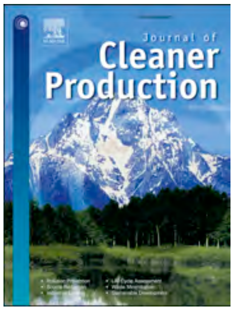

Transitioning from open dumpsters to landfilling in Peru: Environmental benefits and challenges from a life-cycle perspective

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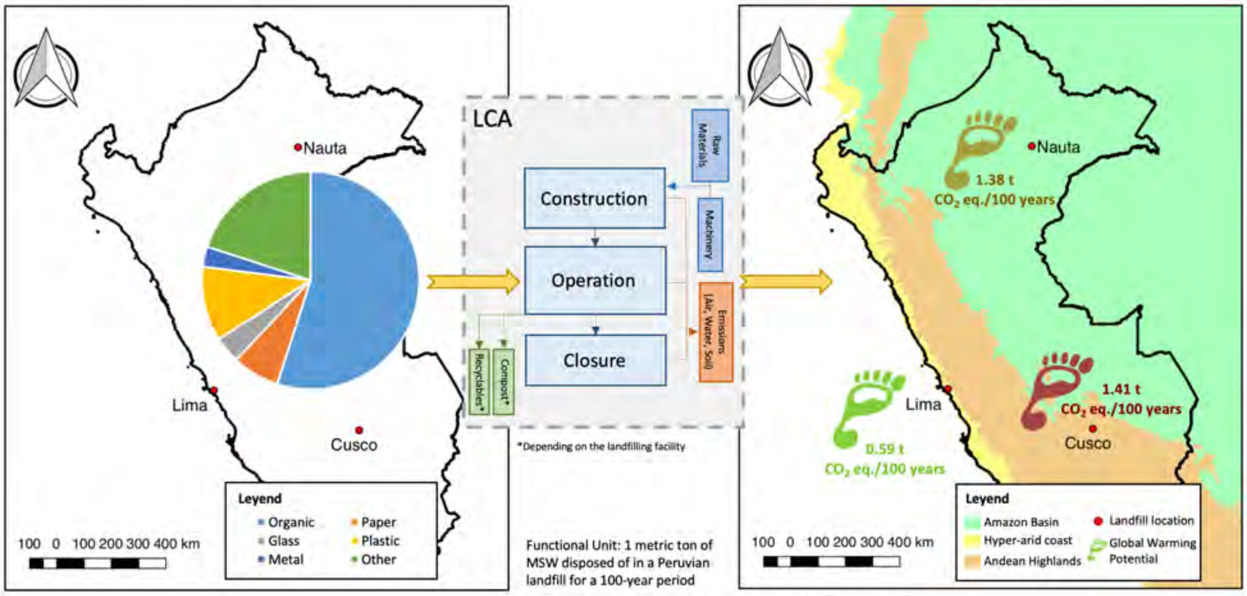

Nauta
Lima
Cusco
Leyend
Organic
Paper
Glass
Plastic
Metal
Other
100 0 100 200 300 400 km
LCA
Raw Materials
Construction
Machinery
Operation
Emissions (Air, Water, Soil)
Recyclables*
Compost*
Closure
*Depending on the landfilling facility
Functional Unit: 1 metric ton of MSW disposed of in a Peruvian landfill for a 100-year period
1.38 t
CO2 eq./100 years
1.41 t
CO2 eq./100 years
0.59 t
CO2 eq./100 years
Amazon Basin
Hyper-arid coast
Andean Highlands
Landfill location
Global Warming Potential

Transitioning from open dumpsters to landfilling in Peru: environmental benefits and challenges from a life-cycle perspective

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Abstract

The Peruvian waste management sector is steadily transitioning from a mostly informal and underdeveloped system based on the use of open dumpsters to a landfill-based system. The environmental consequences of these policies must be evaluated with environmental management tools such as Life Cycle Assessment (LCA). Therefore, the main goal of the study is to analyze the life-cycle environmental performance of waste disposition in three different landfills located in three distinct geographical areas of Peru: i) the hyper-arid coast; ii) the Andean highlands; and, iii) the Amazon Rainforest. With this aim in mind, a comparative analysis is provided regarding the waste treatment process as compared to other landfill technologies (i.e., biogas combustion or energy recovery) and open dumpsters. The modelling of these systems was performed with the EASETECH waste LCA tool, including a sensitivity analysis in terms of waste composition and waste decay rates. Results show that landfill gas (LFG) treatment reduces greenhouse gas (GHG) emissions considerably. However, these remain higher in the Amazon as compared to the Andean Highlands (+105%) and the hyper-arid coast (+17%). Most of the decomposition in

the Amazon basin occurs within 5 years after disposition (80%) due to heat and humidity, whereas in the other regions values were below 55%. LFG treatment or recovery is necessary for these emissions to be lower than in open dumpsters. The implementation of these technologies would strengthen the country's action plan regarding the Paris Agreement in the waste sector. In other impact categories, the transitioning from dumpsters to landfills is most visible in the soil and water compartments.

Keywords: GHG emissions; Latin America; Life Cycle Assessment; sanitary landfills; waste management.

1. Introduction

Waste management still represents a critical challenge for low- and middle-income countries (Aparcana, 2017). Rapid urbanization, erratic municipal solid waste (MSW) management systems or the lack of highly qualified technicians (Guerrero et al., 2013), explain a great part of the lag in comparison to high-income nations (Jambeck et al., 2015). This has led to numerous environmental hazards and social risks (Henry et al., 2006). Greenhouse gas (GHG) emissions linked to uncontrolled open dumpsters are a matter of concern at a regional and global level (Medina, 2010). The reiterative use of open dumpsters or uncontrolled disposal on riverbanks or even in the ocean has generated impacts in terms of toxicity in aquatic and terrestrial ecosystems, eutrophication or acidification, damaging aquifers and rivers (Guerrero et al., 2013). Open burning and hazardous waste mismanagement have been shown to be responsible for certain health problems, including evidence of correlation with cancers (Ray et al., 2009), respiratory illnesses (Ray et al., 2005) or vector-borne diseases (Kathiravale and Muhd Yunus 2008).

Latin America and the Caribbean (LAC) is a region in which open dumpsters are still the final disposition site for over 30% of MSW (Kahhat et al., 2018). Landfilling is the technology selected for the vast majority of the remaining amount, while more sophisticated technologies, such as composting or incineration, are yet to be applied in the region. Despite the delay in upgrading the waste management system, increased interest by policy-makers in LAC nations in reducing illegal dumping is supported by a set of decisions passed in recent years (MINAM, 2015). Firstly, many countries complied with reducing their GHG emissions linked to waste mismanagement as one of the commitments in the Non-Annex I Parties of the Copenhagen Accord in 2009 (UNFCCC, 2018). These initiatives were later improved and expanded in the form of nationally-determined contributions (NDCs) presented by each nation in the frame of the Paris Agreement (Tobin et al., 2018). Secondly, measures to reduce the vulnerability and risk of informal waste management pathways have been implemented through legislation (MINAM, 2013), monitoring (SIGERSOL, 2018) and occupational health and safety regulations (Grau et al., 2015). Finally, environmental legislation for waste disposition has been upgraded to account for the growing sophistication of final disposition technologies (MINAM, 2017a).

In the case of Peru, there were only 29 landfills registered in 2017 (MINAM, 2017b). In contrast, over 1,400 open dumps, spread throughout the nation, were reported in mid-2018 (Technical staff, Ministry of the Environment, personal communication, May 2018). In 2015, Peru disposed of 7.59 Mt of MSW, of which 49.3% was sent to landfills, while the rest remains unreported (Ziegler-Rodríguez et al., 2018). Significantly, if the metropolitan area of Lima is excluded from the statistics, only 7.6% of waste is landfilled. In fact, as of November 2017, 10 out of 25 regions in Peru still lack landfilling infrastructure (MINAM, 2017b).

Approximately 6.0 Mt of CO_2eq in 2012, representing 4% of the country's total

GHG emissions, were emitted by the solid waste management sector (MINAM, 2012). This has led the national government to propose several mitigation NDCs linked to waste management: four independent actions, as shown in Table 1, that add to a reduction of 588 kt CO_2eq (MINAM, 2018). These NDC actions focus on improving the currently scarce landfill network through the implementation of semi-aerobic or landfill gas (LFG) technologies. The Ministry of Environment (MINAM), due to financial limitations and the lack of capacity building to implement these technologies (MINAM, 2018), has discarded more sophisticated technologies, such as incineration or separation and recovery systems. However, preliminary studies show that there is a potential to shift towards waste-to-energy technologies, namely incineration (Kahhat et al., 2018).

>Figure 1<

>Table 1<

Life Cycle Assessment (LCA) has been used in the past to evaluate the environmental impacts of waste management strategies, as well as to compare alternatives to determine environmentally sustainable solutions, allowing the transition to a green economy (Mah et al., 2017). In fact, LCA is seen as a robust environmental management decision-support tool in the solid waste sector (Laurent et al., 2014). Dozens of studies have been developed addressing management alternatives according to different needs, and geographical and political considerations, especially in Europe (Manfredi et al., 2010a). Some examples are those conducted in Belgium (Belboom et al., 2013), Italy (Cherubini et al., 2009), Russia (Starostina et al., 2018 and therein) or Spain (Margallo et al., 2014). In contrast, few efforts, concentrated mainly in South-East Asia, have been performed in developing countries (Laurent et al., 2014), especially in tropical conditions, such as

Thailand (Wanichpongpan and Gheewala, 2007) or Singapore (Khoo et al., 2012). Regarding South America, studies are insufficient. Only a few studies have been developed in Brazil. For instance, Mendes et al. (2004) compared the environmental performance of an incineration plant. More recently, Liikanen et al. (2018) analyzed the environmental impacts of the current MSW management system and future alternatives in São Paulo. Similarly, Coelho and Lange (2018) identified sustainable waste management solutions for the city of Rio de Janeiro, and Lima et al. (2018) addressed existing and alternative options for management of MSW in Brazil. An extensive review performed by Laurent et al. (2014) analyzing over 200 studies linked to LCA in the waste sector concluded that, regardless of discrepancies between studies linked to methodological assumptions or data quality and collection issues, results in this sector are highly site-specific.

Climate conditions and variations in waste composition are two critical site-specific parameters that can considerably influence final environmental impact results (Astrup et al., 2018). Therefore, results from previous LCA studies should be interpreted with caution and site-specific studies should be carried out to support policy-makers. In a recent review by Vázquez-Rowe et al. (2019), the importance of using life cycle methods, namely LCA, to support climate policy, was emphasized. In fact, the holistic nature of LCA, in terms of not only inventory analysis, but also environmental burdens, identifying trade-offs between different types of impacts, allows informed decisions to be made in environmental policy.

