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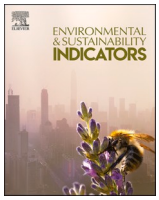

Urban metabolism of human settlements in small island-protected environments

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ABSTRACT

Few studies have succeeded in illustrating the relationships between resources, socio-territorial dynamics, and the environs in protected island environments of Outstanding Value, a quality that positions them as experimental laboratories for the study of human evolution and the planet's ecosystems. The literature reviewed refers to different scientific productions where the analysis of the flow of matter and energy is applied to study urban metabolism. As a methodology, three important phases were established. First, four authors with different approaches to urban metabolism were identified. Second, the study was delimited with a list of seven protected island territories, which meet the following requirements: small scale, possessing human settlements, and having a Cultural/Natural Heritage nomination by UNESCO. Third, the socio-territorial dynamics of the settlement were analyzed with the instrument of five variables: biophysical, demo-geographical, socioeconomic, sociocultural, and regulatory/legislative. A qualitative description of Santa Cruz Island (Galapagos) is made in light of the studies conducted by the authors cited above. The results obtained in this review are the identification of management indicators and positive aspects generated from the transfer of knowledge, based on a qualitative analysis of the measurable relationships that exist between variables-human settlement-territory.

1. Introduction

Every human settlement produces transformations of the natural environment, and the process of urbanization, as well as cities, have become the model of permanent human settlement that contains most of the world's population, despite their growing environmental impact. The ecosystems of small archipelagos—Galapagos Islands in Ecuador, Eolie Islands in Italy, Lord Howe Islands in Australia, Fernando do Noronha Islands in Brazil, Levuka Port Town in Fiji, etc.—show a high ecosystemic fragility and socioeconomic and environmental vulnerability. Thus, despite containing small urbanized human settlements, the environmental impact is considerably high if the urban metabolism is linear. Further, the impact is generated by the transformation of resources demanded by tourist activity—a common element in these enclaves. Therefore, the study of the human settlement model is as relevant to urban metabolism as the knowledge of the fragility of the natural environment from which the settlement captures its resources or discharges its waste (see Table Data 1 and 2).

The United Nations Educational, Scientific and Cultural Organization (UNESCO) defines protected natural environments as natural laboratories that contain the most important habitats for the study of ecological and biological processes in the evolution and development of all ecosystems. (terrestrial, aquatic, coastal, and marine) and plant and animal communities, which transfer them an Outstanding Universal Value (UNESCO, UNESCO, 2021). Some studies highlight the relevance of these environments for understanding various phenomena; for example, the Galapagos Islands are considered important within the theory of evolution by natural selection. (Salinas-de-León et al., 2020). Studies carried out on the volcanic island of Stromboli in the Aeolian archipelago show the discovery of three well-preserved and unprecedented tsunami deposits related to repeated flank collapses during the Late Middle Ages (Rosi et al., 2019).

According to Singh et al. (2020), few studies on small island territories analyze the links between the use of resources by society, the derived benefits, and the environment. This represents a knowledge gap that needs to be addressed. The structure and shape of the territory, the physical environment, and the cultural characteristics of its settlements intertwine the variables that give rise to the metabolism of its cities.

Through a theoretical and qualitative analysis of five identified

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Abbreviature

HS	Human Settlements
St-D	Socio-Territorial Dynamics
PEI	Protected Island Environment
PEI's	protected islands environments
UM	Urban Metabolism

variables, this review manages to obtain a graphic reading of how the metabolic cycles of human settlements originate in these ecosystems. As a result of the relationships between territory-settlement-culture and territory-settlement-economic activities, metabolic cycles are opened by the flows of matter and energy used in the various forms of construction of physical space practiced by the inhabitants of these islands. These open metabolic cycles give way to biological and physical transformations impacting endemic ecosystems and environmental systems. Soil contamination, reduction of water resources, and climate deterioration, as well as the extinction of species in these territories, reflect a metabolism determined by human incursions (settlement mechanism and collective memory). of new cultures migrating to these territories.

2. Materials and methods

To elaborate this review, first of all, four later authors have been identified, which account for the progress of an approach that has been studied for about 50 years. Their work is applied at various scales and offers a broad perspective for the analysis of metabolic flows in cities.

- Abel Wolman and Peter Newman have shown how economic and social aspects of cities are integrated with environmental aspects (Wolman 1965; Newman 1999).
- Chris G. Van Leeuwen offers a theoretical approach through the Ecosystemic approach, which helps to structure the chaotic web of variables and relationships existing between the systems and subsystems of an urban environment (Roggema, 2019).
- Jón Kristinsson focuses his work on the building itself, trying to optimize the indoor and outdoor climate by using technological innovations that take advantage of the different flows available in the environment and aim to close resource and waste cycles in the best possible way (Roggema, 2019).

Second, seven territories located in different regions of the world were identified that meet three predefined criteria: (1) they are small-scale island territories, (2) they contain human settlements; (3) they have UNESCO recognition as World Natural and/or Cultural Heritage; by this document, they are recognized as protected island environments (PIEs). Thirdly, four variables considered in the studies of the cited authors are included: (a) biophysical, (b) demo-geographic, (c) socio-economic, (d) legislative/regulatory; in this review a fifth variable is added: (d) sociocultural, which, according to the historical record of the settlements, has considerable weight when measuring the relationship between the settlement and the territory. Finally, a theoretical description of the urban metabolism of Santa Cruz Island is made under the study optics of the four authors. The study reveals how the urban metabolism of these environments is conditioned by the behavior of each of the identified variables.

Table appended to Fig. 1: Unique biodiversity and geological features of seven global island regions, emphasizing their historical, ecological, and architectural significance.

Arcipelago	Description
1	The Lord Howe Islands, with a distinct biota and the world's southernmost coral reef, comprise three primary islands, the Balls Pyramid, and adjacent islets, showcasing orographically-shaped landscapes.
2	Formed from submerged volcanic peaks, these islands host the Western Atlantic's densest tropical seabird population and unique examples of Atlantic island and oceanic mangrove forests. Fernando de Noronha and Atol das Rocas represent over half of the South Atlantic's insular coastal waters.
3	The Galapagos Marine Reserve boasts diverse underwater life, from corals to sharks. Its geology, originating from the seafloor and rising above sea level, plays a crucial role in influencing the archipelago's ecological, evolutionary, and biogeographical processes. This biodiversity is reflected both on individual islands and the archipelago collectively. Consisting of 234 land units, including 17 islands and islets, the archipelago's dynamic geological nature suggests this number may change over time due to ongoing volcanic activities.
4	Levuka Historical Port Town exemplifies the cultural interchange during European maritime expansion in the 19th-century Pacific Islands, reflecting global European colonization characteristics and institutions.
5	The Aeolian Islands, comprising seven main islands and accompanying islets, offer crucial insights into island formation and volcanic activity, showcasing both vulcanian and strombolian eruption types
6	The Ogasawara Islands demonstrate unique evolutionary processes, showcasing a blend of Southeast and Northeast Asian plant origins. Distinguished by their high concentration of endemism and extensive

(*continued on next page*)

Data Table 1
Identification of protected island environments with human settlements.

