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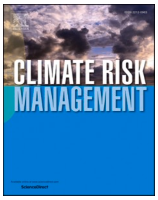

# Multi-dimensional damage assessment (MDDA): A case study of El Niño flood disasters in Peru

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ABSTRACT

Assessing disaster impacts is the pathway to attain informed decision making to mitigate damages. Currently, these impacts are generally analyzed excluding the environmental consequences of disasters. Thus, this study proposes a novel quantitative method, named multi-dimensional damage assessment (MDDA), that integrates the disaster-related environmental impacts with economic and social losses. For this, Life Cycle Assessment was used to measure environmental impacts at the endpoint level for the human health area of protection. The unit of assessment used to merge the three damage dimensions was the disability-adjusted life year equivalent (DALYeq). The damages exerted by floods in Peru linked to El Niño in recent decades were selected as the main case study. Furthermore, other natural disasters (e.g., earthquakes) were included in the assessment for the sake of comparability. The results show that El Niño floods in Peru in 1982–83 and 1997–98 presented higher damage per capita, approximately 2.8 times higher, than the event in 2017. Additionally, the assessment showed that economic damages are the most relevant in El Niño floods, whereas social damages are those prevalent for earthquakes. The results demonstrate that MDDA is an effective measurement for the purpose of damage comparison and, therefore, to implement mitigation strategies. The proposed methodology will allow the development of disaster risk mitigation strategies that will cover all damage dimensions and enable the adoption of improved public policies. Finally, MDDA can be applied to compute any complex array of damages that humans may suffer or infringe as a consequence of their interaction with the environment.

## 1. Introduction

Naturally-driven disasters, hereinafter natural disasters, have caused globally more than 1.3 million deaths, and economic losses near 3 trillion USD in the 21st century, prior to the ongoing COVID-19 pandemic (EMDAT, 2021). It is estimated that 80% of the current century's losses are climate-related, compared to 70% recorded for last century (EMDAT, 2021). In recent years, disasters have become increasingly frequent and complex (Coronese et al., 2019); as a consequence, it is hard to distinguish their origin for prevention purposes, as well as to classify damages as a basis for the development of mitigation strategies. As a result, the development of new strategies to cope with disasters is urgently required (Kushma, 2021).

Natural disasters arise from the exposure of vulnerable human habitats to natural hazards (Mochizuki and Naqvi, 2019). Regardless

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of the recurrent arrival of natural hazards and the uncertainty linked to the level of human contribution to climate variability (Collins and Walsh, 2017), human well-being faces increasing natural disaster risks due to climate change (UNISDR, 2015b).

Disaster risk, understood as a probabilistic combination between hazard and vulnerability (Hore et al., 2019; UNISDR, 2018), is expected to increase due to the exacerbation of natural hazards (Sudmeier-Rieux et al., 2019) and the increase in vulnerability by the effects of both the environment and humans. In this context, impacts linked to climate change are often indirect, and depend on complex interactions between social and environmental factors (Palocz-Andresen et al., 2019). Moreover, the classification of a disruptive event as a disaster requires that the damages it causes exceed the capacity of a community to overcome the effects without foreign aid (Wisner et al., 2012). However, this definition of disaster would exclude slow onset events such as those associated with climate change because they lack a sense of urgency. Consequently, for the sake of this paper, the definition is also extended to slow onset disasters.

Climate change compromises the present and future well-being of humans and ecosystems due to abnormal unleashing of extreme weather events (EWEs), which are mostly characterized by their sudden onset, such as cyclones, storms, floods, forest fires, extreme rains or droughts, among others (Schiermeier, 2018). Climate change also triggers slow onset disasters, such as sea level rise, desertification, salinization, rising temperatures, land and forest degradation, loss of biodiversity, glacier removal and ocean acidification (UNFCCC, 2013; Matias, 2017; UNEP, 2016; UNISDR, 2015b). Natural disasters can be driven by both types of events.

Current models suggest that climate-related disasters may intensify in the near future due to the increased frequency and intensity of abnormal rainfall patterns throughout the world (Gosling et al., 2011; Sarhadi and Soulis, 2017; UNISDR, 2015b). In fact, there is broad consensus among the scientific community that it is highly probable that global temperatures will continue rising and exacerbating EWEs, with anthropogenic greenhouse gas (GHG) emissions constituting a relevant factor contributing to this trend (Blakely, 2019a, 2019b; Kelman, 2015). However, despite the fact that climate change was addressed by the Warsaw International Mechanism for Loss and Damage (WIM) as one of the main drivers of disaster risks (UNISDR, 2015b), disaster damage assessment tends to omit environmental impacts in its metrics (Mechler et al., 2019). Hence, the damage exerted on human health by the long-term effects of climate change is generally discarded. Moreover, the objectives of WIM are loosely aligned with the Sendai Framework for Disaster Risk Reduction 2015–2030 (SFDRR), a global agreement that aims to mitigate the negative effects of disasters through reducing vulnerability and increasing resilience in anticipation of hazard unleashing (Cazeau, 2019).

Disasters involve negative short and long-term social, environmental and economic impacts (Benson and Clay, 2003; CENEPRED, 2014). In fact, when natural- or manmade-driven hazards occur, human lives may be lost, together with numerous economic and material losses. Traditionally, losses are referred to as economic when linked to the monetary cost of replacing lost goods. In parallel, social losses are those that result of mortality and morbidity related to human lives. In addition, although commonly not so visible in the media, an array of different environmental impacts is generated directly and indirectly, due to the run-off of pollutants to the soil, water and air compartments as a consequence of the production of new goods to replace those that have been lost (i.e., stock reposition). Unfortunately, in most cases, the assessment and response mechanisms for natural disasters only portray short term and direct damages, while overlooking long term and indirect consequences (Gall, 2015). Therefore, effects on the economy (Avelino and Dall'erba, 2019) or damage to human health as a result of indirect epidemiological outbreaks tend to be dismissed once the window of time between the disaster episode and the potential consequences enlarges.

In accordance with the WIM framework and aiming to contribute to disaster risk understanding (as is the main mandate of SENDAI), a more comprehensive vision on damage assessment is needed to take into account environmental impacts and their quantitative aggregation with social and economic damages. This perspective would allow generating a metric to evaluate damage severity comparisons originated by different hazards and in different years. Therefore, the main objective of this research study is to merge an environmental impact assessment method (i.e., Life Cycle Assessment – LCA) with those linked to economic and social issues to construct a multi-dimensional damage assessment (MDDA) framework, by quantifying the impact of natural disasters through the use of the disability-adjusted life years (DALYs) index. For this, the damages exerted by floods in Peru linked to El Niño in recent

