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Life cycle inventory and carbon footprint assessment of wireless ICT networks for six demographic areas

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ABSTRACT

The aim of this work is to quantify, assess, and identify hotspots in the environmental sustainability of newly constructed ICT networks designed to provide internet access (4 G LTE mobile technology) to regions still lacking this service. The analysis has been carried out on six demographic areas, from high-density urban and peri-urban to remote rural, using ISO 14,040. A Dynamic Inventory Model (DIM) relating demographic/connectivity features with foreground material and energy inventories was validated using real data from Peru. The results showed carbon footprints between 81 and 103 kg CO_2 eq./subscription/year, equivalent to 1.35 – 1.73 kg CO_2 eq./Gb. Most of this (between 68 and 86%) correspond to end user devices, primarily in the form of embodied emissions. Operational emissions account for about one-third of the total and derive primarily from the electricity consumed by end user devices, and to a lower extent by access networks and data centers. Linear correlations were observed between operational - embodied carbon emissions and the number of subscribers. This trend was overturned in very small ICT networks designed to serve sparsely populated rural areas, due to higher energy consumption and carbon emissions per functional unit generated by access and IP network components. The robustness of these results was studied through sensitivity and uncertainty analyses.

1. Introduction

The Digital Revolution, which marked the beginning of the Information Age in the latter half of the 20th century, is bringing about profound changes in the way we live, work, learn and socialize. At present, internet access is widely regarded as an essential condition for economic growth, social prosperity, modernization and even improved environmental performance (European Commission, 2019; OECD, 2019a; World Bank, 2016). Internet penetration has been growing exponentially over the last few decades to reach a global average of 53.6% in 2019, a marked increase from the 35% rate registered in 2013 (ITU, 2020). However, this digital transformation is not occurring evenly throughout the world. While 87% of the populations in industrialized countries are considered to be active internet users, this value drops on average to 47% in developing areas and to less than 20% in the most economically deprived regions (OECD, 2019b). While the lowest penetration rates are usually found in rural and remote regions, most of the population lacking internet access resides in peri-urban areas around fast-growing metropolises (ITU, 2020).

The 2030 UN Agenda for Sustainable Development includes in Goal 9 Industry, Innovation and Infrastructure a call to “significantly increase access to information and communications technology and strive to provide universal and affordable access to the internet in least developed countries by 2020” United Nations, (2020). Over the last years, governmental, intergovernmental, non-governmental organizations, together with companies in the ICT sector, have all been rather active promoting initiatives aimed at providing reliable and affordable solutions adapted to the needs of these locations (FCLB, 2020; Gelvanovska et al., 2014; Kelly and Rossotto, 2012; OECD, 2019a; US Senate, 2018).

Despite these potential benefits, it should not be overlooked that telecommunications networks themselves are directly responsible for the emission of significant amounts of contaminants affecting the environmental categories of climate change, consumption of natural resources, etc. Notwithstanding major energy efficiency gains over the last decades, digital technologies currently consume around 10% of the electricity generated worldwide, a value that has been rising by 9% per year in the last decade and it is expected to grow up to 21% by 2030

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Abbreviations

4 G LTE	Fourth Generation Long Term Evolution
ACF	Annual Carbon Footprint
CPE	Customer Premise Equipment
DIM	Dynamic Inventory Model
ECF	Embodied Carbon Footprint
EoL	End of Life
EPC	Evolved Packed Core
FU	Functional Unit
GHG	Greenhouse Gas
ICT	Information and Communications Technology
LCA	Life Cycle Assessment
OCF	Operational Carbon Footprint

(Andrae and Edler, 2015). ICT technologies are already responsible for 4% of all anthropogenic greenhouse gas (GHG) emissions, a value comparable to that of the air traffic sector (Ferreboeuf et al., 2019; Malmodin and Lundén, 2018; Mills, 2013).

Given this situation, numerous studies have been conducted to assess the environmental sustainability of internet systems from different perspectives. Most of these are based on Life Cycle Assessment (LCA) methodology and consider climate change emissions and/or energy usage as key performance indicators. A micro level approach has been used to describe the environmental burdens generated by specific electronic devices, equipment and telecommunication infrastructures involved in the provision of digital services (Aleksic and Mujan, 2018; Bovea et al., 2018; Hischier et al., 2015; Moberg et al., 2014a; Schien et al., 2015; Shehabi et al., 2016). Useful (and sometimes conflicting) results have been reported on the environmental sustainability of certain ICT services such as online video (Efoui-Hess, 2019; IEA, 2020a; Preist et al., 2019), online advertising (Pärssinen et al., 2018) or cloud computing (Baliga et al., 2010; Chatzithanasis and Michalakelis, 2018).

Using a macro level top-down approach, additional investigations have been carried out aimed at describing the environmental performance of the global ICT sector and of national ICT networks covering certain geographic regions (Sweden, Germany, US, China, etc.). While some of these investigations focus solely on the energy consumed during its utilization phase (Andrae and Edler, 2015; Aslan et al., 2018; Coroama et al., 2015; Costenaro and Duer, 2012), other studies suggest that most of the carbon footprint in ICT systems is embodied in its hardware components (user devices, equipment and infrastructures) (Belkhir and Elmeligi, 2018; Hischier et al., 2015; Humar et al., 2011; Malmodin et al., 2014; Malmodin and Lundén, 2018; Osei-Bryson and Carter, 2017; Zhou et al., 2019). The inventories on which most of these investigations are based describe a complex overlap of increasingly fast transmission technologies (both wire and wireless) deployed in response to the growing demand for digital communication services.

Despite the interest of the abovementioned investigations, these results are not applicable to describe the environmental sustainability of newly designed networks. As explained, while the inventory data for existing ICT systems would necessarily involve a cohabitation of a wide range of data transmission and processing technologies shaped by market evolution, the latter would depict an optimized architecture and network design aimed at meeting the demand of a client population (in terms of number of subscriptions, traffic volume, penetration rate, bandwidth, carrier frequency, data traffic, aggregated speed, etc.) at the lowest cost.

In view of the rapid surge in the deployment of ICT networks expected in the coming years in developing regions with no pre-existing infrastructures, the main objective of this investigation is to bring light into the environmental sustainability of such interventions. For this purpose, six geo-demographic scenarios have been described (from high density peri-urban to very low density remote rural) and a detailed life cycle inventory has been estimated for each one of them considering the most suitable and cost-effective technology available at present (wireless 4 G LTE). These inventories include both the hardware and energy use of the following components: end user devices, access networks, IP core networks, international infrastructures (undersea cable) and datacenters. The environmental sustainability has been quantified in terms of carbon footprint and considering both embodied (extraction of raw materials, manufacturing, transport, and end of life) and operational impacts.

2. Methodology

This investigation follows the principles and structure for life cycle assessment (LCA) described in the ISO 14,040:2006 and ISO14044:2006 standards (ISO, 2006a, 2006b). This methodological framework considers the following phases: definition of the goal and scope of the LCA, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA) and interpretation of the results.

2.1. *Goal and scope definition*

2.1.1. *Goal definition*

The main goal of this investigation is to quantify the potential carbon footprint associated with the life cycle of 4 G LTE mobile networks designed to provide internet access to six geo-demographic scenarios (from high density peri-urban to very low density remote rural). This assessment has been based on inventory data valid for the period 2015–2020, which has been estimated using a Dynamic Inventory Model (DIM) (Karlin, 1960) that takes into consideration both geo-demographic and connectivity features corresponding to each of these six scenarios. Secondary objectives of this work include: i) evaluating the contribution of each of the life cycle stages (primarily differentiating between embodied and operational emissions); ii) evaluating the contribution of individual processes; iii) defining strategies aimed at minimizing the carbon footprint of such ICT networks.

2.1.2. *Scope definition*

2.1.2.1. Methodology structure. As explained above, this investigation follows the structure for LCA described in ISO 14,040:2006 and ISO14044:2006 (ISO, 2006a, 2006b). These protocols have been applied using the criteria for telecommunication systems described by (ETSI, 2011).

2.1.2.2. System description. In contrast to other pieces of research published in the literature, this study does not refer to any existing scenario, but aims to determine the carbon footprint of six hypothetical networks designed to provide internet access to six geo-demographic areas, from high density urban to low density remote rural. These locations were ascribed to six 6 real administrative district areas in Peru for which detailed information was available about its geo-demographic characteristics. This country was selected as a reference for this investigation due to its developing status in terms of economic growth and digitalization, and due to its diverse population distribution and topography. Another reason for using Peru as a reference was the availability of high quality technical and economic data from recent ICT network deployments based on 4 G LTE technology (OSIPTEL, 2019a).

Current trends in the ICT sector show that global internet traffic is shifting rapidly from wired into mobile technologies. Wireless internet is particularly strong and ubiquitous in emerging markets (OECD, 2020). Hence, in areas with no existing internet coverage, it is most likely that future network deployment will be carried out using wireless technologies. Due to its technical and economic state (market maturity, implementation level, flexibility, network accessibility and quality, deployment, and operating costs, etc.), 4 G Long-Term

Evolution (4 G LTE) technology is currently the most suitable for this purpose. The use of 4 G technologies in low and medium income countries increased by 45% between 2014 and 2018 (GSMA, 2019). According to Cisco, the global average data plans per subscription will reach 9.1 Gb per month by 2022 (CISCO, 2019). Based on this information, the environmental analysis proposed in this work is based on the deployment of 4 G LTE networks.