The objective of the present study is to analyze the life-cycle environmental performance of waste disposition in three landfills located in three distinct areas of the Peruvian geography: i) the hyper-arid coast; ii) the Andean highlands; and, iii) the Amazon Rainforest. A comparative analysis is provided regarding the waste treatment process as compared to other landfill technologies (i.e., biogas combustion or energy recovery) and open dumpsters. There is a lack of studies analyzing final disposition of waste in extreme climates, such as the Amazon Rainforest and the Andean Highlands. The analysis of landfills in these areas, which are highly dependent on the climatic conditions, constitutes the main novelty of the study. The intended audience of the study is mainly policy-makers in, or related to, low- and medium-income nations, in order to facilitate the steering of new policies in the sector, as well as to propose improvement actions to trigger the environmental performance of existing and future landfills. Since LCA-oriented studies on MSW in Latin America are still rare in the literature, it is expected that this study will provide interesting benchmarks for LCA practitioners and scientists, providing novel datasets for waste technologies in developing countries.

2. Materials and Methods

2.1 Goal and scope

The ISO 14040 guideline was followed to carry out the study (ISO, 2006). The function of the production system was the disposition of a certain amount of MSW in Peru once the recyclable fractions have been removed. The functional unit (FU) that was selected to provide the mathematical relation of the production system was 1 metric ton of MSW disposed of in a Peruvian landfill for a 100-year period. This period was fixed based on a consensus timeframe applied in the literature in which it is assumed that biogenic carbon remaining in the landfill cell after 100 years can be considered an avoided emission (Ménard et al., 2004). This avoided emission is computed as a negative contribution to global warming (Manfredi et al., 2010b).

The system boundary includes all operations occurring on the premises of each landfill (Figure 2). Upstream processes of the landfilled materials, as well as MSW collection systems, transportation and waste transfer stations, were excluded. Certain differences were identified between the three landfills, mainly linked to the presence or absence of LFG treatment, on-site segregation, daily capacity or the type of landfill according to Peruvian legislation (MINAM, 2017a).

>Figure 2<

2.2 Selection and description of the case studies

Peru is located entirely in the tropical zone of the southern hemisphere. Given its orography, it is divided into several biomes or climate classification zones. In this sense, three clearly differentiated areas exist based on the five biomes that predominate throughout its geography (see Figure 3), following the Köppen Climate Classification (Rubel and Kottek, 2010). Firstly, the hyper-arid Pacific coast presents minimal rainfall, normally below 10 mm/year (concentrated in the warmer months), only disrupted by the semi-cyclical effects of the El Niño-Southern Oscillation (ENSO) phenomenon. Temperatures are mild to warm all year round, varying from 14°C to 30°C (SENAMHI, 2018). Despite the extreme weather conditions, water is plentiful thanks to aquifers and run-off from the Andes (Schwarz and Mathijs, 2017), explaining why it concentrates two thirds of the Peruvian population (Vázquez-Rowe et al., 2017). Secondly, the Andean Highlands present a variety of climates, although most of the population is concentrated in mid-altitude zones (i.e., between 2,300 and 3,500 m) where the climate is mild all the year round with cold nights and rainfall concentrates in the period November-March (SENAMHI, 2018). This area is home to approximately 20% of the national population (INEI, 2018). Finally, the Amazon basin is considered tropical rainforest, although the northern rainforest is considered fully humid, whereas the southern rainforest presents mostly a monsoonal behavior (Köppen, 1936). Roughly, 10% of Peruvians live in this area, which represents more than half of the total territory. In this context, it is hypothesized that considering the high correlation between site-specific climate conditions and GHG emissions in landfills (Terraza and Willumsen, 2010) is a meaningful strategy to analyze landfills based on their location in the different biomes existing in the country (Amini et al., 2012).

>Figure 3<

The MINAM disclosed a list of waste management operators throughout the country, all of which were contacted. Out of these, six different waste treatment companies, including municipalities, responded. Ultimately, only 50% of the respondents provided inventory data: i) a private company that manages final disposition of waste in the capital city, Lima (coastal zone); ii) the Municipality of the City of Cusco in the Highlands; and, iii) the Municipality of Nauta in the region of Loreto (Amazon basin). The respondents that provided inventory data covered the three climatic regions of the country. Data, shown in Table 2, were released for one single landfill in each city assessed.

>Table 2<

The landfill in Lima is located in the southern exit of the city close to the Panamerican Highway. It became operational in 1996, and by 2016, it was treating approximately 718,000 metric tons of waste annually. It is the only one of the three included in the study that has an LFG treatment system in operation. The site is mainly composed of clay-based landfilling platforms spread out over 80 hectares. The clay used as covering material is extracted from a quarry located in the surroundings of the site. Regarding operational procedures, segregation activities or material recovery are not performed. As soon as the residues enter the venue, the MSW load is weighed and, thereafter, the residues are taken directly to the landfilling platform. Subsequently, the compacting is carried out and the covering material is placed on a daily basis. The leachate is channeled into collection ponds and then reinjected into the platforms. Additionally, LFG collection chimneys are placed in each platform to carry out the capture and flaring of the gas.

The landfill in Cusco is located in Haquira, 10 km outside the city. Originally, this landfill was an open dumpster, but in the period 2014-2015 the municipality converted the site into a landfill. At the time of the study, due to administrative drawbacks, the MINAM had yet to recognize this site officially as a landfill. On-site observations by the project team confirmed that the plant was operating as a regular landfill. The MSW is weighed at a transfer facility in the city. Thereafter, it is landfilled under controlled conditions. This landfill has geogrids to reinforce the terrain, as well as geomembranes to improve the impermeability below the cells. Although the Municipality has a source-segregation program, encouraging recycling among the population, informal recyclers (i.e., waste pickers) are allowed to access the landfill and recover materials prior to the placement of the covering material. Recovering rates are estimated to be ca. 5% of the recoverable fraction. Despite the lack of LFG treatment (LFG is directly emitted via ventilation chimneys), the Municipality plans to include either LFG flaring or energy recovery in the near future. The leachate is also collected in leachate ponds and reinjected through the open cell. However, a project for a leachate treatment facility is underway (Percy Taco Palma, Waste Management Director at the Municipality of Cusco, personal communication, September 2018).

The landfill in Nauta was opened in 2011. As of April 2018, it is only one of two landfills in the entire Peruvian Amazon basin. According to legislation, only landfills that manage above 50 metric tons per day are considered mechanized (MINAM, 2013).

Nevertheless, despite the fact that the landfill at Nauta only treats 17 metric tons per day, it presents a certain degree of mechanization, with front-end loaders on its premises to manage the incoming waste. Given that it is legally considered a manual landfill and located on expansive-clay soils, at the time it was built no extra bottom liner requirements were required. In spite of heavy rainfall throughout the year, the landfill cells are not roofed. This feature hinders the operation during intense rainfall periods (i.e., December to March) and prevents the staff from carrying out segregation activities.

2.3 Data collection

Primary data collection for the foreground system of the landfills was conducted in several phases. Firstly, LCA practitioners provided technical staff from these landfills with basic training on life cycle thinking and modelling. This highlights the importance of collecting robust and detailed data to attain high quality inventory data. Thereafter, a detailed questionnaire was constructed with the main material and energy flows that were necessary to model these landfills (see the Supplementary Material – SM – for a full version of the questionnaire). A research protocol and an informed consent document were elaborated to comply with ethical requirements when collecting data. In parallel, a guided visit to the landfills with technical personnel was established to understand the specific characteristics of each site. Once the completed questionnaires were received and the inventories were being constructed, a round of e-mail exchanges was performed to clarify unclear data or complete data gaps.

The reference year for data collection was 2016 in the case of Lima and Cusco. In the case of Nauta, data were available for the period 2013-2016. However, the depth of data availability was notably higher for the year 2013, which led to the selection of this year to compute the modelling.

Waste composition was obtained from different sources. Firstly, the landfill in Lima does not record the composition of incoming waste, a drawback that prevented an accurate accountability of the different waste fractions. However, the company provided the total amount of incoming waste arriving from the different municipalities. Thereafter, waste composition for each district was obtained from the MSW Information System (SIGERSOL), an online platform provided by the Ministry of the Environment (SIGERSOL, 2018). This made it possible to compute a weighted average of the waste composition entering the landfill. However, this composition is reported based on the fractions collected at source, without accounting for the role of informal collectors in the waste collection system. A sensitivity analysis (SA), described in Section 2.7, was conducted in order to evaluate whether random variations in waste composition influence final environmental impact results. Secondly, technical staff from the landfill in Cusco provided data on total landfilled waste amounts and waste composition. No quantification of the removal of recyclable products by informal collectors was available, but a 5% removal rate of the plastic fraction was assumed, based on qualified estimates by the staff (Percy Taco Palma, Waste Management Director at the Municipality of Cusco, personal communication, September 2017). Finally, in Nauta, data were obtained directly from the landfill's logbook, where the quantification and composition of incoming waste is registered on a daily basis. This landfill has a formal segregation plant on-site, where small amounts of compost are produced, and a small fraction of plastics is separated.

Site-specific waste composition was introduced into the model (see Figure 4), as well as the technical parameters of each facility. In the modelling, for the specific case of Nauta, the segregated plastics were separated from the main material flow, and as the composted material added up to less than 1% it was considered to be negligible.

>Figure 4<

2.4 Life Cycle Modelling and methodological assumptions

The modelling of these three systems was performed with the EASETECH waste LCA tool, developed by scientists at the Technical University of Denmark – DTU (Clavreul et al., 2014). This software enables the LCA practitioner to model almost any waste management system, as it allows the inclusion of several treatment options and different waste fractions with variable physical properties. Moreover, it makes it possible to track the components of every waste fraction throughout the entire system.

EASETECH contains several modules (e.g., landfilling, incineration, etc.) regarding different waste management options. In this case study, the landfilling module was employed. Among these processes, the software models the waste decomposition and LFG generation as a first order decay model, as shown in equation 1:

$$[A] = [A]_0 e^{-kt} \qquad \text{Eq 1}$$

where [A] is the concentration of the reactive after time *t*, $[A]_0$ is the concentration of the reactive at the beginning of the reaction, and *k* is the degradation rate. This equation follows the rationale of previous studies from the US Environmental Protection Agency – USEPA (USEPA, 2005) and the Intergovernmental Panel on Climate Change – IPCC (IPCC, 2006).

The degradation rate *k* considered in the model is dependent on several site-specific parameters such as temperature, precipitation, waste composition and landfill depth, among others (Garg et al., 2006). Despite EASETECH's database containing several *k* rates for different geoclimatic conditions, none of them was comparable to the conditions of the three locations studied, as these model European conditions. Hence, *k* rates reported by the

IPCC (2006), which consider several climatic parameters, such as mean annual precipitation, mean annual temperature or evapotranspiration, were applied. Table 3 shows the *k* rate values used, presented in ranges. A sensitivity analysis (see Section 2.7) was carried out to account for this issue.

>Table 3<

In terms of other limitations, data that were not available were completed using the ecoinvent® database (ecoinvent, 2016). These inventories addressed mainly infrastructure and machinery components, such as cement, reinforcing steel, and HDPE membranes.

