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Development of green infrastructure during the COVID-19 pandemic using spatial analysis methods

Dora Josefina Rocío de los Ángeles Guillén Tamayo [a,*], Leyla Elena Lascar Alarcón de Malpartida [a], Valkiria Raquel Ibárcena Ibárcena [a], Ginna Paola Cano Castro [b], Leslie Janina Mena Alanoca [c], Randy Branny Carreon Oviedo [d], Andreas Braun [e]

[a] *Universidad Tecnológica del Perú, Arequipa, Peru*
[b] *Universidad Santo Tomás – Seccional Tunja, Tunja, Colombia*
[c] *Independent researcher, Pforzheim, Germany*
[d] *Independent researcher, Arequipa, Peru*
[e] *University of Kassel Institute for Sustainability, Kassel, Germany*

A R T I C L E I N F O

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A B S T R A C T

In Latin America, there is a lack of green infrastructure (GI) to enhance urban resilience and reduce the contagion levels, particularly in times of pandemic. Therefore, a simplified method is needed to define GI in critical public health risk scenarios, especially when access to geospatial information is limited. The objective of this study is to propose a simplified method called GreenNet-Covid19 in Peru during critical public health scenarios using spatial analysis methods to define the global GI index (GGII) and select the potential integration areas for GI (PIAGI). This method is based on the approach proposed by Aguileraet al. (2018), which utilized spatial analysis in Metropolitan Arequipa and its surroundings during the COVID-19 pandemic. In this study, in addition to the four dimensions proposed Aguilera et al. (2018), a fifth dimension called 'risk due to COVID-19' was introduced, allowing to obtain the GGII and define the PIAGI. The GGII showed high ecological and biodiversity potentials at the vegetation cover level. However, the loss of GGII connectivity in urban areas posed a threat to the intricate connectivity of the highlands, thus increasing the risk of COVID-19 spread. Meanwhile, the PIAGI exhibited relatively low values compared with those of the GGII. Yet, the loss of PIAGI connectivity in urban areas strengthened the factors contributing to COVID-19 propagation. The intersection between the COVID-19 and PIAGI risk layers at the 'very high,' 'high,' and 'medium' levels demonstrated a high capability for reducing the contagion risk in future pandemics. The introduction and implementation of this method in territorial planning is facilitated by its applicability to any Latin American territory.

1. Introduction

The lack of green infrastructure (GI) proposals as a territorial strategy to increase urban resilience and reduce COVID-19 contagion levels was evident in Latin America during the pandemic. Considering that territorial planning is not significantly developed, there is an absence of rules or plans that offer this type of definition, as observed in Peru (Zucchetti et al., 2020). This gap was attributed to the lack of an ecosystem approach, an official GI definition, as well as the absence of methodological proposals for the creation of GI at the urban level in a pandemic context.

In Europe, GI is defined as a planned and organized network of natural and semi-natural areas comprising ecological components that provide a range of ES (Unión Europea, 2014) in both rural and urban settings (Zucchetti et al., 2020). It is characterized by multifunctionality or different ES that provide predefined benefits within multiscale networks (Benedict and McMahon, 2012; Coutts and Hahn, 2015). This strategy achieves land and species conservation using political and strategic approaches (Pakzad et al., 2017). Furthermore, GI is considered a natural life support system that sustains ecological processes, contributing to improved health levels and enhanced quality of life for

* Corresponding author. 04001, Tacna y Arica 160, Arequipa, Peru.
E-mail addresses: C16959@utp.edu.pe (D.J.R.Á. Guillén Tamayo), C20495@utp.edu.pe (L.E. Lascar Alarcón de Malpartida), valkiria.ibarcena@gmail.com (V.R. Ibárcena Ibárcena), ginna.cano@usantoto.edu.co (G.P. Cano Castro), lesliemenaa@gmail.com (L.J. Mena Alanoca), rcarreon.oviedo@gmail.com (R.B. Carreon Oviedo), andreas.braun@uni-kassel.de (A. Braun).

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Abbreviations

GI	green infrastructure
GGII	global green infrastructure index
PIAGI	potential integration areas for green infrastructure
CES	contribution to ecosystem services
ES	ecosystem services
GIS	geographic information system
GID	dimensions of the green infrastructure
DEM	digital elevation model
ZEE	ecological and economic zoning
FEA	functional ecological area
ECI	ecological connectivity index
RI	relative index
COVID-19	coronavirus disease 2019

European citizens (Calaza, 2019; Valera, 2019). The European Union (EU)-Biodiversity Strategy for 2030 claims Urban Greening Plans" from EU-cities, which are assumed to be ambitious effort to protect and improve urban nature, for enhance biodiversity but also human well-being and climate protection EC, 2020, as cited in Hansen et al. (2023). The R + D project share solutions and recommendations for actions where biodiversity is focused as on the basis for life in cities. Other priorities are motivated by international policies such as the UN Decade for Ecosystem Restoration 2021–2030 which incorporate urban areas as one field of action (Hansen et al., 2023).

Zucchetti et al. (2020) discusses the implementation of the GI concept in Peru, Chile and Argentina. In Peru the GI is associated with natural infrastructures; in Chile, the GI contemplates the rural and peri-urban urban environment; in Argentina, it is integrated in the National Action Plan for Infrastructure, Territory and Climate Change of 2019. According to Alves, 2015, in Brazil, despite the great potential of existing high-value green spaces, there are few projects for the implementation of territorial green connections. Likewise, according to Nóbrega dos Santos et al. (2021) there is a great heterogeneity in the understanding of GI in Brazil. Colombia has the so-called Main Ecological Structure, as an axis of territorial planning which, according to Law 388 of 1997, is the environmental basis that supports the territory (Ministerio de Ambiente Vivienda y Desarrollo Territorial, 2008).

It should be noted that, because the GI is a recent field of research in Latin America, there is still some discussion among the authors about its definition and scope. In this context, territorial urban planning requires using the landscape perspective, generating new ways of relating to the territory, types of use and management as well as ensuring the implementation of uses and activities without deteriorating cultural values, environmental, social and productive.

Latin American cities lack sufficient green spaces and suffer from environmental problems; therefore, the implementation of GI should be a priority. It can be concluded that the concept of GI has been progressively incorporated into urban planning policies over the last decade, under different names, at different socio-political scales and with different objectives through the articulation of the existing legal framework. Despite these advances, they lack continuity due to the existing political instability as well as the lack of instruments and their monitoring.

Currently, there are several studies that relate green areas with COVID-19. Salazar-Galán et al. (2022) have analyzed the effects of the alteration of ecosystems and biodiversity in the increase of health and environmental problems related during COVID-19. In Nordic cities, according to Fagerholm et al. (2022) confirm the importance of GI and outdoor recreation for the well-being of the urban population during the COVID-19 pandemic. Landscape garden cities in China (Ding et al., 2022) have developed the National Landscape Garden Cities policy which has been pushed to address ecological and environmental crises and improve urban disaster preparedness.

Studies in Latin America and Peru are scarce. Sainz-Santamaría and Martínez-Cruz (2022) describe the adaptive governance of urban green spaces in Latin America - Perspectives in the middle of COVID-19. Fernández (2021), reviews historical, ecological, and metropolitan arguments in the provision of public open spaces for the Metropolitan Area of Buenos Aires in perspective with the pandemic context.

It can be observed that in several countries of Latin America and the Caribbean there is an unequal distribution of green spaces being necessary a proposal of equitable distribution of GI in a context of pandemic (Llomparte and Casares, 2023).

Regarding green infrastructure and equity, in the research of Hou and Li (2024) a "structure - function - zoning" analysis framework is proposed in which equity is measured in relation to the spatial distribution around GI. In the Chinese context, the cities of Beijing, Tianjin and Shijiazhuang were selected as study areas to test measures of spatial equity of urban GI along an urban sprawl axis and indices for a comprehensive assessment of the urban GI pattern. The proposed methodology for this research allows not only to study spatial equity but also to carry out comprehensive assessments of the structure and function of urban GI, which allows integrating the analysis indices and monitoring over time.

Similarly, He et al. (2022) analyze the health equity of Wuhan (China) residents in contact with green and blue infrastructure in order to propose priority levels for future urban interventions. The proposed methodology of this research allows not only to study spatial equity but also to perform comprehensive assessments of the structure and function of urban GI by integrating the analysis indices with a follow-up over time. These authors propose an equity valuation model for the allocation of ES at the city level and at the micro scale in order to establish priority levels for future urban interventions.

On topics related to green spaces, public health, and equity, in the research of Ravichandran et al. (2023) unequal access to green spaces generates public health problems, such that the association between Maryland Park Equity Scores and children's health in Baltimore City has been an important concern to observe the relationship between health and equity through a multivariate analysis with a park equity indicator. Likewise, Rigolon et al. (2021) argue that green spaces can promote health equity and provide forms of planning.

On the other hand, in Latin America, there are few studies related to GI and Equity but only with an economic perspective. In Chile, there are studies that focus on GI as a strategy to improve the quality of life. On the one hand, Vásquez (2016) describes the arguments in favour of urban GI and the provision of ES as key components in the face of climate change, in the case study of the Mapocho River riparian corridor in Santiago de Chile. On the other hand, Moreno (2022) states that the GI approach allows for a strategic approach to rethink territories at risk; he also describes that the multifunctionality of GI is what makes it a cross-cutting instrument that can support the development of numerous public policies, adaptation to climate change and disaster risk reduction. Finally, Giannotti et al. (2021) recognize that GI is one of the main strategies for mitigating and adapting to climate emergencies in urban contexts, and there is already a GI Plan in Santiago that considers the high level of social inequality and distribution of green areas. In Argentina, the endowment of public green spaces has been studied in relation to their potential social use, prioritizing their proximity as a determinant of the level of quality of life in the municipality of Santa Fe. These authors state that the availability of public green spaces is directly related to the quality of life in urban areas. (Gomez and Velázquez, 2018).

In Mexico, the distribution of public green spaces has been analyzed in relation to the socio-economic characteristics of the population in Ciudad Juárez; determining the relationship between the characteristics of location, number, size and endowment with respect to the socio-economic characteristics of the population living nearby. These

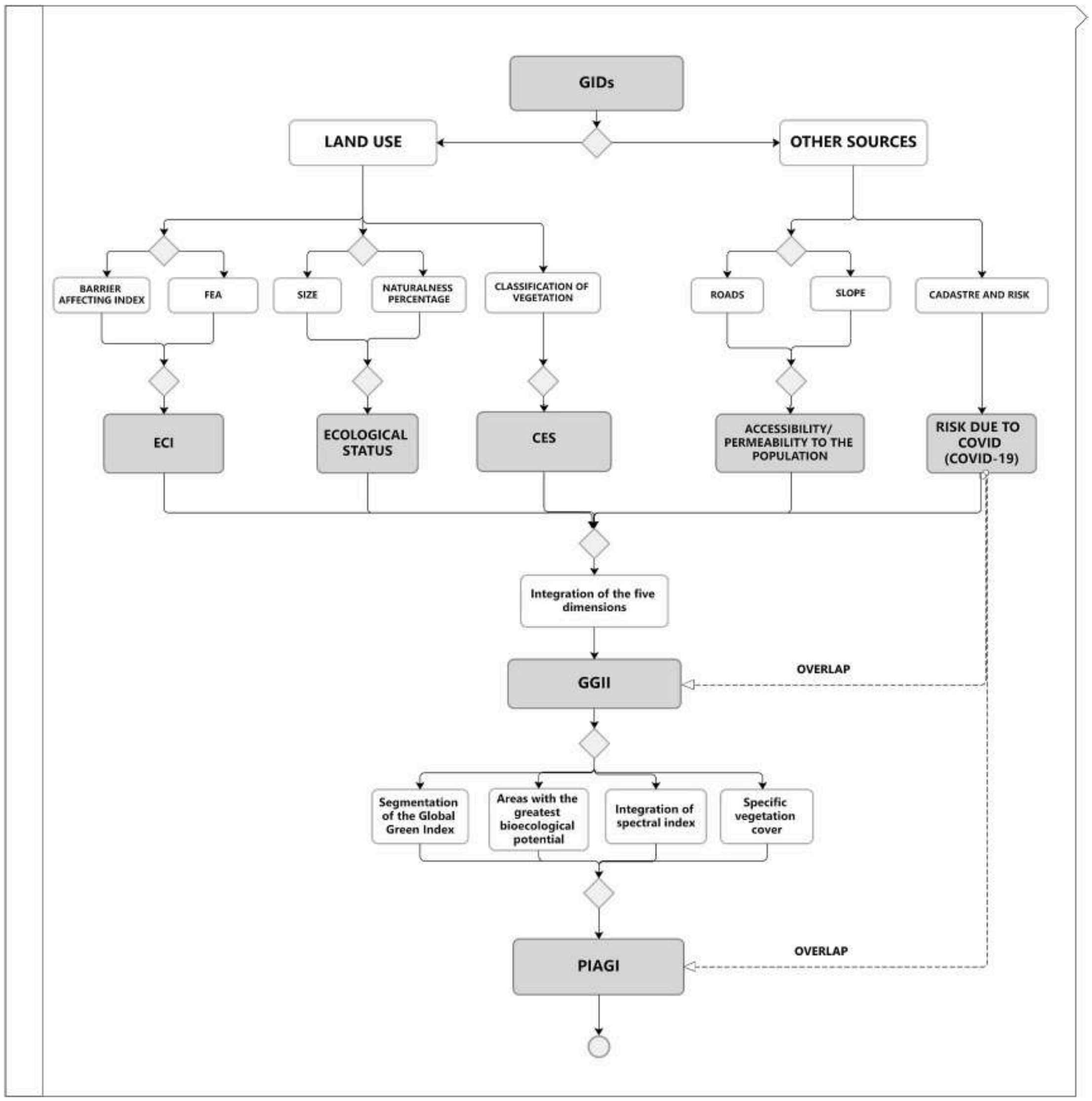

Fig. 1. Methodological proposal for GreenNet-Covid19, based on the method proposed by Aguilera et al. (2018) along with the inclusion of a new dimension called 'risk due to Covid (COVID-19)', designed for a critical pandemic scenario whilst considering the lack of geospatial information. Note: GIDs - dimensions of the green infrastructure, FEA - functional ecological area, ECI - ecological connectivity index, CES - contribution to ecosystem services, GGII - global green infrastructure index, PIAGI - potential integration areas for green infrastructure.

authors verified that as one moves down the socio-economic scale, the quality and quantity of public green spaces also decreases (Herrera et al., 2021).

Bearing in mind that several countries of the world are making theoretical efforts to articulate the concept of GI to the issue of public health - COVID-19 as well as the issue of equity in the distribution of green spaces; the proposal and use of methodologies that can address this complexity of factors in the face of a new crisis becomes prevalent.

To propose a methodology of this complexity for Peru, this study conducted a literature review to identify a general GI benchmarking methodology that can be adapted to the Peruvian context. Hysa (2021) defined the cross-sectional connectivity index as an ecological indicator to classify natural landscape fragmentation in aquatic surfaces. Ko and Lee (2021) developed the social welfare index to evaluate the effectiveness of GI in improving the social benefits of urban sustainability. Rayan et al. (2021) analyzed the relative index (RI) as an adaptation strategy to improve the resilience of cities to increasing environmental and climate risks. Overall, it is evident that RI methodologies are scarce and often focus on specific indices. The same is true in the research of Heckert and Rosan (2016) and Zhu et al. (2019) who developed a methodological proposal for GI equity index associated with stormwater and sewer overflow and local environmental justice indices. However, this research was intended to address a general method in the first instance and not a specific aspect at the socioeconomic or environmental level.