Fig. 1 illustrates the 4 G LTE network architecture considered in this investigation, which includes the following elements: End user devices, eNodeB (Access network), Evolved Packed Core (EPC), Data Transmission (undersea cable and optic fiber), and Data centers.

Table 1 provides a brief explanation of the technical characteristics and the typical components that make up each of these network elements. End users make use of their user devices (mobile and smart phones) and Customer Premise Equipment (CPE) to gain access to internet applications and services through the mobile access network (eNodeB). This access network consists of a series of LTE radio base stations (BS) which are deployed to ensure maximum coverage and the lowest cost. Access networks are in turn connected to the IP core network (EPC), which typically consists of four network components: Serving Gateway (SG), Packet Data Network Gateway (PDN), Mobility Management Entity (MME) and Home Subscriber Server (HSS). Finally, the EPC is connected to the Internet Exchange Point (IEP), which provides access to external networks, routing traffic by undersea cable and optic fiber to data centers, where servers providing applications and services are commonly placed.

2.1.2.3. Life cycle system structure and boundaries. As illustrated in Fig. 2, the carbon footprint assessment of the theoretical ICT networks has considered the following life cycle stages: extraction of raw materials and manufacturing of end user devices and 4 G LTE network, transport of these components to the location site, operation of end user devices, 4 G LTE network, global infrastructures and data centers in terms of power use, and end of life (EoL) activities of end user devices and 4 G LTE network. Embodied emissions refer to those derived from the extraction of raw materials, manufacturing, transport and EoL phases, while operational emissions refer to those attributable to the energy consumed during the utilization phase. As said previously, only operational emissions are included for transmission and data centers. Due to the absence of inventory data and the limited contribution to the overall carbon footprint of the system (Malmodin and Lundén, 2018; Whitehead et al., 2015), embodied emissions from global transmission (undersea cable) and data centers were left outside the systems boundaries of this investigation.

Table 1
Characteristics of the 4 G LTE network elements considered.

User devices	End user device	Smartphones and mobiles phones
	Customer Premise Equipment	Home/on-site networking or Customer Premise Equipment (CPE), i.e., equipment used to access the internet as routers and modems
4 G LTE network	Access network	eNodeB - Equipment connecting subscribers (or users) to Internet Service Provider, in our study, formed by base stations
	IP core network (EPC)	Internet Service Provider equipment forming regional and national networks. This typically includes equipment that uses internet Protocol. In this study the Evolved Packed Core (EPC)
Transmission and data center	Undersea cable	High-bandwidth cable infrastructure connecting continents and countries. Submarine communications cable, etc.
	Data centers	Installations used to carry out a large variety of functions (e.g., e-mail, financial transactions, social media, etc.) and store data. Servers, storage equipment, power and cooling equipment, etc.

2.1.2.4. Environmental categories and impact assessment method. This investigation has only considered the environmental category of climate change. Impact values have been calculated in terms of greenhouse gas (GHG) emissions (kg CO_2 eq.) with 100 year global warming potential. The LCIA methodology employed to transform GHG emissions into impact values was that published by the International Panel on Climate Change (IPCC, 2013).

2.1.2.5. Functionality and functional unit. The functionality of the ICT systems under investigation was defined as “the provision of internet service to a demographic area according to the connectivity features described in Table 2”. The basic functional unit (FU) was 1 year of internet service. Impact values in the climate change category were described in terms of GHG emissions per year and referred to as Annual

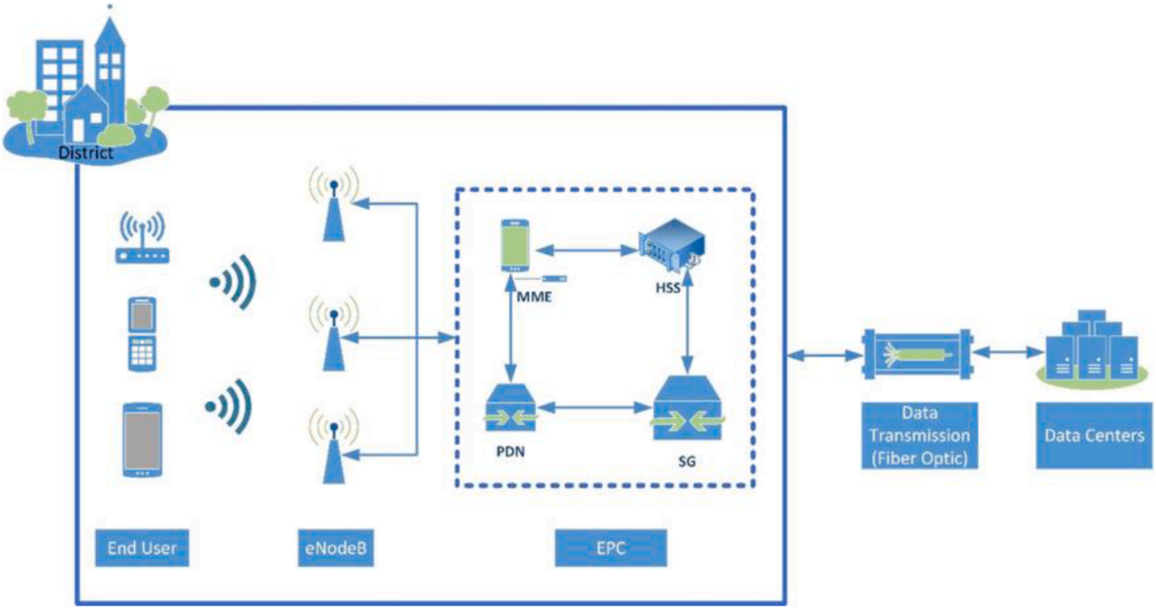

Fig. 1. District level 4 G LTE network architecture and components considered.

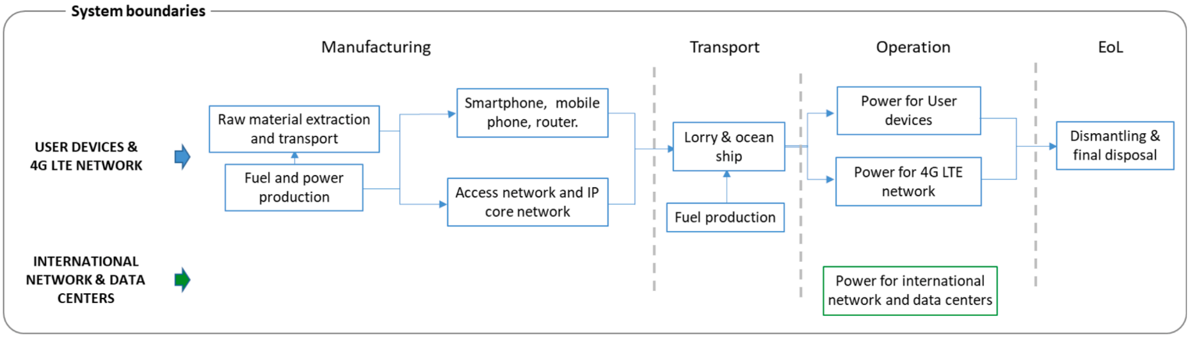

Fig. 2. Life cycle processes and system boundaries considered in the analysis of ICT networks.

Table 2
Geo-demographic and connectivity features of the six scenarios considered in this investigation, and the resulting inventory data calculated for each of them.

		Lima Urban	Ica Urban	Comas Suburban	Santa Rosa Suburban	Iñapari Rural	Huancaya Rural remote
Demograph.	**Area (km^2)**	22	888	49	22	14,854	284
	Population	268,352	150,280	575,800	31,000	2397	596
	Population density (person/km^2)	12,198	169	11,751	1409	0.161	2.100
Connectivity	**Subscriptions**	238,833	118,721	512,462	27,590	2109	530
	Penetration rate (%)	0.89	0.79	0.89	0.89	0.88	0.89
	Bandwidth (MHz)	20					
	Carrier frequency (MHz)	1700					
	Aggregated speed (Mbps/km^2)	486	15	365	45	0.0022	0.0650
Inventory data	**Mobile Phones**	455,793	212,421	977,991	52,653	3712	1012
	Smart Phones	347,155	162,984	744,887	40,103	2979	771
	Modems	2478	632	5317	286	6	6
	Base stations (eNodeB)	470	230	559	34	9	2
	Evolved Packed Core (EPC)	2	1	3	1	1	1

Carbon Footprint (ACF) (kg CO_2 eq/year). To facilitate the comparative assessment of networks of different size and capacity, ACF values were also reported per unit of subscription (kg CO_2 eq./year/subscription) and per unit of traffic data (Gb) generated (kg CO_2 eq./Gb).