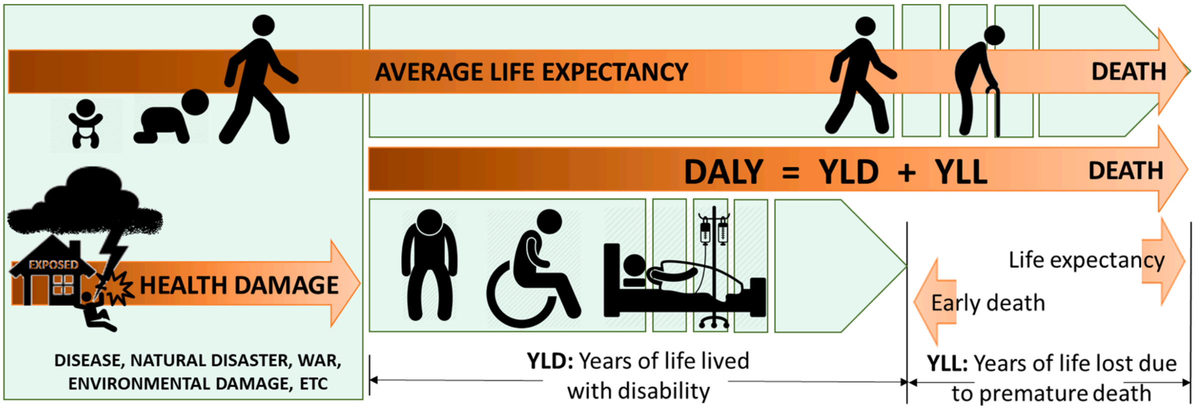

**Fig. 1.** Graphical representation of the DALY index. DALY = disability-adjusted life year.

decades were selected as the main case study, although other natural disasters were included in the assessment for the sake of comparability. The results of this study are intended to provide a novel methodology to combine the different dimensions of damage when assessing natural disasters worldwide. Moreover, it is expected that the results presented will allow policy-makers to obtain a more holistic view of the potential damages generated by natural disasters and, therefore, better informed decision making in order to mitigate and compensate each damage dimension.

## 2. Methodological framework

This section describes the MDDA methodology proposed to compute the economic, social and environmental damages linked to disasters. In order to do so, the DALY index has been chosen as the metric to homogenize the different dimensions included.

### *2.1. DALY index*

The DALY index aggregates premature mortality (i.e., years of life lost) and morbidity (i.e., years lost due to disability) caused by diseases, injuries and others health risk factors, as shown in Fig. 1. Its units are years of human life: 1 DALY equals 1 human year (Donev and Lijana, 2010). The index was developed in the 1990s by Harvard University for the World Bank (2021) with the goal of measuring the global burden of a given disease (Murray et al., 1994). Thereafter, it was adopted and extensively used by the World Health Organization (WHO) (Chen et al., 2015). Its metric relies on the use of disability weight factors, ranging from 0 to 1, for each health type affectation, either physical or psychological (Devleesschauwer et al., 2014; Murray et al., 2015). Moreover, it provides a tool to quantify health loss from several diseases or injuries. Consequently, each year lived with an impact on the quality of life (i.e., morbidity) will be equal to the product of the duration of the affectation multiplied by the disability weight factor. In addition,

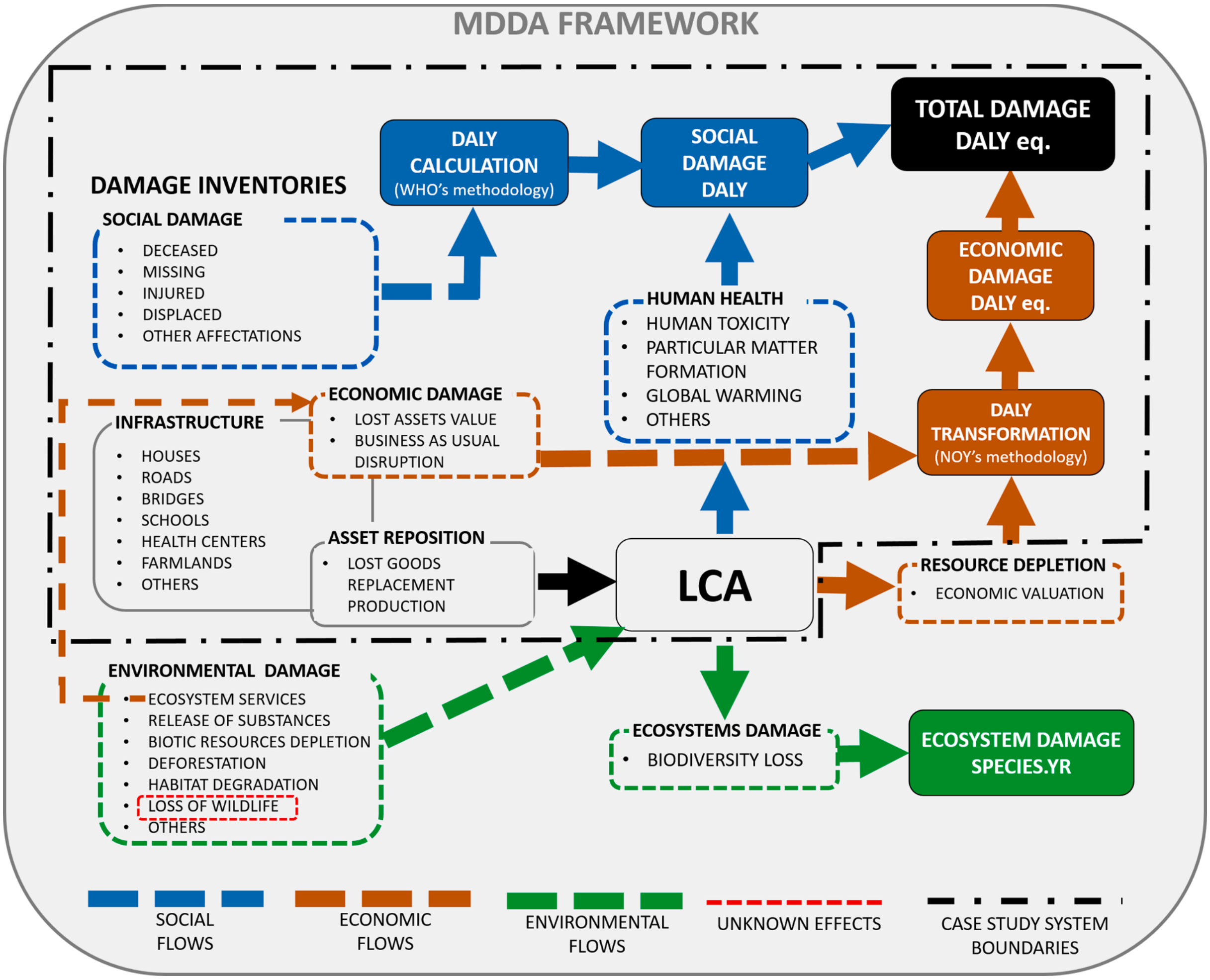

**Fig. 2.** Graphical representation of the methodological framework for MDDA. Economic transformation refers to the methodology developed by Noy (2015), social transformation refers to the Global Burden of Disease (GDB) methodology applied by World Health Organization (WHO), and LCA is the acronym for Life Cycle Assessment. Species.yr is species loss per year.

mortality is calculated as the difference between life expectancy and the age of the deceased person.

### 2.2. Disaster damage quantification

The aggregation of the various damage dimensions in a disaster is feasible given that all are ultimately referred to the human well-being preservation. Social damage refers to the physical and mental health of human beings. This concept ranges from aspects as visible as premature death, disabling wounds and diseases, to other more subtle conditions, such as affectations to habits and practices or religious beliefs, with the consequent psychological stress that they can generate in the affected individual or communities (Rasmussen and Jayawickreme, 2020).

Economic damage is mainly related to the cost of recovering from the disruptive event, an expense that will impair the ability of a community to attain or maintain well-being standards, whether this is expressed in terms of future investment in health or education, or in terms of affectation to cultural development. Hence, economic losses are themselves losses, present or future, of physical or psychological health (Hallegatte et al., 2015) and, therefore, liable to be expressed in DALY units.