Unlike those authors Aguilera et al. (2018) proposed a methodology based on a global green infrastructure index (GGII) that integrated the four dimensions with multi-criteria evaluations. Boulanger (2008) also used multi-criteria analysis from quantitative and qualitative indices (Schuschny and Soto, 2009), focusing his research on the concept of 'strong sustainability', which prioritizes the planet's capacity to sustain anthropogenic needs and maintain a balanced ecosystem, associated with advances in public health - both physical and mental - with GI (Calaza, 2019) and ES beneficial to health (Coutts and Hahn, 2015; Pouso et al., 2021). This can be attributed to the positive effects associated with contact with nature, which can buffer the negative effects of

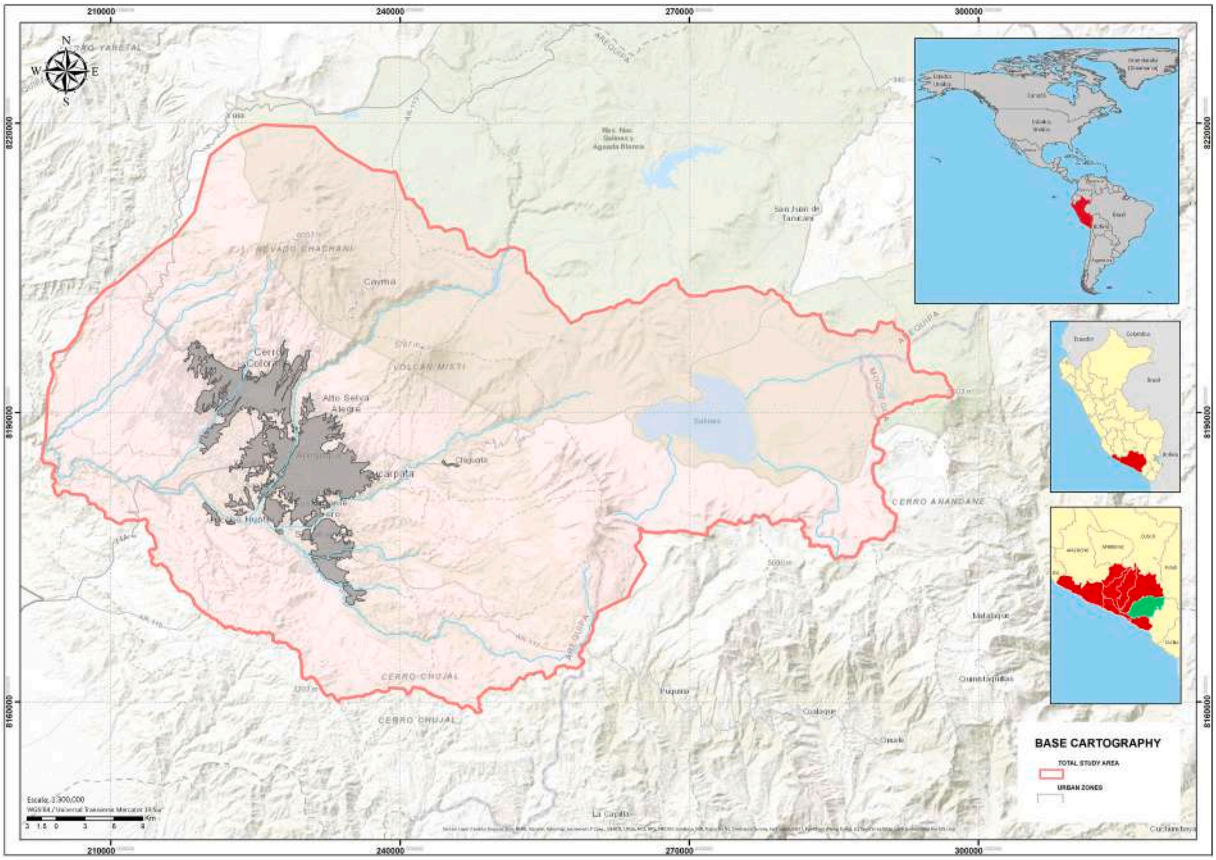

Fig. 2. Base cartography of the metropolitan of Arequipa and its surroundings, which was used as a test area to test the GreenNet-Covid19 method. Note: This map shows the location of the test area with respect to its location in Latin America and Peru.

social isolation on mental health (Cartwright et al., 2018; Yang and Xiang, 2021). In contrast, 'weak sustainability' concepts consider environmental resources and services as material monetary goods (Vega and Pérez, 2020).

In the pandemic context it was important to contemplate this public health dimension since according to Seddighi (2020) defines COVID-19 as a disaster and its impact on mental health (Herman and Drozda, 2021) are consistent with the above statements. Herman and Drozda (2021) asserted that the COVID-19 pandemic was not the first (nor will it be the last) in which citizens turned to outdoor green spaces to alleviate the crisis in hospitals and improve their resilience and ability to cope with new pathogens.

Therefore, at present there are already proposals for complex methodologies such as the methodology of Aguilera et al. (2018) that allows the articulation of new dimensions in view of the need to address public health issues-COVID-19 as well as equity in the distribution of green spaces.

On the other hand, it is also necessary to review progress in planning and territorial management related to GI in Peru, territory in which the methodological proposal of this study is applied. In this way, in Peru Castillo-García (2021) reported that territorial planning has been included in the evaluation, monitoring, and implementation of the "public policy of sustainable development," aligning with the objectives of the 2030 Agenda. However, landscape and GI plans are not yet considered within the territorial regulations in Peru. The Supreme Decree No. 027-2017-EF did not mention the term GI, but instead, it termed natural infrastructures as a 'network of natural spaces that conserve the values and functions of ecosystems' (Zucchetti et al., 2020). Ministerio de Vivienda Construcción y Saneamiento (2021) mentioned ecological infrastructure in the Manual for the Elaboration of Metropolitan Development Plans (MDP) 2020; however, it did not present a method for its implementation. Owing to the COVID-19 pandemic, the Congress of the Republic issued Law No. 31199 (Ley N° 31199, 2021), i.e., the 'Law for the Management and Protection of Public Spaces.' This law addresses the issues of public health, housing, and public spaces but does not include any regulations for GI planning and management. Similarly, according to Ministerial Resolution No. 228-2021-MINAM, the Strategic Environmental Assessment is a participatory process that includes environmental variables within development plans at the public policy level; however, it does not specify GI. Notably, the Centro Nacional de Estimación Prevención y Reducción del Riesgo de Desastres (2021) reported that since the beginning of the pandemic (February 4, 2021), 134,996 positive new coronavirus cases and 2292 deaths were registered in Arequipa, leading to a shortage of intensive care unit beds during January 2021. Therefore, a COVID-19 risk scenario study was conducted to identify the risk level due to COVID-19 in Arequipa, thus allowing local authorities and healthcare providers to focus on strategic interventions.

However, these advances responded to specific initiatives and not to comprehensive proposals. The pandemic revealed an outdated, inefficient, and unsustainable city model in several Latin American countries, specifically Peru, with theoretical gaps and a lack of GI regulations and methodological proposals. Therefore, there is a pressing need for a new city model that will lay the theoretical and methodological foundations of GI in the future (Rivera and Serrano, 2020) as well as equity in the distribution of green spaces. The application of GI methodologies is fundamental for promoting sustainable and resilient city planning, where nature is integrated at different GI scales and is viewed as an integral natural (Calaza, 2019) and semi-natural public health system.

Thus, the objective of this study is to propose a simplified method called GreenNet-Covid19 in Peru during critical public health scenarios using spatial analysis methods to define the global GI index (GGII) and

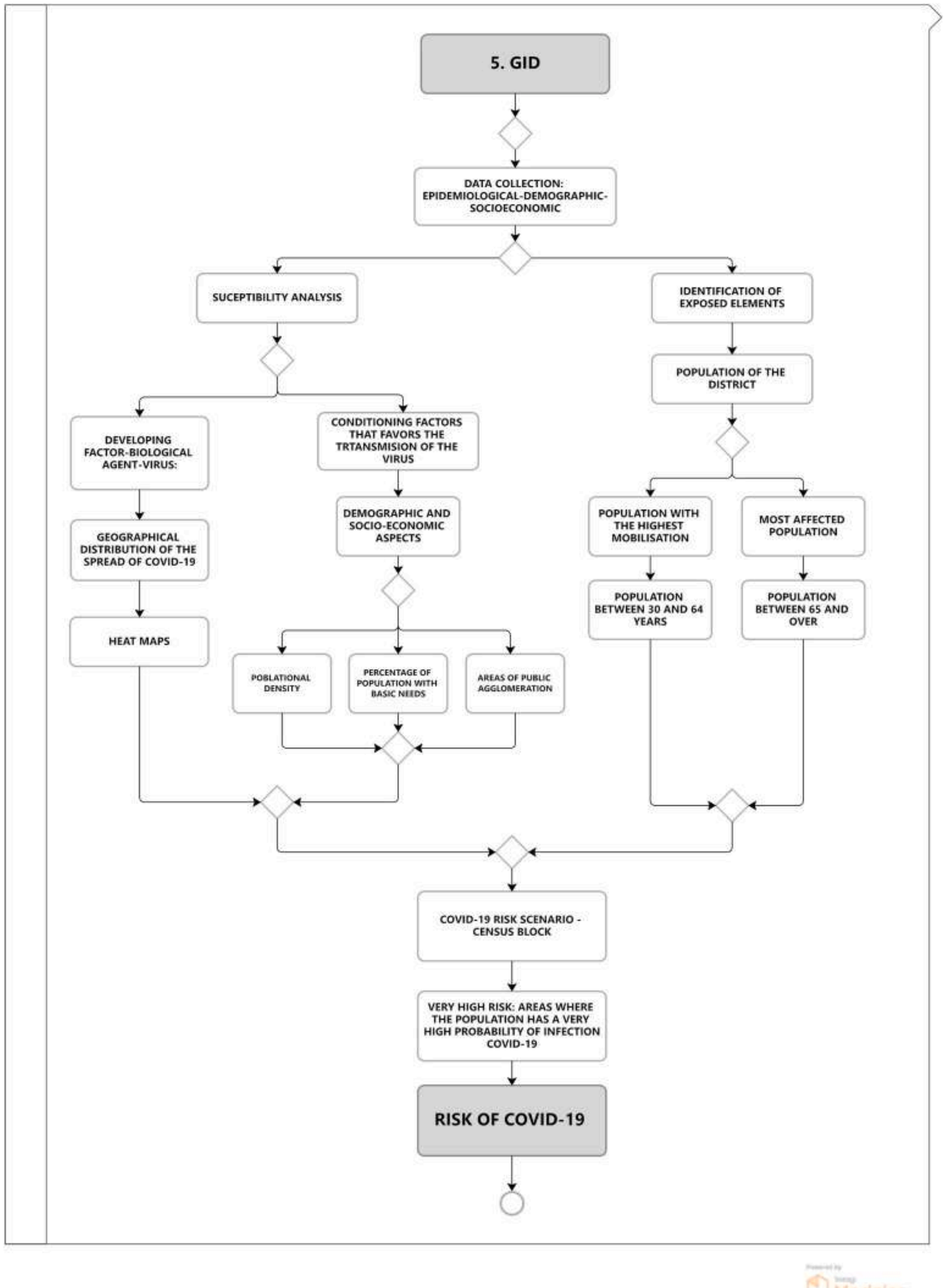

Fig. 3. Methodological proposal for the GID Risk of COVID-19 (Risk Scenario of COVID-19), based on the method elaborated by Centro Nacional de Estimación Prevención y Reducción del Riesgo de Desastres (2021). Note: This diagram shows the methodological steps given by CENEPRED (2021) for the definition of the COVID-19 Risk Scenario.

select the potential integration areas for GI (PIAGI). This method is designed for scenarios with limited access to updated geospatial information, because, in some places there are no specific geospatial information platforms to download raster or shapefiles from. Even when the information is available, it may be outdated from past years, and cannot define the current reality, therefore necessitating data collection from scratch.

To propose the GreenNet-Covid19 method at a theoretical level, different investigations were cited, which apply different indices, such as: the equity index, the social welfare index, the connectivity index, relative index, composite sustainability index and the GGII ; specifically oriented to the GI, but none implements a public health-related variable. Some of these studies name public health as a result of improvement when a GI strategy is implemented in a territory to solve some environmental or ecological problems.

Considering the Peruvian context and critical public health scenarios, such as COVID-19, this research theoretically adapts the methodology of Aguilera et al. (2018) that proposes to delimit the GI from four dimensions; likewise, the proposed GreenNet-Covid19 methodology also increases the 'COVID-19 risk' dimension through the inclusion of the COVID-19 risk scenario of Centro Nacional de Estimación Prevención y Reducción del Riesgo de Desastres (2021) - which intrinsically includes the issue of equity. In this way, COVID-19 risk, and equity issues become part of GreenNet-Covid19. Furthermore,

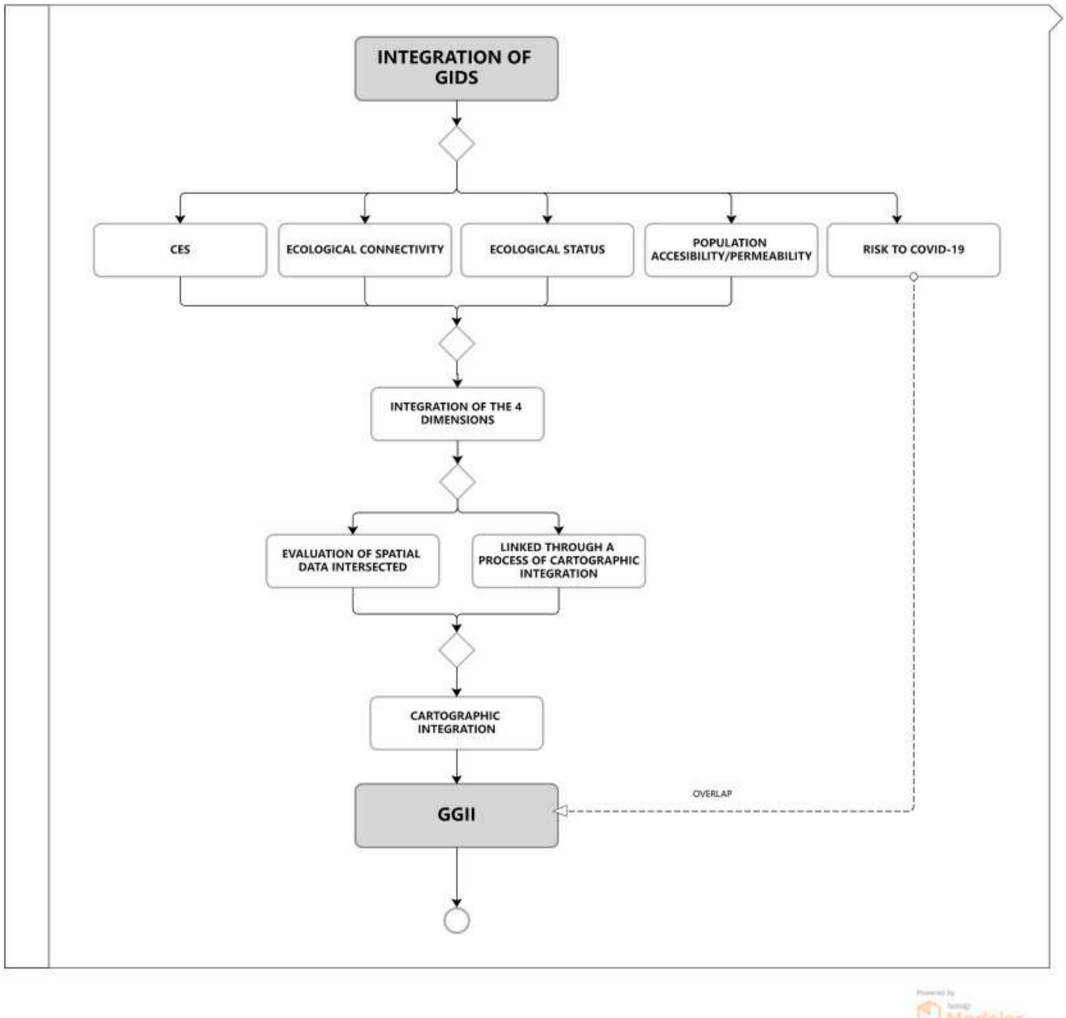

Fig. 4. Methodological proposal for GGII. Note: This diagram shows the process of integration of the 4 dimensions and the overlap of the fifth dimension.