2.1.3. *Embodied and operational carbon footprints*

Identifying the processes and life cycle stages contributing the most to the carbon footprint of a given system is a critical requirement prior to developing strategies aimed at improving its environmental sustainability. Some investigations point out that the energy consumed during the operation of ICT networks is the greatest source of environmental impact (Andrae and Edler, 2015; Aslan et al., 2018; Coroama et al., 2015; Costenaro and Duer, 2012;). However, other studies reveal the significance of the environmental impacts embodied in the devices, equipment and infrastructures that remain upstream and downstream from operation phase (Belkhir and Elmeligi, 2018; Hischier et al., 2015; Humar et al., 2011).

In this study, the ACF was calculated as the sum of the operational carbon footprint (OCF) and the embodied carbon footprint (ECF). OCF include emissions derived from the power consumption of all devices of the ICT network for one year, from smartphones to data center. In the meantime, ECF include those emissions attributable to manufacturing stage (extraction of raw materials and fabrication), transport from fabrication to operating site, and EoL processes of user devices (smartphones and CPE) and 4 G LTE network components (eNodeB and EPC). These embodied emissions were allocated to a year by dividing the total value for each device by its estimated lifetime.

The ECF of the international infrastructures (e.g., undersea cable, optic fiber) and data centers were left outside the system boundaries. This decision was made on the basis of the limited contribution of this life cycle phase (caused by long useful life and relatively high energy consumptions) (Malmodin et al., 2014; Whitehead et al., 2015, 2014) and also the lack of reliable and updated inventory data for the extraction of raw materials and fabrication phases. Hence, the carbon footprint of these components was only based on their OCF.

2.2. *Life cycle inventory analysis*

This section describes the steps followed to determine the inventory data employed to quantify the carbon footprint of the six theoretical ICT networks considered in this investigation. For this purpose, Section 2.2.1 provides a bibliographic review of alternative methodological approaches to life cycle inventory compilation for ICT networks and the decisions taken in the context of this investigation. This is followed by a Section 2.2.2 dedicated to describing the 6 demographic areas covered by these networks, and the administrative districts in Peru to which they have been ascribed. Section 0 describes the use of a Dynamic Inventory Model (DIM) to calculate the hardware requirements to provide the connectivity features demanded by each of the 6 demographic areas. Finally, Section 2.2.4 provides additional information about methodological decisions and assumptions made to compile the inventory data in the context of this investigation.

2.2.1. *Methodological approaches to inventory compilation*

Quantifying the carbon footprint of an ICT network requires compiling a detailed life cycle inventory of material and energy flows. According to the scientific literature, this may be carried out using one of two alternative methodological approaches: the top-down approach relies on compiling information about hardware deployment and energy consumption of an existing network (or part of it) for which key connectivity features are available. This makes it possible to define average hardware and energy requirements per unit of connectivity (e.g., data traffic), an information that may be extrapolated to model other ICT networks based on similar technologies. This top-down approach has been reported to produce robust and realistic results in terms of hardware and energy requirements, as it takes into consideration overheads that usually occur in real ICT networks, such as redundancy, cooling, and overprovisioning. However, it does not allow correlations to be established between inventory data and network design parameters (Ishii et al., 2015; Schien and Preist, 2014).

In contrast, the bottom-up approach to inventory compilation is based on network design principles and collects data at the level of an individual network component. The first step in this approach involves designing the network characteristics (including type and number of components) necessary to provide the connectivity features demanded by the client population. This is done considering the technical characteristics of the ICT hardware components, which typically include usage profiles, network topology and routing, specific power consumption, data processing and transmission, etc. (Coroama and Hilty, 2014). The inventory data for the operational phase is calculated considering the energy intensity for each network device class and aggregating the results to all network devices of the end-to-end connection (Ishii et al., 2015). The bottom-up approach has been reported to underestimate hardware and power use because ideal model on which it is based does not reproduce the technical inefficiencies of real scenarios (Aslan et al., 2018; Schien and Preist, 2014). However, this approach allows network parameters and energy use to be readily correlated, enabling projections, and facilitating the analysis of alternative design and operating scenarios.

These two approaches may be combined to model complex networks made up of different subsystems and also to adapt to the availability of different type of input data for a given system (Aslan et al., 2018; Ishii et al., 2015). This has been the case in this investigation where a plain bottom-up approach has been applied to quantify the OCF and ECF of user devices and 4 G LTE network components. A similar bottom-up approach was also used to determine the amount of data traffic generated by the services demanded by end users. In the absence of specific information for international data transmission facilities (undersea cable and optic fiber) and data centers, a top-down approach to inventory compilation was applied to quantify energy use. Operational emissions for these facilities were calculated considering the amount of data traffic generated by each of the six ICT networks under consideration and the energy intensity reported in the literature, as described below.

2.2.2. Description of scenarios

The LCA carried out in this investigation is based on six theoretical ICT networks designed, constructed, and operated to provide internet service to six demographic areas, ranging from high density urban areas to very low density remote rural. Hence, the first step in this endeavor was to define these six scenarios, which were ascribed to six real municipal districts in Peru for which precise demographic information was available (INEI, 2020). Real and updated information for these districts was available on the number of subscriptions (Internet Monitor, 2020; Sociedad Telecom, 2018), number and characteristics of end user devices (INEI, 2020) and 4 G LTE network infrastructures, including number and technical characteristics of 4 G LTE Base Stations (eNodeB) and Evolved Packed Core (EPC) (More et al., 2019; Sociedad Telecom, 2018).

The definition of these demographic areas as urban, suburban, rural and remote rural was based on the classification published by the Peru's National Institute for Statistics (INEI, 2017a). Table 2 describes the demographic characteristics of each of these six scenarios, the administrative districts in Peru to which they were ascribed and the connectivity features to be attained by the 4 G LTE networks deployed in each of them. The scenarios ascribed to the Lima and Ica districts represent two urban scenarios, the former characterized by a small extension and very high population density and the latter characterized by a very extended surface and consequently lower population density. The scenarios ascribed to the Comas and Santa Rosa districts correspond to two suburban scenarios of reduced extensions, the former characterized by very high population density compared to the situation in Lima district. The scenarios ascribed to the Iñapari and Huancaya districts are classified as rural and remote rural, respectively. The population and population densities of these two scenarios are significantly lower than those corresponding to the urban and suburban areas.

2.2.3. Network dimensioning, inventory compilation and validation

In order to quantify the hardware inventory (eNodeB and EPC) required for each of the six scenarios, a DIM was built based on the based on the premises of (Holma and Toskala, 2009) and the improvements proposed by (Frías Barroso, 2016). The model uses as input data geo-demographic information (area of the territory, population, population density), services (user density, penetration rate, data traffic, radio frequency spectrum, spectral efficiency, bandwidth, number of sectors per base station, data traffic per base station in the rush hour). Conditions affected by other external factors are also considered in the model as meta-parameters, including core-network infrastructure, internet traffic analysis, external services, internet penetration rate and radio-frequency spectrum availability, among others.

The results of the DIM on the number of base stations (eNodeB) were validated against data published by the national ICT regulatory body (OSIPTEL, 2019b, 2019a). A mean deviation of 3.81% was obtained between theoretical and real data for the 1855 administrative districts evaluated, which was deemed to be sufficient for this investigation (OSIPTEL, 2019b). This deviation was attributable to differences between theoretical/real services established as an input data in the DIM, and to the deployment of redundant base stations by competing network service providers, primarily in areas with high demand. Real data on user devices was obtained at a departmental level from national statistics Peru (INEI, 2017b), which was used to validate theoretical data obtained from the DIM.

2.2.4. Assumptions for inventory data

2.2.4.6. Modeling of embodied carbon footprint. Depending on the characteristics of the background inventory data available, three approaches were used to model the manufacturing of ICT components. The most precise and preferred option involved using background inventory data referring to electronic devices/equipment technically like the ones employed in the ICT network under investigation and expressed per unit of product. In this case, the information from the database could be used directly considering only the number of electronic devices required. This approach was used to evaluate the embodied carbon footprint of end user devices and CPE components (routers/modems). When this option was not available, a second less precise approach was used which involved using background inventories describing per unit mass (kg) each of the components that make up the ICT equipment under investigation. Table 3 provides information about the material decomposition of the base station (eNodeB) analyzed in this investigation, which included the following components: Base band Unit, Radio Frequency Unit, Base Band Unit Cabinet, Integrated battery cabinet, Power Bank and 3 Antennas. Finally, the least precise option occurred when background inventory data referred to electronic equipment of similar technical characteristics to the ones employed in the ICT network. In this case, a rescaling had to be performed taking into consideration the size, mass, and capacity of the systems under consideration. The application of these approaches to the analysis of different ICT network components is described in the following sections.

Table 3 provides additional information employed to model the embodied and operational carbon footprint of the user devices and 4 G LTE network, including mass composition, service life and annual power consumption. The ECF refer to those emissions associated with the extraction of raw materials, fabrication, shipment to the place of use (from China to Peru) and end-of-life activities. Background inventory data was obtained from LCI databases including the European Life Cycle Database (European Commission, 2020), Ecoinvent (Wernet et al., 2016) and also from selected publications, as shown in Table 4.

Table 3
Annual power consumption, service life and weight for user devices and 4 G network equipment.

