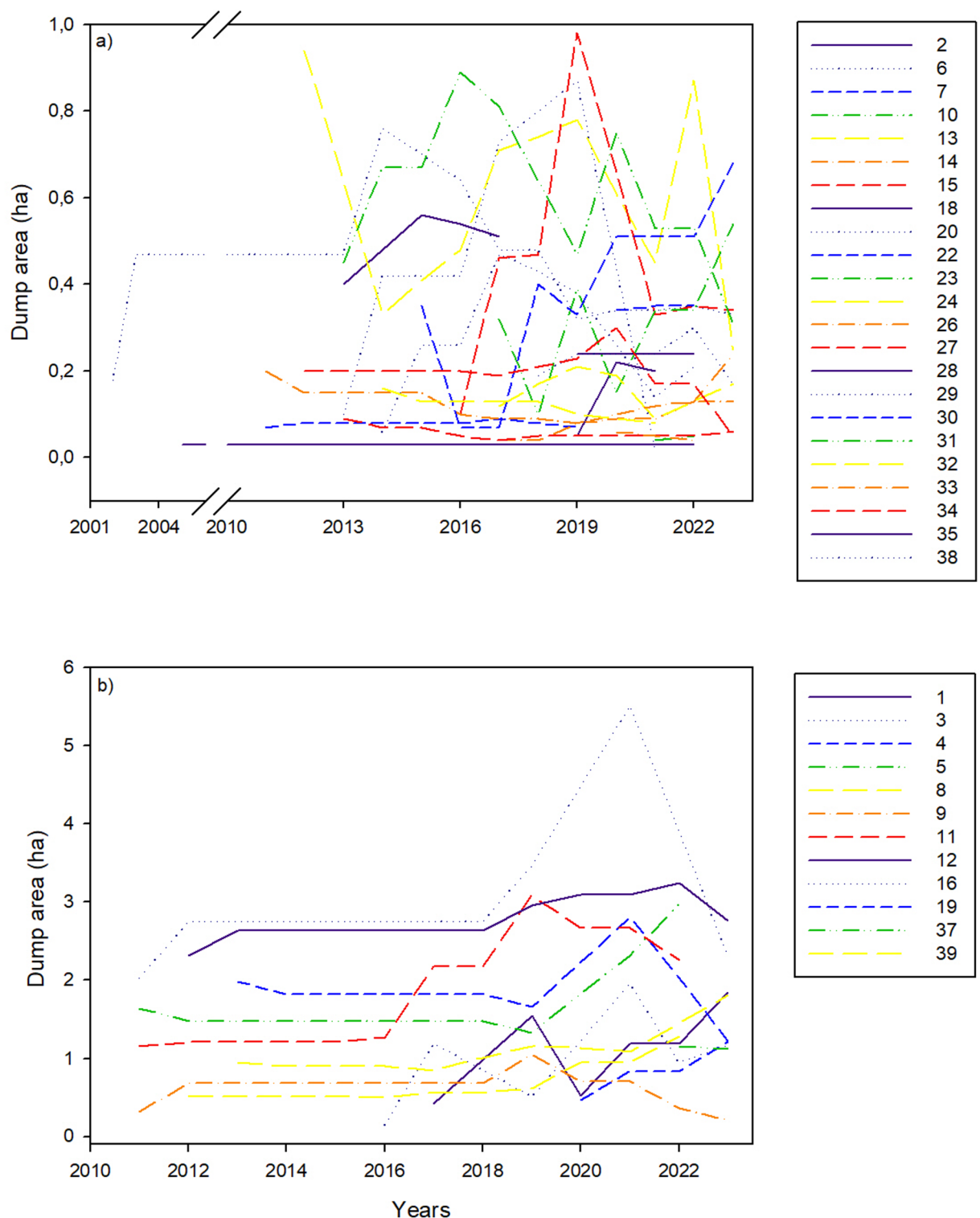


Fig. 3. Area of open dumps over the period 2011–2022 estimated from satellite images for: **(a)** small dumps (> 0.001 and < 1 ha, $n = 23$); and **(b)** large dumps (i.e., those that reached 1 ha or more through time, $n = 12$). Numbers refers to the identifier (ID) of each dump. Open dumps shown here are those for which we obtained data from satellite images through time ($n = 35$) (see **Table S1**).

for Tucumán, mostly located at the south of the province within the Salí-Dulce river basin. The open dumps varied in area through time and, according to UAV images, they also varied in relation to waste concentration (kt ha^{-1}) and the direction of materials' superficial run-off. These results represent a baseline for future monitoring and provide a starting point for delineating remediation actions regarding environmental pollution.