The environmental damage attributable to a disruptive event has been recurrently assessed through LCA methods (Petit-Boix et al., 2017; Mesta et al., 2019). LCA allows the evaluation of a wide spectrum of environmental impacts, which, to date, have been aggregated into three so-called Areas of Protection (AoPs): human health, ecosystem quality, and natural resources (Verones et al., 2017), although some methods differ from this structure (Jolliet et al., 2014, 2003). These AoPs, as defined by Jolliet and colleagues (2003), represent operational groups of items which present a direct value to human society. Consequently, if we consider that LCA aims to measure the impacts on human well-being due to environmental degradation, it seems plausible that all three AoPs should be included in disaster damage quantification. However, in a first proxy of the MDDA, as discussed in subsection 2.3.3, only environmental damage from the human health AoP has been included.

All in all, the social, economic and environmental dimensions of disaster damage gather the main ways in which human well-being can be affected, either directly or indirectly, in the present or in the future and avoiding double counting by conceptual overlapping. Therefore, to express total disaster damage as the sum of economic, social and environmental damage, the DALY index must be calculated for each of them (see Eq. (1)). This allows computing all dimensions in the same unit, that is, DALYs expressed in units of years of human life.

$$\boldsymbol{TD_d} = \boldsymbol{S_d} + \boldsymbol{Ec_d} + \boldsymbol{En_d},\ (life - years\ units) \tag{1}$$

where, $\mathbf{TD_d}$ is total disaster damage, $\mathbf{S_d}$ (life-years) is the social damage in DALY, $\mathbf{Ec_d}$ (life-years) is the economic damage in DALY, and $\mathbf{En_d}$ (life-years) the environmental damage in DALY.

Firstly, the DALY index for social damages is measured by applying the WHO methodology in order to calculate the burden linked to diseases and injuries of those affected by a given disaster (i.e., years of life lost by casualties, psychological affectations of victims, the wounded, the sick as a result of epidemics outbreaks due to disasters, etc.). Secondly, economic-related damage is transformed to DALY equivalents units (hereinafter, DALY values result of transformations from economic losses will be referred to as DALYeq) by applying the disaster metrics adaptation proposed by Noy (2015b). Finally, the inclusion of environmental damage was attained by using LCA to quantify environmental impacts due to a given disaster (see Fig. 2), including those related to the reposition of damaged assets. It must be noted that LCA is a methodology based on the accumulated history of environmental impacts of the entire supply chain from the extraction of natural resources to their use or, eventually, to their final disposition (Hellweg and Canals, 2014).

### 2.3. Data processing

#### 2.3.1. Disaster damage: Social perspective

This assessment considers that social damages are all those related to health affectation (i.e., physical or psychological). The transformation of social damages to DALY units is carried out by means of the sum of mortality (Mt) and morbidity (Mb), as seen in Eq. (2).

$$\boldsymbol{S_d} = \boldsymbol{Mt} + \boldsymbol{Mb}(life\ year\ units) \tag{2}$$

Official datasets gathered after a disaster commonly include number of deaths, as well as missing, injured, displaced or affected persons. These statistics are usually available from both national and international institutions. However, certain assumptions must be considered to calculate DALYs for social damage. In the first place, the number of missing persons was added to the number of deaths. Secondly, despite the fact that the DALY index methodology accepts corrections for social concepts, such as the relative value of a life in relation to age, sex or life expectancy (Donev and Lijana, 2010), these adjustments have not been made in the proposed framework, in order to avoid distortions related to damage caused by a disaster. The reason is that adding this type of considerations to the index would include human welfare measures due to other concepts beyond disaster effects, such as the relation between economic richness or local violence conditions in relation to life expectancy (Chen et al., 2015; Noy, 2016). Moreover, disaster mortality in terms of DALYs is equal to the loss of life years of each deceased person linked to the disaster subject of study, numerical details rarely contained in statistical reports of disasters. Therefore, the reference life expectancy value assumed was 92 years, as recommended by WHO for international standardization purposes, in accordance with projections made for average life expectancy at birth in year 2050 (Noy, 2015a) to perform calculations, and in order to avoid social distortions when comparing disasters. Eq. (3) depicts this calculation as follows:

$$\boldsymbol{Mt} = \boldsymbol{T}_d.(\boldsymbol{92} - \boldsymbol{A}_{av})(life - years\ units) \tag{3}$$

where $T_d$ represents the number of deaths (or missing people) due to a given disaster, and $A_{av}$ the average population age.

The impact on life quality (i.e., morbidity) of those physically injured or psychological affected by a disaster should also be considered. This should include all types of injuries and the cost of their care, hospitalization and rehabilitation time, as well as the impact on the mental health of people who were displaced or whose homes were destroyed. The effects on physical health also include diseases, that sometimes reach epidemic dimensions. The set of effects on mental health of those affected by a disaster also includes the so-called post-traumatic stress disorder (PTSD), which would require a prevalence study for its adequate evaluation. However, in most cases, this information is not available and, thus, a detailed calculation is not achievable (Noy, 2016). Consequently, based on Noýs proposal, a disability factor of 0.054 was applied to the post-disaster recovery time period and added to the sum of the DALYs lost due to other health problems. (see Eq. (4)). This factor is the WHO's weight for disability associated with 'generic uncomplicated disease: anxiety about diagnosis'.

$$\mathbf{Mb} = 0.054.\mathrm{Rt.Taf} + \sum_{i=1}^{Taf} Dfi.ARti(\mathrm{life} - \mathrm{years\ units}) \tag{4}$$

where $R_t$ is the disaster recovery time in years, $T_{af}$ the total affected people due to a disaster, $Df_i$ is the disability weight factor and $ARt_i$ is the affectation recovery time (years) for each type of health affectation (i).

Nevertheless, if detailed information is not available regarding the type of injury for each injured person, as well as the rehabilitation time, their DALY, either individually for each injured person, or adopting a case of "average" health impairment, can be excluded from the previous equation. It is important to note, however, that it is common that the global morbidity in a disaster referred to those affected by physical injuries is significantly lower than the psychological morbidity of large populations affected by stress, referred to the prolonged periods of post-disaster recovery processes.

### 2.3.2. Disaster damage: Economic perspective

Short-run effects on Gross Domestic Product (GDP) appear as an effective way to compare the impacts of a disaster on national economies. Nevertheless, the scale of the disaster is an important aspect to consider, since the economic impact of natural disasters is often related to the total size of the economy of the affected country (Cavallo, 2011). In order to transform economic loss due to disasters into DALY eq units, the framework presented by Noy (2015b) was applied, where a relationship between lost capital assets and infrastructure due to disasters and lost human years was assumed (see Eq. (5)). In the current study, the assumption provided by Noy (2015b) that 25% of people's time is used in work-related activities was followed.

$$\boldsymbol{Ec}_d = \boldsymbol{0.25}.\boldsymbol{E}_L/\boldsymbol{PCI}(life - years\ units) \tag{5}$$

Where $\mathbf{E_L}$ represents the economic loss related to a disaster, and **PCI** the gross annual income per capita.