			Annual power consumption (kWh)	Service life (yr)	Mass (kg)	Source
User devices	**End user devices**	**Smart Phones**	8	2	0.16	Power consumption and mass from retail websites. Service life from (Belkhir and Elmeligi, 2018)
		Mobile Phones				Assumed as smart phone
	CPE	**Modem/router**	69	5	0.3	Power consumption and mass from retail websites. Service life from (Malmodin et al., 2014).
4 G **LTE network**	**Base stations (eNodeB)**	**Base band Unit**	298	10	7	Technical specifications from equipment factsheets. (Huawei, 2011) Standard service life: 10 yr
		Radio Frequency Unit	701	10	12	
		Base Band Unit Cabinet/ power module	13	10	68	
		Integrated battery cabinet	-	10	70	
		Power Bank	-	10	10	
		3 Antennas	-	10	51	
	EPC	**IP core network**	21,024	10	48	

Table 4
Emission factors of all the emission sources (embodied and operational) considered in the life cycle assessment of ICT networks.

Phase	Process	Emission factor	Source
Manufacture	Mobile phone	20 kg CO_2/unit	Belkhir and Elmeligi, (2018)
	Smartphone	60 kg CO_2/unit	Belkhir and Elmeligi, (2018); Ercan et al., (2016)
	Modem	5.84 kg CO_2/unit	Ecoinvent 3.7. Internet access equipment {GLO}
	ICT equipment	34.45 kg CO_2/kg	Ecoinvent 3.7. Router, internet {GLO}
	Power supply unit	33.3 kg CO_2/unit	Ecoinvent 3.7. Power supply unit, for deskop computer
	Chassis for electronic equipment	4.04 kg CO_2/kg	Ecoinvent 3.7. Chassis, internet access equipment {GLO}
	Battery	8.98 kg CO_2/kg	Ecoinvent 3.7. Average of production of several batteries: Battery cell, Li-ion {CN} and {RoW} Battery, Li-ion, rechargeable, prismatic {GLO} Battery, NiMH, rechargeable, prismatic {GLO}
Use	Peru power mix	0.269 kg CO_2/kWh	Electricity mix from (IEA, 2020) and carbon footprint of power generation from Ecoinvent 3.7
	International power mix	0.554 kg CO_2/kWh	
Transport	Lorry transport	0.0656 kg CO_2/ tkm	ELCD 3.2 -Lorry transport, Euro 0, 1, 2, 3, 4 mix, 22 t total weight, 17,3t max payload RER
	Container ship ocean	0.0122 kg CO_2/ tkm	ELCD 3.2 -Container ship ocean, technology mix, 27.500 dwt pay load capacity RER
EoL	Dismantling and EoL of ICT equipment	1.413 kg CO_2/kg	Ecoinvent 3.7. Used IT accessory {GLO}| treatment of used IT accessory, mechanical treatment
	Dismantling and EoL of electronic component	0.310 kg CO_2/kg	Ecoinvent 3.7. Used industrial electronic device {GLO}| treatment of, mechanical treatment
	Battery EoL (average Li-ion/NaCl/NiMH)	1.65 kg CO_2/kg	Ecoinvent 3.7. Average of production of several batteries: Disposal, Li-ions batteries, hydrometallurgical Disposal, Li-ions batteries, mixed technology Disposal, Li-ions batteries, pyrometallurgical Disposal, NiMH batteries

2.2.4.7. User devices. Generic background inventory data per unit of product for end user devices was based on information published by (Belkhir and Elmeligi, 2018; Ercan et al., 2016), who reported embodied carbon footprints for mobile and smartphones in the range between 20 and 100 kg CO_2 eq. per unit. Hence, As shown in Table 4, a carbon footprint of 20 kg CO_2 eq. per unit was considered for lower technology conventional mobile phones and an average of 60 kg CO_2 eq. per unit for higher range smartphones. Background inventory data for CPE (routers and modems) was obtained from Ecoinvent 3.7 (Leuenberger and Büsser, 2010).

2.2.4.8. 4 G LTE network. The embodied carbon footprint of the 4 G LTE network (including eNodeB - BS - and IP core network devices) was modelled considering the technical features and physical characteristics of their components (Huawei, 2011). Table 3 provides information about the mass, service life and power consumption of each of these components. In the case of the base stations, the material inventory includes both electronic devices and metal chassis as follows: Base band Unit, Radio Frequency Unit, Base Band Unit Cabinet/ power module, integrated battery cabinet, Power Bank and 3 Antennas. In the case of the IP core network, information was only available for the electronic modules. The mass and power consumption of each of these components was obtained from technical specifications factsheets.

Mass values were used to calculate ECF (including extraction of raw materials and fabrication, transportation and EoL phases). The analysis considered both the electronics and the metal/plastic chassis of each piece of equipment. The mass of each piece of this ICT equipment were obtained from technical specifications factsheets. Generic background LCI per kg of component were available for batteries, power supplies, electronic components, routers/switches and chassis materials (steel, plastic, aluminum) from Ecoinvent 3.7 (Leuenberger and Büsser, 2010). No background inventory data was available for the manufacturing of the eNodeB antennas, which is why the embodied carbon footprint of this component was left outside system boundaries in the investigation. Additional support structures (towers, posts, masts) often used to protect and secure the base stations in their place of use were also not included.

2.2.4.9. Transport of user devices and 4 G LTE network. Foreground inventory data for the transport of end-user devices and electronic components of the ICT networks has been calculated considering that they were manufactured in Asia and transported to the six location scenarios in Peru by ocean freight. Road transport, from the manufacturing site to the seaport of origin and from the seaport of destination to the installation site, has also been included. Google Maps was used to estimate average distances of 17,200 km by sea and 2000 km by road for all devices and ICT equipment. Background transport inventory data were obtained from the European Life Cycle Database ELCD 3.2 (European Commission, 2020). The resulting emission factors for these processes are reported in Table 4. The packaging of these components has not been considered in this investigation.

2.2.4.10. Operational impact of user devices and 4 G LTE network. As shown in Table 3, annual power consumption (kWh) of user devices was obtained from “The Power Consumption Database” website (TPCDB, 2020) considering standard consumption patterns for mobile phones, smartphones, and routers. The annual consumptions of each of the electronic devices that make up the 4 G LTE network was calculated considering their power capacity (W) (as stated in commercial specifications factsheets) and assuming continuous use throughout the year. Operational emission factors for end user devices and ICT network components deployed in Peru were calculated considering the electricity mix for this country as reported by the International Energy Agency (IEA, 2020b).

2.2.4.11. Useful lifetime of user devices and 4 G LTE network. As shown in Table 3, an average service life of 2 years has been considered for end user devices (mobile and smart phones) and 5 years for CPE (routers/ modems). This value represents an average of values published by other authors (Belkhir and Elmeligi, 2018; Moberg et al., 2014b) and the situation reported by the National Institute for Statistics of Peru (INEI, 2017a). A standard 10 year lifespan has been assumed for the access network (eNodeB) and IP core network (EPC) equipment. This estimation corresponds to the anticipated commercial lifetime, which in many cases is substantially shorter than the technical lifetime (Humar et al., 2011).

2.2.4.12. End of life of user devices and 4 G LTE network. The EoL phase has been modelled using an allocation cut-off approach, where the border between two adjacent life cycles is the point where the material flow has its lowest market value. In this approach, which aligns with the “polluter pays principle” (OECD, 1972), both the production of raw materials and their treatment at the end of their useful lives are allocated to the primary user. In turn, recyclable materials are cut off from the system boundaries at the beginning of the treatment processes, becoming available burden-free for following uses (Ecoinvent, 2021).

The EoL modeling of the network components (including both user and 4 G LTE network) was performed considering the nature of the component (electronic, metal, plastic) and its mass. The model included both the mechanical disassembly of the components and the final disposal of non-recoverable fractions. Specific background inventory data for the end-of-life of batteries and ICT equipment was obtained from Ecoinvent 3.7 (Hischier et al., 2007; Scharnhorst et al., 2005). Recoverable fractions (e.g., plastics and metal parts from chassis) were assumed to be recycled. Recycling processes assume, on the one hand, a negative impact derived from the operations of waste upgrading (cleaning, remelting of plastics, refining of metals, etc.) but also a positive impact from displacing the production of primary raw materials.

2.3. Sensitivity and uncertainty analysis

The robustness of the results has been assessed by means of a sensitivity analysis and an uncertainty analysis. In the sensitivity analysis, all the input data values have been varied individually by 50% to evaluate their influence on the overall ACF of the different scenarios. Although this 50% variation does not necessarily represent a realistic spread for each of the input data considered (either by excess or default), this value was selected to ensure consistency.

The uncertainty analysis was carried out considering an uncertainty interval for each of the input data considered in the modeling of the ICT systems and then carrying out a Monte Carlo analysis for the complete model. Individual uncertainty intervals were based on published information (see Table 6) with numerical signs (+, -, ±) indicating the direction of uncertainty. The simulation was run 300 times, varying the input data randomly within the assigned uncertainty intervals and considering a homogeneous probability distribution.