Archipelago	Islands/Cities	Origin	Land Area km^2	Population	Data inscribed	Category	Criteria UNESCO	State name	Region
Lord Howe Island Group	Lord Howe	a	56	382	1982	c	vii, x	Australia	Asia and the Pacific
Fernando do Noronha and Atoll das Rocks Reserves	Fernando do Noronha	a	26	2630	2001	c	vii, ix, x	Brazil	LATAM and the Caribbean
Galapagos Islands	Santa Cruz/Puerto Ayora City	a	116	15,393	1978/ 2001	c	vii, viii, ix, x	Ecuador	LATAM and the Caribbean
Levuka Historical Port Town	Levuka/Levuka City	a	106,4	4250	2013	d	ii, iv	Fiji	Asia and the Pacific
Aeolian Islands	Lipari/Lipari City	a	88,61	11,386	2000	c	viii	Italy	Europe and North America
Ogasawara Islands	Ogasawara/Chichi Jima	b	23,8	3029	2011	c	ix	Japan	Asia and the Pacific
Cultural and Historic Ensemble of the Solovetsky Islands	Historical, Cultural, and Natural Site of Solovetsky	b	246	300*	1992	d	iv	Russian Federation	Europe and North America

This table locates us geographically in the archipelagos containing the identified islands and highlights the land area of the entire heritage property. (*): These data correspond to the historical record on the website: (СОЛОВКИ.РУ! 2021).
Oceanic origin (a); Volcanic origin (b); Natural Category (c); Cultural Category (d).
Source: own elaboration as a result of the review of the bibliography consulted https://whc.unesco.org/en/list/186#media.

(*continued*)

Arcipelago	Description
	adaptive radiation, especially in land snails and vascular plants, these islands stand out in illustrating evolutionary phenomena, particularly given their limited size.
7	The Solovetsky Islands ensemble, encompassing six islands, exhibits unique architectural integrity through its distinctive facade design and dense building placement in confined spaces.

[1]**Source:** own elaboration based on the review of the bibliography consulted https://whc.unesco.org/en/list/186#media

3. Urban metabolism study approach

Urban metabolism was introduced by Wolman in 1965, (Palme and Salvati, 2020), it is a study approach that was born as a response to the need to achieve greater sustainability in cities. This paper aims to review whether this approach applied in a different and bigger scale context such as a city, can be used for the analysis of the urban metabolism produced by human settlements in small-scale protected island environments, considering that the residual entropy of large cities is also present in these territories through culture and their socioeconomic activities, (Bettignies et al., 2019; Zazo-Moratalla et al., 2019; Takebayashi and Kyogoku, 2018).

3.1. What contributions do the study approaches of these cited authors have to offer?

In an attempt to simplify the approaches, their results are described in response to the following questions: *1) What do these theories say? 2) In which case studies were these theories applied? 3) What were the variables applied to the case? Y 4) What was the contribution of this theory?*

- ***The Metabolism of Cities, (Wolman, 1965):*** The metabolic requirements of a city can be defined as all the materials and products needed to sustain its inhabitants at home, at work, and leisure. Over some time these requirements include even the construction materials needed to build and rebuild the city itself. The metabolic cycle is not completed until the wastes and residues of daily life have been removed and disposed of with a minimum of nuisance and hazard. Each item is shown in tons per day for a hypothetical U.S. city with a population of one million. In his analysis, he used three inputs: water, food, and fuels; and three outputs: wastewater, solid waste, and air pollutants. He projected that water demand for this city (hypothetical 1 million inhabitants) would grow by 200 billion gallons per day over 20 years (1980–2000). Demonstrating that consumptive water use is inefficient and that more than 80% of the water used in the production and consumption cycles is not captured for new uses, because of contamination by solid waste and emissions (carbon and sulfur).
- ***The Ecodevice Model, (Van Leeuwen, Chris G.; 1981):*** The integration of urban flows as part of an ecological conceptual model. In this model, the objectives for the sustainable management of the city's flows were established. The ecosystems approach is a theoretical approach that helps to structure the chaotic web of variables and relationships. The ecosystems approach has its origins in biology. It helped biologists to understand the complexity of organisms and the delicate relationship between populations and their environment. Because subsystems are smaller, i.e. they consist of fewer variables and interrelationships; it is easier to get to know them or to develop some understanding of the mechanisms at work in the system. In turn, subsystems can be split up into smaller subsystems. For example, when studying sea level rise in low nations, such as the Netherlands, or some tropical island groups as the Maldives, you may conclude that sea level rise is a problem that requires investing in higher levees. When studying sea level rise on a regional level, you may conclude that it could be wiser to invest in the reallocation of human settlements. Spatial scales Lifecycle stages, Flows. The ecosystems approach suggests that –analytically– we can distinguish subsystems that together constitute this one big system. Because subsystems are smaller, i.e. they consist of fewer variables and interrelationships; it is easier to get to know them or to develop some understanding of the mechanisms at work in the system. In turn, subsystems can be split up into smaller subsystems. Where to draw the line between systems and subsystems, is thus purely a theoretical exercise. However, the chosen system boundaries are of great influence on the problem diagnosis and potential solutions.
- ***The Extended Metabolism Model, (Newman, 1999):*** It is possible to define the goal of sustainability in a city as the reduction of the city's use of natural resources and production of wastes while simultaneously improving its livability so that it can better within the capacities of the local, regional and global ecosystems. This is set out in a model that is called the 'Extended Metabolism Model of the City'. Metabolism is a biological system's way of looking at the resource inputs and waste outputs of settlements. This approach has been developed by a few academics over the past 30 years, though it has rarely if ever been used in policy development for city planning. The approach adopted here is based on the experience of the Human Settlements Panel in the Australian State of the Environment Reporting process (see Newman, 1999) and on the experience of making a sustainability Plan for Philadelphia with the graduate students at the University of Pennsylvania in 1995 and 1997, as well as awareness of the World Bank/UN-Habitat project on developing sustainability indicators for cities (World Bank, 1994). Traffic and mobility, working with the parameters in an integrated way to create a spatial perspective. The metabolism approach to cities is a purely biological view, but cities are much more than a mechanism for processing resources and producing wastes, they are about creating human opportunity. This basic metabolism concept has been extended to include livability in these settlements so that the economic and social aspects of sustainability are integrated with the environment.

Table 2
Relationship between author-study approaches and multidisciplinary observation methodology.

Variable Authors	Biophysical	Demo-geographic	Sociocultural	Socioeconomic	Regulatory
Wolman, Abel	Water/air/soils	hypothetical population	X*	Water production and consumption costs	Water resource uses and water resources management
Van Leeuwen, Chris G.	relationship between population and environment	City of flows	X*	urban design	X*
Newman, Peter	land, water, biomass, energy, building materials, imported goods	Australia City and Pennsylvania	cultural institution	traffic and mobility	creation of sustainability indicators
Kristinsson, Jón	biotic, abiotic, urban, and atmospheric systems	Dutch town of Venlo	X*	integration of technological innovation to take advantage of air conditioning	closure of resource and waste cycles

This table reviews whether the variables identified for the study of the urban metabolism of human settlements in small-scale PEIs have been considered by the authors.
X*: data not collected.
Source: own elaboration because of the review of the bibliography consulted

– ***Integrated Sustainable Design, (Kristinsson and Timmeren, 2008):*** Integrated sustainable design theory. He invented a three-dimensional model in which, for each layer, specific flows were symbolized as inflows or outflows, which could re-enter the system at another level. In this way, a complete three-dimensional model of a city could be drawn, and the city is seen as an ecosystem in itself. Villa Flora is an office building in the Dutch town of Venlo. Construction began in 2010 and was completed in early 2012. With the completion of his masterpiece, Villa Flora, Kristinsson again sets the benchmark for sustainable architecture. Biotic, abiotic, urban, and atmospheric systems. Most of Kristinsson's work focuses on the building itself, trying to optimize the indoor climate and the direct environment of the building, using technological innovations that take advantage of the different flows available in the environment and aim to close the resource and waste cycles as well as possible.