GreenNet-Covid19 considers the United Nations Organization Sustainable Development Indicators 2030, thus denoting the need to adapt the GGII as a composite indicator, which can be defined by the sum of simple indicators, owing to the complexities of information standardization. In this way the results of the GreenNet-Covid19 application will give a basis for future GI projects to establish biodiversity as the basis of life in cities, emphasizing the need to position biodiversity protection as a essential cross-cutting and integrating element of Green Infrastructure Urban Planning, articulating the biodiversity protection objectives of upgrade, connect, restore, create, promote and manage ecologically - the urban nature; with the urban sustainability objectives of health, quality of life, environmental justice; climate adaptation, resilience; social cohesion, participation; Green, Building Cultur; sustainability, mobility, transition; and economic development (Hansen et al., 2023).

2. Materials and methodological adaptation

2.1. Selection of reference method

The following literature was reviewed: Aguilera et al. (2018), Dörgő et al. (2018), Heckert and Rosan (2016), Hysa (2021), Ko and Lee (2021), Rayan et al. (2021); Rodríguez et al. (2015) and Zhu et al. (2019). The methodologies in these studies were described sparsely and primarily focused on the proposal of specific indices. However, Aguilera et al. (2018) interrelated four GIDs (contribution to ecosystem services [CES], ecological connectivity, population accessibility/permeability, and ecological status [which allowed the selection of the PIAGI]) using geographic information system (GIS), landscape ecology, and participatory and expert valuation methods. This approach was developed in three phases: (1) evaluation and mapping of the GIDs, (2) integration of GI through multicriteria evaluations and generation of the GGII, and (3) selection of the PIAGI'. For the new 'risk due to COVID-19' dimension included in our GreenNet-Covid19 approach, the COVID-19 risk scenario of the National Center for Estimation, Prevention, and Reduction of COVID-19 was considered (Centro Nacional de Estimación Prevención y Reducción del Riesgo de Desastres, 2021). Although this method originated from a European context, it was simplified for application in Latin America, considering the urgency caused by the COVID-19 pandemic. This was necessary for the swift generation of territorial plans that incorporate the implementation of PIAGI to ensure sufficient green areas to reduce the risk of future pandemics. We selected and adapted this method because it is simple and replicable, thereby allowing the assessment and elaboration of the PIAGI for Peru, and eventually, all Latin America. It is important to clarify that the new 'risk due to COVID-19′ dimension included in our GreenNet-Covid19 approach, the COVID-19 risk scenario elaborated by Centro Nacional de Estimación Prevención y Reducción del Riesgo de Desastres (2021) is directly related to the issue of public health, which in turn addressed the issue of equity in an intrinsic way. Therefore, the difference between the methodologies proposed by Aguilera et al. (2018) and GreenNet-Covid19 is the inclusion of the dimension of the green infrastructure (GID) called 'risk due to COVID-19' using the risk map by

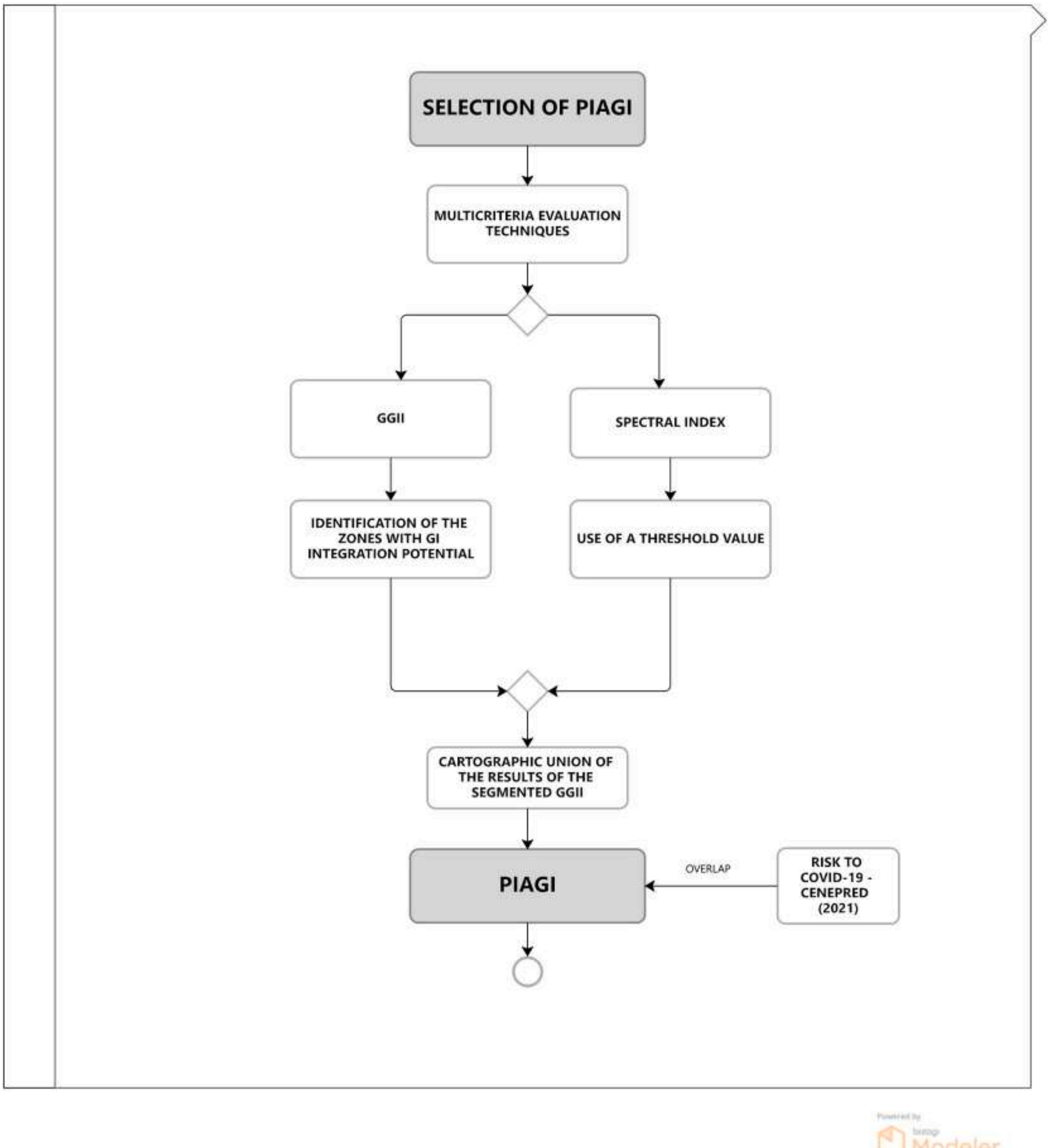

Fig. 5. Methodological proposal for PIAGI. Note: This diagram shows the process of integration through multi-criteria techniques and the overlap of the fifth dimension.

COVID-19 (Centro Nacional de Estimación Prevención y Reducción del Riesgo de Desastres, 2021). It was therefore necessary to use the risk map by COVID-19 from the Centro Nacional de Estimación Prevención y Reducción del Riesgo de Desastres (2021) to evaluate COVID-19 risk scenarios for the city of Arequipa, through a process of overlapping. It is necessary to clarify that in this overlay no geoprocessing was carried out, which implies the intersection or union of layers with others, this layer was only superimposed for visualisation and graphic representation of the covid 19 risk cases. It is also important to highlight that for the elaboration of this map, this institution of the Peruvian Government includes official information related to equity such as the Basic Unmet Needs and age groups thus identifying the most vulnerable population in COVID-19 pandemic situations.

2.2. Methodological proposal for GreenNet-Covid19

This study used a mixed approach, i.e., quantitative (using GIS) and qualitative (evaluations by experts) approaches. The scope was sequential-explanatory, and the design was non-experimental.

To reiterate, the differences between the methodologies of Aguilera et al. (2018) and GreenNet-Covid19 are the inclusion of the GID called risk due to COVID-19 and the use of landscape tools at the inventory stage. Therefore, the GGII and PIAGI phases responded to this new dimension (Fig. 1).

The GreenNet-Covid19 technique involved a process of geospatial mapping analysis in a GIS using data from primary and secondary sources together with integrative geo-referenced information. Remote sensing was used to measure the properties of objects without the need for field surveys, which was crucial during the pandemic. Finally, a GIS expert mapped, adapted and compiled information from the public portals of various institutions, although the spatial data available was not detailed. Furthermore, this research elaborated the baseline with the methodology of Ordenamiento Ecológico Territorial of the University of Universidad de Chile et al. (2002), due to the importance of geospatial information obtaining a relatively more detailed level of the territory. This baseline provides cartographic information on air/climate, climate change, groundwater, surface water, soil, vegetation and fauna, vegetation analysis 1985–2020, scenic landscape, current use mapping and

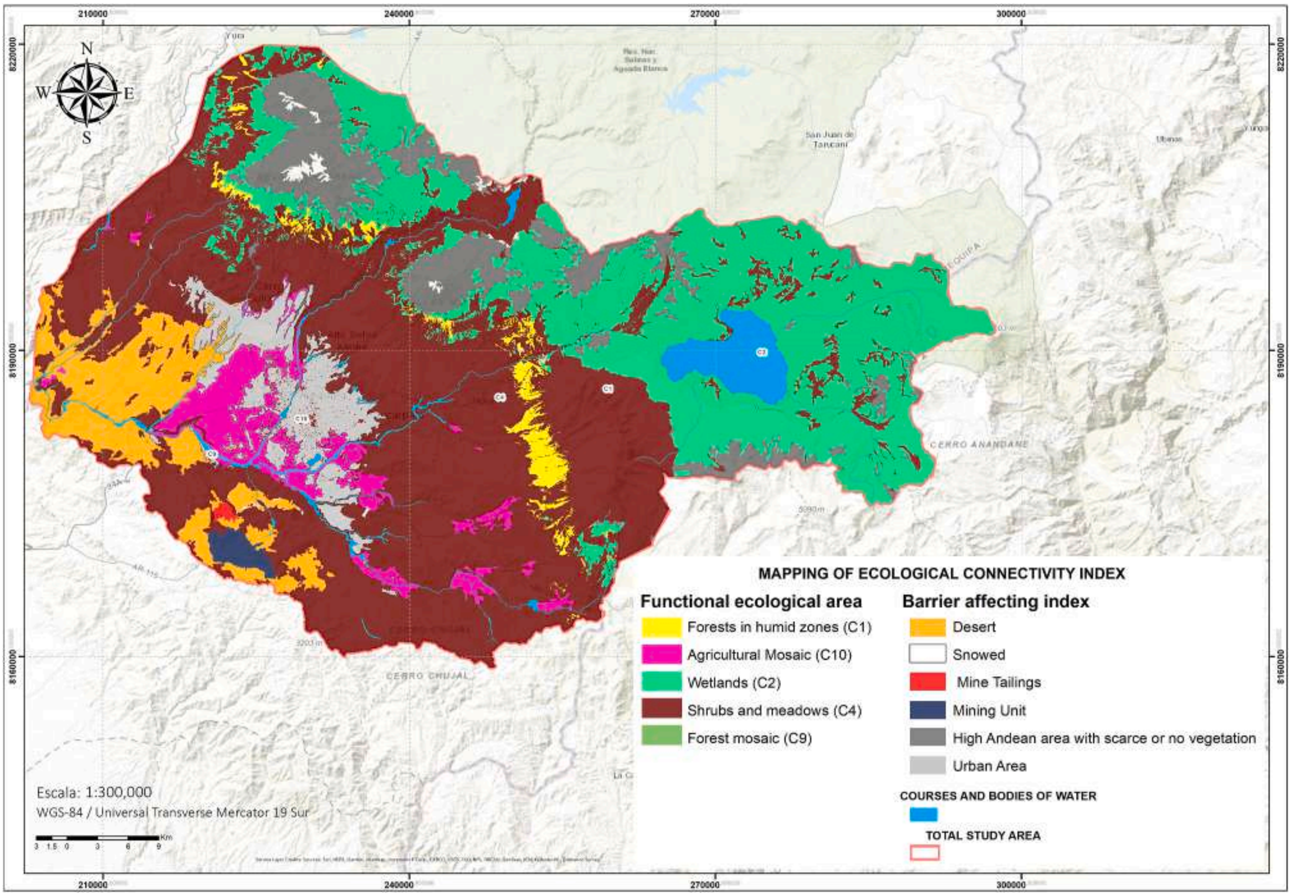

Fig. 6. Ecological connectivity index (ECI) of the test area. Note: FEA- Functional ecological area; where the FEAs are made up of forest in humid zones (C1), agricultural mosaic (C10), wetlands (C2), shrubs and meadows (C4) and forest mosaic (C9) showing the barrier affecting index with existing barriers such as desert, snowed, mine tailings, mining unit, High Andean area with scarce or no vegetation, urban areas; and courses and bodies of water.
Source: Author's elaboration and adaptation based on Aguilera et al. (2018), Gobierno Regional de Arequipa (2018) and Universidad de Chile et al. (2002).

habitats (University of Universidad de Chile et al., 2002).

Arequipa, one of Peru's intermediate cities, with the second largest number of inhabitants (Cuisano and Guillén, 2015), was selected as the test area (Fig. 2). Arequipa is characterized by high biodiversity, fragmented green areas, isolated life zones, unplanned land use, and the impact of climate change. Notably, it lacks articulated planning levels or landscape plans that employ an ecosystem approach.

The test area has urban conurbations and agricultural areas within its immediate geographical environment. It has a total area of 318474.98 ha and comprises 21 districts, with urban areas spanning 37,107 ha and green areas spanning 9321 ha Instituto Municipal de Planeamiento (2015). Furthermore, it has 1,080,365 inhabitants, of which 947,927 reside in urban areas (Instituto Nacional de Estadística e Informática [INEI], 2017). According to the Instituto Municipal de Planeamiento (2015), the test area has an overload of road infrastructure, disorderly and unplanned urban growth, high occupation, consolidated settlements in danger zones, and scarcity of metropolitan green areas. Furthermore, Zucchetti et al. (2020) estimated that Arequipa had 0.5 m^2 of green area per inhabitant during 2020, which is significantly below the level recommended by the World Health Organization (WHO), which suggests a minimum of 9 m^2 of green area per inhabitant (UN-Habitat, 2015).