3. Results and discussion

3.1. Carbon footprint per functional unit

Table 5 shows the carbon footprints estimated for each of the 6 demographic areas considered in this investigation. The results have been calculated per network year (kg CO_2 eq./yr), per subscription year (kg CO_2 eq./subscription yr), and per unit of data traffic (kg CO_2 eq./Gb). The top three rows describe the ACF expressed in the three functional units defined in the study. The bottom two rows show the embodied and operational contributions, which are identical for the three functional units considered.

As expected, the results show significantly higher yearly emissions from larger networks designed to cater for higher population density urban and peri-urban areas ($2.04{\bullet}10^7$ kg CO_2 eq/year for the Lima district totaling 238,833 subscriptions) and significantly lower values in smaller networks designed for rural lower density areas with fewer subscriptions ($5.49{\bullet}10^4$ kg CO_2 eq/year for a Huancaya district providing service to only 530 subscriptions). When dividing total carbon emissions by the number of subscriptions, the results show values in the range between 81.2 and 103 kg CO_2 eq./subscription yr., with higher relative values corresponding to smaller networks (CF emissions per subscription for remote rural Huancaya are 20.5% higher than for high population density urban Lima). Emission values per unit of population may be calculated using the penetration rates stated in Table 2, which range between 79% and 89%. A similar pattern may be observed when total carbon emissions are divided by data traffic volume, with lowest values corresponding to the demographic areas with the highest population densities and number of subscriptions (Comas).

These values are in the lower range of the carbon emissions calculated by other authors, which range between 100 and 300 kg CO_2 eq./ user, depending primarily on the connectivity features (broadband services, Internet Protocol Television (IPTV), etc.) and the electricity mix considered. This lower range is due to the optimized architecture and improved energy efficiency associated with newly constructed networks (Malmodin et al., 2014; Malmodin and Lundén, 2018).

Carbon footprint emissions are substantially reduced when the analysis focuses solely on the OCF of the ICT networks, leaving out the embodied emissions associated with the manufacturing, transportation, and end of life of the electronic devices and network equipment. However, the generic pattern remains the same, with comparative higher emissions corresponding to the networks supporting a larger number of subscriptions, but lower relative values when these results are represented per unit of connectivity function (subscription or data traffic).

For ICT networks designed to cater for high density large urban demographic areas (Lima or Comas), the results show that the operational carbon footprint represents between 25.7% and 22.7% of the total emissions, while the rest (74.3% and 77.3%) corresponds to embodied

Table 5
Total and operational carbon footprints (kg CO_2 eq.) represented per network and year, per subscription year and per unit of data traffic (Gb) for the 6 demographic areas.

			Lima	ICA	Comas	Santa Rosa	Iñapari	Huancaya
ACF	Functional unit	Yr	$2.04\bullet10^7$	$9.63\bullet10^6$	$4.20\bullet10^7$	$2.28\bullet10^6$	$1.98\bullet10^5$	$5.49\bullet10^4$
		subscription•yr	85.5	81.2	82.0	82.7	94.0	103
		Gb	1.42	1.35	1.37	1.38	1.57	1.73
ECF	Contribution (%)		74.3%	73.7%	77.3%	76.6%	65.1%	61.9%
OCF			25.7%	26.3%	22.7%	23.4%	34.9%	38.1%

emissions associated with the construction, transportation, and end-of-life of the hardware components. This operational contribution is higher in smaller networks (Iñapari, Huancaya) designed to provide service to rural areas (between 34.9% and 38.1%).

Fig. 3 illustrates the ACF per subscription, as generated by the ICT networks designed for each of the six demographic areas. These include both operational and embodied emissions. The results illustrate the prevalence of the end user devices, which remain rather constant in all the six scenarios considered (between 68 and 71 kg CO_2 eq./subscription) while the emissions attributable to all other network components are higher in smaller rural networks. This is due to the improved energy efficiency achieved by ICT networks designed to serve more densely populated locations, a more homogeneous distribution pattern and more efficient sharing of access network and IP core network equipment. In less densely populated regions, the access network and IP core network are not optimized for their full coverage capacity. The higher operational emissions per functional unit of this equipment leads to an increased operational footprint of the ICT network as a whole, as described in Fig. 4.

3.2. *Contribution of network components*

Fig. 4 illustrates the percentage contribution to ACF of each of the devices, equipment and infrastructures that make up the internet. The components contributing the most to the carbon footprint of ICT networks are by far the end user devices. This is higher in highly populated regions (up to 86%) and comparatively lower in rural networks (68% in Huancaya) due in this latter case to the greater relative impact of shared ICT infrastructures (access network and EPC). Nearly all (> 99.7%) of the impact attributed to user devices corresponds to smartphones and mobile phones, while the contribution of CPE (modems and routers) is insignificant.

The smaller the network and the lower population density it caters for, the higher the relative contribution of the shared ICT infrastructures (access network and EPC) and consequently the lower the share attributable to end user devices (which remain the highest contributors). Thus, access networks contribute to 9% of the carbon footprint emissions in ICT networks designed to operate in high population density urban areas (e.g., Lima). This contribution rises to 14–18% in ICT networks designed to operate in low population density rural areas. Similarly, the contribution of EPC components represents less than 0.1% in urban ICT networks but over 11% in networks designed to operate in rural areas. The contribution of global infrastructures (such as undersea cable and data centers) is not significantly affected by the size and population of the demographic areas analyzed.

Figs. 5 and 6 illustrate the carbon footprint profile of the four most representative demographic areas. This profile describes the contribution to the ACF by the network components (left) and by the life cycle processes (right) in terms of embodied and operational carbon footprint. The environmental profile of the ICT network for Ica is very similar to that of Lima (the other urban area) and the profile of Santa Rosa is very similar

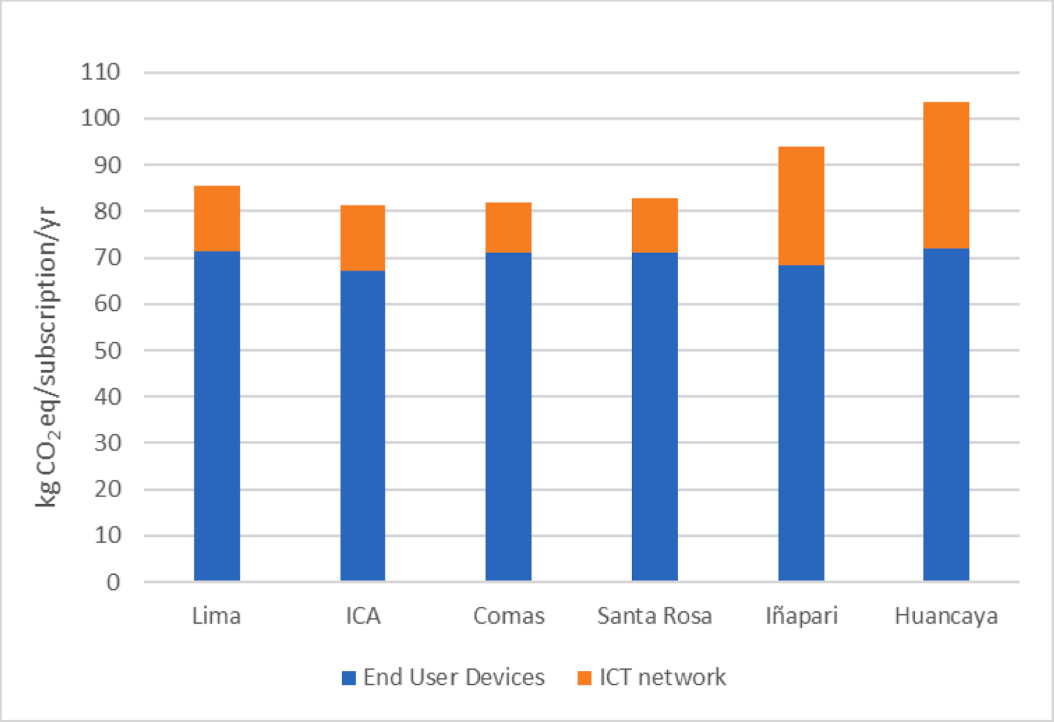

Fig. 3. Annual Carbon Footprint (ACF) per subscription•yr estimated for each of the 6 demographic areas and showing the differential contribution of user devices and the ICT network.