The studies of urban metabolism conducted by these authors consider four of the five variables identified in the proposed observation methodology. The interaction of the sociocultural variable with the territory during the entire metabolic process of a settlement—inputs/dynamics/outputs—is not included in these works. Newman (1999), in his analysis of the Extended Metabolism Model, considers "cultural institutions" as one of the dynamics mentioned. However, no works integrate the sociocultural aspect as a variable that can determine the metabolism of an urban settlement or city. This review finds it indispensable to include it to observe its behavior and impacts on the territory.

Nevertheless, the urban metabolism approach has been studied in cities, but the concept of the city itself may not be adequate for applying this approach to small islands. The city is the major scenario of transformation of the inhabited and living space in which human beings develop (Maslow, Sthepen, and Gary, 1998). The city as a concept has evolved around the multiple processes of change, giving it the attributes of a living organism, which can create, produce, and expand. The definition of a city has been discussed over the years and developed according to different disciplines. Below are some of its definitions:

- The European Statistical Conference of Prague, held in 1966, proposed, without acceptance, to consider as cities the agglomerations of more than 10,000 inhabitants and those of between 2000 and 10,000 inhabitants if the population dedicated to agriculture did not exceed 25% of the total.
- The political concept of the city is applied mainly to urban conglomerates with capital entities and greater importance in the region and that which assume the powers of the State or nation.
- In the religious concept, both in the High Middle Ages and other periods such as the Renaissance and before the twelfth century, a city only had a cathedral within its walls where a bishop held his chair because, in the past, cathedrals were also educational centers.
- Urban ecology studies the city as an ecosystem and analyzes the flows of matter and energy between the city and its surroundings (Maslow, Sthepen, and Gary, 1998).

Configuring the above definitions, a city can be studied from different perspectives: a living organism, if we focus on production and consumption as its main arteries. However, if a city can satisfy a standard of living with equality for all its inhabitants, it can be considered an "entity of common welfare." Nevertheless, if statistics—by the number of inhabitants it possesses—determine its development, then politics confers on it an "administrative" nature. Last but not least, technology seeks its re-emancipation by abstracting it from all its human peculiarities, giving it life through efficient intelligent management models.

Unlike the accelerated pace at which cities on continents currently grow, island human settlements are formed with other temporal characteristics, which are closely linked to the availability of their resources. Lipari Island, for example, has a record of settlements developed over approximately 6000 years, although it had a population of approximately 20,000 inhabitants in 15o0 A.D.; today it has only half that number. Another case is experienced by Levuka—the arrival of its first migrants is recorded in 1800 A.D.; however, currently, it only has approximately 4200 inhabitants (see Figs. 2 and 3). Another distinction between the concept of "city" versus that of "human settlement" is the productive matrix they have. In the case of the settlements, the economic activities are based on agriculture, fishing, and tourism. Conversely, in the cities, the socioeconomic offer has diverse scales. Finally, notably, human settlements always develop geographically in territories that contain a considerable base of natural resources to guarantee the satisfaction of their habitability needs (Wolman, 1965). Achieving an adequate definition will allow an understanding of the functioning of PIEs (Steffen et al., 2015) (see Fig. 4).

3.1.1. *Let us look at Santa Cruz Island through the studies of these authors*

The Galapagos archipelago has an enormous natural base: 96.7% (7731 km^2) of its land area corresponds to the Galapagos National Park, and 3.3% (264 km^2) is occupied by human settlements on four islands: Floreana, Isabela, San Cristobal, and Santa Cruz. The Galapagos marine reserve corresponds to 100% of the marine zone within a 40 nautical mile band. The archipelago comprises 234 emerged land units, islets, and rocks—this figure remains open due to the dynamic nature of the geological processes that form this volcanic archipelago (Galápagos, n.d.).

Santa Cruz Island is located in the center of the archipelago, with an area of 986 km^2 and a maximum altitude of 864 masl, and is 3.6 million years old (Hole et al., 1999). The surface temperature of the island is abnormally cold and presents uncommon Australian characteristics regarding its location on the tropical equator. According to the work of (Auken et al., 2008), Santa Cruz Island has 38 watersheds; the Pelikan Bay watershed with an area of 42 km^2 provides water to the entire population. However, additional studies indicate the existence of a subway aquifer reserve of approximately 50 km^2. It is located where the Parque Artesanal and other population centers are currently located, which would require strict waste disposal standards to avoid contaminating the subway layer (Acciarri et al., 2021; Wolman, 1965), in his study of water flow analysis, proposes managing the resource by improving consumptive use, wastewater treatment, and reduction of atmospheric pollution. In recent years, the city of Puerto Ayora decided to transition away from home wastewater treatment plants (Ragazzi et al., 2016). This delay in urban management, combined with the city's recent urban expansion and the absence of a suitable model (Collivignarelli et al., 2012), has led to a decline in both the quality and quantity of resource replenishment黄静 (2020), (Pryet et al., 2012). Reports (Galápagos, n.d.) have highlighted a concerning decrease in the city's aquifer water levels. This decline necessitates an increase in drinking water imports from the continent, leading to an additional environmental concern of air pollution — a consequence that Wolman associated with the preservation of water sources.

Short-lived climate pollutants, such as black carbon, are powerful climate forcers with possible negative consequences on global warming and its impact on health (Highwood and Kinnersley, 2006). This is produced by the incomplete combustion of fossil fuels such as diesel and fuel oil and the burning of wood and other biomass (Rehman et al., 2011). Further, a few studies explore air quality in small cities (Liang and Gong, 2020). In the relationship between human settlements and sustainability made by (Newman, 1999) for the case of New Zealand, coastal cities are the least sustainable. They depend on automobiles, and their sustainability-transportation relationship is linked, causing greater fragility in their aquatic, marine, and terrestrial ecosystems. The city of Puerto Ayora is part of the "Zero Fossil Fuels for Galapagos" program, which involves the progressive reduction and replacement of fossil fuels for electricity generation and transportation (Galápagos, n.d.) (p. 127). According to (Eras-Almeida et al., 2020), this program can help reduce diesel consumption and electricity generation costs, leading to an