Notably, Arequipa is part of the Atacama Desert. Therefore, it is a desert area with a dry climate, low humidity, elevated levels of UV radiation, and low levels of urban greenery and is extremely vulnerable to droughts and heat waves. The lack of urban policy regulations and effective sanctions has favored informal urbanization processes. To address land speculation, corruption, and institutional weakening, there is a need for a proper interpretation of the norms and control measures (IMPLA, 2015). Consequently, desertification has increased in Arequipa due to reduced environmental compensation zones and green areas. The COVID-19 pandemic, which is classified as a natural hazard or disaster (Seddighi, 2020), escalated this situation as the inhabitants of Arequipa were quarantined without access to green areas and public spaces. Consequently, the Law for the Management and Protection of Public Spaces – Law No. 31199 (2021–1999) – was enacted (Seddighi, 2020). Notably, this law does not consider GI and defines public spaces as a network of open spaces within the District and Provincial Plans of Public Spaces. Furthermore, despite its enactment, it has not yet been implemented in Arequipa (Ley N° 31199, 2021).

The test area was delimited considering the urban limits and immediate surroundings of Metropolitan Arequipa. Furthermore, urban and peri-urban aspects and the distribution of hydrographic basins were considered at a scale of 1:300,000 and 318,474.98 ha, respectively. Geomorphological and climatic factors, arid temperate climates, mountainous ecosystems, unique habitats, and their immediate surroundings in the metropolitan context were also considered.

Vector and raster data were required between the scales of 1:155,000 and 1:300,000. For the vector data, information was collected from the COVID-19 risk scenario of the Centro Nacional de Estimación Prevención y Reducción del Riesgo de Desastres (2021). Data on main roads and district boundaries, rivers and streams, urban growth, land use, soil types, fauna, and vegetation cover were collected from the Instituto Geográfico (2016), Ministerio de Educación (MINEDU) (2019), and Ministerio del Medio Ambiente (MINAM) and Gobierno Regional de Arequipa GRA (2018), respectively. For the raster data, air quality information, climatology–bioecological classification, and DEMs and

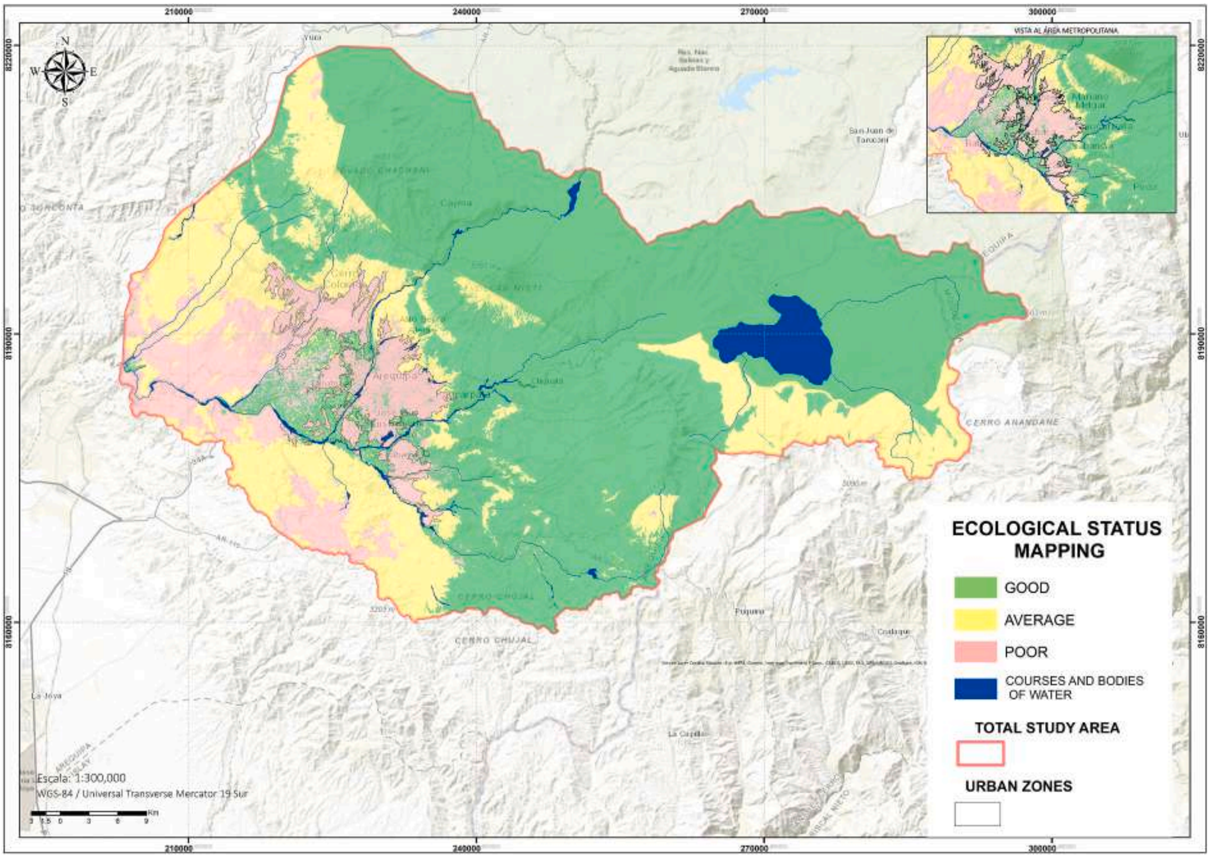

Fig. 7. Ecological status of the test area. Note: In the mapping of Ecological status of the test area the valuation levels used are good, average y poor. Of these, the one that occupies the largest area is that of "good".
Source: Author's elaboration and adaptation based on Aguilera et al. (2018), Gobierno Regional de Arequipa (2018), and Universidad de Chile et al. (2002).

medium spatial resolution satellite imagery were collected from the Gerencia Regional de Salud (2021), Ministerio del Ambiente (MINAM) and Gerencia Regional Ambiental de Arequipa (GRA) ZEE (2018), and Science for a changing world-USGS and LANDVIEWER (2021), respectively. The baseline was elaborated, and categories of interest for the study area, such as climate change, and an analysis of vegetation from 2020 were added using these data.

2.3. Evaluation and mapping of the GIDs

In the first methodological phase, four GIDs were evaluated and mapped. At the CES level, geospatial information, and land-use data from the ecological and economic zoning (ZEE) of Arequipa and baseline data were used. The ES elements were identified and selected based on different classifications proposed by the European Environment Agency and were divided into four categories: (1) habitat, (2) regulation of ecological processes, (3) supply, and (4) cultural services (Unión Europea, 2014) and expert assessments. The areas providing ES were identified, delimited, selected, quantified, and defined as the aggregate contributions of a given ecosystem to its immediate surroundings. The information collected was adapted to the study area because it was general and not specific. The qualitative assessment was conducted by a single expert, not a panel of experts, as in Aguilera et al. (2018). The measurement scale was in units of area per proposed subcategory. The area units adapted and used in the summation were habitat, provisioning and cultural services, and regulation of ecological processes.

Geospatial and land-use information from the ZEE of Arequipa (vegetation cover) and baseline data were used at the ecological connectivity level. Ecological connectivity areas with unique and critical ecological characteristics were delimited, quantified, grouped, and integrated according to functional ecological areas (FEAs) and the barrier-affecting index. To generate the FEAs, we used land-use and vegetation cover mappings classified according to the criteria set by Aguilera et al. (2018). In addition, territorial elements functioning as barriers were identified for the barrier-affecting index. This adaptation was made to adequately generate the ecological connectivity index (ECI) despite the lack of information regarding the study area. We worked in area units from each subcategory, as proposed by the reference method. To integrate the ECI, the area units adapted for the sum of the FEA and barrier affecting index layers were forest and agricultural mosaics, mining tailings and units, snow-capped mountains, humid area forests, urban and humid areas, deserts, high Andean areas with little or no vegetation, shrubs, and meadows, among others.

Geospatial and land-use information from the ZEE of Arequipa (vegetation cover) and baseline data were used at the ecological status level, respectively. Areas of ecological status were delimited and quantified according to the state of the ecosystems and grouped into critical zones based on their ecological status. The 'naturalness' percentage of the territorial elements was evaluated according to land use. The distributions of wetlands in the highlands, scrublands, and agricultural areas of the middle and desert areas are highlighted in the maps produced (see Results). The measurement scale considered by the GIS expert was applied to the grouped layer according to the following criteria: 'good, regular, and deficient' for areas with naturalness percentages of $\geq$50%, $\leq$50%, and $\leq$20%, respectively.

For population accessibility/permeability, roads were found, and slopes were generated via the digital elevation model (DEM) to find roads with very steep slopes. Geospatial information from the ZEE of Arequipa was used as the base layer for the neighborhood, departmental, paved, and unpaved road networks. Compared to the reference

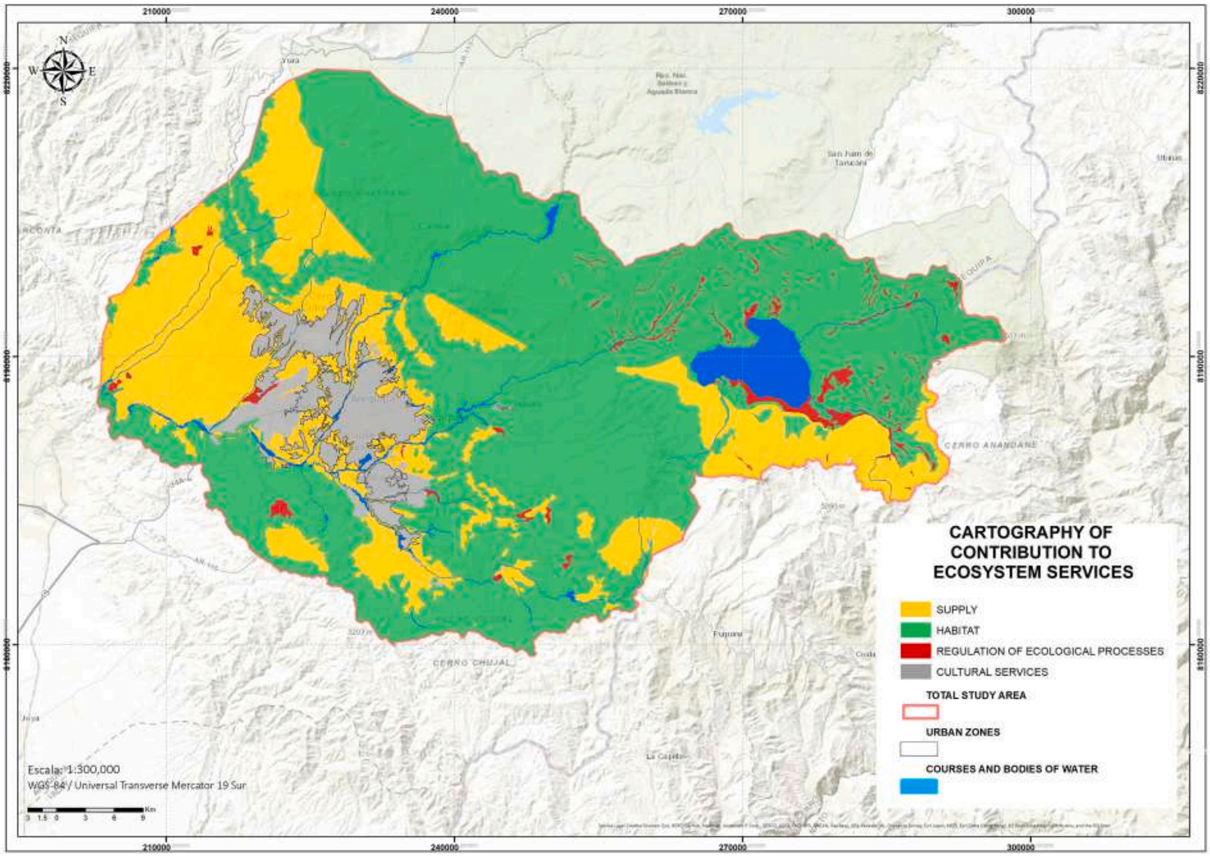

Fig. 8. Contribution to Ecosystem Services (CES) in the test area. Note: In the mapping of Contribution to Ecosystem Services the categories that are shown are supply, habitat, regulation of ecological processes and cultural services. Of these, the one that occupies the largest area is that of habitat.
Source: Author's elaboration and adaptation based on Aguilera et al. (2018), Gobierno Regional de Arequipa (2018), and Universidad de Chile et al. (2002).

method, this method did not analyze either the contrast or travel costs due to a lack of information. The areas with access roads within the study area were determined, allowing the population to move from urban areas towards the peripheral areas and other study area zones. Fauna within the population were not considered because of the lack of geospatial information.

The level of risk dimension by COVID-19 represents a methodological contribution of GreenNet-Covid19. It was proposed based on the existing COVID-19 risk level, because this project considers epidemiological aspects, highlighting not only the intervention and proposal of a GI, but also the development, capacities, opportunities, etc. of a given territory in pandemic conditions, also considering the population in evident pandemic and its relationship with the GI. In this aspect, the COVID-19 risk scenario information elaborated by Centro Nacional de Estimación Prevención y Reducción del Riesgo de Desastres (2021) was used, which is the product of the intersection of different geospatial layers, which had a previous treatment; for the generation of this dimension, stages were considered according to Centro Nacional de Estimación Prevención y Reducción del Riesgo de Desastres (2021), specifically four stages: a) data collection (epidemiological, demographic and socioeconomic) these data were spatialized for analysis within a GIS environment; b) susceptibility analysis which is composed of a triggering factor determined by the areas of contagion with COVID-19 which is the geographical distribution of the spread of COVID-19 according to heat maps; and a conditioning factor which are the factors that favour the transmission of the virus, which are demographic and socioeconomic aspects such as population density, percentage of population with Unsatisfied Basic Needs and areas of public agglomeration (especially food markets); c) identification of the exposed element, that is, the population with greater mobilization between 30 and 64 years of age and the most affected population between 65 and older; d) and finally determining the risk scenario for COVID-19. (risk of infection by COVID-19 at block level as a product of the previous stages and represents different levels of risk) (Fig. 3).

2.4. GGII

In the second methodological phase, the GIDs were integrated. For the GGII, the reference method integrated four GIDs: (1) CES, (2) ecological connectivity, (3) ecological status, and (4) population accessibility/permeability, whereas the GreenNet-Covid19 approach included an additional GID, namely, the risk due to COVID-19 dimension. The reference method considered for this integration included multicriteria evaluations of the four dimensions and their combinations, while the GreenNet-Covid19 methodology integrated five dimensions, evaluating the spatial data intersected and linked through a process of cartographic integration and where the COVID-19 risk layer was finally intersected as the fifth dimension Centro Nacional de Estimación Prevención y Reducción del Riesgo de Desastres (2021). GreenNet-Covid19 delimited, quantified, and defined the GGII in the test area as the distribution of specific areas and their connection relationships. The adaptation criterion for integrating the five dimensions was the quantitative and qualitative valorization of intersecting spatial data, in which the important relationships were integrated as part of the GGII. Furthermore, considering weather conditions, an added criterion was the importance of biodiversity and the temporary permanence of the vegetation (Fig. 4).