2.5 Life Cycle Inventory

The life cycle inventory (LCI) is one of the most effort-consuming steps and consists in the collection and interpretation of the data necessary for the environmental assessment of the system observed (Iannone et al., 2014). In this study, the LCI was divided into three main subsystems (see Figure 2). Firstly, the construction phase included the building of all design components of the landfill: geogrids, geomembranes, pipes, when present, excavation of the landfill cells or deforestation of the land, when necessary. Secondly, operation and maintenance activities comprised on-site segregation of residues (when applicable), the disposal of the final waste, including machinery use, landfill daily cover, LFG collection and treatment (if any) and leachate recirculation. Finally, the closure phase included final cover operations and maintenance of the cells. A detailed description of the datasets that were modified from the ecoinvent® database to account for geographical, temporal or technological specificities is shown in Table 4. Table 5 presents the LCI values.

>Table 4<

>Table 5<

2.5.1 Landfill gas (LFG) emissions

LFG generation was modelled based on a first order decay rate (Christensen et al., 2009), following eq. 1. EASETECH assumes that only material fractions containing biogenic carbon can decompose into CO_2 and CH_4. Considering eq. 1, the greater fraction of gas release occurs in the first years after waste disposition. Moreover, LFG contains trace gases, which due to lack of monitoring in the landfills studied, were not site-specific (see Section S1 in the SM). These gases were added into the LFG composition as concentrations based on the database provided by EASETECH (see Section S2 in the SM), which includes the most frequently reported trace gases and compositions reported in the literature (Olesen and Damgaard, 2014).

To model LFG flaring, when applicable, the LFG collection efficiency was defined considering the default values provided by EASTECH, which are based on information given by landfill operators and the available literature (Clavreul et al., 2014). For the first 5 years (operating cell) an efficiency of 30% was assumed. For the intermediate cover, during years 5 to 15, a collection efficiency of 45% was applied, and for the following 40 years (final cover) an efficiency of 55% was considered (Spokas et al., 2006). No flaring was assumed for the final 45 years. Due to the fact that combustion efficiency data were not provided by the operators, the EASETECH database was used, assuming a CH_4 combustion rate of 98%. In other words, 98% of the flared methane is decomposed into CO_2 and H_2O. Regarding landfills with no LFG treatment, these were modelled as if the collected gas were emitted directly into the atmosphere.

Finally, soil cover oxidation rate default values from EASETECH were computed for each landfill. This rate considers soil permeability, the height of the cell and the density of the landfilled waste (Olesen and Damgaard, 2014). This means that infiltrating and uncollected biogas reaches the surface of the landfill, and, due to chemical reactions, part of the CH_4 is oxidized into CO_2 and H_2O (USEPA, 2011).

2.5.2 Leachate recirculation

Leachate generation was estimated based on local geoclimatic parameters. No treatment was considered, given that the leachate is recirculated into the cells. The leachate is assumed to infiltrate into the soil, and to calculate this rate, soil-specific permeability coefficients were employed. Considering that the facilities analyzed are all located on clay soils, these rates reached an order of magnitude of 10^{-10} m/s. The final infiltration values are also directly correlated to annual rainfall, rainfall intensity and the level of saturation of the residues in the cell. Leachate infiltration into marine water was considered for Lima, and into surface water for Cusco and Nauta.

Finally, considering that no measurements were performed on-site, the composition of the leachate in the three facilities was unknown. The leachate composition was modelled based on the EASETECH database (see Section S3 in the SM), which considers trace contaminant concentrations reported in the literature (Olesen and Damgaard, 2014).

2.5.3 Emissions from open dumpsters

When modelling open dumpsters, GHG emissions were estimated using IPCC guidelines (IPCC, 2006). In other words, a methane generation correction factor is applied to a landfilling baseline scenario for these informal or illegal sites. The correction factor is applied to reduce methane generation in the dumpsite considering the aerobic conditions that occur in these facilities. These factors vary between 0.4 and 0.8, depending on whether the dumpsite is shallow (< 5 m deep) or deep (> 5 m deep). These corrections were then applied to the methane curve obtained from EASETECH. To address other environmental impact categories, an alternative scenario was developed, taking into consideration the conditions of open dumpsters usually present in the Amazon Basin. This translates into lack of bottom liners, top covers, MSW compacting, leachate and rainwater management, among other missing features; leading to a greater exposure to the surrounding environment.

2.6 Life Cycle Impact Assessment

The IPCC 2013 100-year assessment method was considered to calculate GHG emissions (IPCC, 2013). Its selection was justified seeing that when the study was conducted, it was the most recently updated and comprehensive assessment method available to calculate global warming potential (GWP). The 100-year time horizon was chosen to present the results for two main reasons. On the one hand, the climate change community considers this horizon as a consensus framework, making it the most commonly used in the literature. On the other hand, it represents a hierarchist perspective, which coincides with the perspective of the Cultural Theory that was selected for the other assessment method used (i.e., ReCiPe 2008). The remaining impact categories selected to perform the analysis were computed using the ReCiPe 2008 method (Goedkoop et al., 2009). The selection of impact categories was performed considering the environmental compartments affected: soil, water and air emissions. Air-related categories, such as ozone depletion (OD) or particulate matter formation (PMF), water-related categories, such as eutrophication and eco-toxicity, and soil-related categories (e.g., terrestrial acidification – TA, or terrestrial eco-toxicity – TET), were included in the assessment, together with human toxicity (HT). Resource depletion categories (i.e., water, fossil fuels…) were discarded due to the low amount of materials needed in these end-of-life infrastructures. As stated, the computation of environmental impacts was performed using EASETECH.

2.7 Sensitivity analysis modelling

An SA was carried out in terms of the *k* values used for primary decay. IPCC provides a range of values for different geoclimatic zones. These ranges become a wide spectrum of values with possible results. In this study, the upper and lower values of the range were selected to avoid the computation of a single, deterministic literature-based *k* value for an unstudied area.

The lack of primary waste composition data for the landfill in Lima, as well as the presence of informal recyclers in Cusco, led to an SA that implied varying the MSW composition in these cities. In the case of Lima, the composition was modified based on the variation of the organic composition by ±10% of the total waste composition, with a subsequent normalization of the other fractions to add up to 100%, whilst in Cusco the composition was varied considering a recycling rate of 5% regarding plastics. These variations were considered taking into account typical waste fraction ranges in LAC (Hoornweg and Bhada-Tata, 2012.). It should be noted that segregated recyclables were excluded from the system boundaries to avoid allocating the impacts of recycling, which is beyond the scope of the study.

3. Results and discussion

3.1 Global Warming Potential environmental impacts

The highest environmental impacts in terms of GHG emissions, when using the mean *k* values, are observed for the landfill in Cusco, 1.41 t CO_2eq per FU, 2.3% higher than for Nauta (1.38 t CO_2eq per FU) and 137% higher than for Lima (594 kg CO_2eq per FU). However, in the case of Lima, the existence of an LFG treatment system implies a reduction of 58% in GHG emissions due to methane decomposition with respect to a situation with no LFG treatment (see Figure 5).

>Figure 5<

The way in which Figure 5 is plotted shows the temporal evolution of the landfilled waste. For instance, 1 t of MSW landfilled in Nauta, considering a mean *k* value, will have emitted 80% of its GHG emissions by year 5 and 96% by year 15. The trends identified in Cusco and, more significantly, in Lima, were somewhat different, with a higher percentage of emissions lagging towards later years after waste disposal. In the case of Cusco, the emissions in the first 5 years added up to 51%, whereas 84% was concentrated in the first 15 years. Finally, in the case of Lima, 28% of GHG emissions are emitted in the first 5 years, and 59% in the first 15 years. Interestingly, no substantial relative differences would be observed for Lima if it lacked a LFG treatment system. If the upper and lower ranges are analyzed, it is observed that in all cases the upper scenario, which assumes a higher *k* value (i.e., a higher decomposition rate), presents a higher concentration of emissions in the first 5 years, whereas the lower scenario tends to lag a significant amount of these emissions towards later stages. It should be noted that the pattern variation in each curve at years 5 and 15 represents the increase in the gas collection efficiency due to the transition from the operating cell to the placement of the intermediate cover (see Figure 5).

When analyzed per operational stage, as shown in Figure 6, capital goods and machinery represented a minimal proportion of total GHG emissions, ranging from 0.2% to 1.2% depending on the landfill, substantially lower than the 10% threshold identified by Brogaard and Christensen (2016). In contrast, on-going chemical reactions in the landfill cells accounted for the major part of GHG emissions, but also, in some cases, carbon sequestration. In landfills with no LFG treatment the oxidation processes that take place on the surface of the landfill cells play, together with carbon sequestration of organic matter, an important role in mitigating emissions.

>Figure 6<

3.2 Other environmental impact categories

Characterization results for the remaining impact categories show that landfilling with LFG treatment (i.e., Lima) presents lower impacts for freshwater and marine eutrophication, as well as for eco-toxicity-related categories (see Table 6). The sole addition of flaring in Lima reduces ozone depletion (OD) emissions considerably. This is due to the combustion process decomposing not only methane, but also other pollutants such as dichloromethane, carbon tetrachloride and dichloroethane into non-ozone-depleting substances. Nevertheless, it should be noted that ReCiPe 2008 does not include N_2O as a substance that depletes ozone. The calculations were performed to include N_2O, following the suggested characterization factor of 1.1E-2 kg CFC-11eq/kg in the revised version of the method, ReCiPe 2016 (ReCiPe, 2016). When included, N_2O emissions accounted, in all cases, for less than 0.2% of total ozone-depleting emissions. Interestingly, OD reductions in the landfill in Lima as compared to Nauta and Cusco occur at the expense of increased PMF and TA emissions, since flaring triggers the release of several contaminating particles (e.g., SO_x and NO_x for TA and $PM_{2.5}$ and PM_{10} for PMF) into the atmosphere. Nevertheless, this issue could be addressed in the future with the inclusion of several filters in the chimneys to prevent undesirable particles being released into the atmosphere.

>Table 6<

In terms of eutrophication and eco-toxicity-related categories, the landfill in Nauta presents significantly higher environmental impacts. This phenomenon occurs due to very high rainfall in the northwestern zone of the Amazon basin, as well as the lack of control regarding this issue in the facility. As a considerable amount of precipitation enters and floods the landfill, important pollutants such as phosphates, nitrates, and heavy metals (e.g. mercury and lead), are washed out of the cell and infiltrate the aquifer. In order to prevent this kind of impacts in high-precipitation areas, it would be advisable to implement rainwater collection systems and impermeable bottom liners and top covers, such as roofing systems (only feasible in small landfills), as well as an appropriate drainage system to separate rainwater from leachates.

3.3 Sensitivity analysis results

The *k* decomposition rate variation displayed a wide range of possible decay trends over time, which at the same time represented the behavior of waste in several potential geoclimatic conditions. Interestingly, these trends showed similarities between extreme values of contiguous regions (e.g., Lima's upper k rate curve and Cusco's lower k rate curve). The behavior of these curves (shows that the understanding of how the geoclimatic conditions affect waste is crucial in order to determine its impacts over time (see Figure 7). Considerable variations in the distribution of emissions over time have been identified as temperatures and humidity increase. For instance, in Nauta, the variation between the average *k* rate values and the upper-boundary *k* rate values implied a higher percentage of emissions released into the environment during the first 5 years. For the lower boundary, the emissions during the first 5 years reached 54% of the total emissions, whereas for the average value (80%) and the upper boundary (90%), this percentage increased. In contrast, variations between the lower and upper *k* rate boundaries for Cusco and Lima are not as drastic as in Nauta, since the emitted percentage of total emissions only varies between 35% and 55% in Cusco, and 20%-30% in Lima. Considering that in Nauta and Cusco no LFG treatment is carried out, the *k* rate variations do not imply a significant variation in the overall 100-year impact (below 2%). In contrast, as LFG is flared in Lima, the *k* rate variation would affect the amount of gas treated. Nevertheless, these variations only implied a swing between 4% less emissions for the lower boundary and 6% more emissions for the upper boundary when compared to the average values.