### 2.3.3. Disaster damage: Environmental perspective

Environmental disaster damage is related to the reposition of assets affected by disasters. The current methodological framework proposes the calculation of environmental damages through the use of LCA. For this, the ReCiPe 2016 assessment method was used to compute environmental impacts at an endpoint level in accordance with the AoPs mentioned in Section 2.2 (Huijbregts et al., 2016). It should be highlighted that the hierarchical endpoint perspective was selected because it is the consensus model within ReCiPe computations. Finally, SimaPro 9.0 was the software used to compute the environmental impacts (PRé., 2019). In the first place, the human health AoP accounts for the changes in the natural environment that affect the health of human communities and, therefore, their well-being (Sonderegger et al., 2017). This AoP, which is measured in DALY units, resembles the description provided by the social damage dimension, since it engenders a direct health effect on humans, although in most cases it will show a slower onset of health affectations. Consequently, its inclusion within the MDDA method proposed is straightforward and does not require conversion.

Secondly, ecosystem quality damage represents the direct degradative effects that human interventions exert on ecosystem components beyond the technosphere. It is commonly measured in local loss of species integrated over time (i.e., species per year) or other equivalent units (Jolliet et al., 2003; Huijbregts et al., 2016). From an anthopocentric view, these indirect characteristics will ultimately engender effects on human health and well-being (Sonderegger, 2020). However, the conversion of these damages into DALY units derives in a complex array of assumptions that would generate a spiral of uncertainty, explaining, as shown in Fig. 2, why the AoP has been removed from the system boundaries of the case studies proposed herein.

Finally, in terms of natural resources, the third AoP, it is important to note that its role is still a source of controversy and debate in the LCA community (Mancini et al., 2013; Dewulf et al., 2015). In fact, some recent studies have suggested that the metrics for resource depletion should be revisited by implementing more sophisticated impact categories (Berger et al., 2020; Schulze et al., 2020a, 2020b). Therefore, while changes in the provision of natural resources present a direct effect on human well-being, the fact that no consensus has been developed on how this AoP should be improved has led to the decision to exclude this metric from the system boundaries established in the case studies.

Consequently, for the sake of this study, the computational framework is limited to account for the indirect environmental damage caused by the replacement of damaged infrastructure using the human health AoP exclusively.

In order to address the environmental damage ($En_d$) of the reposition of assets, it is necessary to estimate the replacement factor of the affected infrastructure. In fact, in some cases, the damaged assets will be substituted by assets of different characteristics (e.g., less precarious housing, retrofitted bridges, etc.). For this reason, the replacement factor (*Rf*) should represent the average ratio between the environmental impacts of the replacement infrastructure and the damaged one. In this study, the replacement factor was considered as the relationship between the replacement cost and the valuation of loss. Moreover, it is expected that replacement of damaged stocks will not be immediate. Therefore, future replacement values must be expressed at current values. In order to do so, a discount rate (*dr*) is applied to obtain the present value of future environmental impacts.

Furthermore, it should be noted that environmental impacts are referred to prior and future affectation, since they account for upstream and downstream impacts along the life cycle of different infrastructure and, therefore, go beyond geographical and temporal boundaries. Consequently, the results obtained in terms of environmental damage will account for impacts on human health as a consequence of the replacement of damaged assets that involve past and future lives in regions much broader than the area directly affected by a given disaster. The current study, therefore, proposes adding a factor that considers different cultural and moral considerations related to the relative value of foreign or future generation life (*F*), in relation to current population (see Eq. (6)).

$$\mathbf{En_d} = Rf.F.(1-dr)^{t}\sum_{(i=1)}^{n} EPi.Qi \tag{6}$$

Where *Rf* is the replacement factor, that is, the cost ratio between the reposition of assets and the lost value of assets, *t* is the delay in reconstruction time, *dr* is the discount rate, “n” is the total types of accounted infrastructure (i.e., housing, roads, etc.), *EPi* is the endpoint impact to human health of each type of infrastructure per unit and *Qi* is the number of damaged units of each type of infrastructure.

The current assessment considered $F = 1$ for disaster comparison purposes and according to the moral evaluations of the authors. Finally, a *dr* equal to 3% was considered, which is the value proposed by the WHO (2013), oriented at valuing current lives more than future ones (Devleesschauwer et al., 2014; Donev and Lijana, 2010).

### 2.3.4. Disaster damage: Total quantification

Based on all the considerations for each of the three dimensions modelled for disaster damage, and on the basis of Eq. (1), the current methodological approach can be summarized in the Eq. (8):

$$\mathrm{TD} = 0.25.\mathrm{E_L}/\mathrm{PCI} + \mathrm{Td}.(92 - \mathrm{A_{av}}) + 0.054.\mathrm{R_t}.\mathrm{T_{af}} + \sum_{i=1}^{Taf} Dfi.ARti + \mathrm{Rf}x\mathrm{Fx}(1-dr)^{t}.\sum_{(i=1)}^{n} EPi.Qi \tag{8}$$

Where TD is total damage, EL, the economic losses, PCI, the gross annual income per capita, Td, the number of deaths (including missing people) due to the disaster assessed, $\mathrm{T_{af}}$, total affected people and $\mathrm{A_{av}}$, average population age.

## 3. Multi-Dimensional damage assessment (MDDA) of El Niño floods in Peru

### 3.1. Description of the case study

Peru is the most affected country per capita by natural disasters in South America, and the first in casualties due to natural disasters in the past 100 years (EMDAT, 2021). On the one hand, El Niño exposes the country to semi-cyclical EWEs (Feba et al., 2019; Sulca et al., 2018; Yan et al., 2017). On the other hand, its location in the Circum-Pacific belt implies recurrent seismic events (INDECI, 2016). The events in the window of time abovementioned generated damages at a magnitude that compromised the economic development of the country, acquiring the connotation of national disaster (Andina, 2009; Rocha Felices, 2007). In this context, floods have been identified as the main causes of disaster damage in Peru, jeopardizing national development (SINPAD, 2020). In fact, in the past 15 years, 31% of national emergencies were directly attributed to EWEs. Moreover, 80% of houses affected by natural disasters were linked to these events, and damnified persons tend to double of those generated by earthquakes (SINPAD, 2020). When El Niño floods occur, the affected area covers an important part of the Peruvian territory. However, usually a gradient of affectation is experienced, in which the northern coast is more affected than other areas of the country (Muenchow et al., 2020).

For the current case study, a retrospective evaluation of disasters was carried out to assess the overall damages caused by El Niño-related events in Peru. Based on their magnitude, those that were ultimately selected were those corresponding to the 1982–83 and 1997–98 episodes, as well as the more recent event in 2017. Moreover, in order to have a benchmark for comparison, these three El Niño events were compared to two additional types of events. On the one hand, weather-related events occurring in the 21st century, such as Hurricane Katrina in New Orleans in 2005. On the other hand, earthquake-driven disasters were also included. For the latter, two of the most devastating earthquakes in recent Peruvian history, those of Ancash (9°28′S;78°19′O) in 1970, and Pisco (13°21′S;76°30′O) in 2007, were included in the assessment. Two additional seismic events in the 21st century (i.e., Indonesia 2004 and Haiti 2010) were also included in the comparative analysis.

### 3.2. Data acquisition and validation

Information regarding disaster inventories can be found in some international datasets like the Emergency Events Database (EM-DAT), gathered by the Centre for Research on the Epidemiology of Disasters (CRED) with the support of WHO and the Belgian Government, or DesInventar, which is a tool for the generation of National Disaster Inventories damage, losses and others effects of disasters (DESINVENTAR). These were used for data acquisition related to international disasters. Nevertheless, it must be noted that inventories regarding damages from international disasters usually lack the details regarding typologies of the infrastructure affected. Therefore, and depending on the scope of the MDDA to be carried out, the damage records of each country or region or specific case studies should be identified and used accordingly.