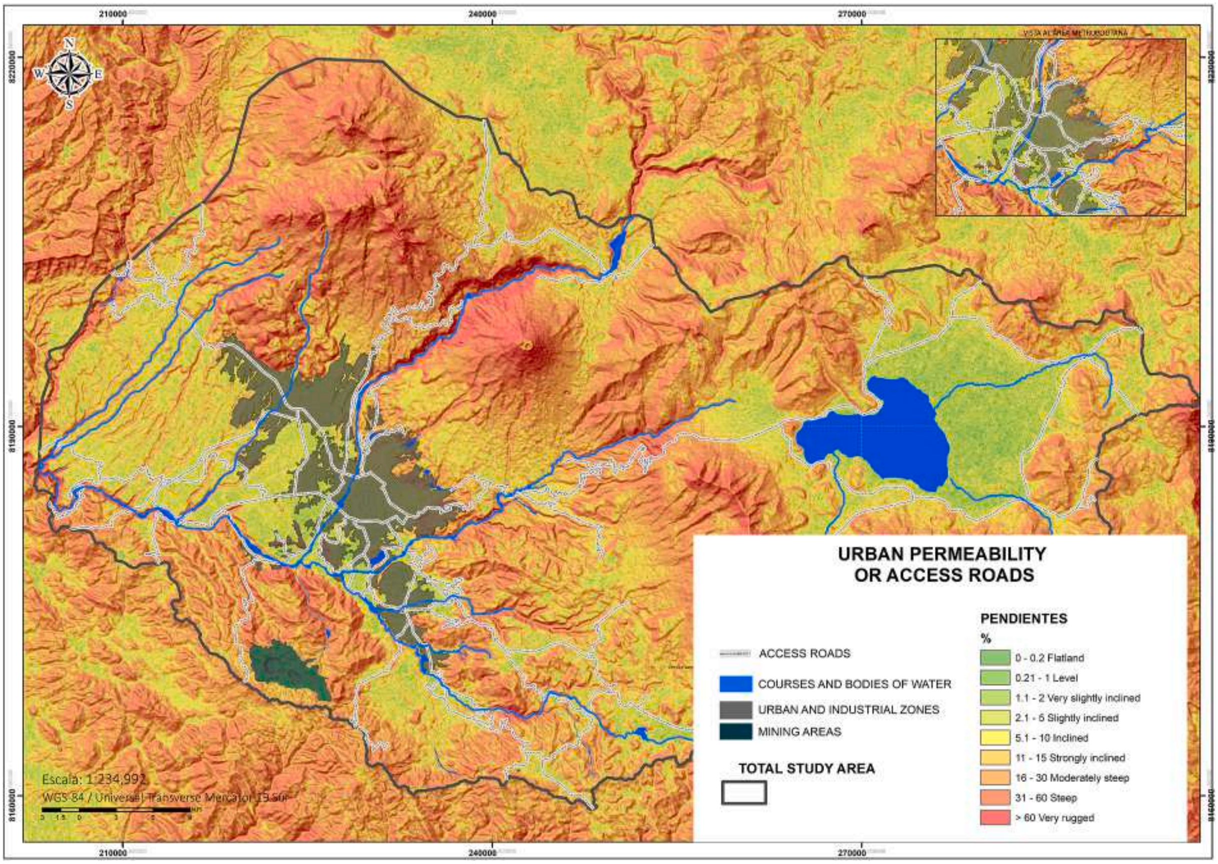

Fig. 9. Population permeability in the test area. Author's elaboration and adaptation based on Aguilera et al. (2018), Gobierno Regional de Arequipa (2018), and Universidad de Chile et al. (2002). Note: The permeability mapping shows the possible accesses to the study area as well as a slope classification given in percentages ranging from 0 to 60%.

2.5. *Selection of the PIAGI*

In the third phase, the PIAGI was selected using multicriteria evaluation techniques, and a map was obtained with an individual value for each pixel that synthesized the assessment of the four dimensions. Furthermore, the zones or pixels with GI integration potential were identified by analyzing the resulting fit frequency distribution, and the pixels that needed to be retained were defined using a threshold value. Owing to the non-normality of the data, a position measure was used to keep the values within the first quartile, and the final PIAGI map was obtained. GreenNet-Covid19 generated segmented areas with high bioecological potentials using the adaptation criterion, which was applied to the GGII layer, considering areas with high bioecological potentials, such as forests in humid zones, wetlands, agricultural mosaics, forests, areas that harbor habitats, and areas with ecological process regulation. Subsequently, it used the integration criterion with detailed information and the normalized differentiated vegetation index to form vegetation cover. In addition, the behavior, distribution, and permanence of the vegetation in rainy and non-rainy seasons were considered. Spatial reclassification of the results using quintiles of the seven spatial subclasses was performed. The interaction between the first and second steps was proportional, considering the input information from the GGII segmentation and spectral index results. The cartographic union of the results of the segmented GGII and the spectral index generated the PIAGI, which was intersected with the risk layer by COVID-19 from Centro Nacional de Estimación Prevención y Reducción del Riesgo de Desastres (2021). Statistical analysis was not used for this study (Fig. 5).

3. Results

3.1. *GIDs*

3.1.1. *Ecological connectivity*

Firstly, the ECI results showed the areas with potential connectivity, with a total area of 318474.98 ha (100%). The FEAs with a total test area of 234362.23 ha (74%), is comprised of forests in humid zones (6286.00 ha; 2.0%; C1), agricultural mosaics (13262.24 ha; 4.2%; C10), wetlands (87808.28 ha; 27.6%; C2), shrubs and grasslands (126977.24 ha; 39.9.9%; C4), and forest mosaics (28.47 ha; 0.0%; C9). Secondly, the ECI results showed the existing barriers between each zone, which were classified within the barrier affecting index (with a total of 84112.75 ha; 26%) and comprised mining tailings (283.37 ha; 0.1%), snow-capped mountains (1094.64 ha; 0.3%), mining units (1732.60 ha; 0.5%), urban areas (15715.51 ha; 4.9%), desert (20953.32 ha; 6.6%), high Andean areas with little or no vegetation (37116.75 ha; 11.7%), and other areas (7216.56 ha; 2.0%) (Fig. 6).

The results of the ecological status mapping were based on a total area of 318474.98 ha (100%). The 'Good, average, and poor' status areas were deemed to have 188457.42 ha (59.2%), 86534.13 ha (27.2%), and 43357.66 ha (13.6%), respectively (Fig. 7).

3.1.2. *CES*

The results of this dimension were based on the classification of the European Environment Agency, with a total area of 318474.98 ha (100%). Habitat, supply, cultural services, and regulation of ecological processes had areas of 201469.33 ha (63.3%), 84886.90 ha (26.7%), 20652.32 ha (6.5%), and 11173.38 ha (3.5%), respectively (Fig. 8).

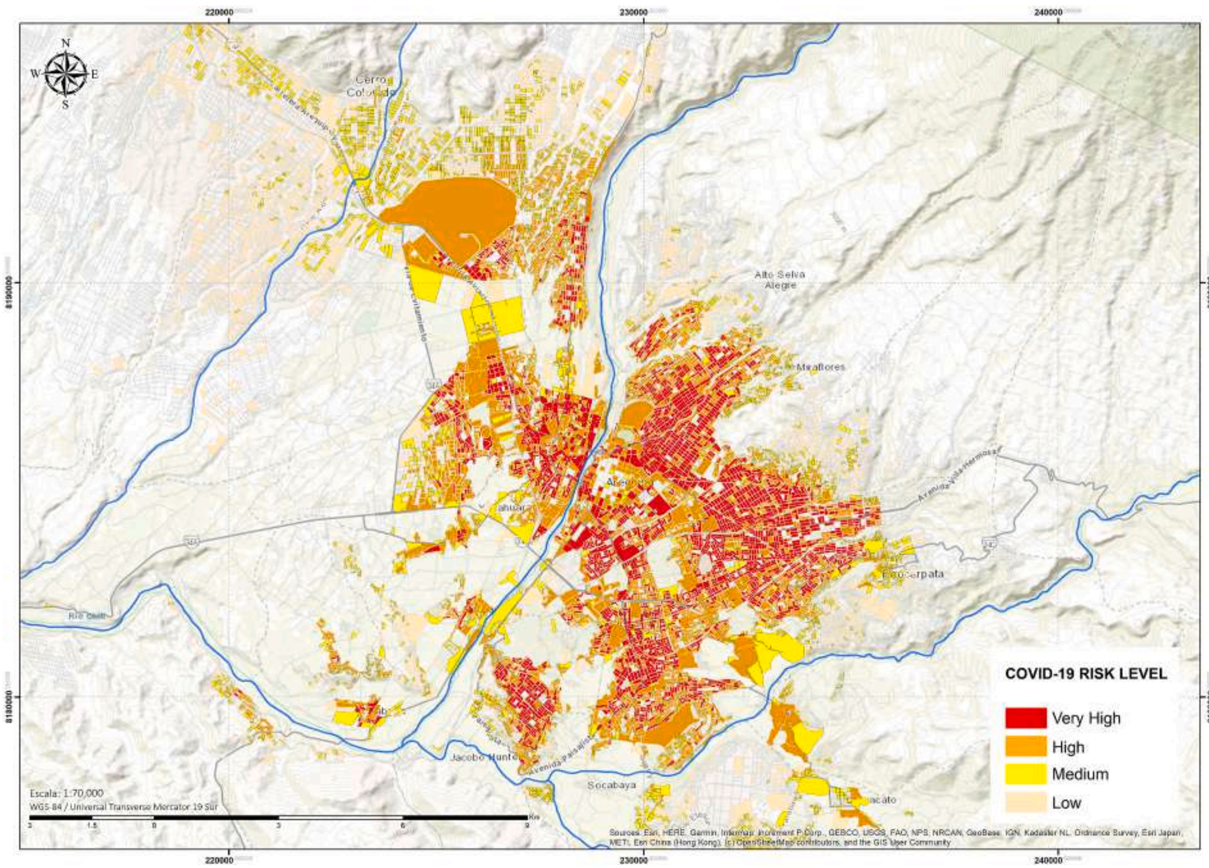

Fig. 10. COVID-19 RISK SCENARIO for Metropolitan Arequipa. Note: Most of the positive cases were in the districts of Arequipa, Paucarpata, Cerro Colorado, José Luis Bustamante y Rivero, Mariano Melgar, Miraflores, Alto Selva Alegre and Jacobo Hunter and coincides with high population density areas.
Source: Centro Nacional de Estimación Prevención y Reducción del Riesgo de Desastres (2021)

3.1.3. Population accessibility/permeability

Connectivity and permeability consider the accessibility of the population through access roads (paved and unpaved roads) to the different zones. Likewise, the most accessible zones through paved and unpaved roads are much closer to the urban zones, and the altitude in meters above sea level (m.a.s.l). The higher the altitude, the lower the accessibility due to the lack of paved and unpaved roads in the zones or towns at higher altitudes.

The analysis of this dimension revealed a vital network of roads in the test area, which extended from the urban areas to the highlands and subsequently entered the Salinas Reserve and Aguada Blanca. The altitude mapping (DEM) results exhibited elevation ranges in m.a.s.l. to represent the altitudes and relief (shadow map). The lowest and highest altitudes were above 1558 m.a.s.l. and at 6043 m.a.s.l., respectively (Chachani Volcano) (Fig. 9).

3.1.4. Risk due to COVID-19

The results presented by Centro Nacional de Estimación Prevención y Reducción del Riesgo de Desastres (2021) are shown (at block level), in relation to the level of susceptibility analysis and identification of exposed elements, which determine the Risk of COVID-19 (Risk Scenario).In the susceptibility analysis, it was found that 36.1% (342,800) of the total population, present a very high risk level and 32.3% (306, 067) a high risk level; and that the urban population with a very high risk level is composed of 17% (161,914) of men and 19% (180,886) of women. In relation to the geographical distribution and spread of COVID-19, most positive cases with the highest number of people at very high risk are found in Arequipa, Paucarpata, Cerro Colorado, José Luis Bustamante y Rivero, Mariano Melgar, Miraflores, Alto Selva Alegre and Jacobo Hunter. At the level of conditioning factors that favour the transmission (demographic and socioeconomic aspects in terms of population density), it was found that the districts with the highest population density were almost the same as those identified with the highest number of positive cases (with the exception of Arequipa and Paucarpata); in most cases, the high densities were found in the central urban environment of each locality, and in areas of commercial and economic development. Also, 52.4% of the total population is considered within the highest density classification, who lives in densely populated blocks, close to the city's commercial, service and residential centers. At the level of the percentage with Basic Unmet Needs, low levels of poverty predominate in Arequipa, while the population with high levels of poverty live in the outskirts of the city. Only 2.9% of the total population is located between the Very High and High Basic Unmet Needs. At the level of public agglomeration areas were identified 158 public agglomeration areas around the entire city, most of these were in the center of the city, between the districts of Arequipa, Yanahuara and Cayma. In the identification of the exposed elements it was considered the population with the greatest mobilization between 30 and 64 years, an economically active population with the greatest spatial displacement where the 70.1% of this age group predominates in the study area and mainly located in the central sectors of the urban area of the several districts; it was also considered the most affected population aged 65 years and older, where the 80.2% of this age group is predominantly placed in the central area of the city (Fig. 10).

3.2. GGII

In GGII mapping 2021, the final intersection of the five GID layers highlighted the final overlap with the risk due to the COVID-19 layer. The GGII first showed the high bioecological value of the area harboring

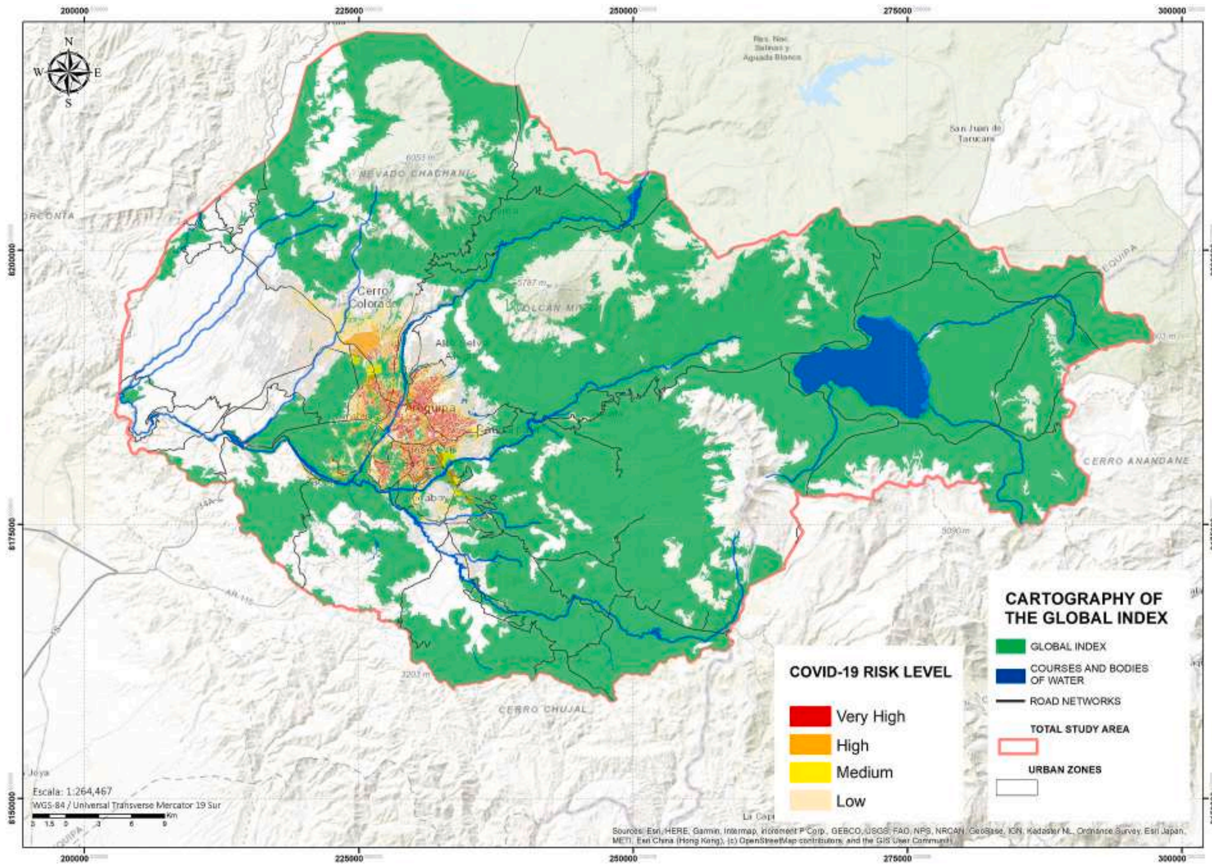

Fig. 11. GGII for Metropolitan Arequipa and its surroundings in the test area scale. Note: GGII mapping is shown at the study area level where the four dimensions of GI are integrated and overlapped with the fifth dimension of GI, i.e., with the levels of risk by COVID 19 at the metropolitan level.
Source: Author's elaboration and adaptation based on Aguilera et al. (2018), Gobierno Regional de Arequipa (2018), and Universidad de Chile et al. (2002).

and surrounding the urban areas. Thus, out of a total area of 318474.98 ha (100%), the GGII exhibited 215296.84 ha (67.6%) as high ecological potential areas. At the Metropolitan Arequipa level, the intersected area for risk due to COVID-19 and the GGII was 1187.52 ha. The 'very high, high, medium, and low' levels had areas of 27.54 ha (2.31%), 403.28 ha (33.96%), 461.47 ha (38.86%), and 295.23 ha (24.87%), respectively (Figs. 11 and 12).