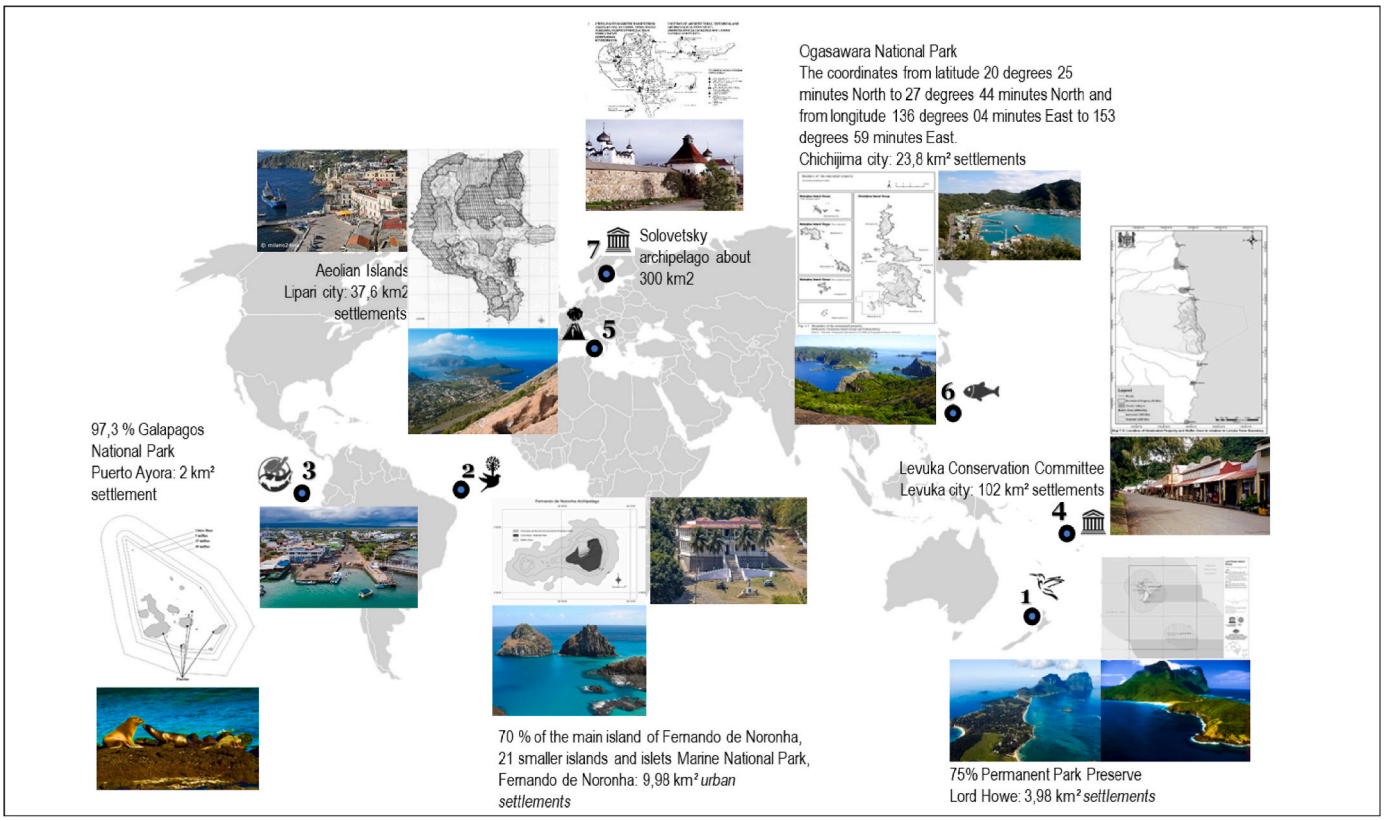

Fig. 1. Geographic identification of the seven island territories identified as having natural and cultural protection categories.
[1]**Source:** own elaboration based on the review of the bibliography consulted https://whc.unesco.org/en/list/186#media
(1)Lord Howe Islands Group; (2)Fernando do Noronha and Atoll das Rocks Reserves National Park; (3)Galapagos Islands; (4)Levuka Historical Port Town; (5)Aeolian Islands; (6) Ogasawara Islands; (7)Cultural and Historic Ensemble of the Solovetsky Islands.

increase in habitability levels and a waste reduction, as stated (Newman, 1999). Further, (Torsten Hardter et al., 2010) report on several projects and funding managed by the World Wildlife Fund for waste management. They warn that environmental safety in landfills is not satisfactory, lacking a measurement system to ensure respectful management of the environment in these sites, emphasizing the essential conservation of soils for the sustainability and preservation of water resources.

In the city of Puerto Ayora, 83% of the population resides in the urban area and 17% in rural areas, the first of which is formed by an urban port core with the role of port and which articulates with the rural area through a road axis from which the city expands (Galápagos, n.d.) (p. 56). The evolution of human settlements in these PIEs cannot be explained by a "staged urban development" approach (Re, 2012) (Figs. 2 and 3). This is because there are underlying mechanisms, such as touristification (Cakobau, 2013; De Oliveira and Marquesan, 2019; Hiernaux and González, 2014), that impact their metabolism. Alternatively, the ecosystemic approach of (Leeuwen, 1945) (Bueren et al., n.d.), helps understand the relationships between these two identified subsystems: urban transport and urban form. A possible outcome would be to know to what extent these scales determine the degree of sustainability of the city.

With half of the world's population living in urban areas and with the construction sector being the largest industrial sector and generator of approximately 40% of CO2 emissions per year, large cities suffer dramatic environmental changes and an evident reduction of sustainable livability for their inhabitants (Hung et al., 2019; Stocchero et al., 2017; Wang et al., 2021). These impacts are not indifferent to PEIs that must resist human incursions and atmospheric pressures that threaten their natural ecosystems and conservation. The carbon footprint of the city of Santa Cruz is 49,616 t CO2e and represents approximately 0.01% of Ecuador's emissions. Of this total, 18% corresponds to the residential sector (Cruz & Cruz, n.d.). Approximately 80% of the houses in the Puerto Ayora settlement have used concrete as the main material in their construction process, and 12% of the houses have been built progressively. As a result of this common construction system and the materials used, which, in many cases, employ inadequate techniques, 40% of the houses are currently showing signs of deterioration.

Construction accounts for 13% of global GDP—approximately $13 trillion per year (estimated for 2022). It is the largest industry in the world and is the most inefficient sector (Nahmens and Ikuma, 2012; Yılmaz and Bakış, 2015). In his Integrated Sustainable Design, Jón Kristinsson (Timmeren, 2008) proposes a three-dimensional model. Here, specific flows as inputs or outputs, which could re-enter the system on another level, are symbolized by layers. Thus, a complete three-dimensional model of a city, which is considered an ecosystem in itself, can be drawn. The projection of emissions on Santa Cruz Island according to the BAU scenario represents the growth of emissions until 2040 in the absence of reduction actions. The projections show that, up to 2040, total emissions could increase by 55% (from 49,616 t CO2,e in 2015 to 76,921 t CO2,e in 2040) (Cruz & Cruz, n.d.). Of this, approximately 45% of emissions will be produced by the residential sector. This is because discussing the materiality used in the production of physical space, as well as the impacts generated on the biophysical environment, is urgent for this environment. Explanation graph sheet in annexes. Fig. S3.

3.2. Five key variables for the study of urban metabolism in human settlements in protected island environments

Metabolism is the system of material and energy input, transformation and output, or waste generation in a city. This is because of its social, economic, political, and cultural dynamics, which interact at