ID 15, Arcadia



ID 12, Concepción



Fig. 4. Examples of the temporal dynamics observed at one small (upper panel: Arcadia, ID 15) and one large (lower panel: Concepción, ID 12) dump between 2012 and 2022. Images were freely obtained from Google Earth Pro (https://www.google.com/intl/es_ALL/earth/about/versions/#download-pro) and were used to measure dumps' area through time and two size groups were characterized, where small dumps were more variable than large dumps (see Fig. 3). Proper attribution to Google is provided within the figures.

Based on satellite images, the temporal dynamics of small and large dumps was contrasting, while many of open dumps (i.e., 20 out of 35) showed an increase in area during the period 2011–2023. The driving forces of dumps' dynamics through time may differ between small and large dumps, as shown by our results. Small dumps were more variable in area than larger ones, which were more stable and underlied the general pattern of area increase over time. Based on these results, some remediation actions may be highly efficient in small dumps. For example, biochars can be successfully used to adsorb contaminants, both organic and inorganic, from dump soils²⁹. The area increase was related with net population increase, but, when examined in combination with expected waste mass increase, these results did not always agree with population sizes in nearby cities, suggesting that temporal dynamics of dumps should be evaluated under the light of different socio-environmental processes³⁰. For example, according to the surveyed data, Alberdi's dump (ID 4) occupies 3.79 ha, and it has a waste mass of 13.86 kilotons according to the average density of waste materials considered in Table 1. With a population of more than 34,189³¹ and an estimated rate of 1 kg of waste produced per person per day³, this site would accumulate a theoretical mass of 12,479 kilotons annually. The satellite data suggests that this site has at least 9 years of activity, thus possibly accumulating 112,311 kilotons of waste since then. Nevertheless, 112,297 kilotons are unaccounted for from the UAV collected dataset. These differences in waste mass may be the result of a multiplicity of factors and processes' interactions. For example, if waste was discarded and accumulated in a topographical depression (i.e. trench) it would be undetectable from the UAV images. In addition, processes as diverse as the intensity of erosional forces, the amount of summer precipitation that may be related to river floods and consequent waste 'washing', and/or management actions intended to decrease waste volume (i.e. fires) or illegal dumping to or from populations outside the designated municipalities determine the final area that the remote sensors measure. Burning is a highly prevalent practice (i.e. we detected fires in 30 out of 35 dumps) to reduce waste mass when management is inadequate or limited, contributing to environmental degradation and posing health risks to nearby populations^{32,33}. Other explanations for the missing waste mass may include picking material for recycling purposes, although this process would be of minor importance (less than 6%³⁴).

The mapping of the area, mass, and mass per area of each dump in Tucumán contributing to the Salí-Dulce basin is a first step not only to understand the socioecological dynamics of these disposal sites, but also serves as an input to delineate or design remediation strategies. For example, we identified some dumps (e.g. ID 12: Concepción) as the most critical, since they combine the highest values of waste area, waste mass and also relatively higher values of mass per area. Another example site is dump ID 6 (Ranchillos, already inactive), which shows a high value of mass per hectare but a relatively small area. This suggests that the material is concentrated, so eradication and remediation would be more efficient than in dumps such as dump ID 3 (Famaillá), where the area is relatively large and the waste is more dispersed (lower waste mass per hectare). This way, our results enable a ranking of dumps according to their volume and concentration on the terrain. This input may support sustainable management practices, including national and local initiatives that attempt to address the eradication of these dumpsites³. Such ranking efforts have been conducted in other regions of the world using a limited number of dumps. For example, Mahmood et al.³⁵ ranked four municipal dumps according to resident's concerns, groundwater vulnerability, and surface facilities, and Guleria and Chakma³⁶