### *3.3. Disaster inventories*

The list of damages caused by disasters in Peru shown in Table 1 was obtained from official sources such as the National Civil Defense Institute (INDECI) and its national emergency registry: National Information System for Response and Rehabilitation (SINPAD) (SINPAD, 2020; INDECI, 2016, 2017). Demographic data were obtained from the National Institute of Statistics (INEI) through its REDATAM (2019) system. Epidemiological disease data were obtained from the National Center for Epidemiology, Prevention and Disease Control (CDC) of the Ministry of Health (MINSA) and complemented with El Niño assessments (Rocha Felices, 2007). Finally, the information used for the GDP values were obtained from the World Bank's online database. The flows described were used as input for estimating the damage in terms of the DALYeq units.

Regarding international disasters, as well as the 1970 earthquake in Ancash (Peru), damage inventory data were obtained from the records of EMDAT and DESINVENTAR (see Table 2). As mentioned above, these databases lack the specificity linked to infrastructure affected and, therefore, the evaluation of the damages in DALYeq units was limited to the social and economic dimensions for the sake of comparability.

## 4. Life cycle assessment of the main damaged infrastructure, assumptions and limitations

Damage inventories in Peru were gathered to include the main types of infrastructure affected. These included roads, housing and crops, as well as other typically affected structures, such as health centers, schools and bridges. Affected assets by disasters potentially include additional typologies beyond those described (e.g., public service networks, irrigation channels, cars, furniture or electronic

**Table 1**
Disaster damage inventory relative to the main natural disasters occurred in Peru in the period 1971–2020.

| General description | Unit | El Niño events | | | Pisco earthquake |
|---|---|---|---|---|---|
| | | 1982–83 | 1997–98 | 2017 | 2007 |
| Population | People | 18,125,025 | 24,073,312 | 31,237,385 | 28,220,764 |
| Average age | Years | 26.00 | 27.60 | 32.00 | 28.90 |
| GDP | Million US $ | 21,800 | 58,100 | 211,000 | 102,000 |
| GDP per capita | US$ | 1202 | 2415 | 6767 | 3620 |
| Economic losses | Million US$ | 1000 | 3500 | 3124 | 221 |
| Social losses | | | | | |
| Directly deceased | People | 512 | 366 | 165 | 595 |
| Missing | People | 0 | 0 | 19 | 0 |
| Wounded | People | 1304 | N.A. | 500 | 2,044 |
| Epidemic disease | People | 25,100 | 64,217 | 50,934 | |
| Acute diarrheal diseases | People | 168,575 | 33,226 | | 0 |
| Dengue | People | | 0 | 50,934 | 0 |
| Cholera | People | 7,866 | 41,717 | 0 | 0 |
| Malaria | People | 31,103 | 22,500 | 0 | 0 |
| Total damnified | People | 1,267,730 | 549,000 | 285,955 | 392,106 |
| Total affected | People | 1,300,000 | 549,000 | 1,615,946 | 169,668 |
| Infrastructure losses | | | | | |
| Transport | | | | | |
| Destroyed roads | km | 2600 | 884 | 4667 | 368 |
| Damaged roads | km | N.A. | 6395 | 12,781 | N.A. |
| Collapsed bridges | Units | 55 | 59 | 444 | 3 |
| Damaged bridges | Units | N.A. | 89 | 876 | N.A. |
| Dwellings | | | | | |
| Destroyed | Units | 98,000 | 42,342 | 37,254 | 34,672 |
| Damaged | Units | 111,000 | 108,000 | 377,857 | 84,958 |
| Schools | | | | | |
| Destroyed | Units | N.A. | N.A. | 140 | 605 |
| Damaged | Units | 875 | 2873 | 3642 | 614 |
| Affected pupils | Months | 538,000 | 130,000 | N.A | N.A |
| Health centers | | | | | |
| Destroyed | Units | | 5 | 31 | 14 |
| Damaged | Units | 260 | 511 | 1146 | 112 |
| Agricultural land | | | | | |
| Destroyed | has. | 36,000 | 73,000 | 50,226 | 0 |
| Damaged | has. | 84,000 | 131,000 | 107,165 | 0 |

NA: Not Available. Destroyed: Sufficiently damaged to require a full replacement.

**Table 2**

Disaster damage inventory of a selection of natural disasters.

| Event | Hurricane Katrina (United States) | Earthquake in Ancash (Peru) | Earthquake in Haiti | Earthquake and tsunami in Indonesia |
|---|---|---|---|---|
| Year | 2005 | 1970 | 2010 | 2004 |
| Total deaths | 1836 | 66,794 | 222,570 | 165,708 |
| Population millions | 296 | 12.3 | 10 | 224 |
| Death/100,000 hab. | 0.06 | 50.07 | 222.57 | 7.41 |
| Affected people millions | 15 | 3.22 | 3.7 | 0.53 |
| Losses, million US$ | 160,000 | 530 | 8000 | 4450 |
| Destroyed Houses | 800,000 | 93,905 | 106,000 | 68,000 |
| Damaged Houses | NA | 1,056,769 | 300,000 | NA |
| GDP/ per capita | 44,307.90 | 2857 | 662 | 1,149.00 |
| Average age | 36.2 | 24.76 | 21.5 | 23.7 |

NA: Not Available.

appliances), but these could not be traced due to lack of data and remain outside the scope of the current study.

In relation to the infrastructure inventoried (see Table 2), these also lack the ideal specificity to determine the individual characteristics of each type of infrastructure damaged. For this reason, it is assumed that environmental damage due to the reposition of assets is proportional to national reconstruction budgets. Therefore, environmental damages of schools and health centers were computed according to the proportional reconstruction cost of each unit in relation to dwelling reposition costs. Similarly, environmental damages of each affected unit were computed as a fraction of a destroyed housing (see Table 3).

### *4.1. Life cycle assessment of dwellings*

The system boundaries in the LCA conducted for housing units were limited to the main construction materials, such as concrete, mortar, bricks and reinforced steel. Data for the dwellings were retrieved from Mesta and colleagues (2019), in which construction areas and material intensities for the city of Chiclayo were collected (see Support information tables S.I.2 to S.I.4). These values have been used as average values of the affected dwellings along the Peruvian coast. The functional unit considered was 1 dwelling, rather than using a square meter functional unit, which is common in housing. The reason for this was the fact that available data does not provide specific details on the size of affected dwellings, but just reports the number of units affected. Consequently, an average value was assumed for the three different types of dwelling typologies considered (see Table 4). Results were considered for all categories related to the human health AoP (see Tables S.I.5-S.I.7 in the SI).

### *4.2. Life cycle assessment of roads*

The Panamerican Highway, which runs parallel to the Peruvian coast, was used as a proxy to assess the impacts of roads from an LCA perspective. This assumption was based on the fact that the areas affected by El Niño events have a relatively high proportion of tarmacked roads as compared to unpaved roads and lanes (SINPAD, 2020). Table 5 shows the environmental impacts regarding the main categories, which were performed based on the main constituent materials calculated by Verán-Leigh and colleagues (2019). Further information can be observed in Tables S.I.8-S.I.10 in the Supporting Information.