>Figure 7<

Even though no site-specific measurements have been carried out under similar conditions, it is hypothesized that, due to the climatic characteristics at each landfill, the real-life curves will be more similar to the average values for Lima and Cusco, and to the upper boundary in Nauta (Kim and Townsend, 2012). On the one hand, for the cases of Lima and Cusco this is due to seasonal rain intermittence and temperature oscillation. Consequently, as aforementioned, these regions resemble temperate conditions in other areas of the world. However, the picture in Nauta is very different. Whilst temperatures fluctuate from 21°C to 36°C, heavy precipitations occur all year round: no dry season takes place, as would happen in other Amazonian regions, such as the non-equatorial (southern) Amazon rainforest, or the Brazilian eastern rainforest (Fu et al., 2001). Moreover, Kim and Townsend (2012) found that *k* rates for wet landfills in north Florida, a subtropical area, and, in consequence, a cooler and less humid region (average temperature: 20°C; average precipitation: 1,300 mm/year), presented rates as high as 0.47 yr^{-1}, a higher value with respect to the average *k* value applied for the case study. In this context, it is plausible to assume that decomposition rates for Nauta must be located in the upper range of the spectrum.

Regarding the SA scenarios varying the MSW composition in Lima, results show a high impact-dependence on the amount of landfilled organics. When the organic fraction was increased by 10% to reach 62%, the overall GHG emissions increased by over 20%

(see Table 7). This trend is also visible when addressing the SA results for Cusco. Moreover, when the plastics fraction was reduced by 5%, the remaining fractions, including organics, increased their proportion per FU, with a consequent increase in GHG emissions. However, in the case of Cusco, this variation only translated into an increase of ca. 6% of total GHG emissions. This relationship demonstrates the high dependence of climate change potential impacts concerning the composition of the waste disposed of. However, the negative impact of considering the reduction of the plastic fractions among the landfilled residues might be countered by considering the recycling process in the system boundaries. This might lead to positive results being obtained due to the beneficial environmental effects of recycling.

>Table 7<

3.4 Temporal, technological and geographical implications of the results

This LCA study exemplifies the variation of waste management systems under different operational and climatic conditions. In terms of GWP, the largest environmental impact contributions in all cases occur in the earlier stages of waste disposal. However, the speed with which the residues decompose and the distribution of their impact over time varies considerably between each one of the geoclimatic regions studied. With this in mind, Figure 5 shows that the release of GHG emissions into the atmosphere accelerates in warm and wet tropical climates (i.e., the Amazon basin), in comparison to dryer and colder climates, such as Cusco or Lima.

From a technological perspective, it is imperative to address the fact that shifting from open dumpsters to controlled landfills without any LFG treatment does not imply GHG reductions, contrary to common belief and what the Peruvian NDCs suggest. As shown in Figure 8, when open dumpsters and different levels of landfill sophistication are compared, it is in fact the opposite case. This is a result of aerobic reactions taking place in the unconfined environment that occur in an open and uncontrolled dumpsite, in contrast to the anaerobic atmosphere that takes place in a landfill. A distinction between shallow and deep open dumpsters is made in the modelling. The reason for this is that shallow dumpsters have increased aerobic conditions as compared to deep dumpsters. However, shallow dumpsters tend to be uncontrolled disposal sites that do not have the capability to absorb relevant amounts of waste, but rather emerge due to the existence of inefficient waste collection and disposal management systems.

>Figure 8<

It is following the abovementioned statement that LFG treatment options appear as high-benefit opportunities that Figure 8 demonstrates that the sole inclusion of LFG flaring in any of these landfills reduces the GWP impact by a considerable amount ranging from 50%-76%, as compared to a no-treatment scenario. However, when these GHG emissions are compared to disposal in deep open dumpsters, the GWP reductions are somewhat lower, ranging from 39% (Nauta) to 70% (Cusco). Beyond flaring, LFG energy recovery emerges as a treatment method that would not only provide further GHG emissions mitigation, but also contribute to a circular economy society by converting disposed waste into energy. According to the model applied, it is the only method that, considering the appropriate system expansion, would have lower GWP impacts with respect to shallow dumping.

The application of this technology may render additional benefits if it is considered for cities that are located in the Amazon basin where the use of fossil fuels is still very high.

However, in view of the high investment costs of this technology (Fei et al., 2018), it does not seem feasible for it to be implemented in facilities receiving less than 200 ton/day (Carlos Silva, landfilling expert, Peru Waste Innovation SAC, personal communication, October 2018). In fact, even though MINAM was considering this technology as an option in its first NDC proposal back in 2015, it has now been discarded due to budget constraints, while promoting the proliferation of landfills with flares or semi-aerobic technology.

Despite the fact that migrating to landfills would increase GHG emissions in the Peruvian waste sector, the conversion of open dumpsters into landfills would deliver important environmental benefits (Wiedinmyer et al., 2014). To a certain extent, there is a degree of parallelism with wastewater treatment plants: treatment allows substantial reductions in environmental impact in the water compartment, but the energy intensity of the treatment process may increase GHG emissions (Lorenzo-Toja et al., 2016). However, in the case of landfills, it is not the energy intensity of the disposal process that triggers the augmentation, but rather the conversion of the decomposition of biogenic carbon towards anaerobic conditions (Henriksen et al., 2017). One such benefit is the removal of large amounts of MSW from riverbanks, from the ocean or simply from uncontrolled disposal sites that constitute a hazard to ecosystems (Kanmani and Gandhimathi, 2013) and human health (Baalbaki et al., 2016).

In fact, some of these benefits are visible through the direct computation of some of the impact categories computed. When the landfill in Nauta is compared with shallow and deep open dumpster conditions (see Table 8), environmental impacts linked to water and soil compartments, such as eco-toxicity and eutrophication show substantial gains, in some cases of several orders of magnitude. In contrast, impact categories linked to the air compartment (e.g., PMF) show increased impact due to the use of fossil fuels.

>Table 8<

3.5 Policy support

The current Peruvian NDC proposal includes an ambitious plan to obtain succulent GHG mitigation actions through the implementation of a set of landfill sites across the nation. Some of these (5) are intended to be large, centralized LFG treatment landfills (e.g., Arequipa or Trujillo), others are medium-sized landfills (20) which are intended to be semi-aerobic, whereas a final group of 11 smaller landfills will have a decentralized LFG system. With these new landfills, the Peruvian government is making a clear statement on how it intends to formalize the sector and upgrade the current precarious waste management situation. These measures will surely improve the local and regional sanitation, as well as mitigate health and environmental issues embedded in the open dumpster usage. With this in mind, it would be critical that the main actions were not only focused on the major demographical nodes such as Lima, Trujillo and Arequipa, but also throughout the Amazonian regions, where residue decomposition rates, and in consequence the GHG emission rates, have been estimated to be higher. For instance, the city of Iquitos, which is the region's largest city with nearly half a million inhabitants has as of today only a collapsed open dumpster operating as the city's sole means of disposal, instead of a properly working waste treatment facility[1]. By intensifying waste management activities in the Amazon basin, greater amounts of GHG emissions could be reduced in the short term in

[1] It must be noted, however, that by late 2018 there were two landfills under construction for the city of Iquitos (Joel Inga, Environmental Manager at the municipality of Maynas, Iquitos, personal communication, September 2018).

comparison to landfills in hyper-arid areas of the country. This strategy, without neglecting other major population nodes, would indeed assist the accomplishment of Peru's commitments to the Paris Agreement in the waste sector.

If two landfills with similar technical specifications were opened simultaneously, one of them located in a region with similar geoclimatic conditions to Nauta and the other in a region with similar conditions to Lima, by the year 2030 the one in the Amazon would have emitted almost double that of its counterpart on the coast per t of waste. Moreover, if the Amazonic landfill had flares, by that year it would still have emitted around 25% more than the flareless landfill on the coast. Year 2030 is an important milestone in international climate policy mitigation actions. If MINAM prioritizes the technification of landfills in the Amazon basin, a higher mitigation incidence with respect to current emissions would be attained.

5. Conclusions

The results in the current study demonstrate that the transition from open dumpsters to sanitary landfills generates a stronghold of environmental and public health benefits in several impact categories, even in those facilities that lack biogas treatment. However, biogas treatment appears as a critical aspect to be taken into consideration in order to mitigate GHG emissions. In fact, the retrofit or implementation of landfilling facilities with these technologies will strengthen the country's commitment and action plan regarding the Paris Agreement. The reductions in GHG emissions were as high as 50%-76% in comparison to a no-treatment scenario with the sole inclusion of LFG flaring. Consequently, to better address Peru's climate commitments, it is imperative to understand the rates at which residues decompose under different geoclimatic and technological conditions. This would allow the country to mitigate in a more effective way the different negative effects that the inappropriate management of waste causes, an issue that no previous national plan has ever considered.

As proven in the current study, comprehending and accounting for site-specific geographical and climatological conditions is imperative when addressing waste treatment systems, especially landfills. Wet tropical climates greatly increase the rate at which residues decompose. This implies that the adequate management of waste is fundamental in these regions in order to control and minimize its potential impacts. Moreover, adequate infrastructure is critical to address local conditions that can strongly flip the system's balance, especially in vulnerable environments such as those in the Amazon basin, or where the ENSO phenomenon has a significant influence. Waste management system planning must take into account these issues to provide improved treatment to MSW. Further research must be carried out to fully understand the behavior of waste in tropical conditions, as well as to propose suitable, more sophisticated technologies for waste treatment adapted to local conditions.

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Table and Figure captions

Table 1. Actions described in the Peruvian Nationally-Determined Contributions (NDCs) to mitigate GHG emissions in the waste management sector linked to landfills (MINAM, 2015).

Table 2. Description of the landfills assessed in the current study.

Table 3. Mean k rate ($year^{-1}$) values employed for each case study. The values in brackets represent the upper and lower ranges in which these values waver.

Table 4. List and description of the main datasets and dataset modifications obtained from the ecoinvent® v3.4 database that was performed for the computation of the results.

Table 5. Landfilling life-cycle inputs and outputs (FU= 1 metric ton of landfilled residues).

Table 6. Total environmental impacts per landfill for selected impact categories using the ReCiPe midpoint-H 2008 methodology. NOTE: SOD= stratospheric ozone depletion; PMF= particulate matter formation; TA= terrestrial acidification; FE= freshwater eutrophication; ME= marine eutrophication; HT= human toxicity; TET= terrestrial eco-toxicity; FET= freshwater eco-toxicity; MET= marine eco-toxicity; L= Lima; C= Cusco; N= Nauta.