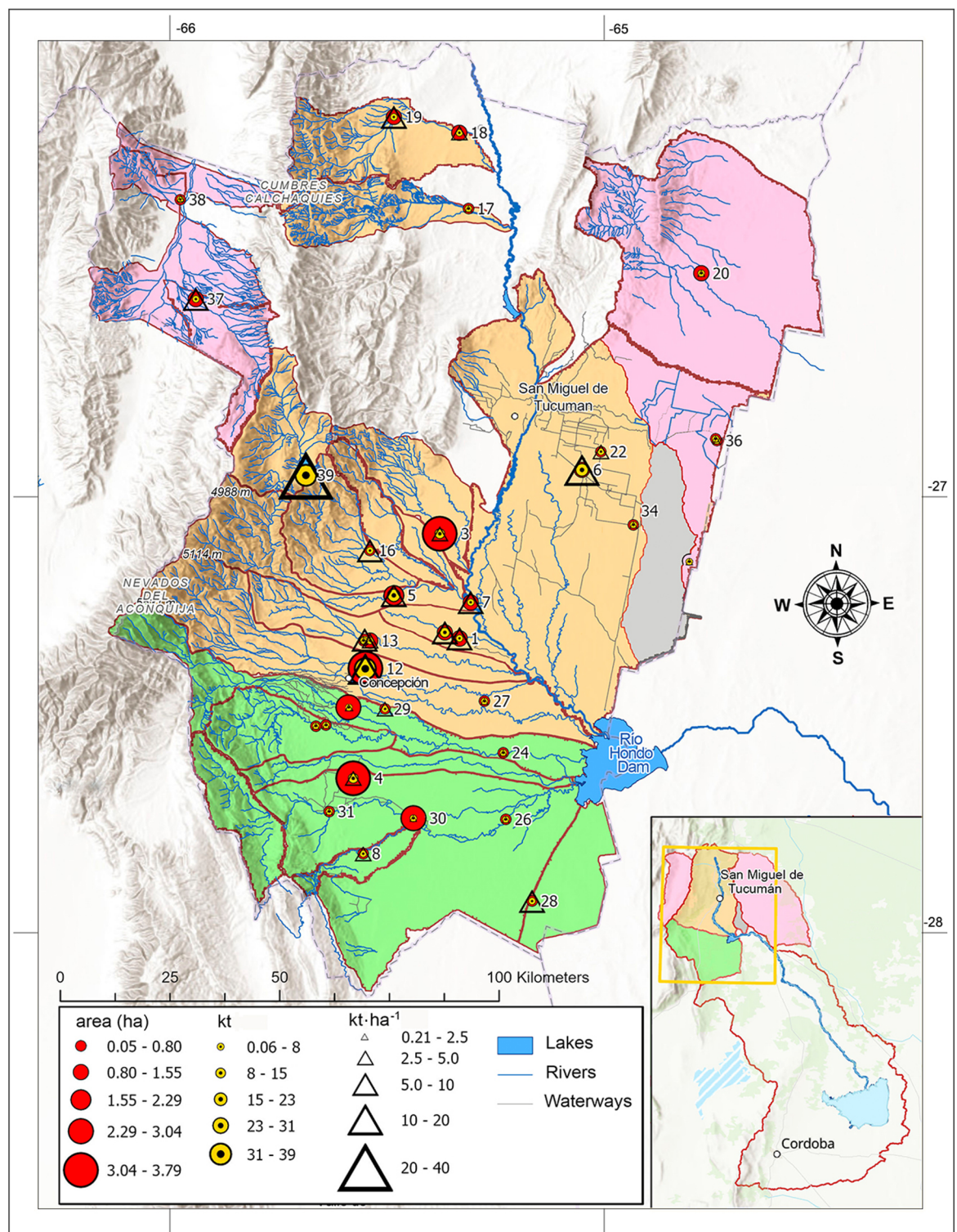


Fig. 5. (a) Map of open dumps registered within different basins of Tucumán (see Fig. 1a for details). Red circles represent the area of each open dump in hectares measured by the UAV. Yellow dots represent the mass in kilotons (1 kt = 1000 tons) and the black triangles show the kilotons per hectare for each open dump. Maps was created using hydrographic layers freely obtained from the National Geographic Institute of Argentina (<https://www.ign.gob.ar/NuestrasActividades/InformacionGeoespacial/CapasSIG>) and ArcGIS Pro version 3.0.2 (<https://www.esri.com/en-us/arcgis/products/arcgis-desktop/overview>). (b) Area of the open dumps expressed in hectares (blue bars, with the exact value written above) in relation to total mass of waste (red line, kt) and to the mass per hectare (yellow line, kt ha⁻¹). Numbers on the map and in the X axis refer to the identifier (ID) of each dump. Open dumps shown here are those for which we obtained data using the UAV flights ($n = 35$) (see Table S1).