### *4.3. Life cycle assessment of crops*

An LCA was performed for the main crops affected by El Niño floods in the northern-coastal regions of Peru (Tumbes, Piura, Lambayeque, La Libertad, Ancash and Lima), by using production ratios corresponding to 2017. The system boundaries assumed included the entire production process of the crops but excludes post-harvesting stages. The functional unit considered was 1 ha of farmland, in line with this territorial perspective in which the focus is on the amount of farmland lost. The datasets were retrieved from the Ecoinvent v3.6 database. Table 6 shows the main results linked to agricultural production in the area of interest in 2017. Further information on crop data are visible in Tables S.I.11–S.I.13 of the Supporting Information.

Results in Table 6 show that rice and asparagus were the two crops that presented highest human health related damage per metric

**Table 3**

Environmental impact transformation factors: damaged/destroyed ratios for critical infrastructure (based on *Reconstruction con Cambios*, 2017). For further details, please refer to the Supporting Information Table S.I. 1.

| | Damaged/destroyed ratios | Equivalent dwelling |
|---|---|---|
| Dwelling | 3.0% | 1 |
| Schools | 41% | 72 |
| Health Centers | 11% | 377 |
| Roads | 31% | |
| Bridges | 18% | |
| Farmland | 9% | |

**Table 4**
Total environmental damage reported in DALY for different types of dwellings in Peru.

| Impact category | Type I | Type II | Type III |
|---|---|---|---|
| Climate Change - human health | 1.03E−1 | 8.78E−3 | 6.39E−2 |
| Human toxicity | 1.73E−2 | 8.33E−4 | 1.13E−2 |
| Particulate matter formation | 5.71E−2 | 2.21E−3 | 3.74E−2 |
| Other categories | 8.36E−5 | 7.26E−5 | 6.76E−6 |
| Total | 1.78E−1 | 1.18E−2 | 1.13E−1 |

*Type I: brick house; Type II: adobe house; Type III: building housing (i.e., apartment). Other categories: ozone depletion, photochemical oxidant formation and ionizing radiation.*

**Table 5**
Human Health damage reported in DALY per km of constructed road for Peruvian roads.

| Impact category | Total |
|---|---|
| Climate Change - human health | 1.56E−3 |
| Human toxicity | 2.15E−4 |
| Particulate matter formation | 7.77E−4 |
| Other categories | 2.44E−6 |
| **Total DALY, per km 14.4 mts. wide** | **2.55E−3** |

Other categories: ozone depletion, photochemical oxidant formation and ionizing radiation.

**Table 6**
Agricultural production data and derived damage results in the Peruvian regions affected by the 2017 El Niño phenomenon based on MINAGRI (2018) production datasets. The regions included are Tumbes, Piura, Lambayeque, La Libertad, Ancash and Lima.

| Product | Harvested Area has. | Total Production × 1000 TM. | Environmental damage DALY |
|---|---|---|---|
| Rice | 152,992 | 1174 | 4068 |
| Barley grain | 33,641 | 63 | 106 |
| Onion | 2,388 | 73 | 73.3 |
| Corn (all types) | 135,818 | 1489 | 1142 |
| Potato | 37,711 | 655 | 307 |
| Wheat | 54,897 | 87 | 189 |
| Carrot | 2650 | 53 | 29.9 |
| Lemon | 19,717 | 127 | 116 |
| Mandarin | 6283 | 204 | 328 |
| Orange | 2577 | 43 | 23.0 |
| Apple | 8,624 | 142 | 134 |
| Sugar Cane | 89,820 | 10,415 | 2382 |
| Asparagus | 18,268 | 203 | 473 |
| Grapes | 14,908 | 361 | 194 |
| Avocado | 25,212 | 313 | 581 |
| Banana | 21,642 | 318 | 190 |
| **TOTAL** | 627,148 | 15,720 | 10,338 |

ton of production. In terms of total DALYs generated in crop production, rice, sugar cane and maize are the three crops which generate most damage given their importance in the agricultural sector in coastal Peru. It should be noted that the average damage linked to crop production per hectare in the region of interest was 2.11E-2 DALYs.

### 4.4. Assumptions in infrastructure replacement

A set of criteria were established to account for the environmental impacts that must be included in this study related to replacement of infrastructure damaged by a disaster. This was necessary for all the infrastructure that was included within the scope of the study (e.g., roads, health centers, schools) and is detailed in Table 7.

### 4.5. Disaster burden of epidemic diseases

Epidemics, bacteriological or viral, are also a type of natural disaster that compromises human well-being. These may constitute a natural biological disaster on their own, as has happened recurrently through history with devastating consequences. However, in many cases they can also be an indirect consequence of other types of disasters. This is the case of El Niño-related floods in Peru, where abnormal warmer seasons and heavy rainfall in otherwise hyper-arid areas are usually a prelude for dengue, malaria and other

**Table 7**

Total human health damage per level of damage and type of stock due to the El Niño phenomenon.

| Level of damage per type of stock | Unit | Daly | Adopted criteria |
|---|---|---|---|
| Destroyed roads | km | 2.55E−3 | Road Inventories based LCA of Peruvian main road (Verán-Leigh et al., 2019). |
| Damaged roads | km | 7.99E−4 | % of destroyed roads |
| Destroyed bridges | p | 2.37E−4 | 60 m length, 6 m wide bridge, 1830 kg $CO_2$/km (Charles et al., 2014) |
| Damaged bridges | p | 1.63E−5 | % of destroyed bridges |
| Destroyed dwellings by floods | p | 1.18E−2 | Dwelling inventories based on Chiclayo city housing typologies, type II (Mesta et al., 2019). |
| Damaged dwellings by floods | p | 3.59E−4 | % of destroyed houses |
| Destroyed dwellings by earthquake | p | 1.71E−1 | Weighted average between Dwelling inventories based on Chiclayo city housing typologies, type I and III. |
| Damaged dwellings by earthquake | p | 5.20E−3 | % of destroyed houses |
| Destroyed Schools | p | 8.55E−1 | 72 dwelling units equivalent |
| Damaged Schools | p | 3.47E−1 | % of destroyed schools |
| Destroyed Health Center | p | 4.46E0 | 377 dwelling units equivalent |
| Damaged Health Center | p | 4.86E−1 | % of destroyed Health Centers |
| Destroyed Farmland | ha | 2.32E−2 | Based on 2017 north coastal production (MINAGRI, 2018) production |
| Damaged Farmland | ha | 2.12E−3 | % of destroyed farmland |

infectious diseases (Lai et al., 2012). Consequently, for a more complete view on disasters and their indirect consequences, a disability weight factor was considered (see Table 8) in order to account morbidity burden related to epidemic diseases.