3.3. PIAGI

The results showed that in areas with a high and very high level of COVID-19 risk, the PIAGI are low; likewise, the behavior of PIAGI decreases where there are urban areas, and they coexist minimally; therefore, the greatest proliferation of PIAGI is outside urban areas. Thus, out of a total area of 318474.98 ha (100%), the PIAGI exhibited 103901.02 ha (33%) as high ecological potential areas. The results obtained for Metropolitan Arequipa showed the areas of intersection between COVID-19 risk and PIAGI, with a total area of 1386.32 ha. The 'very high, high, medium, and low' levels had areas of 91.93 ha (6.63%), 514.08 ha (37.08%), 481.01 ha (34.70%), and 299.68 ha (21.61%), respectively (Figs. 13–16).

The detailed maps shown in Figs. 15 and 16 demonstrate the possibilities of PIAGI within the dense urban fabric of the city of Arequipa, showing that to the northeast of the city of Arequipa, in the districts of José Luis Bustamante y Rivero and Paucarpata, PIAGI's connections between urban areas are evident. It is important to remember that the COVID-19 risk levels are associated with the areas of infection by COVID-19, the population density indicators, percentage of population with Basic Unmet Needs and areas of public agglomeration. socioeconomic factors, aspects of social agglomeration for reasons of economic activity, displacements of the economically active population, as well as social inequality, therefore the influence of these factors is important in the results at the level of this zone.

On the other hand, a detailed view of the historical center of the city is also shown, where the PIAGI are clearly evidenced next to the Chili River, which is part of the countryside of the city of Arequipa.

4. Discussion

The findings indicate that the simplified GreenNet-Covid19 methodology presented in this study represents a methodological advance that attempts to serve as an example for other cities allowing future innovations in territorial planning that incorporate GI plans that address public health and complementarily of equity concerns.

At a conceptual level our study has found that the concept of GI in Europe is consensual and standardized according to the Unión Europea (2014), (Benedict and McMahon, 2012; Calaza, 2019; Coutts and Hahn, 2015; Pakzad et al., 2017 y Valera, 2019). This concept has therefore been considered for the present study; given that in Latin America no clear or standardized definition of this concept has been found as mentioned by Alves (2015), Nóbrega dos Santos et al. (2021), Zucchetti et al. (2020). From the point of view of environmental management, it is necessary to reach a consensus and to the approval of a Latin American standard the definition of GI and set common objectives for its implementation. Likewise, there are few studies that relate green areas to COVID-19 such as Ding et al. (2022), Fagerholm et al. (2022), Fernández (2021), Sainz-Santamaría and Martínez-Cruz (2022) and Salazar-Galán et al. (2022). Given that the present study was intended to be a rapid response to critical public health situations in a context of scarce information, it was not intended to address the issue of equity in itself, but

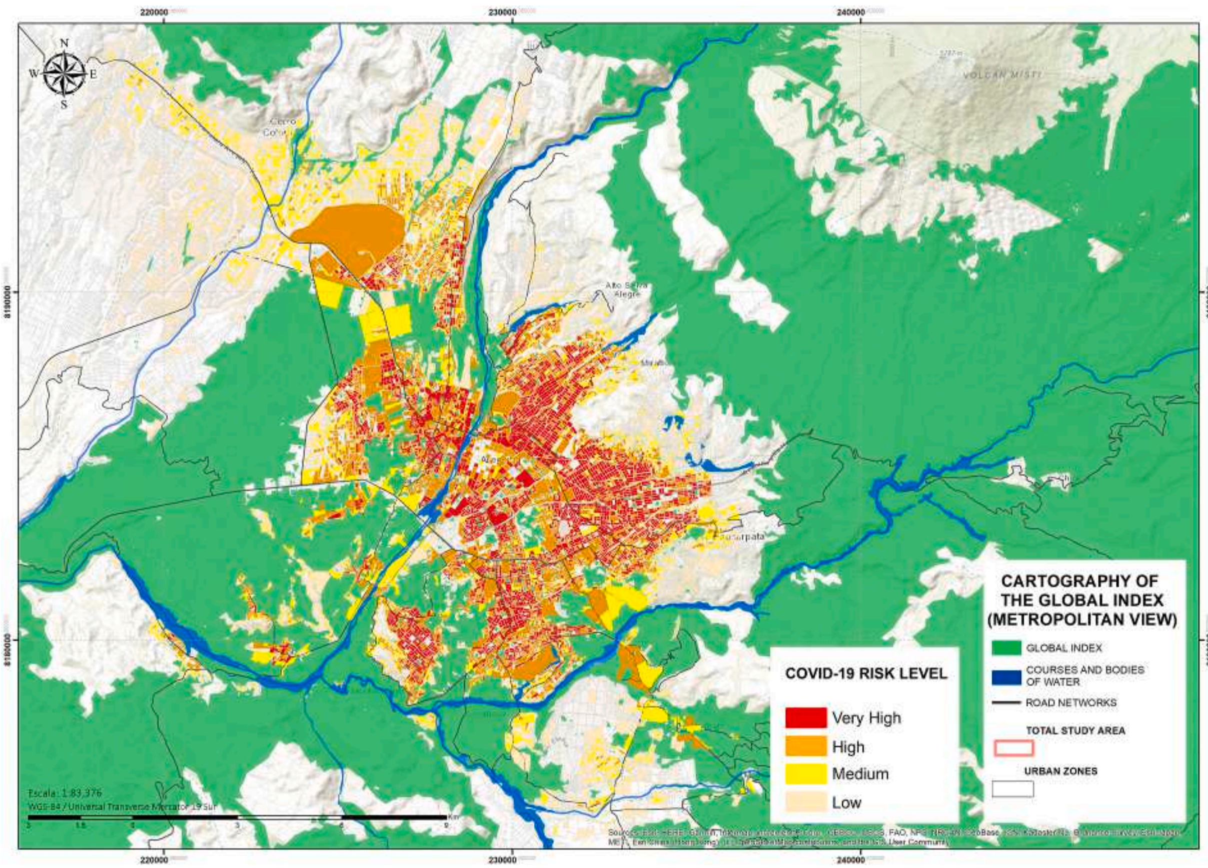

Fig. 12. GGII, the global green infrastructure index, of the Metropolitan Arequipa for 2021. Note: A specific view of Metropolitan Arequipa is shown, visualizing the GGII where the four dimensions of GI are integrated and overlapped with the 5. dimension of GI, with the levels of risk by COVID 19 at the metropolitan level. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
Source: Author's elaboration and adaptation based on Aguilera et al. (2018), Gobierno Regional de Arequipa (2018), and Universidad de Chile et al. (2002).

rather to use the official information from the Peruvian government considered by Centro Nacional de Estimación Prevención y Reducción del Riesgo de Desastres (2021). Despite this, it is necessary to mention that in a pandemic context, the direct relationship between GI and equity is undeniable; it is priority to develop more specific research in the future taking into account the advances made by Hou and Li (2024) who argue the equity measure in relation to the spatial distribution around GI and present indices for a comprehensive assessment of the urban green infrastructure pattern; and He et al. (2022) who propose priority levels for future urban interventions. Finally, thinking with criteria prevention about a new future pandemic context; the direct relationship between GI, public health (COVID-19) and equity is high priority for which it is necessary to take into account the advances made by authors such as Ravichandran et al. (2023) who argue that an unequal access to green spaces generates public health problems; likewise, Rigolon et al. (2021) who argue that green spaces can promote health equity and provide forms of planning. Likewise, at the Latin American level there are some advances on this relationship considering it mainly as a strategy to improve quality of life, socio-economic aspects as well as focusing on climate change, such as Vásquez (2016) who describes the arguments in favour of urban GI and the provision of ES as key components in the face of climate change; Moreno (2022) who states that the GI approach allows for a strategic approach to rethink territories at risk; Giannotti et al. (2021) who recognize that GI is one of the main strategies for mitigating and adapting to climate emergencies in urban context and consider the high level of social inequality and distribution of green areas; Gomez and Velázquez (2018) who state that the availability of public green spaces is directly related to the quality of life in urban areas; and finally Herrera et al. (2021) who verified that as one moves down the socio-economic scale, the quality and quantity of public green spaces also decreases. As can be seen, these are important advances, leaving the task of further clarifying the relationship between GI, public health (COVID-19) and equity.

Taking into account the aforementioned conceptual foundations, the present study considered it pertinent to select a reference methodology that would allow the use of indices for the definition of GI, prioritizing the direct relationship between GI, public health (COVID-19) due to the situation of confinement that was being experienced at the time and indirectly that of equity due to the context in which it would be applied. In this way, during the process of selecting the most appropriate reference methodology for the present study, it has been found that most of the literature reviewed like Heckert and Rosan (2016) Hysa (2021), Ko and Lee (2021), Rayan et al. (2021) and Zhu et al. (2019) focused on specific indices, except the study by Aguilera et al. (2018), which defined GI and integrated the dimensions of GI through multicriteria evaluation, generated a GGII, and defined PIAGI as well. Consequently, GreenNet-Covid19 was based on this study, with the addition of the dimension 'risk by COVID-19' which for its elaboration considered some aspects related to the equity promoted by Heckert and Rosan (2016); in the case of the present investigation as conditioning factors such as population density, percentage of population with Basic Unmet Needs and the areas of public agglomeration.

In the implementation of GreenNet-Covid19 methodology developed for the present study, at the GID level the ECI shows a high percentage of ecological connectivity index at the FEA level (74%). This high percentage of ecological connectivity index found at the FEA level can be directly related to the good Ecological Status (59.2%) found in the study area as well as with the CES level, where the habitat category had the

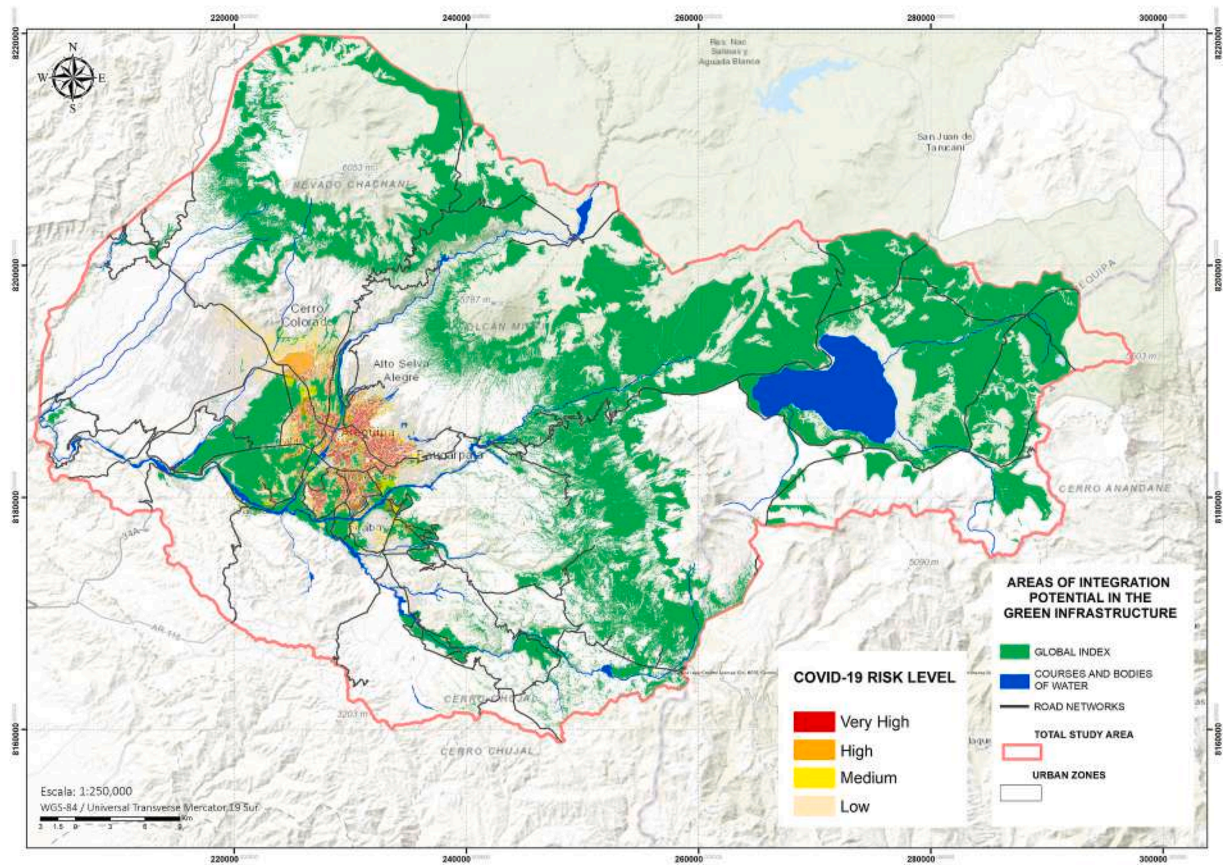

Fig. 13. PIAGI, the potential integration areas for green infrastructure, of Metropolitan Arequipa and its surroundings in the test area scale for 2021. Note: The mapping of the PIAGI at the study area level is shown with the corresponding overlap with the fifth dimension of GI, that is, with the levels of risk by COVID 19 at the metropolitan level. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
Source: Author's elaboration and adaptation based on Aguilera et al. (2018), Centro Nacional de Estimación Prevención y Reducción del Riesgo de Desastres (2021), Gobierno Regional de Arequipa (2018), and Universidad de Chile et al. (2002).