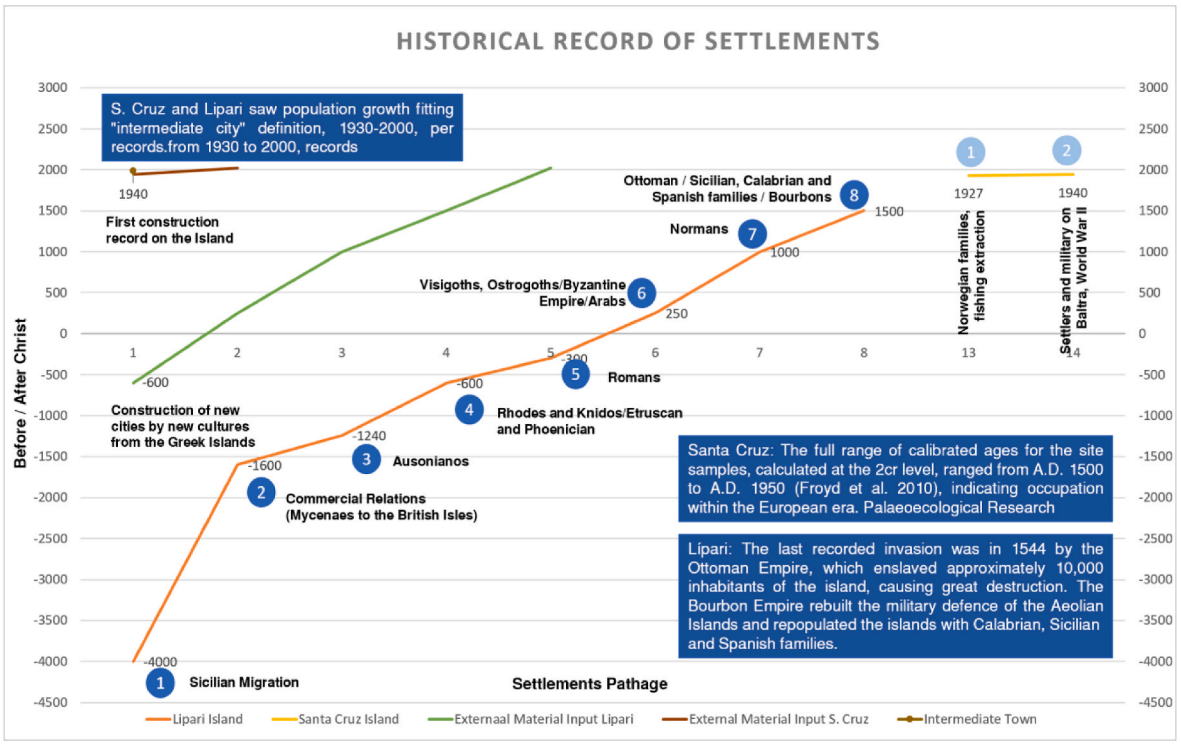

Fig. 2. Historical record of settlements on Santa Cruz and Lipari Islands

[2]| **The** historical record of human settlements marks the beginning of new metabolic cycles in these enclaves determined by the incursion of new cultures that introduced new architectural codes through the construction systems developed and the materials used. In some cases (Lipari and Levuka) these incursions have contributed positively, generating a balance between the habitat's needs and the biophysical environment's resources. In other cases (Santa Cruz and Fernando do Noronha), the forms of settlement and continental cultural processes have.

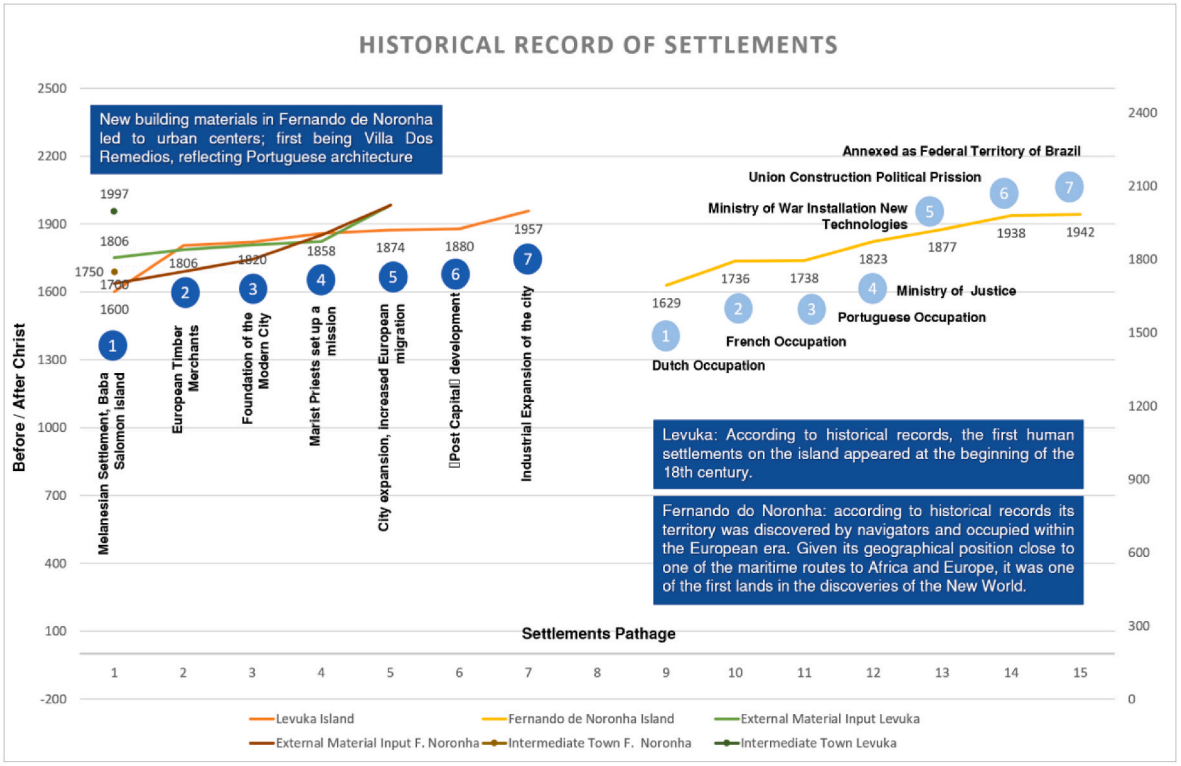

Fig. 3. Historical record of settlements on Fernando de Noronha and Levuka.
Source: own elaboration with data from the cited bibliography.