## 5. Results and discussion

MDDA results, computed for the past three El Niño Peruvian disasters, show that the damage caused by the event in 2017 added up to 202,000 DALYeq (see Fig. 3). This value is significantly lower than the damages caused by the same phenomenon in previous events analyzed. More specifically, the El Niño event in the period 1982–83 caused damages 56% higher (i.e., 315,000 DALYeq), while in the event in the period 1997–98 a value of 430,000 DALYeq was obtained (+113%). When each disaster dimension is analyzed separately (see Tables S.I.14–S.I.16. in the SI), it can be observed that their relevance can vary significantly between disasters as a result of variation in exposure and vulnerability. For instance, it is particularly interesting to note that El Niño 1997–98 generated more economic and less social losses (including damage from epidemics) as compared to the event in 1982–83. The most likely explanation for this variation is the increased exposure of infrastructure and the greater preparedness of the population for floods in the 1997–98 event. However, the results obtained for El Niño in 2017 challenge this interpretation, since the damage generated in this case shows a higher proportion of social-related damages as compared to previous El Niño events. We hypothesize that this circumstance may be explained by uncontrolled urban expansion in areas that are more exposed to floods. In fact, it should be considered that the population in many urban areas in northern Peru has more than doubled throughout the period analyzed (INEI, 2017). In other words, it should be expected that overall social preparedness, including improved emergency response plans, better education or increasingly resilient infrastructure, should reduce the damage through time. However, informal urban sprawl in areas with higher exposure to natural disasters may neutralize social advances in this respect.

When the damage is reported per capita, that is, considering the quotient of total DALYeq damage among the population of the affected region, a clearer view in terms of damage intensity can be obtained. In this sense, the study shows that the events in 1982–83 and 1997–98 presented similar damage intensity (6.3 and 6.5 DALYeq per capita, respectively). In contrast, the damage per capita in 2017 was significantly lower, 2.4 DALYeq per capita. Moreover, the results from the three El Niño events analyzed were compared to the damage caused by the earthquake in the city of Pisco in 2007 (see Fig. 4). The comparison shows that this earthquake generated lesser damage per capita: nearly three times lower that the El Niño event in 2017, and approximately 7 times less intense than the 1997–98 event.

Another relevant aspect is that the magnitude of the environmental impacts related to the earthquake in Pisco are of a similar magnitude to the economic damages. This is explained by the fact that the environmental impacts linked to the replacement of housing damaged by earthquakes tends to be more noticeable in dwellings built with highly industrialized abiotic resources (i.e., concrete,

**Table 8**

Disability weight factors for some common disease and injuries related to disasters.

| Disease/Injurie disability | Severity | Average | Low range | Upper range | Disability days |
|---|---|---|---|---|---|
| Diarrheal diseases[a] | Moderate | 0.188 | 0.125 | 0.264 | 3 |
| | Severe | 0.247 | 0.164 | 0.348 | 5 |
| Dengue[a] | Fever | 0.197 | 0.172 | 0.211 | 5 |
| | Hemorrhagic | 0.545 | 0.475 | 0.583 | 5 |
| Malaria[a] | Episodes | 0.191 | 0.172 | 0.211 | 3 |
| Meningitis[a] | | 0.615 | 0.613 | 0.616 | 5 |
| Injuries | Mild | 0.074 | 0.049 | 0.104 | 7 |
| Cholera[b] | | 0.324 | 0.237 | 0.421 | 3 |

[a] Salomon et al. (2013); [b] Ock et al. (2016)

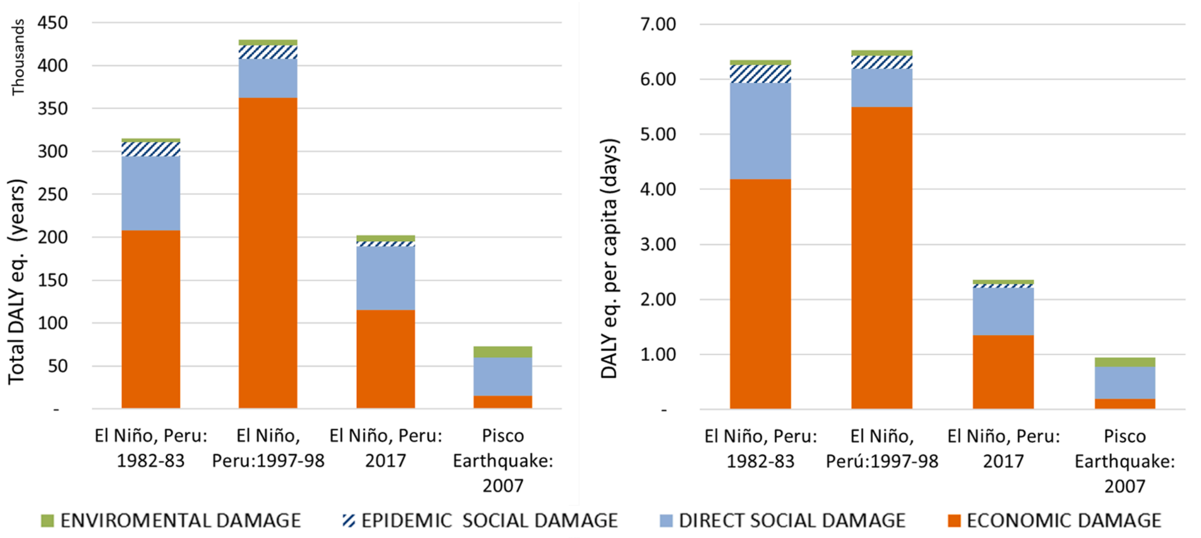

**Fig. 3.** Damage due to disasters in Peru, represented in total DALYeq units (left) and DALYeq per capita (right). Tabulated results can be seen in the Supporting Information.

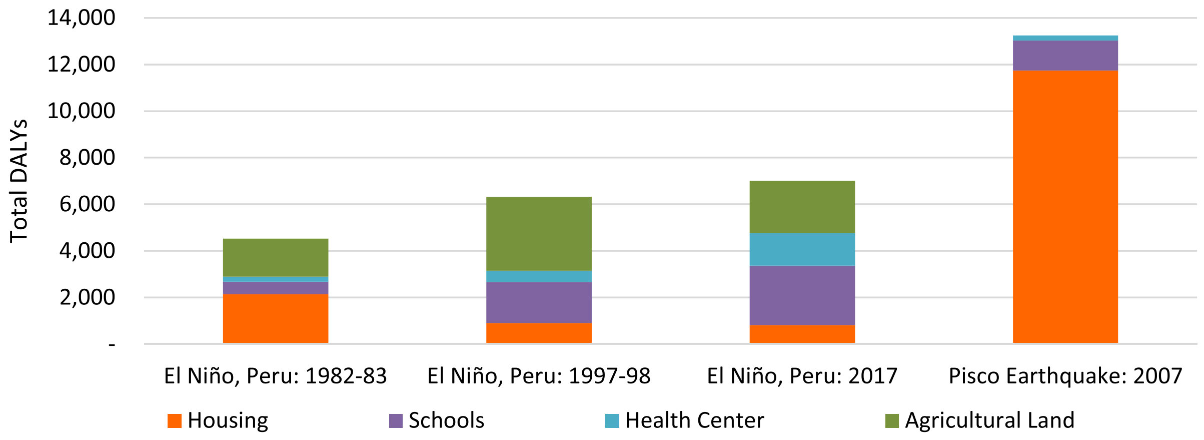

**Fig. 4.** Disaggregated environmental damage related to the human health Area of Protection (in DALY). Data includes both damage and destroyed infrastructure.

bricks or steel), compared to replacement of houses affected by floods and other disasters caused by weather, since the latter are generally built with materials such as wood or adobe. Moreover, an interesting result observed for El Niño events is the fact that a sustained increase in environmental damage over time is visible, mainly linked to impacts on schools and health centers, as well as agricultural land (see Fig. 4). Regarding the increase in environmental damage related to public infrastructure affected by disasters, we hypothesize that it is due to an increase in the exposure of this type of infrastructure in areas susceptible to floods as a consequence of urban expansion. As already documented by numerous studies, urban expansion processes press for the occupation of natural lands, the same ones that are usually occupied by segments of the population with fewer economic resources (ISRAM, 2014; Stefanidis and Stathis, 2013).