highest percentage (63.3%) indicating a prominent level of richness and bioecological values and its relevance for protecting and conserving unique ecosystems, protected areas, and important bird sites, such as the Salinas National and Aguada Blanca Reserves. Our findings point to the watercourses and water bodies as important connecting factors in riparian forests. On this basis it can be stated that conditions exist for the maintenance and provision of a wide range of ecosystem services that support human life and well-being despite the fact that the barrier-affecting index suggested the high significance of these existing barriers, in more than a quarter of the test territory such as las High Andean areas with little or no vegetation, urban areas expansion, deserts as well as mining tailings. According to Coutts and Hahn (2015), the provisioning of services considered natural products is essential for human health as they allow us to exist. Similarly, Wong et al. (2018) highlighted the importance of assessing the overall sustainability of GI projects and their dependence on the water infrastructure. Therefore, the conservation, restoration, ecological development and sustainable management of these habitats are essential to ensure that these services continue to be available for present and future generations, especially in times of crisis and public health risk. Despite these positive and encouraging results at the level of ECI, Ecological Status, CES; due to the lack of detailed information available at the level of the species that inhabit these habitats it can only be deduced that there is also a great richness and a high variety of species that deserve to be investigated (e.g. in the case of fauna, it was not considered because of the lack of geospatial information) and documented in detail and urgently in future research. Furthermore, despite these positive and encouraging results at the level of ECI, Ecological Status, CES; regarding population permeability, access roads exhibited a vital network of roads distributed from urban areas to the highlands that has a positive side of connection for the population but above all facilities negative impacts considering that there are no adequate control and surveillance mechanisms. Rodríguez-Loinaz et al. (2018) reported that the contributions of GI to human welfare are well recognized, but local governments do not correctly implement them. In relation to the results obtained from the COVID-19 risk Centro Nacional de Estimación Prevención y Reducción del Riesgo de Desastres (2021), it can be highlighted that the study focused on urban areas, as these were the sectors of greatest contagion. In the city of Arequipa a total of 68.2% (648,867 inhabitants) of the population was at High risk levels, in addition to Very High risk. There was no major difference in terms of gender but in terms of age highlighting age groups such as the most vulnerable group, aged 65 years; as well as the economically active population group aged 30–64 years, where 70.1 % of it was an economically active population with greater spatial displacement, localized in the central sectors of the urban area of the districts and therefore considered the most mobile exposed population. This situation is related to the statement that the districts with the highest number of positive cases played an important role by the high densities in the central urban environment of each local area as well as by the residence of the population in high density blocks. This study also states that in Arequipa low levels of poverty predominate, while the population with high levels of poverty is in the outskirts of the city. It can be affirmed that although the low poverty ranks were in the outskirts of the city, they were equally affected by the urgency of satisfying basic needs in the city center as well as by the mobilization to the centers of the nearby districts.

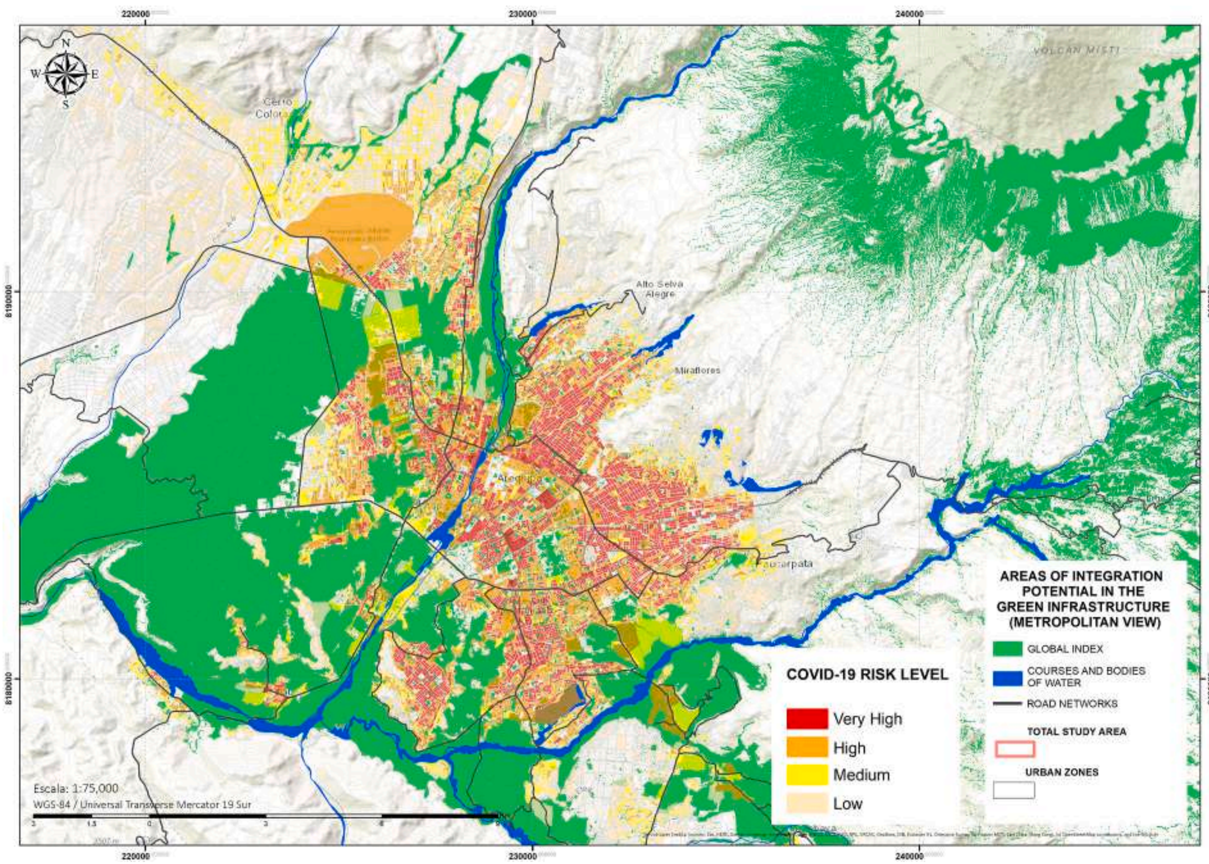

Fig. 14. PIAGI, the potential integration areas for green infrastructure, of Metropolitan Arequipa for 2021. Note: A specific view of the PIAGI at Metropolitan Arequipa level is displayed as well as the corresponding overlap with the fifth dimension of GI, that is, with the levels of risk by COVID 19 at the metropolitan level. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
Source: Author's elaboration and adaptation based on Aguilera et al. (2018), Centro Nacional de Estimación Prevención y Reducción del Riesgo de Desastres (2021), Gobierno Regional de Arequipa (2018), and Universidad de Chile et al. (2002).

It can be stated that the factors of greatest contagion interacted negatively with each other thus increasing the level of COVID-19 risk in a metropolis of more than one million inhabitants, where there was a lack of prevention, urban planning that included public health aspects as well as a lack of control of the factors that determined these high levels of contagion during the COVID-19 pandemic.

GGII mapping exhibited the bioecological capacities and values of the surrounding urban areas and their relationships with COVID-19 risk (Centro Nacional de Estimación Prevención y Reducción del Riesgo de Desastres, 2021). GGII exhibited areas with high ecological potential and crucial biodiversity in vegetation cover levels. Bioecological capacities were observed to be much stronger in higher areas than those farther away from urban areas, while these capacities were not observed within urban areas. The loss of GGII connectivity in urban areas posed a threat to the high connectivity of the highlands, thereby decreasing biodiversity and public and recreational spaces but increasing temperature, pollution levels, flooding, and climatic changes, which increased the risk of the spread of COVID-19. The result of the overlapping dimensions intersected with the COVID-19 risk layer (Centro Nacional de Estimación Prevención y Reducción del Riesgo de Desastres, 2021), implying that a high percentage of the area at risk by COVID-19 had a GGII that could reduce the 'very high, high and medium' risk levels of COVID-19, in so far as it has been established as a planned and organized network of natural and semi-natural areas comprising ecological components that provide a range of ES (Unión Europea, 2014) in both rural and urban settings (Zucchetti et al., 2020). Therefore, using GGII at various levels of spatial planning is crucial, as it can aid decision-making (Brom et al., 2023).

In considerable detail, the PIAGI exhibited the relationships between green spaces and their distributions and behaviors in rural and urban areas. Compared with the GGII, it demonstrated relatively low values for the research area (Fig. 17).

These areas had high vegetation cover and bioecological values throughout the year, not only in rainy seasons. Therefore, their conservation is essential. A similar relationship between green spaces and their distributions and behaviors in rural and urban areas was visualized compared with that for the GGII; that is, a continuous and more substantial relationship was observed in the high areas, which were far from the urban areas, whereas it was not observed in the urban areas. Furthermore, it was again observed in the agricultural areas. The loss of PIAGI connectivity in urban areas posed a threat to the existing high connectivity in the uplands and further increased the factors contributing to the risk of COVID-19 spread. In contrast, out of a total area of 1187.52 (100%), the intersection between the COVID-19 (Centro Nacional de Estimación Prevención y Reducción del Riesgo de Desastres, 2021) and PIAGI risk layers with the "very high," "high" and "medium" levels reached 891.99 ha (75.13%), which implies a high capacity to reduce contagion risk levels in future pandemics (Fig. 18).

Finally, it is presented some limitations as well as complementary contributions of the study. The analysis elements of the five dimensions of GreenNet-Covid19 respond to the resources and cartographic databases collected for the testing territory as the use of the official proposal of the Peruvian government for the fifth dimension based on risk by COVID-19, Centro Nacional de Estimación Prevención y Reducción del Riesgo de Desastres (2021). However, it lacked landscape baselines, field surveys, and updated and detailed geospatial information, which

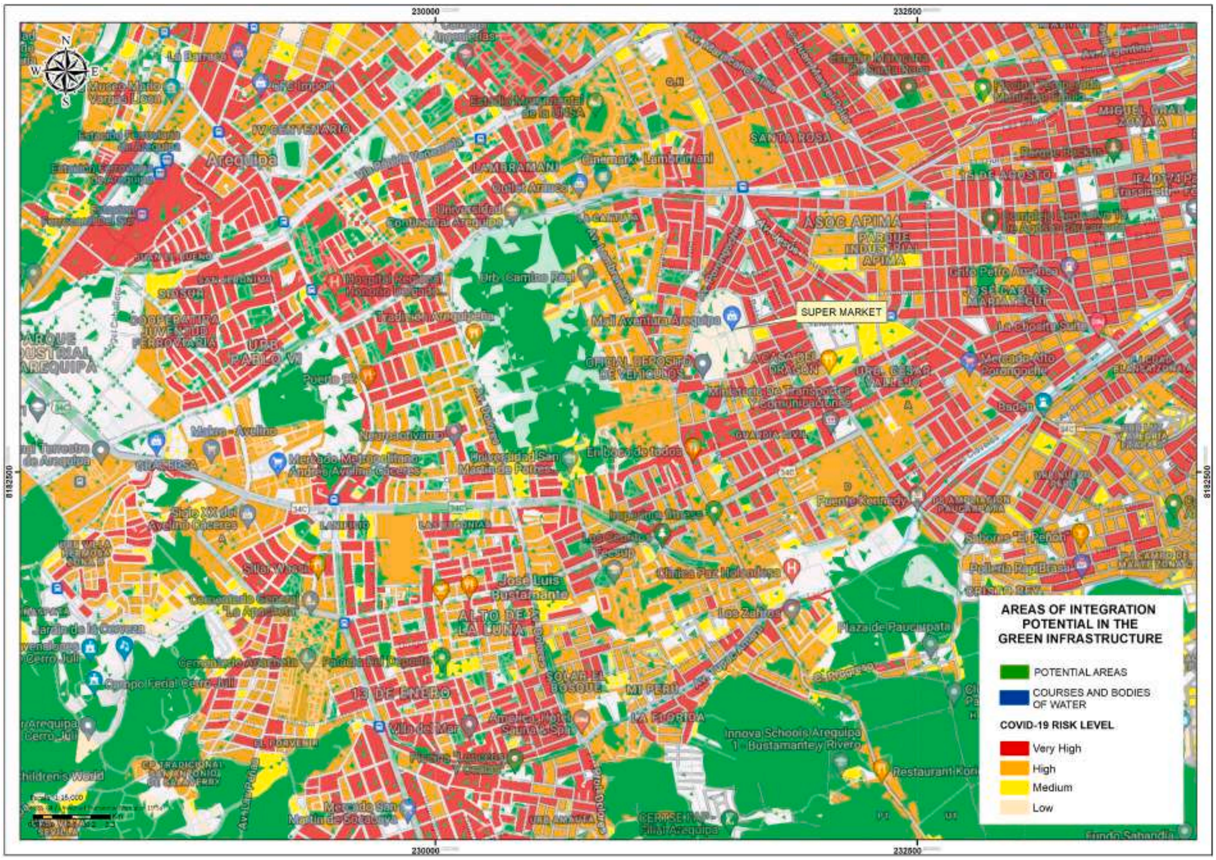

Fig. 15. Detailed view of the northeast of the city of Arequipa, specifically of the districts of José Luis Bustamante y Rivero and Paucarpata. Note: The PIAGI are visualized within the dense urban fabric, where the levels of risk of covid-19 cases were considered, also considering socioeconomic aspects, social inequality, as well as demographics and covid-19 cases respectively.
Source: Author's elaboration and adaptation based on Aguilera et al. (2018), Centro Nacional de Estimación Prevención y Reducción del Riesgo de Desastres (2021), Gobierno Regional de Arequipa (2018), and Universidad de Chile et al. (2002).

determined that some layers were not consulted using the Aguilera et al. (2018) method in the cases studied. Thus, the limitations for a more effective development of the mapping were the absence of data collection at a detailed level, which could have helped to identify some species that may be endemic; on the other hand, it would help to understand their territorial extent and evidently their ecosystemic relationship. The data collection that was obtained for the development of the maps did not necessarily show the level of detail required because the information was outdated and that implied a great challenge. It was not possible to carry out field visits to calibrate or corroborate the information that was being handled, and logistical and operational resources were scarce and were a major constraint. Finally, it should be mentioned that the issue of GI and its relationship with COVID-19 have not been investigated in Peru. Therefore, no investigations could have served as benchmarks, and it has not been possible to compare other investigations with different results. For this study, an added value was the fact that we found the existence of endemic species on the slopes of Misti Volcano, as well as the existence of high Andean wetlands in the district of Chiguata and mostly in the Salinas y Aguada Blanca Reserve, thus evidencing their existence with a visible and singular distribution from a cartographic perspective, which warrants further investigation.

GreenNet-C19 aims to be a breakthrough as a theoretical and practical methodological contribution, considering methodological simplification and adaptation, the treatment and post-processing of geospatial data in the absence of information, the adaptation of new processes in an environment with urban and peri-urban areas and the current risk to COVID-19.