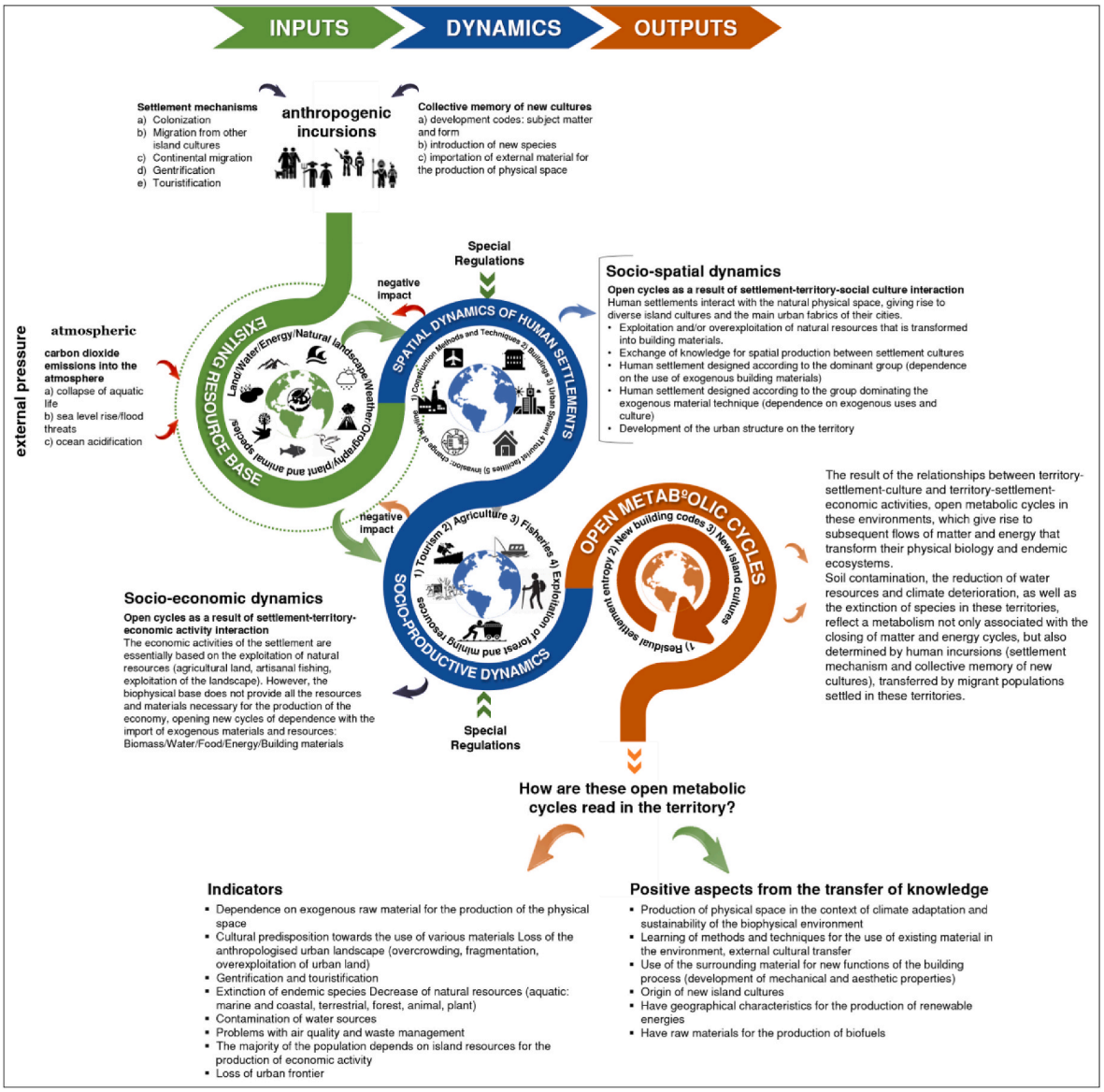

Fig. 4. Origin of metabolic flux: production of physical space by human settlement of a protected natural environment.
The graph of the spatial dynamics of human settlements corresponds to Graphic 2 of this article.
[5]**Source:** own elaboration based on the analysis of the case studies

different scales with the physical environment, generating systemic flows of matter and energy. PIEs, due to their fragile territorial structure—delimitation, smallness, isolation, fragmentation, and amplification by compression—(Rodríguez, 2016), face significant challenges of climate adaptation and sustainability. With less than 1% of emissions, these ecosystems are among the most vulnerable to climate change. Further, their greatest affectation is reflected by the variation of their temperatures, the alteration of their precipitation, and the rise in sea level (Veron et al., 2019). Simultaneously, however, these territories have in their genesis responses to the phenomena and transformations of the planet's natural ecosystems. For example, the Galapagos could become a "great laboratory" for a low-carbon development model, a totally clean energy system, and better management of tourism and fishing activities (Erazo).

The theoretical assumption is then related to each of the variables identified in the model of human settlement in these protected island environments.

3.2.1. *Variable 1. territorial characteristics: biophysical*

The biophysical attributes of a territory inherently influence the formation and sustainability of human settlements, especially in PIEs. These attributes shape the urban metabolism of a settlement, determining its material and energy flow. Territories rich in natural resources allow settlements to be more self-sufficient, drawing directly from the environment to satisfy habitat needs. Conversely, territories lacking these resources lead to greater dependence on external, or exogenous, materials. Such external dependencies can complicate a city's metabolic pathways and alter its environmental metabolism. This dynamic between the biophysical landscape and urban development highlights the importance of sustainable planning and resource management. Understanding this relationship is crucial for assessing the ecological footprint of PIEs and ensuring their sustainable growth.

For example, in the historic town of Port of Levuca, an interdependent relationship between human settlement and the ecosystem can be observed. Considered an "exceptional example of a South Pacific port of the late nineteenth century" (Harrison, 2010), this heritage represents in its construction technique a combination of the architectural codes of

British colonization and the use of wood as the predominant material in the production of physical space. Contrary to this, the construction system of the city of Puerto Ayora on Santa Cruz Island reflects a dependence on exogenous materials, accompanied by a cultural predisposition of its inhabitants. Even though the ecosystem can offer them a vast base of natural resources, the inhabitants reproduce the construction codes of continental Ecuador, with the use of reinforced concrete as the main characteristic element of the housing model (Galápagos, n.d.)(p. 78). In the case of Galapagos, the lack of techniques and knowledge for the management of local resources can increase this type of homogeneity.

3.2.2. Variable 2. origin of the settlements: demo-geographic

In the records of historical analysis, island communities' emergence and evolution are inexorably influenced by their interactions with continental human settlements. Especially, islands that hold strategic geographic significance between vast continental expanses have often emerged as crucial nexuses, fostering multifaceted exchanges, spanning commercial, military, and economic domains(Maxwell et al., 2020). It's imperative to note that a distinctive feature of these insular terrains is the presence of a migrant populace, largely a byproduct of their geospatial attributes and historic interplays. PIEs, or Pacific Island Ecosystems, are emblematic of unique geological evolutions that shape their topographical and morphological characteristics, thereby influencing patterns of human habitation. Take, for instance, the case of Lord Howe Island, whose geomorphic attributes are conducive to fostering compact human habitats. Such compactness not only underscores efficient space utilization but also is paramount in ensuring the conservation of its endemic biota and undisturbed landscapes – a challenging endeavor given its limited habitable span of 3.82 km^2 inhabited by a modest populace of roughly 400.

Yet, this narrative isn't universally applicable across all PIEs. A myriad of islands, due to variegated continental migratory patterns and a confluence of diverse settlement strategies (including conquest, colonization, gentrification, and touristification), have witnessed pronounced shifts in their inherent landscapes and ecosystems. The Galapagos archipelago offers a case in point. Mainland migratory surges from Ecuador, juxtaposed with an evolving matrix of land-use dynamics, have precipitated multifarious challenges. These span from land fragmentation and shifts from pastoral to urban landscapes to an erosion of agrarian capacities and the emergence of food security challenges. An ancillary complication surfaces in the form of skewed land ownership dynamics, wherein land concentration in the hands of a few exacerbates speculative land valuation while impeding the emergence of cohesive urban habitats. It is pivotal to emphasize that such anthropogenic interventions have been identified as primary culprits behind the erosion of biodiversity in the Galapagos (Watson et al., 2010).

The deleterious impacts of anthropogenic activities transcend beyond biotic disturbances. Lithic extractions, especially those conducted in open terrains, have profoundly reshaped island morphologies. Such topographical shifts invariably hold ramifications for the local climate. An illustrative example is provided by Fernando de Noronha, wherein unchecked deforestation, largely aimed at converting pristine forests to secondary vegetative states for sustenance, has endangered its native gastropod species (Lucci Freitas et al., 2020)These anthropogenic footprints, woven intricately across various PIEs, have manifested in reduced biodiversity, altered land-use patterns, and fluctuations in atmospheric compositions, thereby warranting urgent scholarly and policy attention.

3.2.3. Variable 3. dynamics, use of natural resources as sources for production and development: socioeconomic variable

Initially, the economy of the island territories developed through the "exchange" of existing resources. On Lord Howe Island, for example, the settlers exchanged with the whalers their reserves of water, wood, vegetables, meat, fish, and bird feathers for clothing, tea, sugar, tools, tobacco, and other products not available on the island (Harold, 1940). This form of economy allowed the ecosystem to maintain a balance in its urban metabolism. With the arrival of colonization, these territories began a new economic period that led to the overexploitation of their biocapacities (Martínez Iglesias, 2018).

Artisanal fishing has long represented the main source of economic income for family sustenance in these settlements(Dominguez et al., 2016). Other important sources have been forestry and mining resources, currently reduced due to the decline of natural resources and legislative restrictions implemented by regulatory bodies. The population affected by these restrictions has seen tourism services as a new source of economy, giving rise to a new problem facing these territories: gentrification and touristification (Hiernaux and González, 2014). The tourist exploitation of their landscapes, the excessive use of water and electricity resources, and the high cost of living for their inhabitants are some of the negative effects derived from this new problem. The sustainability and conservation of ecosystems and their settlements are threatened by the impact of these socio-economic phenomena. Among the most negative impacts caused by tourist gentrification is the cultural disappropriation of the physical space (uses and customs), and the expulsion of its inhabitants, who are forced to move in search of housing according to their economic possibilities due to the rising cost of living (Lees et al., 2007).