Overall, the applied methodology suggests a different damage configuration when comparing floods and earthquakes. On the one hand, as previously discussed, the results indicate that there is a prevalence of economic damage when analyzing El Niño events. On the other hand, for the earthquake in Pisco the main driver appears to be social damage due to the high cost in lives and injuries, while environmental and economic damage have a similar weight.

The MDDA was also applied to other disasters for the sake of comparability, in which the assessment of the environmental component was omitted due to lack of information. The results obtained show that El Niño damages (1982–83 and 1997–98) were 23 times lower in intensity than the earthquake in Ancash in 1970, which delivered a total damage of 144 DALYeq per capita (see Fig. 5). Similarly, other seismic events in the 21st century presented very high damage intensity per capita. In contrast, the comparison with other weather-related disasters shows that the intensity of the economic damage per capita of the El Niño in 1997–98 was 5 times

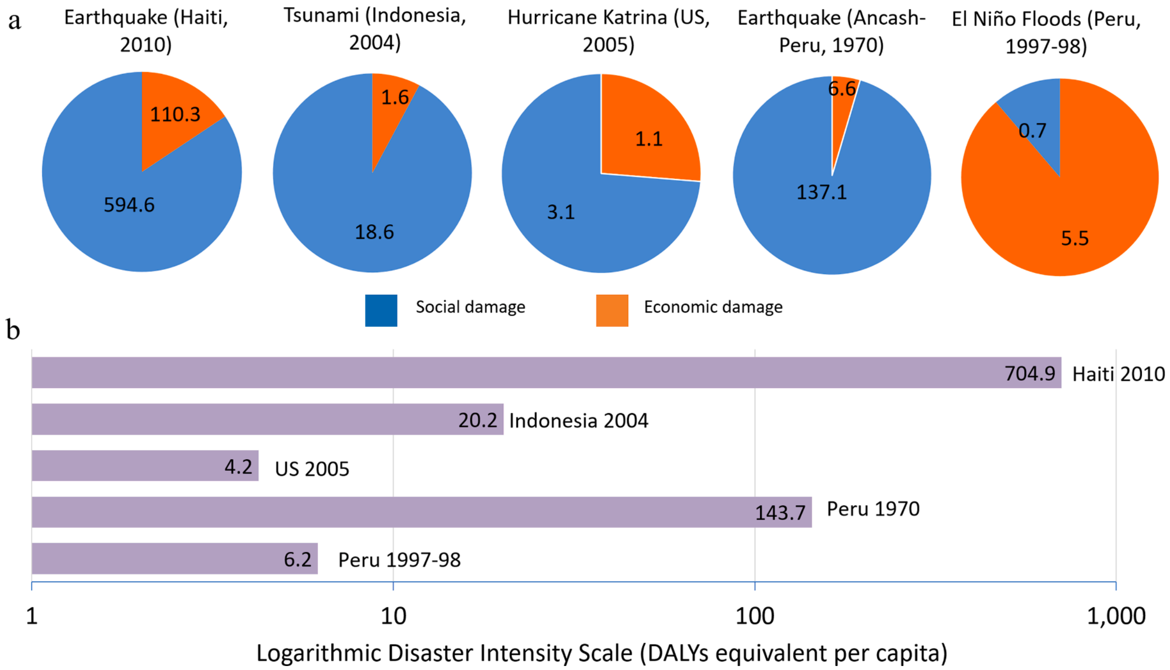

**Fig. 5.** Economic and social DALYeq per capita for selected disasters used for comparison purposes. Fig. 5a shows the proportion between the economic and social components of each disaster; Fig. 5b presents the comparison between the intensity (per capita) of disasters.

greater than the economic damage caused by Hurricane Katrina, the disaster with the highest economic cost recorded in EM-DAT.

Social damage linked to high-magnitude seismic events seems to be a determining factor for the higher MDDA values reported for these types of events. However, under *ceteris paribus* conditions, it is plausible to assume that as seismic magnitude decreases, social damage also decreases and economic damage becomes more relevant. Something similar happens with disasters caused by weather-driven events, in which economic damages become more relevant, since these affect large territorial surfaces and, consequently, can potentially damage a wider range of infrastructure.

Based on the results provided, the MDDA methodology allows a better understanding of disaster epidemiology, improving the quantitative basis of comparison between different types of disasters worldwide. Moreover, the methodology resurfaces aspects that otherwise would remain unnoticed, such as environmental damages due to the reposition of damaged assets, which are particularly relevant in earthquakes (i.e., Pisco 2007), representing 18% of total damage.

The MDDA methodology proved to be an efficient communication tool to highlight the relevance of environmental damage, which represents an extension of social damage differed in time and, therefore, it is reasonable to be added to other damage dimensions. This novel method also allows a better evaluation of exposure to risk damage, due to the addition of an environmental dimension linked to the replacement of damaged infrastructure. In fact, this perspective sets the basis for damage assessment to evolve towards a sustainable development approach. This constitutes a paradigm shift, with deep implications in disaster risk science, since it may promote the use of environmentally-friendly infrastructure beyond temporal housing (Atmaca and Atmaca, 2016) for the replacement of damaged dwellings. Furthermore, the MDDA methodology will allow the measurement of the level of risk considering the environmental performance optimization of the future infrastructure to be built.

The results demonstrate that the MDDA methodology allows the adoption of damage mitigation strategies with a broader perspective beyond an economic evaluation. Consequently, the proposed MDDA methodology for disaster assessment will require that those responsible for governance should manage disaster risk in a contemplative manner, considering also social and environmental repercussions.

## 6. Conclusions

Comparing the damage exerted by disasters can result in a challenging task. An important milestone of the MDDA method presented is the incorporation of the environmental damage assessment of a disaster, allowing a change in paradigm that goes beyond the current perspective that focuses on economic costs of infrastructure reconstruction and the subsistence care provided to the victims. The results presented suggest that MDDA is an effective method for measuring the overall impacts of a disaster for comparison purposes. In fact, it allows quantifying short and long-term impacts on human health and the environment, as well as direct and indirect damages (e.g., epidemiological outbreaks). Moreover, the results indicate that the DALY index can be used for damage assessment, providing a holistic tool for policy-makers to understand the full range of damage potential that natural disasters may generate. In fact, we argue that MDDA is liable to be applied to compute the total measure of impacts linked to any human intervention in the natural environment, in which different damage dimensions are generated.

The MDDA methodology highlights the need for innovation in damage mitigation policies, in order to incorporate compensatory concepts linked to the effects on human well-being and the environment. In other words, comprehensive damage mitigation (i.e., sustainable disaster management) will only be achieved when the balance of mitigation actions equals zero DALYeq. Moreover, from a computational perspective, the current method excluded the conversion of environmental impacts linked to ecosystem quality and natural resources. Although the damage derived from these two AoPs has not been converted into human health damage in existing metrics, their affectation to the anthroposphere and, ultimately, to human well-being is something to be considered in upcoming studies. However, further research and consensus building around more sophisticated and robust assessment methods in LCA will be needed in order for these additional environmental aspects to be included in the MDDA method.

## Declaration of Competing Interest

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

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.crm.2021.100329.

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