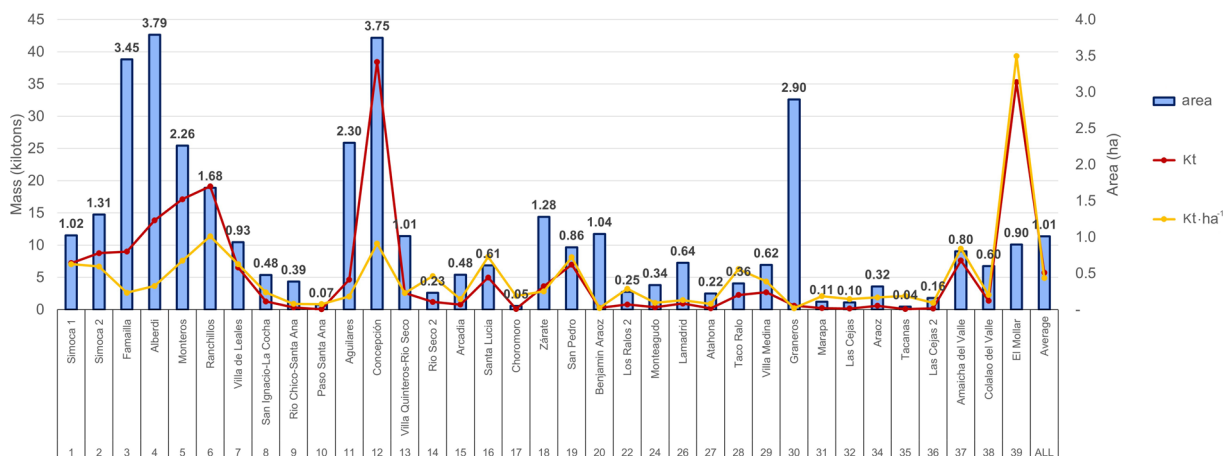


Fig. 5. (continued)

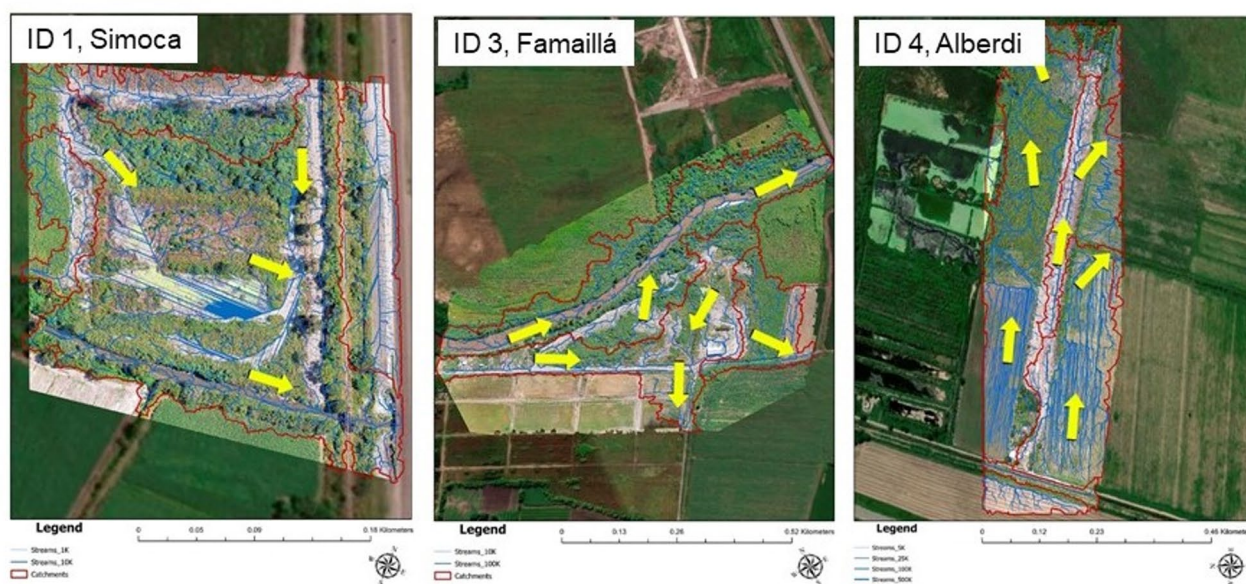


Fig. 6. Open dumps showing different situations regarding surface run-off. In the image on the left the open dump (Simoca 1, ID 1) drains directly into the adjacent watercourse; in the central image most of the dump (Famaillá, ID 3) drains mainly in the opposite direction of the watercourse, into crop fields; and in the image on the right the open dump (Alberdi, ID 4) is immersed in an agricultural matrix and drains in all directions. Red polygons indicate watershed divisions, and blue lines indicate water flows in the relief. The arrows indicate the potential direction of waste movement, given topography. All dumps for which we obtained data using the UAV flights are shown in **Figure S1** ($n = 35$). Images were created using DroneDeploy Software version 2.119.0 (www.dronedeploy.com) and ArcGIS Pro version 3.0.2 (<https://www.esri.com/en-us/arcgis/products/arcgis-desktop/overview>).