Table 7. Alternative composition scenarios for MSW disposal in landfills as considered in the sensitivity analysis (SA).

Table 8. Environmental impacts of selected impact categories for shallow and deep open dumping as compared to landfilling in Nauta, Peru (Amazon basin). Data reported for the mean k value per functional unit (FU): 1 metric ton of MSW disposed of in a Peruvian landfill for a 100 year period.

Figure 1. Graphical representation of the location of the existing landfills in Peru as of November 2017 (MINAM, 2017b). The regions of Tumbes, Piura, Lambayeque, Amazonas, San Martín, Ucayali, Madre de Dios, Puno, Moquegua and Tacna lacked landfill infrastructure by late 2017. The over 1400 active open dumpsters that were identified in Peru as of May 2018 are not included.

Figure 2. Graphical representation of the system boundary of the production system under study. The yellow box represents the entry of Municipal Solid Waste (MSW) into the landfill, blue boxes represent the operational activities in the landfill, red boxes represent emissions to air, water or soil from the landfill and green boxes represent the recovered waste fractions in the landfill.

Figure 3. Graphical representation of climate classification zones and biomes in Peru (Adapted from Köppen, 1936; Rubel & Kottek, 2010).

Figure 4. Relative contribution (%) by weight of different landfilled waste fractions to total waste composition in each landfill assessed. Note that the organic fraction includes garden waste and foliage, food waste and other putrescible fractions.

Figure 5. Temporal distribution of GHG emissions linked to landfilled municipal solid waste (MSW) based on the medium decomposition rate value for biogenic carbon in the three cities. Results reported per functional unit (FU): 1 metric ton of MSW disposed of in a Peruvian landfill for a 100 year period, but displayed for the first 30 years.

Figure 6. GHG emissions per operational stage at the landfills analyzed. Results reported per functional unit (FU): 1 metric ton of MSW disposed of in a Peruvian landfill for a 100 year period.

Figure 7. Sensitivity analysis results for the three locations, regarding the variation in their respective k decomposition rates, and their behavior in time. The figure only displays the curves for the first 30 years.

Figure 8. Environmental comparison of municipal solid waste (MSW) disposal scenarios for the three cities analyzed. Results reported per functional unit (FU): 1 metric ton of MSW disposed of in a Peruvian landfill for a 100 year period, but displayed for the first 30 years.

Table 1. Actions described in the Peruvian Nationally-Determined Contributions (NDCs) to mitigate GHG emissions in the waste management sector linked to landfills (MINAM, 2019).

Action description	**Mitigation in kt CO_2eq**
Methane capture and combustion in landfills (NAMA[1]) - Centralized	173
Energy recovery of methane in landfills	281
Semi-aerobic technology in landfills	130
Composting in landfilling facilities	4
TOTAL	*588*

[1] NAMA: nationally appropriate mitigation action.

Table 2. Description of the landfills assessed in the current study.

Landfill	Lima	Cusco	Nauta
Location	Hyper-arid coast	Andean highlands	Amazon rainforest
Köppen – Geiger climate classification	Arid, desert, hot arid (BWh)	Warm temperate, winter dry, warm summer (Cwb)	Equatorial, fully humid (Af)
Average temperature (°C)	18.7	11.2	26.6
Average annual precipitation (mm)	16	693	2448
Altitude (masl*)	350	4,000	150
Daily capacity (metric tons)	2,000	380	17
Type (according to Peruvian legislation)	Mechanized (>50 metric ton/day)	Mechanized (>50 metric ton/day)	Semi-mechanized (<50 metric ton/day)
Estimated lifetime	30 years	8 years	12 years
Area (ha)	80	9.5	2
Landfill gas (LFG) treatment	Flare	None	None
Bottom liner	Clay	HDPE membrane	Clay
Leachate treatment	Recirculation	Recirculation	Recirculation
Reference year for data collection	2016	2016	2013

* Meters above sea level.

Table 3. Mean k rate ($year^{-1}$) values employed for each case study. The values in brackets represent the upper and lower ranges in which these values waver.

	Mean, upper and lower degradation *k* rates ($year^{-1}$)		
Waste type	**Lima**	**Cusco**	**Nauta**
Food waste	0.06 (0.05 – 0.08)	0.185 (0.1 – 0.2)	0.4 (0.17 – 0.7)
Other organic putrescible	0.05 (0.04 – 0.06)	0.1 (0.06 – 0.01)	0.17 (0.15 – 0.2)
Wood waste	0.02 (0.01 – 0.03)	0.03 (0.02 – 0.04)	0.035 (0.03 – 0.05)
Paper/textile waste	0.04 (0.03 – 0.05)	0.06 (0.05 – 0.07)	0.07 (0.06 – 0.085)

Table 4. List and description of the main datasets and dataset modifications obtained from the ecoinvent® v3.4 database that was performed for the computation of the results.

Dataset	Ecoinvent name	Description
Concrete production, normal	Concrete, normal {RoW}, unreinforced concrete production	Represents concrete production outside Europe. It presents similar results and parameters to those from a recent cement LCA study in Peru (Vázquez-Rowe et al., 2019).
Gravel production, crushed	Gravel, round {RoW}, gravel and sand quarry operation	Represents the production and acquisition of gravel outside Europe.
Steel production, hot rolled	Steel, chromium steel 18/8 {RoW}, steel production	Represents the production and acquisition of hot rolled steel outside Europe.

Table 5. Landfilling life-cycle inputs and outputs (FU= 1 metric ton of landfilled residues).

	Unit	Lima	Cusco	Nauta
Inputs				
Municipal solid waste	t	1	1	1
Sand	m^3	--	--	5.76E-06
Concrete	m^3	9.67E-09	5.17E-08	4.92E-06
Steel	kg	1.57E-06	7.11E-07	5.62E-05
Earthworks	m^3	6.05E-05	6.75E-5	4.29E-05
Gravel	t	--	1.68E-02	1.18E-04
Clay	m^3	--	--	1.94E-05
Diesel	L	8.31E-04	2.38E-04	2.16E-04
HDPE	kg	--	7.66E-03	--
PVC	kg	--	1.08E-04	--
Outputs				
Emissions to air				
Methane, non fossil	kg	31.84	56.51	54.74
Methane, dichlorodifluoro-, CFC-12	kg	4.1E-4	6.9E-4	6.7E-4
Methane, chlorodifluoro-, HCFC-22	kg	2.4E-4	4.1E-4	3.9E-4
Methane, trichlorofluoro-, CFC-11	kg	6.9E-5	1.3E-4	1.2E-4
Dinitrogen monoxide – N_2O	kg	1.1E-4	3.2E-5	4.5E-5
Carbon dioxide, non fossil – CO_2	kg	91.95	79.89	48.69
Nitrogen oxides – NO_x	kg	5.5E-2	2.9E-2	8.4E-3
Ethene, tetrachloro	kg	8.7E-4	1.4E-3	1.4E-3
Mercury	kg	1.9E-7	2.1E-7	2.6E-7
Sulfur dioxide – SO_2	kg	1.3E-2	3.2E-2	2.8E-3
Emissions to water				
Phosphate	kg	2.5E-5	8.4E-4	1.1E-3
Ammonium, ion	kg	1.2E-3	5.1E-3	1.8E-1
Arsenic, ion	kg	1.1E-6	3.6E-6	1.9E-5
Copper, ion	kg	1.6E-6	6.0E-5	7.3E-5
Nickel, ion	kg	5.7E-6	3.1E-5	2.2E-4
Zinc, ion	kg	8.1E-6	1.4E-4	4.5E-5
Silver, ion	kg	1.1E-7	9.1E-7	9.2E-6
Emissions to soil				
Phosphorus	kg	2.6E-8	2.6E-8	8.1E-7
Zinc	kg	7.5E-6	2.2E-6	3.0E-6

	Copper	kg	1.9E-6	5.4E-7	5.2E-7
	Mercury	kg	1.9E-8	5.4E-9	5.1E-9

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Table 6. Total environmental impacts per landfill for selected impact categories using the ReCiPe midpoint-H 2008 methodology. NOTE: SOD= stratospheric ozone depletion; PMF= particulate matter formation; TA= terrestrial acidification; FE= freshwater eutrophication; ME= marine eutrophication; HT= human toxicity; TET= terrestrial eco-toxicity; FET= freshwater eco-toxicity; MET= marine eco-toxicity; L= Lima; C= Cusco; N= Nauta.

Impact category	City	Oxidation	Combustion	Ventilation	Infrastructure	Leachate	TOTAL
SOD (kg CFC-1eq)	L	5.35E-4	8.69E-6	0.00	1.56E-9	0.00	**5.44E-4**
	C	3.22E-4	0.00	5.92E-4	6.63E-9	0.00	**9.13E-4**
	N	5.79E-4	0.00	3.06E-4	8.39E-8	0.00	**8.85E-4**
TA (kg SO_2eq)	L	0.00	3.22E-2	0.00	1.26E-2	0.00	**4.47E-2**
	C	0.00	0.00	0.00	5.00E-2	0.00	**5.00E-2**
	N	0.00	0.00	0.00	7.81E-3	0.00	**7.81E-3**
FE (kg Peq)	L	0.00	0.00	0.00	2.57E-6	3.53E-6	**6.10E-6**
	C	0.00	0.00	0.00	1.57E-5	6.37E-5	**7.94E-5**
	N	0.00	0.00	0.00	2.77E-5	1.94E-4	**2.21E-4**
ME (kg Neq)	L	0.00	1.43E-3	0.00	8.89E-4	9.29E-4	**3.24E-3**
	C	0.00	0.00	0.00	1.28E-3	3.97E-3	**5.25E-3**
	N	0.00	0.00	0.00	3.93E-4	1.93E-1	**1.94E-1**
PMF (kg PM10eq)	L	0.00	1.32E-2	0.00	5.52E-3	0.00	**1.87E-2**
	C	0.00	0.00	0.00	1.71E-2	0.00	**1.71E-2**
	N	0.00	0.00	0.00	4.05E-3	0.00	**4.05E-3**
HT (kg 1,4 DBeq)	L	4.08E-1	4.73E-1	0.00	4.93E-2	6.25E-3	**9.36E-1**
	C	2.45E-1	0.00	4.45E-1	1.46E-1	2.84E-2	**8.64E-1**
	N	4.39E-1	0.00	2.30E-1	1.81E-1	3.56E-1	**1.21**
TET (kg 1,4 DBeq)	L	1.49E-5	1.41E-5	0.00	3.61E-5	1.19E-8	**6.52E-5**
	C	8.89E-6	0.00	1.54E-5	6.30E-5	2.59E-8	**8.73E-5**
	N	1.58E-5	0.00	7.96E-6	2.27E-4	7.13E-8	**2.51E-4**
FET (kg 1,4 DBeq)	L	1.54E-6	2.56E-6	0.00	1.17E-4	2.75E-4	**3.96E-4**
	C	8.91E-7	0.00	1.60E-6	3.04E-3	2.14E-3	**5.17E-3**
	N	1.60E-6	0.00	8.28E-7	5.11E-4	1.73E-2	**1.78E-2**
MET (kg 1,4 DBeq)	L	2.01E-4	8.47E-5	0.00	2.57E-4	2.40E-4	**5.82E-4**
	C	1.19E-4	0.00	2.11E-4	1.38E-3	1.88E-3	**3.59E-3**
	N	2.13E-4	0.00	1.09E-4	2.12E-3	1.49E-2	**1.74E-2**