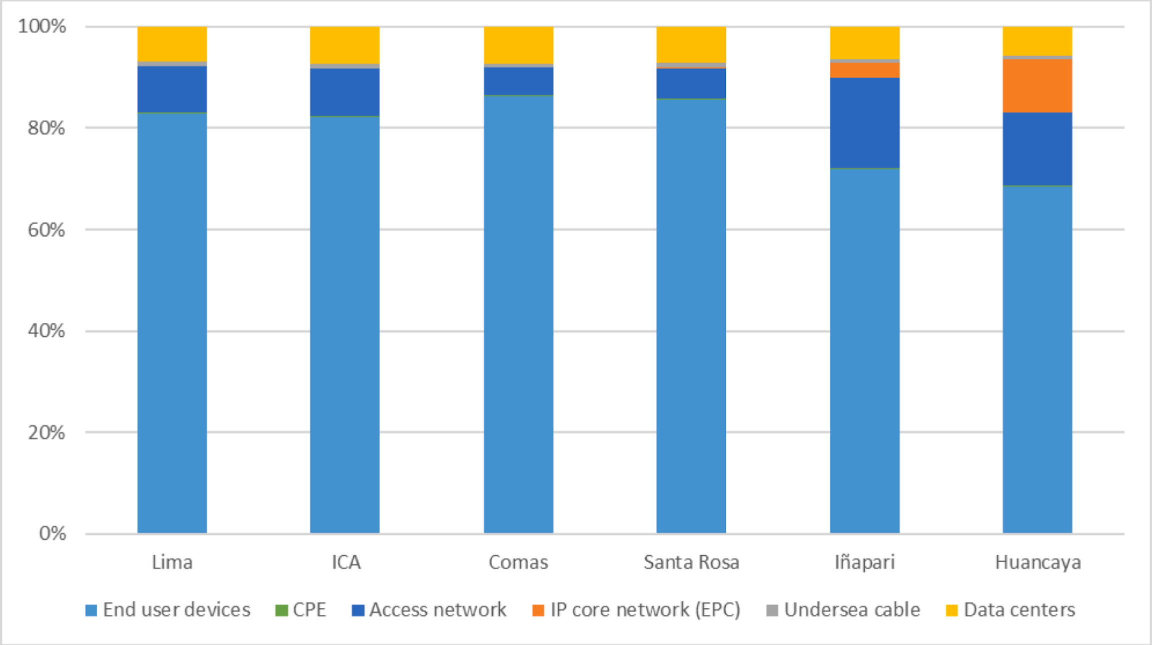

Fig. 4. Contribution to Annual Carbon Footprint (ACF) of different network components, as estimated for each of the 6 demographic areas.

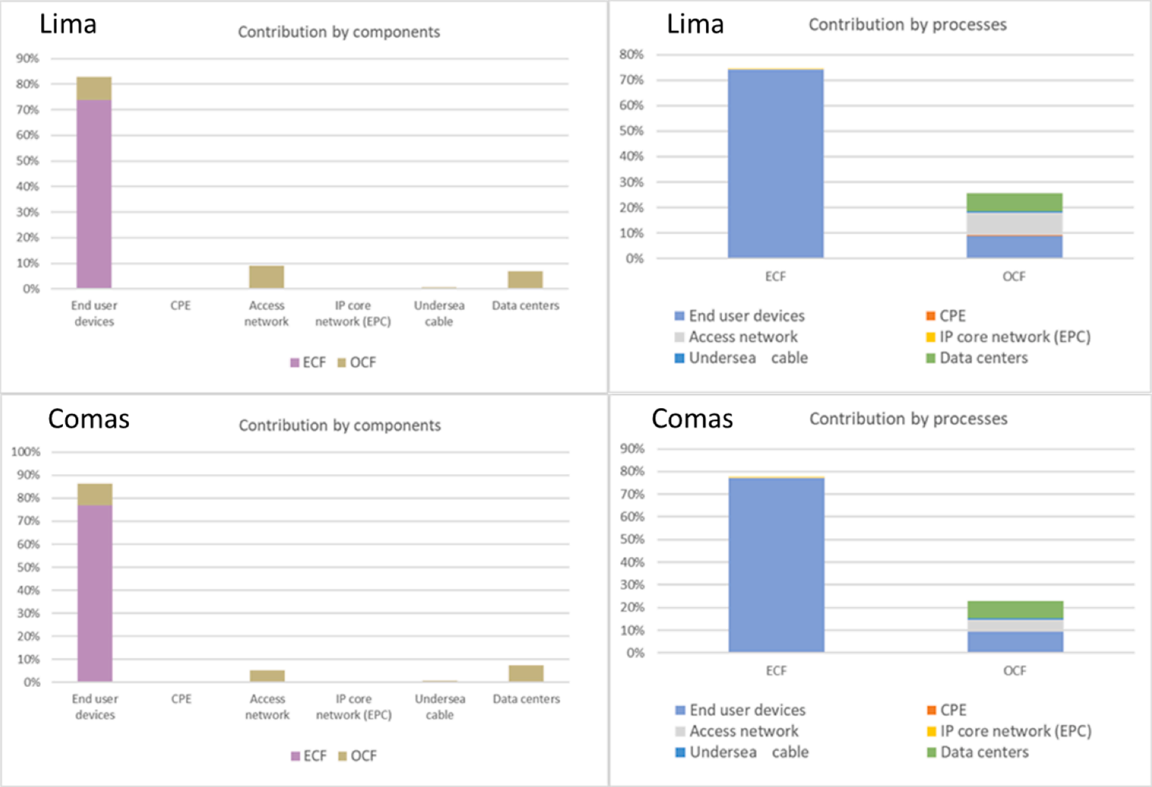

Fig. 5. Carbon footprint contribution by components/processes of high density urban (Lima) and suburban (Comas) demographic areas.

to that of Comas (the other suburban area). Hence, to avoid repetition, only those of Lima and Comas have been shown and discussed.

Regarding the urban and suburban scenarios, Fig. 5 (left) shows that the carbon footprint patterns for the Lima and Comas geotypes is dominated by the end user devices (smart phones and mobile phones), contributing to 81–86% of the emissions. Most of these emissions (between 72 and 76% of the total) are attributable to their manufacturing phase, which includes extraction of raw materials, fabrication, and transport. The energy consumed during the utilization of these end user devices contributes to only 7–8% of all the emissions. The contribution of CPE (both in terms of embodied and use phase emissions) is negligible.

In contrast, the carbon footprint generated by shared ICT equipment (access networks and EPC) is attributable primarily to their energy use, with a negligible contribution from their embodied emissions. The vast

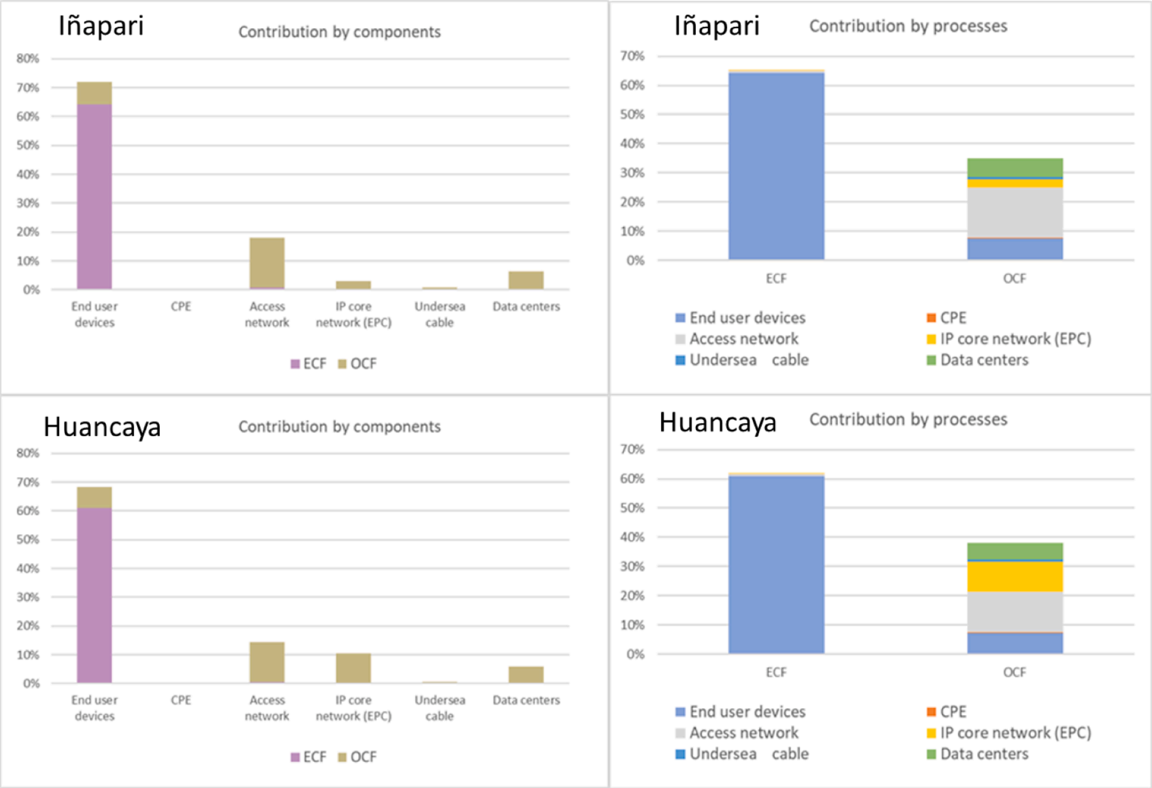

Fig. 6. Carbon footprint contribution by components/processes of rural (Iñapari) and remote rural (Huancaya) demographic areas.

processing capacity, continuous operation, and long lifetimes (compared to user devices) means that the materiality of these equipment required to provide the necessary data transmission and processing capacity is very limited and significantly lower than that generated by the end user devices. Note that impacts embodied in the international network infrastructures (undersea cable and data centers) are outside the system boundaries. The contribution of the CPE (modems) and IP core network (EPC) to the overall carbon footprint of the ICT network is negligible.