A basic general structure of the PIAGI is offered to avoid the risk of accelerated loss of strategic areas with essential life zones for structuring the integral ecological network of GI, which redirects ecosystem resources in the future to be able to define prevention strategies for critical public health situations and allows contributing to the adaptation and mitigation of climate change. The preservation of PIAGI areas intersected with high COVID-19 risk level is recommended through a comprehensive GI proposal with health and equity criteria. Within these areas, it is recommended to prioritize the districts of Arequipa (Cercado), Paucarpata, Cerro Colorado, José Luis Bustamante y Rivero, Mariano Melgar, Miraflores, Alto Selva Alegre, Jacobo Hunter, Yanahuara and Cayma, paying attention to the central sectors of the urban area as well as the central environment of the city, giving priority to the Urban Basin of the Chili River and its countryside to ensure its connectivity and preservation. For the implementation of GI projects based on the findings of the GGII and PIAGI, permanent protection strategies can be defined through green infrastructure projects on an urban scale, and thus control and monitoring mechanisms with citizen participation can be proposed in an efficient way.

The implementation of new policies and management instruments is recommended, as in the case of Germany, where urban management has the capacity to promote the planning and implementation of green and blue spaces with a focus on urban sustainability and where urban management concepts are directly related to socio-political priorities. In this way the urban GI planning approach highlights the role of biodiversity in an urban context by reconciling interests and striving to achieve the same objectives. Biodiversity protection is therefore defined as a means of connecting human needs with ecological issues, which is closely linked to the problem of climate change and public health.

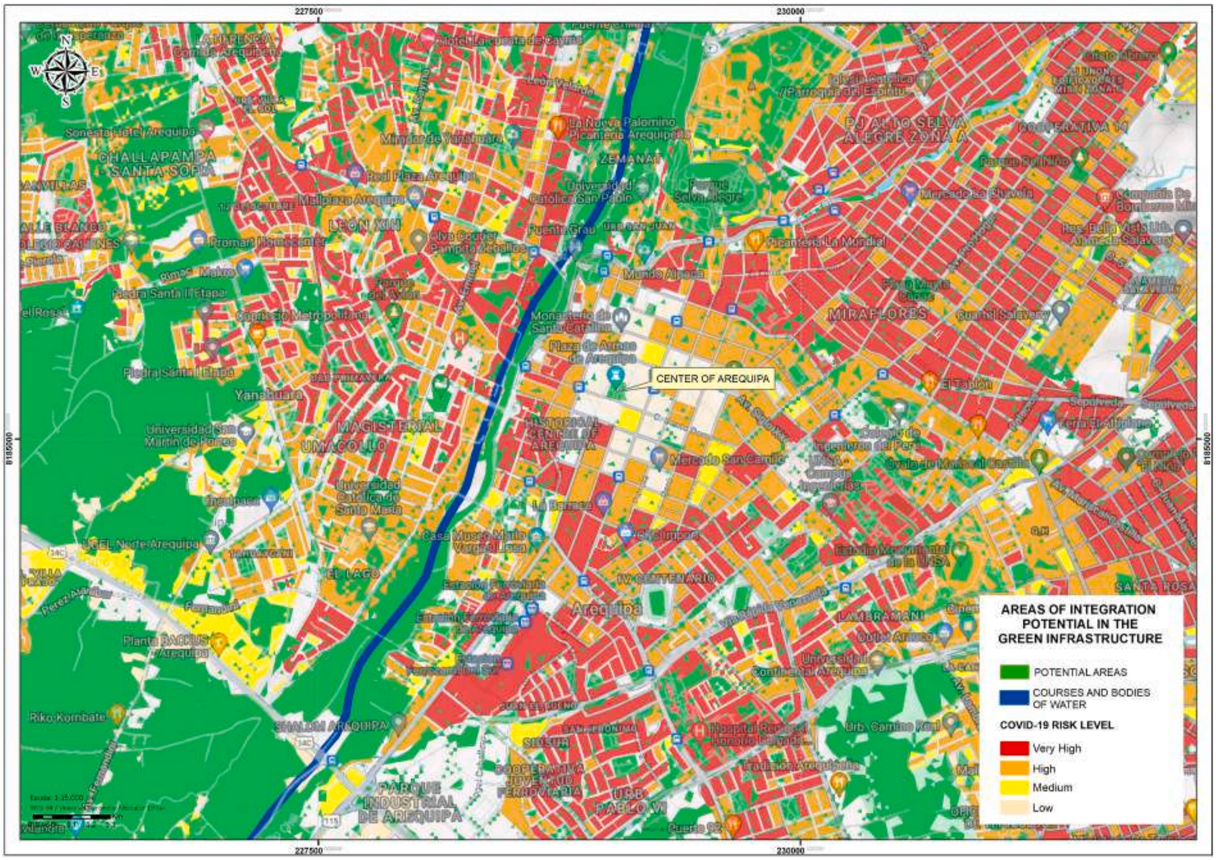

Fig. 16. Detailed view of a part of the historic center within the city of Arequipa, Note: The PIAGI are visualized within the urban fabric, as well as the levels of risk of covid-19 cases, where it also considers socioeconomic aspects, social inequality, as well as demographics and covid-19 cases respectively.
Source: Author's elaboration and adaptation based on Aguilera et al. (2018), Centro Nacional de Estimación Prevención y Reducción del Riesgo de Desastres (2021), Gobierno Regional de Arequipa (2018), and Universidad de Chile et al. (2002).

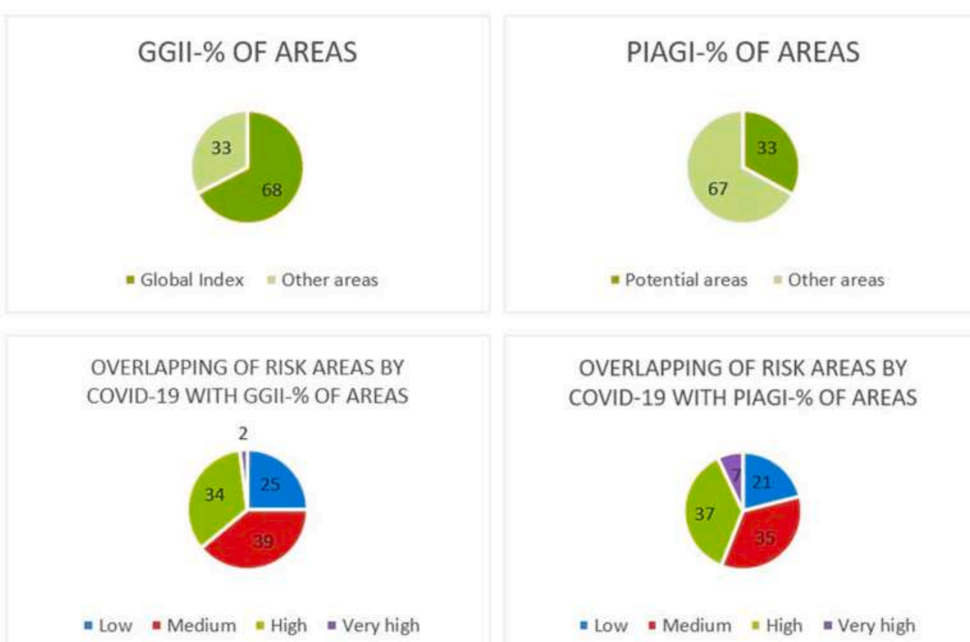

Fig. 17. Comparison between the percentages of the GGII areas and those of the PIAGI areas and their corresponding overlaps with the risk due to COVID-19 areas of the Centro Nacional de Estimación Prevención y Reducción del Riesgo de Desastres (2021) for Metropolitan Arequipa. Note: GGII – global green infrastructure index, PIAGI – potential integration for green infrastructure. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
Source: Author's elaboration based on Centro Nacional de Estimación Prevención y Reducción del Riesgo de Desastres (2021).

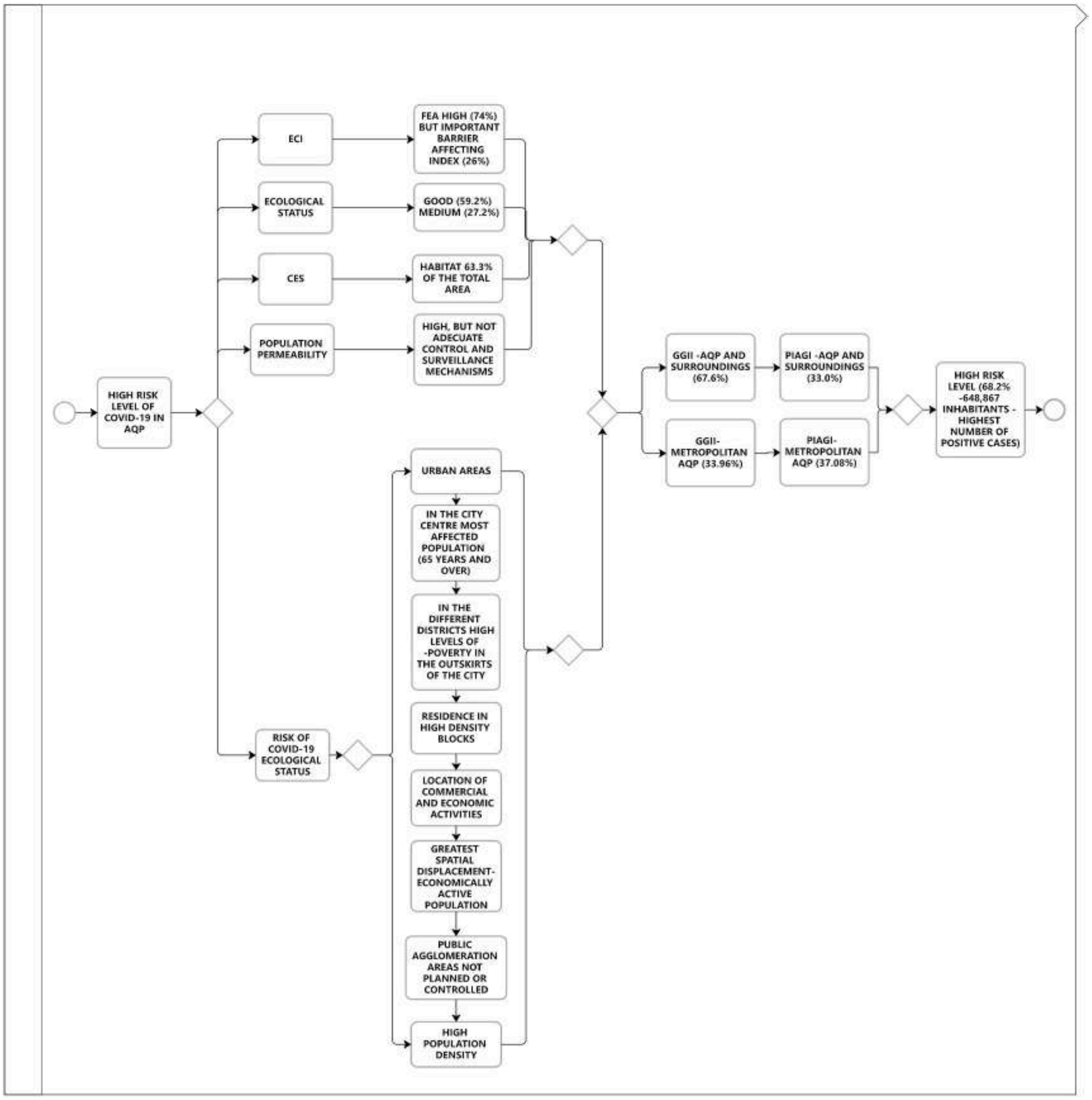

Fig. 18. Diagram of the explanation of the High Levels of Risk to COVID-19 through the application of the GreenNet-Covid19 methodology in the city of Arequipa. Note: Explanation of the High-Risk Levels for COVID-19 through the application of the GreenNet-Covid19 methodology in the city of Arequipa applying the different methodological steps including the overlap of Risk by COVID-19.
Source: Author's elaboration and adaptation based on Aguilera et al. (2018) and Centro Nacional de Estimación Prevención y Reducción del Riesgo de Desastres (2021).

Having the same objectives will mean, depending on each reality, reconciling the biodiversity objectives with the Urban Sustainability objectives (Hansen et al., 2023). It is recommended that financing mechanisms like those in Colombia, where the Urban Environmental Management Policy - PGAU is mainly financed with resources from the responsible institutions, such as the Ministry of Environment, Housing and Territorial Development, environmental authorities, territorial entities, research institutes, and trade unions, among others (Ministerio de Ambiente Vivienda y Desarrollo Territorial, 2008). The Ministry of Environment can manage the procurement of additional resources, such as credit or international cooperation resources, to strengthen its financial execution.

The possibilities of future investigations are abundant, taking this investigation for green infrastructure in Arequipa and Peru as a base. Future research should include methodological proposals with detailed spatial information, specific ecosystem distribution in rural areas and watersheds, permeability to fauna, valuation of ES in rural and natural areas, GI contributions to climate change mitigation and adaptation, and reclassification using a more detailed and updated database for defining the PIAGI. It is recommended that specialized GI studies at the urban scale be implemented within the ZEE to allow a more detailed application of methodologies such as GreenNet-C19 and thus obtain a more detailed GGII and PIAGI.

Our results encourage the dissemination and use of the GreenNet-Covid19 method, thereby promoting GI, GGII and PIAGI development that we consider strategic for the reduction of the risk due to COVID-19.

5. Conclusions

The structure of the GreenNet-Covid19 methodology defined the GGII and PIAGI in the absence of updated geospatial information for critical COVID-19 contexts, considering the methodological proposal by Aguilera et al. (2018) as a reference along with an additional fifth dimension called risk due to COVID-19 (Centro Nacional de Estimación

Prevención y Reducción del Riesgo de Desastres, 2021); was validated in the testing area of Metropolitan Arequipa and its surroundings being defined for this area the GGII and the PIAGI which, can be considered for land-use planning at distinct levels and thus begin the process of defining GI proposals for this territory.

It can be concluded at the level of the GID that the dimensions analyzed have a common constant and that is the fact of having obtained positive ratings at the level of ECI, ecological status, ecosystem services as well as accessibility and permeability to the population, but also negative ratings due to the existence of barriers. In the COVID-19 risk dimension, most of the population present levels of very high and high levels in urban sectors (central, commercial and economic areas) where the GID present higher levels of weakening through barriers, contamination, change of land use, among others.

It can be also concluded that the GGII showed high ecological and biodiversity potentials at the land cover level, and the ecological potential is visible in rainy seasons and much more visible in the higher Andean zones and far from urban areas. The loss of GGII connectivity in urban areas posed a threat to the high connectivity of the highlands, thus increasing the risk of COVID-19 spread and climate change. A high percentage of areas at risk due to COVID-19 had a GGII that could reduce the levels of contagion risk.

Regarding the PIAGI, it is concluded that these show relatively low values compared to the GGII, being areas with vegetation and a high bioecological value throughout the year and not only in rainy seasons, so their conservation is essential. A similar but reduced pattern can be visualized when comparing the GGII, characterized by being continuous and more permanent in the high Andean parts and far from urban areas.

It can also be final concluded that the loss of PIAGI connectivity in urban areas strengthened the factors contributing to COVID-19 propagation and climate change risk and that the intersection between the COVID-19 and PIAGI risk layers demonstrated a high capability for reducing the contagion risk in future pandemics.

CRediT authorship contribution statement

Dora Josefina Rocío de los Ángeles Guillén Tamayo: Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Leyla Elena Lascar Alarcón de Malpartida:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Valkiria Raquel Ibárcena Ibárcena:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Ginna Paola Cano Castro:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Leslie Janina Mena Alanoca:** Writing – original draft, Investigation, Conceptualization. **Randy Branny Carreon Oviedo:** Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Andreas Braun:** Writing – review & editing, Conceptualization.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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