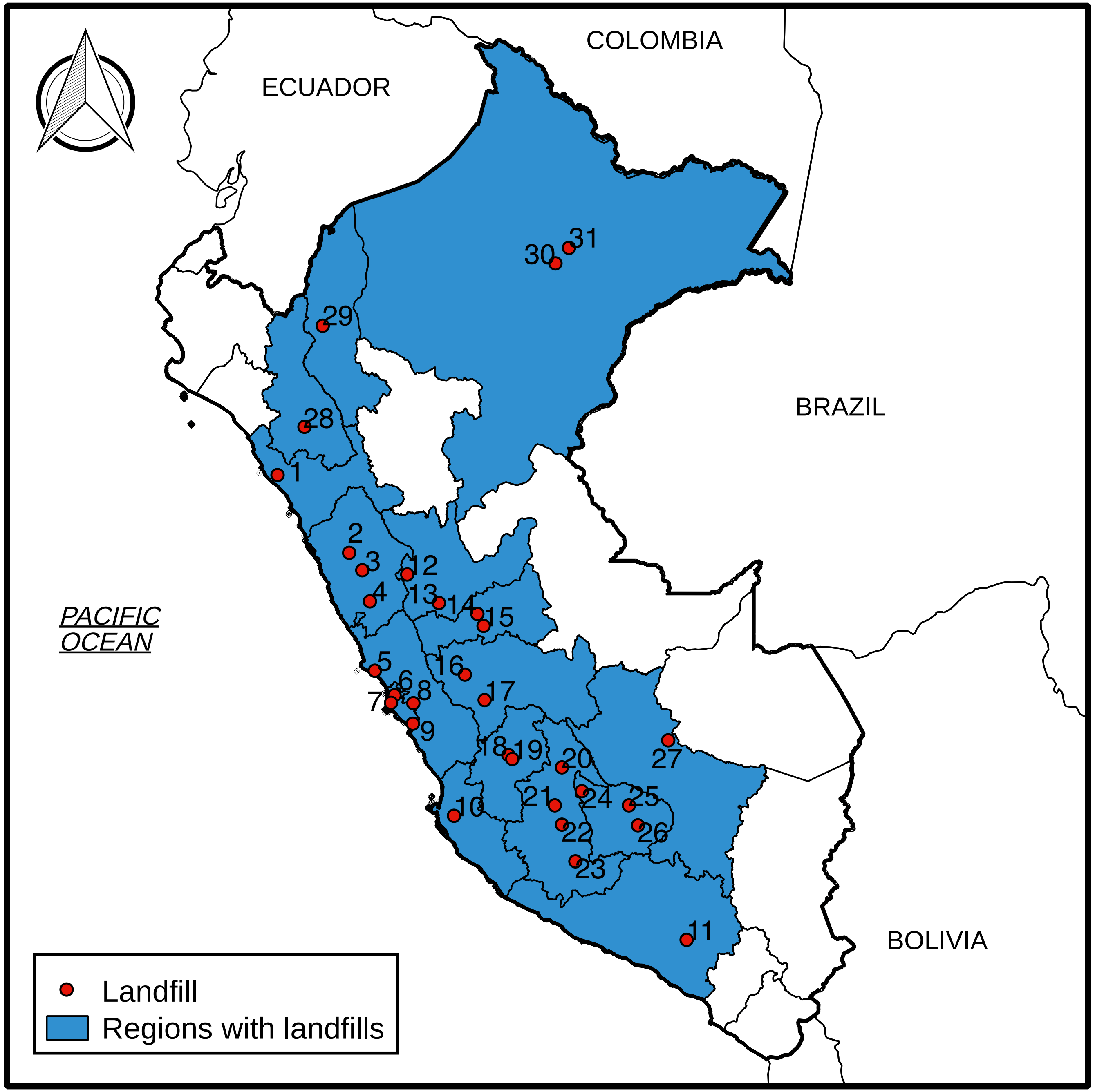
Table 7. Alternative composition scenarios for MSW disposal in landfills as considered in the sensitivity analysis (SA).

Landfill	Scenario	Baseline scenario impact (kg CO_2eq)	SA impact (kg CO_2eq)	Porcentual variation (with respect to baseline scenario)
Lima	Increase of 10% in organic waste	594	717	Increase in 21% of GHG emissions.
Lima	Reduction of 10% in organic waste	594	469	Decrease in 21% of GHG emissions.
Cusco	Reduction of plastic fraction by 5% due to informal recycling	1,407	1,488	Increase 6% of GHG emissions.

Table 8. Environmental impacts of selected impact categories for shallow and deep open dumping as compared to landfilling in Nauta, Peru (Amazon basin). Data reported for the mean k value per functional unit (FU): 1 metric ton of MSW disposed of in a Peruvian landfill for a 100 year period.

Impact category	Unit	Landfilling	Shallow dumpster	Deep dumpster
GW	kg CO_2eq	1376	523	1138
SOD	Kg CFC-11eq	8.88E-4	1.05E-3	1.05E-3
TA	kg SO_2eq	7.81E-3	0.00	0.00
FE	kg P eq	2.21E-4	1.21	1.03E-2
ME	kg N eq	1.94E-1	25.06	7.40
HT	kg 1,4-DCBeq	1.21	1.13E4	19.70
TET	kg 1,4-DCBeq	2.51E-4	2.15	3.12E-5
FET	kg 1,4-DCBeq	1.78E-2	1.95E2	9.19E-1
MET	kg 1,4-DCBeq	1.74E-2	64.00	7.95E-1
PMF	kg PM10eq	4.05E-3	0.00	0.00

GW= global warming; OD= stratospheric ozone depletion; TA= terrestrial acidification; FE= freshwater eutrophication; ME= marine eutrophication; HT= human toxicity; TET= terrestrial eco-toxicity; FET= freshwater eco-toxicity; MET= marine eco-toxicity; PMF= particulate matter formation.