Commerce is another source of economy that has come to supplant the previous activities. From canned goods to electric power, all these products are consumer goods needed to supply the incessant demand of the resident population and the high flow of tourists that annually visit these islands (Marino, 2016). This situation increases imports and raises the impact left by waste and residues dumped in the territory, which represent high management costs and become permanent sources of atmospheric pollution when not properly treated(Santamarta et al., 2014). These interactions emit negative metabolic signals that directly impact the physical environment of these islands.

3.2.4. Variable 4. Historical Memory and physical built space: sociocultural

Urban metabolism, with its intricate web of material and energy flows, intricately links with the cultural fabric of cities located in protected island ecosystems. Scholarly discourse highlights how the profound intersections of cultural development and spatial dynamics reverberate through centuries, informing our built environment (Heijnis and Rhodes, 2016) Embedded within the matrices of space is not merely physical matter, but also a tapestry of historical, temporal, and sociocultural narratives. (Urtubey, 2018) underscores that space emerges from multifaceted socio-territorial interactions, thus embodying both symbolism and substance. This duality is pronounced in Protected Island Ecosystems (PIEs) where human settlements have historically engaged with natural geographies, giving birth to distinctive island cultures that subsequently shape urban frameworks. A testament to this can be observed in how collective memories of inhabitants materialize into tangible infrastructures, bearing codes reflective of broader societal dynamics—ranging from identity and progress to instances of disparity and subjugation (Pérez, 2015).

Two exemplary PIEs, crowned as Cultural Heritage of Outstanding Value by UNESCO, encapsulate the essence of this synthesis. Lipari, with anthropological traces extending back to 4000 BC, is emblematic of the confluence of diverse cultures. The architectural lexicon of Lipari, often termed "Aeolian architecture," is a mosaic of Greco-Roman and Islamic influences from the XVI century. The island's ethos towards sustainability is evident in the persistent utilization of indigenous materials: foundations laid with volcanic lava stone, pumice stone-clad external walls, and tufa terraces. Even contemporary edifices in Lipari uphold this commitment by eschewing cement in favor of traditional stone and lime (Papadia and Il, 2021). Such practices, rooted in culturally transmitted knowledge, augment the island's environmental sustainability quotient.

On the other hand, the Solovetsky Monastery Architectural

Ensemble, nestled within the Solovetsky Archipelago, stands as an unparalleled architectural marvel (UNESCO, 2021). This complex exudes a unique character, amalgamating monumentality with individuality, achieved through the meticulous blending of local boulders, rare bricks, and artisanal wrought iron sourced from Solovki. Beyond mere structural aspects, the ensemble's distinct linear facade design, juxtaposed with the dense congregation of buildings in confined areas, elevates its architectural articulation.

In summation, the nexus between urban metabolism and cultural expressions in PIEs underlines the symbiotic relationship between humans and their environment. As communities continue to navigate their spatial terrains, the resultant material and immaterial outcomes offer profound insights into the intricate choreography of culture, nature, and urbanism.

3.2.5. *Variable 5. special regulations: legislative*

The World Heritage Convention is one of the most important conservation instruments in the world. Created in 1972, its main mission is to identify and protect natural and cultural heritage, considered to be of Outstanding Universal Value. However, contrary to these conservation objectives, the laws governing these territories do not strike a balance between meeting the needs of the population and the appropriate use of natural resources. For example, 70% of Lord Howe's land area is protected, and no tourist visits of more than 400 people per day are allowed. Further, the island's only sources of external income are the cultivation of kentia palms and tourism. The remaining 30% of the area is not fully habitable or cultivable. This is compounded by land tenure problems (Armstrong et al., 1988), which further limit development and generate greater dependence on other economic activities supported by imported exogenous materials. In this case, this limitation may not generate major effects, as this island has a small population of approximately 400 people. A remarkable effect of this limitation is reflected in the phenomenon of emigration of its inhabitants to the continent, in search of improving their life possibilities.

4. Results of the qualitative analysis of the relationship between each variable-human settlement-territory

Now, we will study the urban metabolism of the EIPs by zooming in on the settlement-territory relationship, where we will observe the possible scenarios according to each variable. The metabolic flow we are interested in analyzing is the production of physical space through a Graph Sheet. Starting from a biophysical base altered by anthropogenic incursions direct and indirect, we will visualize the cycles that open the relationships: settlement-territory-culture and settlement-territory-economic activities. This graph helps the reader understand the causes and states of metabolic cycles occurring in the settlement to produce habitability in spatial terms (see Table 3).

To understand the relationships as a function of each variable, the following data table is proposed.

The results shown in this table show the relationship between human settlement and the territory according to each variable (biophysical, demographic, socioeconomic, sociocultural, regulatory), for which hypothetical scenarios were designed and can be reviewed in the attached material.

Table 3
Conceptual table.

	Implications of each variable as a function of human settlement production and its metabolism		
Inhabitant behavior as a function of human settlement production and metabolism	1. 2. 3.	1. 2. 3.	1. 2. 3.

4.1. *Indicators*

1. Dependence on exogenous raw materials to produce the physical space
2. Lack of knowledge of using and handling the surrounding material
3. Loss of the anthropologist urban landscape (overcrowding, fragmentation, overexploitation of urban land)
4. Gentrification and touristification
5. Extinction of endemic species and decrease of natural resources (aquatic: marine and coastal, terrestrial, forest, animal, plant)
6. Contamination of water sources
7. Problems with air quality and waste management
8. Land tenure makes compact and sound planning impossible
9. Most of the population depends on island resources for economic activity

4.2. *Positive aspects of the transfer of knowledge*

A. Production of physical space in the context of climate adaptation and sustainability of the biophysical environment
B. Learning methods and techniques for using existing material in the environment; external cultural transfer
C. Using the surrounding material for new functions of the building process (development of mechanical and aesthetic properties)
D. Origin of new island cultures
E. Geographical characteristics to produce renewable energies
F. Raw materials to produce biofuels; land tenure makes compact and sound planning impossible

5. Discussion

A study in the journal Nature reveals that in 2020, the mass of what is manufactured by humankind (anthropogenic mass) exceeded in weight the mass of living things (biomass) for the first time in history (Hamilton, 2018). Owing to the alterations that humans are generating in the climate and biodiversity of the planet, some experts consider that we have entered the Anthropocene, a new geological epoch characterized by the impact of man on the Earth (UNESCO, ONE WORLD ONE MULTIPLE VOICES, 2021). This review has made visible that human incursions affect the biophysical system of the PEIs, opening new cycles of residual entropy, due to the socio-territorial dynamics of their settlements. According to data from the Assessment on the Conservation of All Natural World Heritage sites, the International Union for Conservation of Nature (IUCN) 2020 warns about the current conservation status of these natural sites and their main threats at the regional level. The most common threats are climate change, tourist visits, and the entry of invasive species (Osipova, E., Shi, Y., Kormos, C., Shadie, P., Zwahlen, C., Badman, 2014). According to this report, the Lord Howe Island Group has the best conservation status, while the Galapagos archipelago has had a "significant concern" since 2010 after overcoming a critical situation (for three years). The Fernando de Noronha Reserve from 2017 to the present has descended to the red list and presents a "critical" status with potential threats that may harm its natural value. The Eolie and Ogasawara archipelagos have maintained a "good conservation status but with certain recommendations" that imply improving their management in the face of the eventual threats mentioned (Osipova et al., 2020).