The results in Fig. 5 (right) also show that most of the emissions (75–78%) associated with the life cycle of the urban and suburban networks (Lima and Comas) are embodied into the electronic devices and equipment. The contribution of transport and EoL processes to the manufacturing phase is in all cases negligible. The manufacturing of all other components (CPE, access networks, EPC, undersea cable, datacenters) is insignificant (< 1% in total). While the carbon footprint of the manufacturing phase is completely dominated by the end user devices, environmental burdens in the use/operation phase are shared quite evenly between three ICT elements: end user devices, access network and data centers.

Fig. 6 shows the same profiles as generated by the ICT networks designed for rural areas. The results follow a similar pattern to that described for urban and suburban ICT networks, although some notable differences may be observed. For instance, regarding the analysis by components (left), the results show that the contribution of end user devices is still dominant (68–71%) but slightly lower than in urban networks. In turn, there is a relatively higher contribution of the access network (15–19%), EPC (3–11%) and data centers (5–6%). This is due to the fact that individual network equipment is allocated to a low number of subscribers, as a result of the lower density and heterogeneous distribution of the client population in rural areas.

When analyzing the contribution by processes (right), the results show a clear dominance of the embodied impacts (61–65%) that is not as strong as that observed in urban networks. The emissions in this phase are almost completely attributable to the end user devices. The operational carbon footprint in rural ICT networks contributes to between 35 and 38% of the emissions. Most of it is derives from the energy consumed by the access network (13–15%), with smaller contributions coming primarily from the end user devices (7–8%), data centers (6–7%) and IP core network (3–10%). The carbon contribution from other network elements (undersea cable and CPE) in the operation phase is negligible.

Fig. 7 focusses on the operational carbon footprint to evaluate the contribution of different ICT components when the network is designed to operate in the four most representative demographic areas. The results show most of the contribution coming from the energy consumed by end user devices, access networks and data centers. The operational emissions of the access networks and IP core networks is more relevant in rural scenarios. This is due to the fact that access network equipment and EPCs must be allocated to a low number of subscribers. As a result, the relative contribution of end user devices in these rural scenarios is reduced. The opposite is observed in higher population density urban and suburban scenarios, where the relative contribution of access networks and particularly EPC is lower, due to the larger number of subscriptions they cater for.

The results show that the contribution of transport and end-of-life processes to the embodied carbon footprint of the user devices and 4 G LTE network components is negligible, representing less than 0.5% of the total value in all cases. In other words, essentially all the embodied in the electronic components used to utilize and operate the ICT networks lies in the raw material extraction and manufacturing stages. However, it should be noted that end-of-life processes may have notable consequences on other environmental impact categories that were not evaluated in this study such as ecotoxicity and human health (Hong et al., 2015).

3.3. Correlation analyses

Fig. 8 illustrates a strong linear relationship between annual carbon footprint of the ICT network, including embodied and operational, and

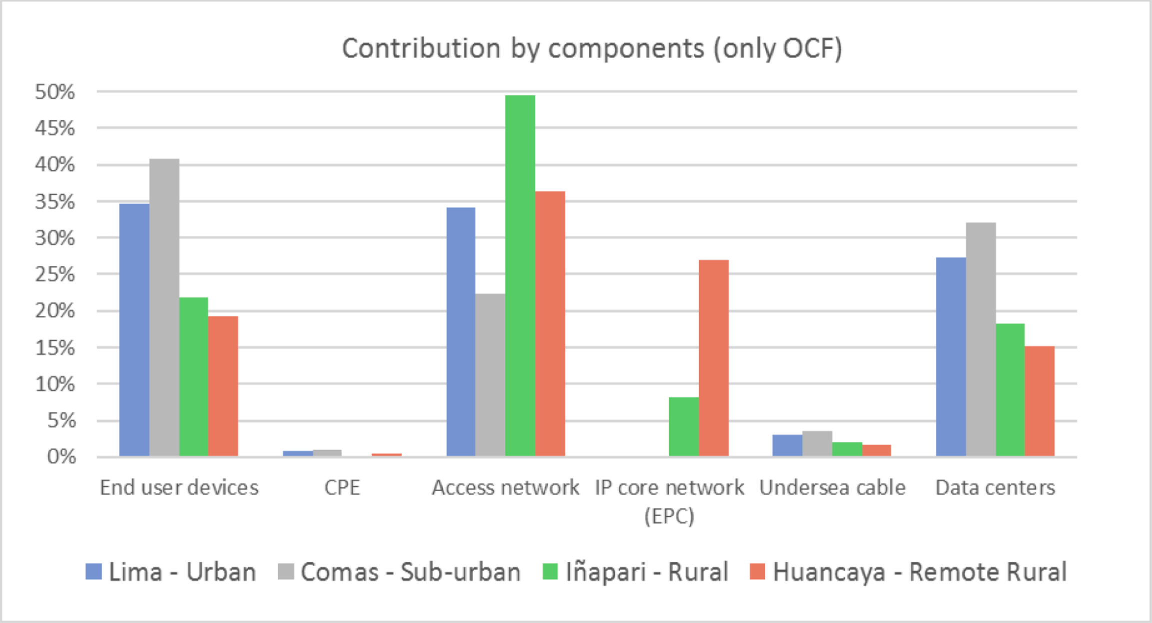

Fig. 7. Contribution by components to the operational carbon footprint of four representative demographic areas (from urban to remote rural).

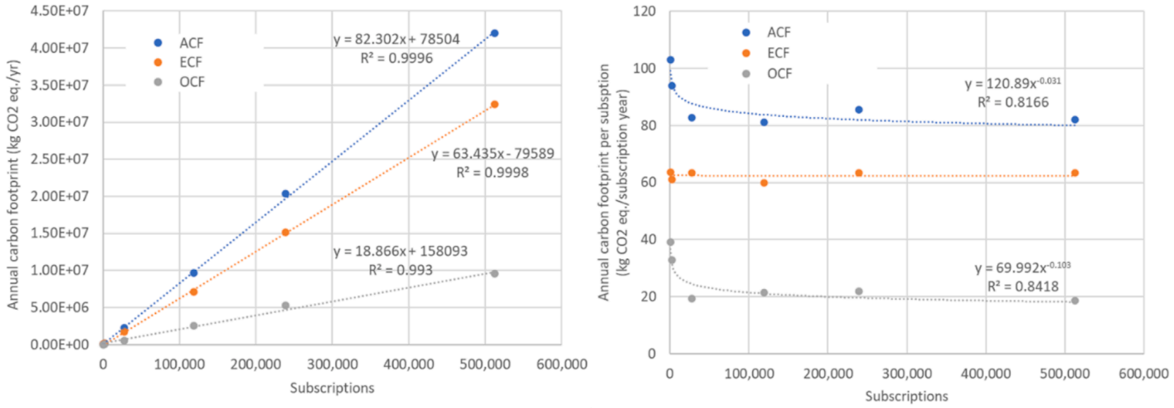

Fig. 8. Correlation analysis between number of subscriptions and annual carbon footprint (ACF) represented in terms of total emissions (left) and emissions per subscriber (right).

the number of subscriptions (Subs) as follows:

$\mathrm{ACF} = 82.302 \bullet \mathrm{Subs} + 78{,}504 R^2 = 0.9996$

$\mathrm{ECF} = 63.435 \bullet \mathrm{Subs} + 79{,}589 R^2 = 0.9996$

$\mathrm{OCF} = 18.866 \bullet \mathrm{Subs} + 158{,}093 R^2 = 0.993$

Note that the number of subscriptions and the total population of any geographical scenario are directly related through penetration rate. This linearity applies to the total (ACF), embodied (ECF) and operational (OCF) carbon emissions, with correlations coefficients $R^2 > 0.993$ in all cases. This suggests that the demographic characteristic of the scenarios has a limited influence on the carbon emissions generated by the ICT systems.

However, when the number of subscriptions is represented against the ACF per subscription, it was possible to pinpoint the higher footprint values generated by the ICT systems required to serve rural locations with a very small number of subscriptions (< 2100). The results show higher emissions which are attributable to the operational phase, while embodied emissions remain constant even in all scenarios. The higher OCF observed in ICT systems covering a small number of subscriptions is caused by the relatively higher amount of electricity per functional unit consumed by the access network and IPC network equipment. In contrast, ECF emissions remain relatively constant due to the fact that these are primarily influenced by end user devices, the number of which per unit of subscription remains essentially constant in all demographic scenarios.

Fig. 9 illustrates the lack of correlation between carbon footprint and demographic parameters such as area and population density. Although these variables have an influence on the design and operation of ICT systems, they do not directly determine the construction and operational activity variables that define their carbon footprint.

3.4. Sensitivity and uncertainty analyses

Table 6 shows sensitivity and the uncertainty analysis carried out on the model to evaluate the robustness of the results. Regarding the sensitivity assessment, the results show the mean, maximum and minimum spreads resulting from varying individual input data by 50% (see Table 4 for input data values). The input data have been ordered from highest to lowest considering their mean ACF increase. Only processes generating ACF variations greater than 0.15% have been included.