ranked five dumps focusing on groundwater contamination due to metal leaching. Here we demonstrated that combining free satellite images with UAV images is a low-cost methodology for performing dumps' rankings based on size and spatial configuration.

At a landscape scale, the land uses that were contiguous or near open dumps were consistent. Most open dumps were either close to watercourses (river, streams, channels) and/or adjacent to crops (32 out of 35, 91% total). At the local scale, some dumps drained directly to the river (i.e. in Simoca, ID 1; Monteros, ID 5 and San Ignacio-La Cocha, ID 8), while others drained directly to adjacent crops (i.e. in Alberdi, ID 4, Los Ralos2, ID 22

and Villa medina, ID 29). In addition, there were other dumps where both situations occurred, that is, drainage was directed to watercourses and to crops (i.e. Famaillá, ID 3 and Rio Chico-Santa Ana, ID 9). This uncontrolled leachate drainage could pose direct threats to water and crops linked to human food consumption. For example, in India, Kiran et al.³⁷ studied heavy metals in a 5 km² range of dumping near agricultural lands and water sources. They found that heavy metal concentration in water, crops, and soils were higher than the permissible limit; affecting crops and human health due to the leaching of waste into the environment. Future steps include evaluating contamination in nearby watercourses and crops soils, and also in groundwater sources, as leachates could be negatively impacting underground aquifers. It is essential to consider hydrogeological factors, such as soil infiltration capacity, and the relationship between surface and groundwater, which directly affects local water reservoirs.

For our large-scale study of dumps we tested a combined methodology that included using a government database of dumps' locations as a first step, free satellite imagery for determining activity status and examining temporal dynamics, and UAV for on-site mapping. The method showed advantages and disadvantages for the evaluation of dumps. The main advantage was its relatively low cost, which makes it applicable in other countries under similar socio-economic conditions to those in Argentina (e.g.³⁸). In addition, using a domestic UAV was sufficient to collect high-resolution images (between 0.5 and 5 cm/pixel depending on flight altitude), that had less impact from cloudiness than satellite images, and enabled a local, micro-scale analysis of drainage systems. Both UAV and satellite datasets showed to complement each other to evaluate temporal and spatial aspects of the dynamics of dumps. Dump area determined from UAV in our study was consistently higher compared to that determined from satellite imagery, suggesting that studies reporting dump area from satellite imagery underestimate this metric. Main disadvantages were: the dependence on available, public, updated data on the location of dumps, which is generally missing in developing countries (but see³⁹), but may be solved by training on satellite image visual interpretation to locate the dumps, the availability of cloud-free satellite images, and the size of UAV files, which may involve acquiring devices with high storage capacity.

Some aspects that were not included in this study were estimating the emission of greenhouse gases, such as methane and carbon dioxide, from our dumps which would enable a more comprehensive ranking in a global context, given the different efforts that are being conducted (e.g.⁴⁰). In addition, incorporating chemical analyses of water samples collected upstream and downstream from the contiguous watercourses and detecting pollutants in underground water reservoirs would be important in order to identify leachate leaks that contaminate relevant and highly-connected components of the ecosystem⁴¹. Third, the analysis of municipal solid waste transport costs given a road network configuration would serve to contrast socio-political patterns with geographic patterns and to identify management actions that can be improved at the scale of large jurisdictions.

Data availability

All data generated or analysed during this study are included in this published article (and its Supplementary Information files).

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Author contributions

AM, AG-C, EM, PGGE, JF, ACM-G: conception and design of the work; acquisition, analysis, and interpretation of data; write and revise original draft preparation. AM, AG-C, ACM-G: resources and project administration. AG-C, EM, PGGE, JF: software and data curation. All authors have read and approved the submitted version of the manuscript and have agreed both to be personally accountable for the author's own contributions and to ensure that questions related to the accuracy or integrity of any part of the work.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

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