COLOMBIA
ECUADOR
BRAZIL
BOLIVIA
PACIFIC OCEAN
1
2
3
4
5
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10
11
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14
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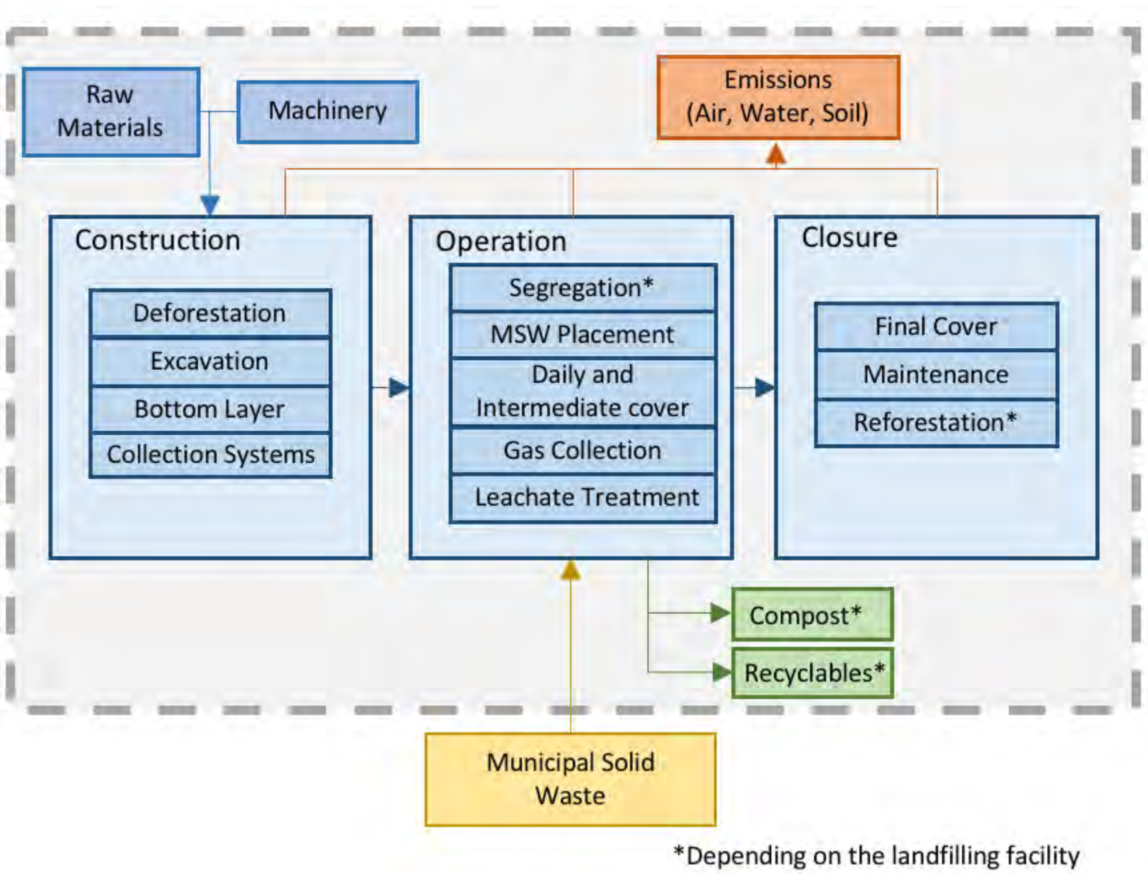
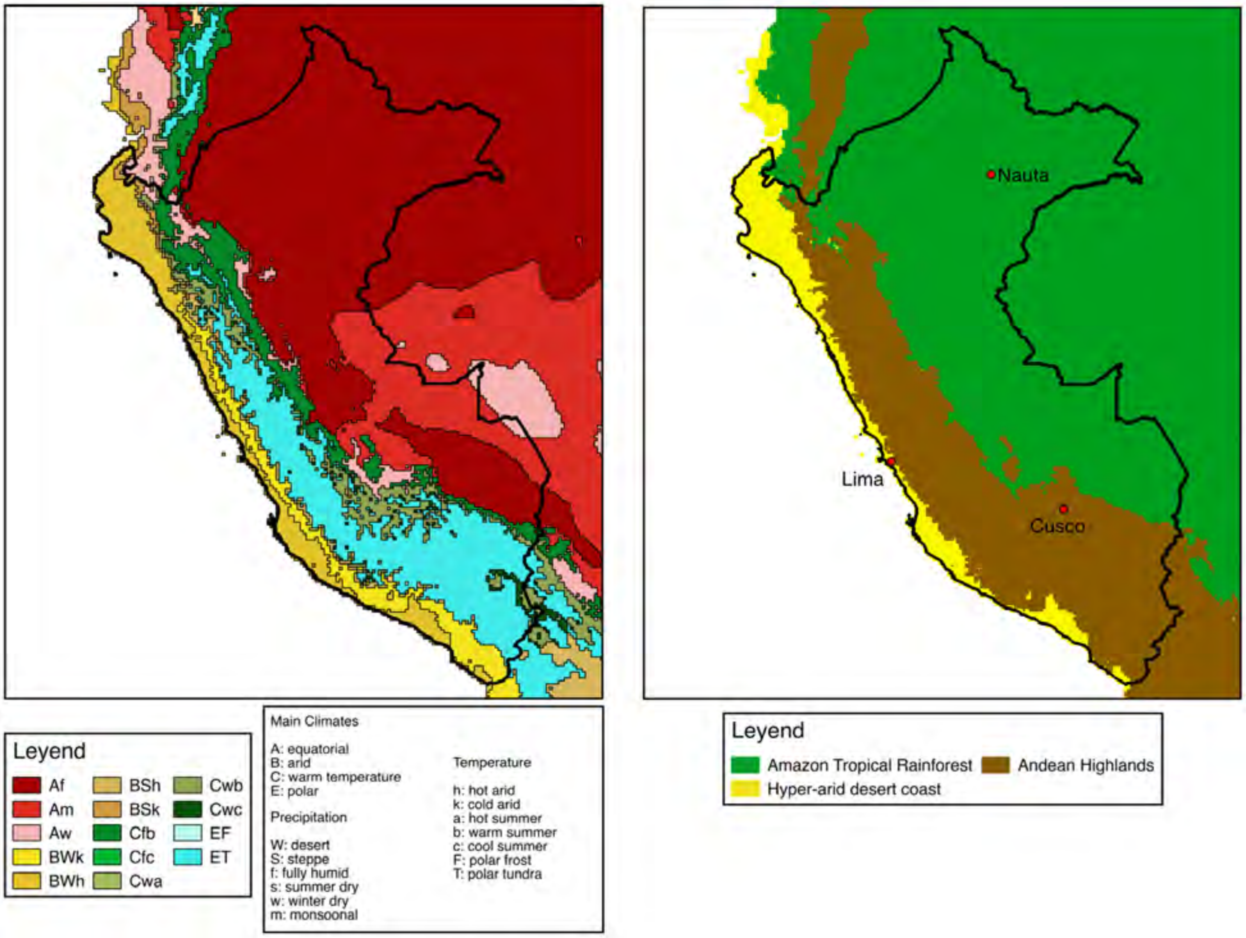
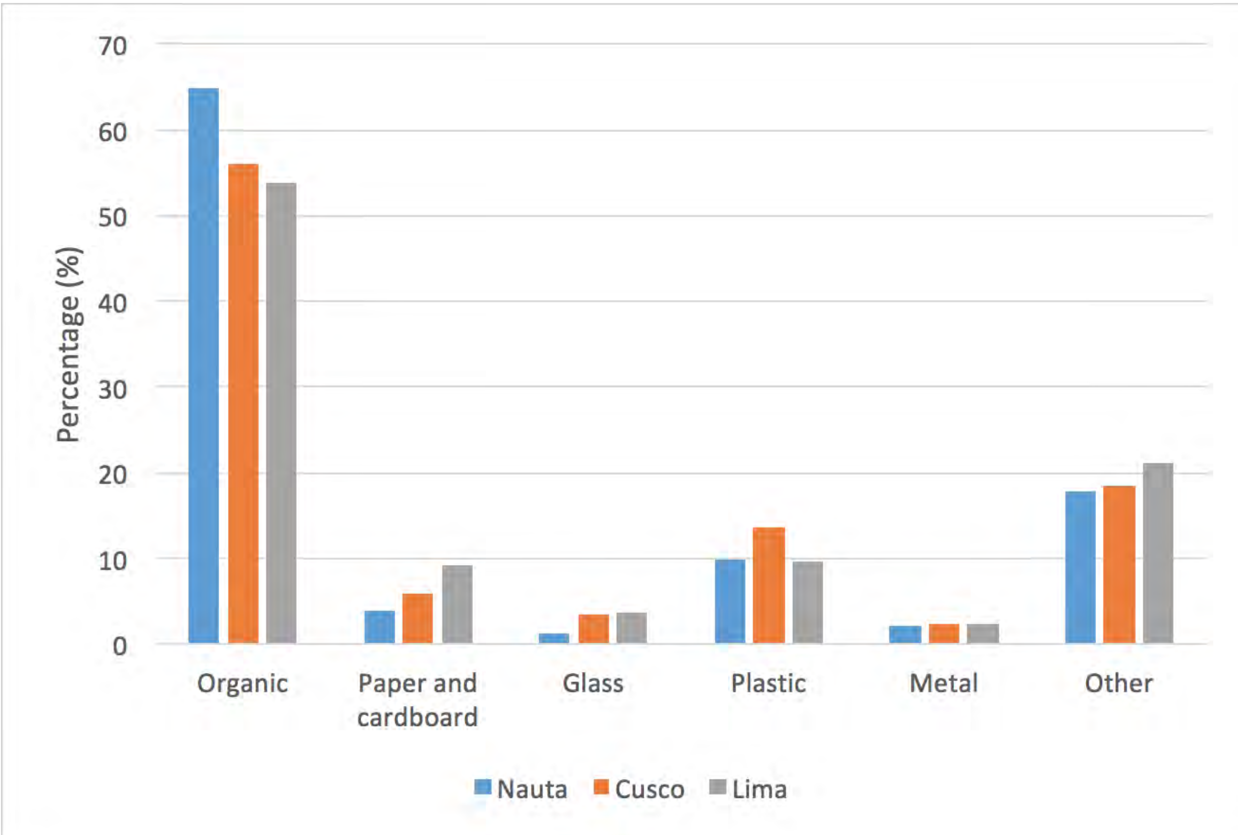
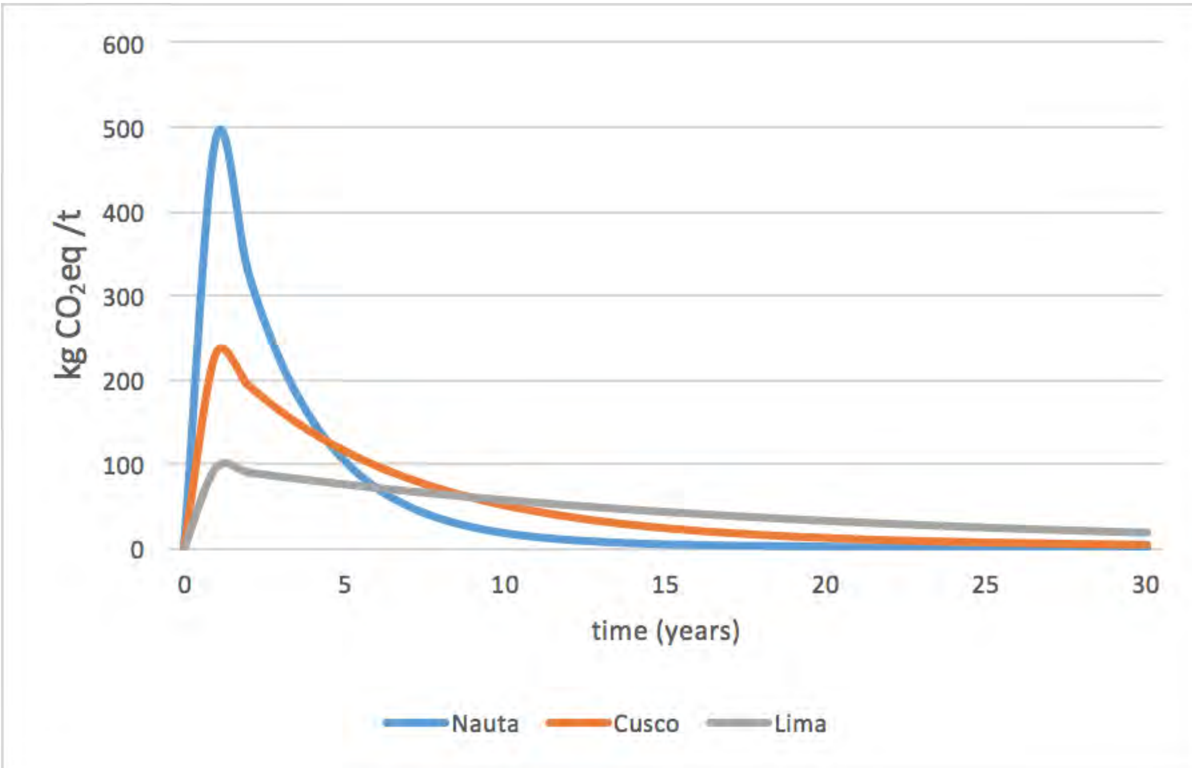
31
Landfill
Regions with landfills

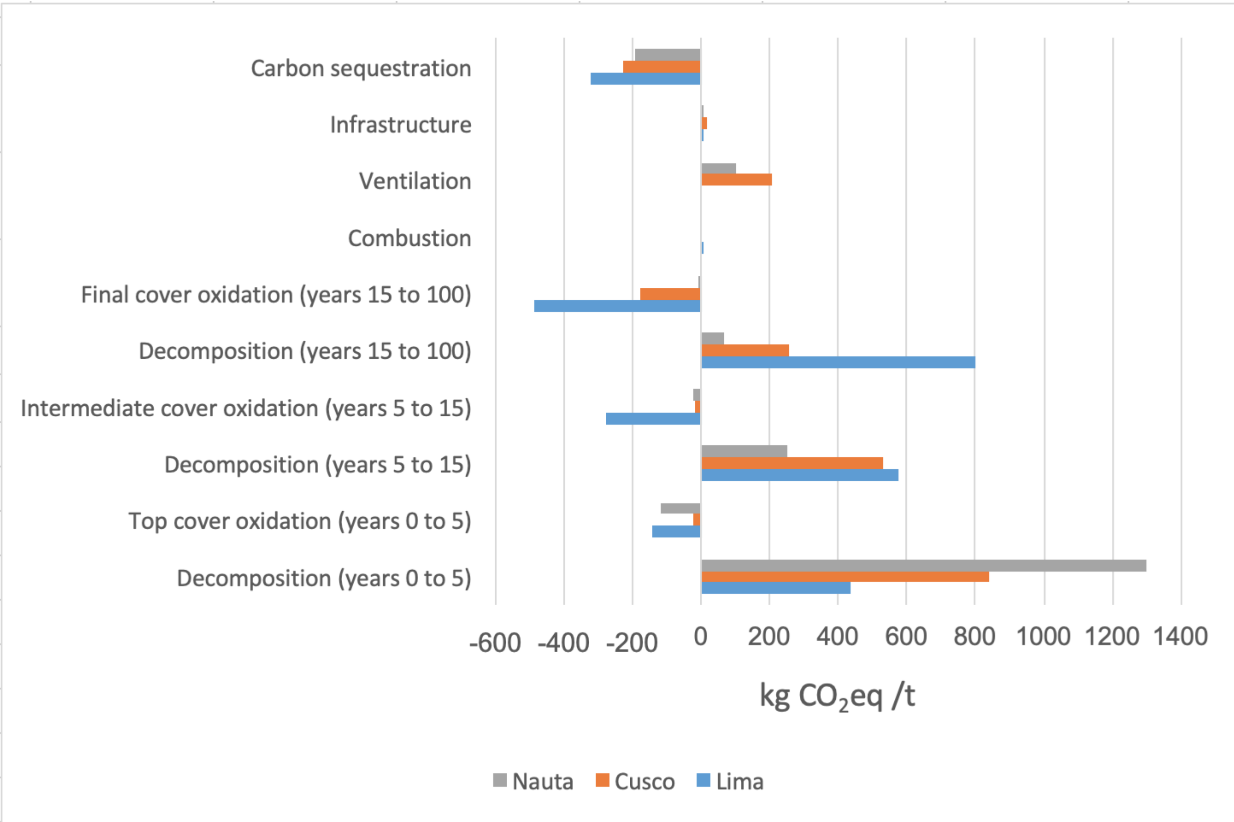

Raw Materials
Machinery
Emissions (Air, Water, Soil)
Construction
Deforestation
Excavation
Bottom Layer
Collection Systems
Operation
Segregation*
MSW Placement
Daily and Intermediate cover
Gas Collection
Leachate Treatment
Closure
Final Cover
Maintenance
Reforestation*
Compost*
Recyclables*
Municipal Solid Waste
*Depending on the landfilling facility