The results show that the emission factors (embodied carbon footprint) of the end user devices (mainly smart phones but also mobiles phones) have the greatest influence on the sensitivity of the model, with

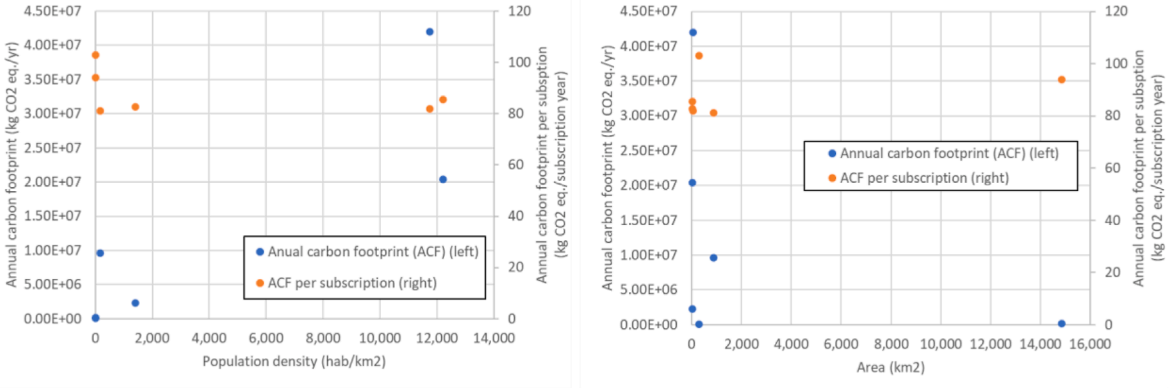

Fig. 9. Correlation analysis between carbon footprint vs. population density (left), and vs. area.

Table 6
Sensitivity assessment (average, maximum and minimum variation of ACF) resulting from increasing input data by 50% and variation intervals applied to the input data for the uncertainty analysis.

Input data	ICT network component	Sensitivity Δ ACF			Uncertainty	Source/hypothesis
		Average	Min	Max	Uncertainty interval	
Emission factor of smart phones	End user devices	24.4%	21.1%	26.3%	± 25%	Belkhir and Elmeligi, (2018); Ercan et al., (2016)
Useful lifetime of smart phones	End user devices	16.6%	14.1%	18.1%	+ 50%	Minimum 2 years (base scenario), maximum 3 years
Emission factor of mobile phones	End user devices	10.5%	9.2%	11.4%	+ 25%	Belkhir and Elmeligi, (2018); Ercan et al., (2016)
Emission factor of power mix of Peru	End user devices, eNodeB and IP core network	10.2%	6.9%	15.8%	± 33%	Ecoinvent 3.7
Useful lifetime of mobile phones	End user devices	7.4%	6.2%	8.1%	+ 50%	Minimum 2 years, maximum 3 years
Power consumption of radio frequency unit	eNodeB	4.5%	2.1%	8.0%	- 5%	The base scenario is the maximum value (continued operation)
Emission factor of international power mix	Undersea cable and data center	3.7%	3.2%	4.0%	± 26%	Ecoinvent 3.7
Power consumption of data centers	Data center	3.3%	2.9%	3.6%	± 25%	Assumption
Power consumption of mobile phones	End user devices	2.3%	2.1%	2.4%	- 5%	The base scenario is the maximum value (continued operation)
Power consumption of smart phones	End user devices	1.7%	1.6%	1.8%	- 5%	The base scenario is the maximum value (continued operation)
Power consumption of EPC	IP core network	1.0%	0.2%	5.1%	- 5%	The base scenario is the maximum value (continued operation)
Useful lifetime of base station	eNodeB	0.28%	0.19%	0.36%	+ 50%	Minimum 10 years (base scenario), maximum 15 years
Power consumption of international data transmission	Undersea cable	0.23%	0.14%	0.35%	± 25%	Assumption
Useful lifetime of EPC	IP core network	0.17%	0.03%	0.26%	+ 50%	Minimum 10 years (base scenario), maximum 15 years

a 34.9% ACF emission variance resulting from a 50% input data rise. The other key issue affecting the sensitivity of the model is the lifetime of smart phones and mobile phones, which were originally, considered to be 2 years. A combined average ACF increase of 24% resulted from a 50% input data rise (3 years). The emission factor of Peru's electricity mix (10.2% average ACF variation) is the other key element in the sensitivity analysis, which defines the carbon emission generated by end user devices and the 4 G LTE network devices (eNodeB and IP core network). The average sensitivity of the model to all other input values was in all cases below 5%.

Table 7 shows the uncertainty values calculated for each of the six demographic scenarios investigated in terms of their 95% confidence interval. The results show uncertainty values ranging between 33.5% and 43.6%. The slightly lower values observed in lower population density rural areas may be associated with the lower relative contribution of end user devices, which have higher uncertainty intervals primarily regarding their service time.

Table 7
Uncertainty values for the six demographic areas (95% confidence interval).

Lima	ICA	Comas	Santa rosa	Iñapari	Huancaya
± 39.0%	± 39.8%	± 43.6%	± 41.4%	± 37.4%	± 33.5%

3.5. Limitations of the investigation and future work

In assessing the sustainability of ICT networks, the present work has several shortcomings, which should set the basis for future work. The main limitation relates to the consideration of GHG emissions as the only indicator of environmental performance. In future work it would be of interest to address the assessment of other environmental indicators, such as those related to human toxicity and ecotoxicity, and depletion of resources. In order to obtain a more reliable picture of the sustainability of ICT network deployment, it would also be necessary to address the assessment of economic and social aspects using both a conventional attributional approach and a consequential approach that takes into account the economic and societal transformations derived from facilitating access to existing digital services and those that are still to come (such as Internet of Things).

4. Conclusions

- This investigation describes the carbon footprint generated by wireless ICT networks based on 4 G LTE technology designed to provide internet access with the same connectivity features to six demographic areas in Peru, from high density urban to very low density remote rural.
- As expected, annual carbon emissions generated by the larger ICT networks catering for high density urban and suburban areas and comparatively greater (up to three orders of magnitude) than those produced by smaller networks designed for lower population density rural scenarios. However, when these emissions are referenced to a subscription for one user, or 1 Gb of data, this situation is reversed, and the highest carbon emissions correspond to the rural scenarios with a lower population density: 103 kg CO_2 eq./ subscription•yr and 1.73 kg CO_2 eq./Gb for remote rural scenario vs. 81.2 kg CO_2 eq./ subscription•yr and 1.35 kg CO_2 eq./Gb for high density urban scenario. The higher emissions observed in lower population density scenarios are due to the fact that 4 G LTE network equipment (access network and IP core network) is shared by a fewer number of subscribers, thus incrementing the operational and embedded share corresponding to each of these users.
- Most of the carbon footprint generated by the ICT networks (about 75% in urban areas and 63% in rural areas) correspond to embodied emissions in all devices and equipment. These embodied emissions are attributable almost entirely to the manufacturing of mobile phones and smartphones, with negligible contributions coming from their transport and end of life phases. Carbon emissions embodied in other network components (access network and IP core network) are also insignificant. The operational carbon footprint represents about 25% of the life cycle emissions in urban networks and 37% in rural networks. In all cases, these operational emissions are contributed primarily by access networks, end user devices and data centers while the contribution of data transmission operations is negligible.
- Good linear correlations were observed between annual carbon footprint (including both OCF and ECF) and number of subscribers. However, this correlation was not valid for very small ICT systems ($<$ 2500 subscriptions) due to the less efficient operation of access network and IP network components, resulting in higher electricity use and carbon footprint per functional unit.
- In view of these results, a strategy to improve the environmental sustainability of newly designed ICT networks should focus primarily on reducing the embodied carbon footprint associated with user devices (mobile phones and smartphones). This can be achieved both by reducing the carbon footprint of devices and by extending their useful lifetime. Other areas of potential emissions savings would be the energy consumption of access networks, end-user devices and, to a lesser extent, data centers.
- Policies aimed at reducing the planned and psychological obsolescence of mobile phones and smartphones should be addressed to manufacturers and buyers respectively. Business-to-consumer environmental communication could also contribute to raising awareness among users of these devices. On the other hand, local network designers should optimize access networks and power them with renewable electricity mix. Optimization and use of renewable energies should also be the main premises to be developed in the design of data centers.
- In order to obtain a broader representation of the sustainability of ICT networks, further work should be carried out to evaluate additional environmental impacts categories, as well as the economic and social consequences (both positive and negative) not only of direct impacts but also of those induced by increasing digitalization.

5. CRediT authorship contribution statement

D. Ruiz: Investigation, Conceptualization, Methodology, Data curation, Writing- Original draft; **G. San Miguel:** Conceptualization, Methodology, Resources, Data curation, Writing- Original draft, Resources; **J. Rojo:** Investigation; **J. G. Teriús-Padrón:** Investigation; **E. Gaeta:** Conceptualization, Discussion of results; **M.T. Arredondo:** Resources; **J.F. Hernández:** Conceptualization, Discussion of results; **J. Pérez:** Conceptualization, Discussion of results, Resources

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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