According to the UN Refugee, nearly 70 million people were living in forcibly displaced in 2018 (FRONTERAS, 2021). Further, according to data from the World Bank (Mundial, 2020), approximately 55% of the world's population lives in cities. It is believed that this trend will

continue and that cities will continue to grow, especially in developing countries (Noticias, 2018). The scale of urbanization poses challenges, such as meeting the growing demand for affordable housing, well-connected transportation systems, and other types of basic infrastructure and services (Mundo, 2020). These large migratory flows also affect island territories. Migration from other island communities and the mainland population is becoming more frequent (Proceso & Actual, n.d.). The growth trend is toward low- and middle-income territories still considered development niches. It is also important to observe the effects of tourism on the islands, such as the case of Fernando de Noronha, which, between 1992 and 2002, saw its number of visitors grow from 10,094 tourists to 62,551—an increase of 520% in ten years. Its resident population also grew by 54% in the same period. Santa Cruz has also experienced a steady growth in tourist visits from 1992 to 2014 with several visitors of approximately 32,541 and 170,395, which corresponds to an increase of 500% (Galápagos, n.d.). Tourism in the islands, especially in the case of the PEIs, should be considered part of their human demographic geography. Although growing at a faster rate than the resident population, the human demographic geography has a more aggressive impact on the urban metabolism of these settlements due to the high consumption of material and energy from tourism activities.

As in large continental cities, island territories do not escape socioeconomic problems. Environmental and sustainability problems reflect an imbalance between the natural limits of the territory and the development of the settlement. Human activities are causing unprecedented stress on the systems that sustain the land because of the economic growth model they pursue (Raworth, 2017). One of the challenges for the governance of these settlements is to design and implement a socio-productive matrix according to the territorial vocation and the natural limits of the environment (Unidas), which allows a process of urban decarbonization and improves the conditions of unsustainability of their economic sectors (Eras-Almeida et al., 2020). Approximately 60% of the area that will be urban in 2030 is still to be built—if we do not improve current technologies and construction processes, the production of physical space in the following decade will have unprecedented ecological and social implications (Nieto, 2017; Gusev, 2021; Feng et al., 2019). In this area, the economy plays an important role in the development of eco-technologies for the production of new building materials and the gearing of efficient building systems (Kristinsson and Timmeren, 2008; Profile, 2014). Local and national governments must work with other actors to create conditions to improve the quality of life of the population. Access to housing is an indicator that promotes livability.

The impacts on the environment, as well as the cultural predisposition for the use of certain materials and construction processes used in these environments, can be explained by their migratory flows. Social aspirations are one of the five factors that allow us to point out natural limits to the environment according to Raworth (2017). Development codes, sustained by the social aspirations of a population, determine the balance of urban ecosystems on these islands. Tourist gentrification is an external pressure, which has an impact on the physical-spatial misappropriation and the culture and identity that characterize a settlement. The change in social aspirations and the meaning of development—at an urban and architectural scale—proposes a turn toward the sustainability of these environments. Culture is everything that constitutes our being and shapes our identity. Making culture central to development policies is the only way to ensure that development is human-centered, inclusive, and equitable (Hosagrahar). The paradigm of development based on economic growth and excessive consumption must be revised, (see Table 4). Sustainable development offers a different perspective in the search for balanced development between the economy, society, and environment (Piñeiro Pagliere, 2010).

The control and regulation efforts implemented for the protection of these environments at the local and national governance levels do not effectively achieve the conservation objectives for these habitats. Currently, these territories and their population communities are threatened by various factors inherent to their socio-territorial dynamics. Governance challenges pose a series of interactions at the political, cultural, and economic levels, which, in turn, respond to the interests of various stakeholders present in the territory. The fundamental objective for the following years will be to reduce the anthropogenic pressure on these ecosystems. However, factors such as the limitation of economic activities, the use or exploitation of resources, and the number of tourist visits must be rethought to slow down the problems pointed out by the IUCN in its report (Osipova et al., 2020).

6. Conclusions

The studies reviewed offer an understanding of the metabolism of large cities from the behavioral analysis of different variables. However, PIEs must be analyzed, including all the complex characteristics and dynamics that this study has tried to illustrate. Scale, symbol, matter, culture, and human incursions are some of the criteria that must be present in the dimension of the study of the metabolism of urban human settlements in these territories. This review helped us study the defined sites (seven islands) from a methodological approach of multidisciplinary observation, articulated by five variables present in the socio-territorial dynamics of these enclaves. With this approach, we identified several metabolic cycles that can be opened by the circulation of the flow "production of physical space," while considering inputs such as settlement, economy, resources, imports of materials, energy, water, and biomass.

Delving deeper into the case of Puerto Ayora makes it possible to build a more solid approach for the study of the urban metabolism of these environments. The four works reviewed for the elaboration of this article are proposed as the basis for a new study proposal, which can be structured from the variables—the Metabolism of Cities (Wolman, Abel) and the Extended Metabolism Model, (Newman, Peter)—and/or the theoretical conceptions—the Ecosystemic Model (Van Leeuwen, Chris) and the Integrated Sustainable Design (Kristinsson, Jón). This dimension of study will depend basically on the scales (architectural or urban) and relations being observed. In the construction of the metabolic flow in Puerto Ayora, open cycles are shown that agree with reports from international organizations, such as the UN, UNESCO, and IUCN, which warn of a "natural risk" conservation perspective on this island. The socioeconomic limitations resulting from the morphology and biophysical composition of its territory are a key factor to be resolved.

Table 4
Main qualitative results of the relationships between human settlement and territory as a function of the five variables.

Islands Variables	Lord Howe	Fernando do Noronha	Santa Cruz	Historic Port Town of Levuka	Lipari	Ogasawara	Historical, Cultural, and The natural site of Solovetsky
Biophysicist: composition	1; 5 - E; F	1; 5;6 - C; E	1; 5;6; 7 - C; E; F	1; 5;6; 7 - C; F	1; 6;7 - C; E	1; 5 - E	C
Demo- geographic		3	3	3	3		
Sociocultural	1	1; 2 - D	1; 2	1 - A; B; D	A; B; D	1; 2 - D	A; B;
Socioeconomic	9	4; 9	4; 9	4; 9	4; 9	9	9
Regulatory		4; 8	4; 8	4; 8	4		

[5]**Source:** own elaboration because of the review of the bibliography consulted.

National and regional efforts should contribute to the objectives set out in the conservation agenda.

The line that indicates progress and the development code based on "social aspirations" is opposed to sustainability. Therefore, designing a model of economic development and growth based on the natural limits of the territory and not merely in terms of economic flows presupposes a positive impact on its conservation (Raworth, 2017). Unlike continental areas, island regions have high self-dependence on the biophysical system—all the activities developed by the settlement have a direct impact on it. The change of the productive model is another alternative that is gaining ground in these territories. The circular economy, for example, offers a framework of systemic solutions for economic development, deeply addressing the cause of challenges such as climate change, loss of biodiversity, and increase of waste and pollution, while revealing significant growth opportunities. Driven by design and underpinned using renewable energy and materials, the circular economy revolutionizes the way we design, produce, and consume.

Rethinking the production of physical space by adopting a new material culture based on the criteria of environmental, economic, and social sustainability is the starting point in developing a new cosmovision of the built space in these urban enclaves. These enclaves are configured by the natural limits of the territory and the usual architecture—spatial functionality, formal adaptation to the environment, and aesthetics—but designed from its materiality.

CRediT authorship contribution statement

Juana Mercedes Perlaza Rodríguez: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Resources, Writing – original draft, Writing – review & editing. **Antonella Grazia Guida:** Supervision. **Ángela María Díaz Márquez:** Supervision.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Juana Mercedes Perlaza Rodriguez reports administrative support was provided by Decentralized Autonomous Government of the City of Puerto Ayora.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.indic.2023.100324.

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