Leyend
Af
Am
Aw
BWk
BWh
BSh
BSk
Cfb
Cfc
Cwa
Cwb
Cwc
EF
ET
Main Climates
A: equatorial
B: arid
C: warm temperature
E: polar
Precipitation
W: desert
S: steppe
f: fully humid
s: summer dry
w: winter dry
m: monsoonal
Temperature
h: hot arid
k: cold arid
a: hot summer
b: warm summer
c: cool summer
F: polar frost
T: polar tundra
Nauta
Lima
Cusco
Leyend
Amazon Tropical Rainforest
Andean Highlands
Hyper-arid desert coast

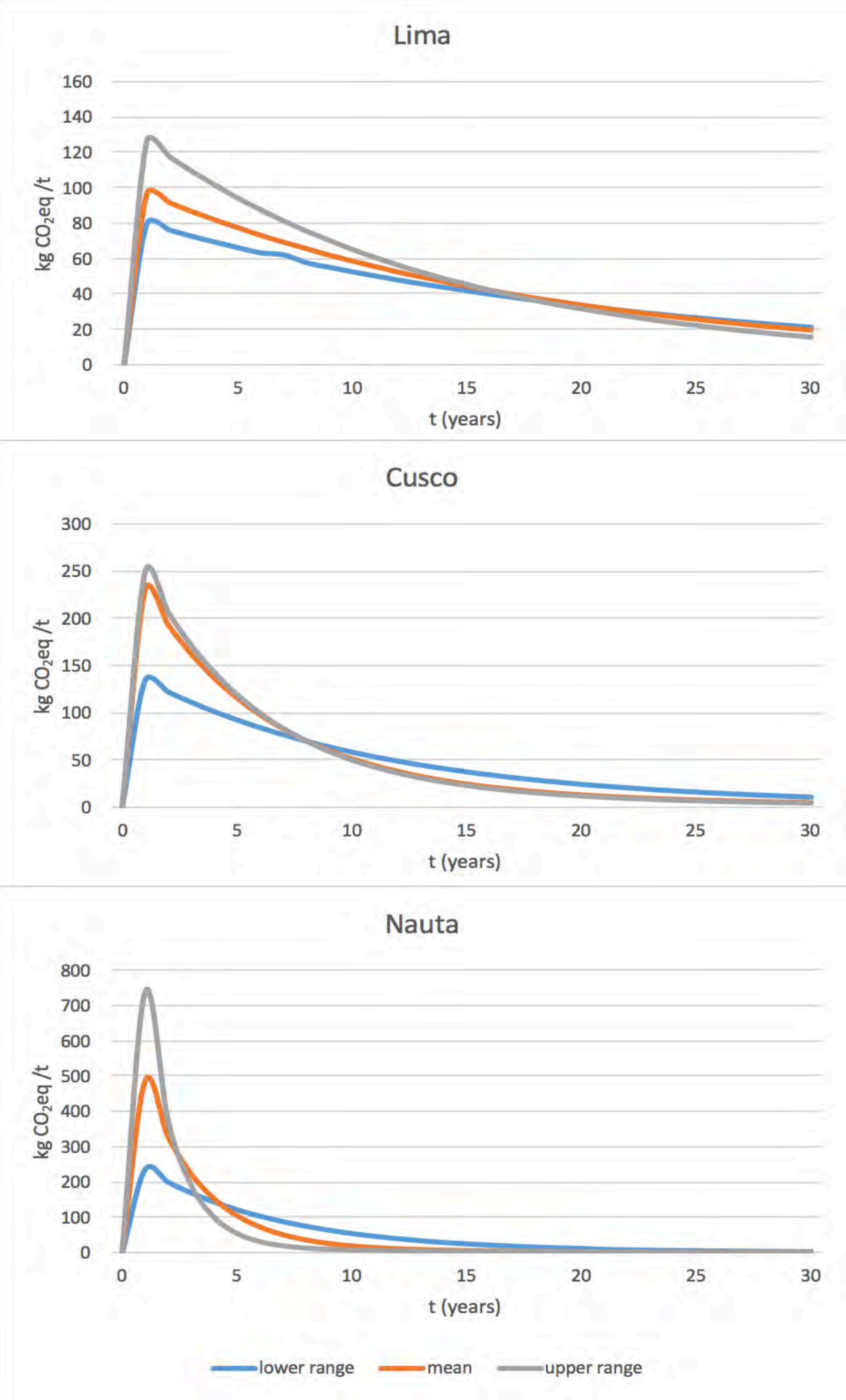


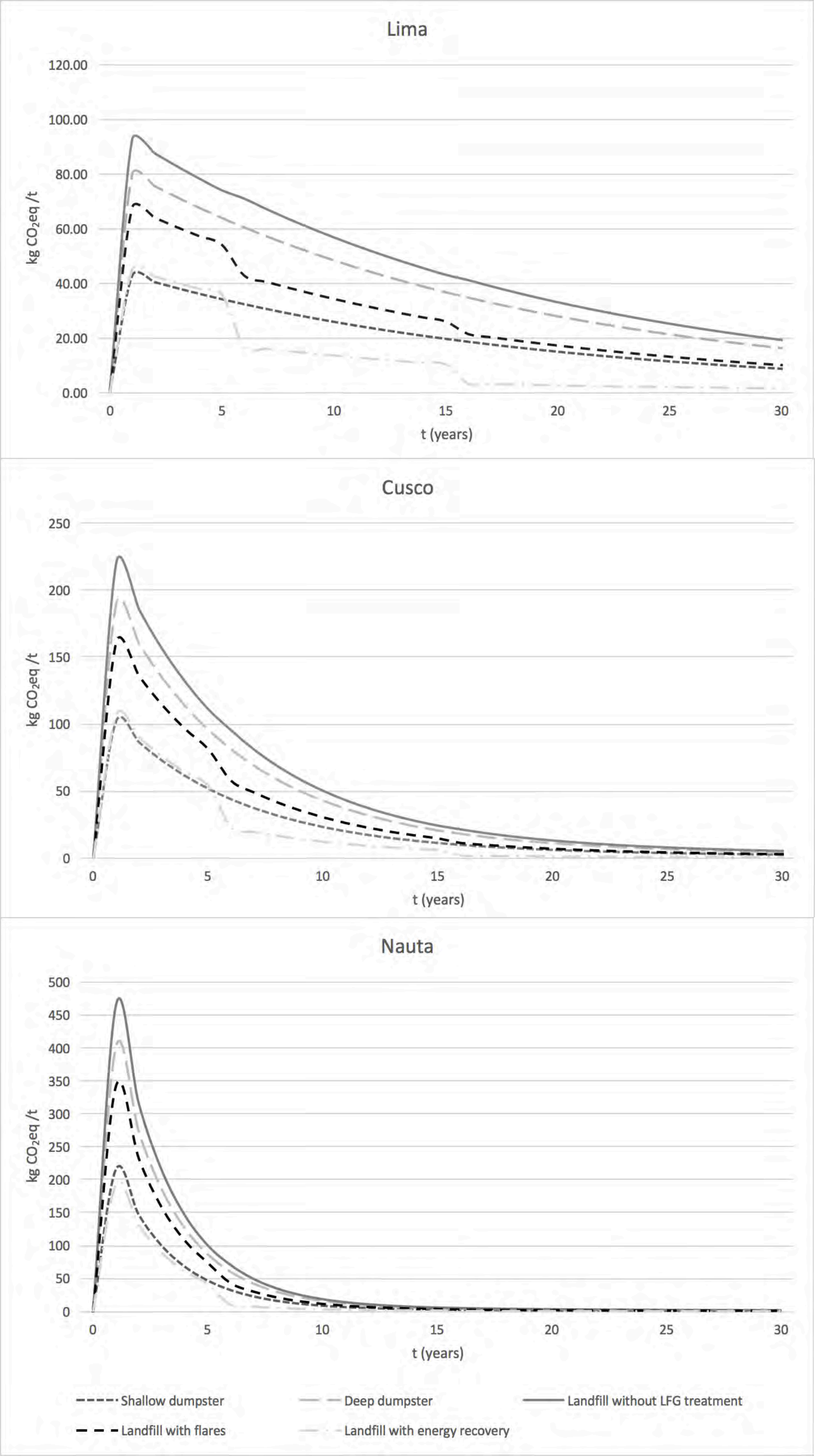
70
60
50
40
30
20
10
0
Percentage (%)
Organic
Paper and cardboard
Glass
Plastic
Metal
Other
Nauta
Cusco
Lima


600
500
400
300
200
100
0
kg CO_2eq /t
0
5
10
15
20
25
30
time (years)
Nauta
Cusco
Lima



Carbon sequestration
Infrastructure
Ventilation
Combustion
Final cover oxidation (years 15 to 100)
Decomposition (years 15 to 100)
Intermediate cover oxidation (years 5 to 15)
Decomposition (years 5 to 15)
Top cover oxidation (years 0 to 5)
Decomposition (years 0 to 5)
-600 -400 -200 0 200 400 600 800 1000 1200 1400
kg CO_2eq /t
Nauta
Cusco
Lima


Lima
160
140
120
100
80
60
40
20
0
kg CO_2eq /t
0
5
10
15
20
25
30
t (years)
Cusco
300
250
200
150
100
50
0
kg CO_2eq /t
0
5
10
15
20
25
30
t (years)
Nauta
800
700
600
500
400
300
200
100
0
kg CO_2eq /t
0
5
10
15
20
25
30
t (years)
lower range
mean
upper range


Lima
120.00
100.00
80.00
60.00
40.00
20.00
0.00
kg CO_2eq /t
0
5
10
15
20
25
30
t (years)
Cusco
250
200
150
100
50
0
kg CO_2eq /t
0
5
10
15
20
25
30
t (years)
Nauta
500
450
400
350
300
250
200
150
100
50
0
kg CO_2eq /t
0
5
10
15
20
25
30
t (years)
Shallow dumpster
Deep dumpster
Landfill without LFG treatment
Landfill with flares
Landfill with energy recovery