

Assessing the impact of tropical cyclones on economic sectors in Costa Rica, Central America

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Abstract

Tropical cyclones (TC) pose a persistent natural hazard to Costa Rica. Exposure to natural hazards, such as mass movements and floods, is compounded by a growing urban population and inadequate land use planning. This study conducted a comprehensive analysis of the economic impacts of TC of Costa Rica from Hurricane Joan in 1988 to Hurricane Eta in 2020, assessing the impact by municipality and economic sector using baseline information of the Ministry of National Planning and Economic Policy. According to the study, road infrastructure (933.8 US million), agriculture (280.5 US million), river rehabilitation (153.96 US million), housing 98.26 (US million), and health (81.74 US million) were among the sectors most severely affected by TC over the past 30 years. The Pacific basin municipalities in Costa Rica were found to be the most vulnerable, primarily due to the indirect impacts of TC. The study's results offer useful information on the economic sectors and municipalities that are most exposed from TC in Costa Rica and provide a replicable methodology for other regions and countries facing similar tropical phenomena. © 2024 The Authors. Publishing services by Elsevier on behalf of KeAi and The Shanghai Typhoon Institute of China Meteorological Administration. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

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1. Introduction

Tropical cyclones (TC) are powerful weather systems that can cause widespread destruction and loss of life in coastal regions along low latitudes. They form over warm ocean waters and are characterized by high winds, heavy continuous rain, and storm surges (Klotzbach et al., 2022). Among the most affect areas along low latitudes by TC includes the tropical Atlantic and Pacific Oceans (Das et al., 2021; Pinos and Quesada-Román, 2021; Bandyopadhyay et al., 2023), the Gulf of Mexico, the Caribbean Sea, and the Indian Ocean

(Bhatia et al., 2019; Quesada-Román, 2024a; 2024b). TC can cause severe damage to infrastructure, homes, and businesses, disrupt transportation systems, and result in widespread power outages (Noy, 2016). It is crucial for residents of these areas to stay informed and prepare for the potential impact of a TC by following evacuation orders and having emergency plans in place (Robertson et al., 2020).

Under-developed countries are disproportionately affected by the devastating impacts of TC, which can have far-reaching and long-lasting consequences on their communities, economies, and ecosystems (Adam and Bevan, 2020). The lack of resources and infrastructure to prepare for and respond to TC exacerbates the impact. Many under-developed countries are in coastal areas, which are particularly exposed to the high winds and storm surges associated with TC (May et al., 2013; Nadal-Caraballo et al., 2020). Developing countries face more acute

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impacts due to floods than the developed world (Benito et al., 2021; Biswas and Pani, 2021; Quesada-Román, 2022a). In fact, floods are compounding the risk of TC, exacerbating their economic and social impacts on vulnerable communities (Ghosh et al., 2023). Moreover, mass movement processes are common during the influence of cyclones producing huge impacts (Quesada-Román et al., 2019; Geertsema and Alcántara-Ayala, 2023). In addition, under-developed countries often have limited access to healthcare and resources in general, making it difficult for residents to recover from the damage caused by these storms causing residual vulnerabilities (Sharifi et al., 2021). The lack of resources and capacity to adapt to the changing climate also means that under-developed countries are more likely to experience repeated, and increasingly severe, impacts from TC in the future (Noy, 2009).

Recent studies have revealed an increasing frequency of disturbances in regions historically situated on the periphery of tropical cyclone activity (Altman et al., 2018). According to projections, the probability of intense TC worldwide is expected to more than double (Bloemendaal et al., 2022). The increasing warmth of the planet will also result in a progressive expansion of the destructive reach of cyclones inland (Li and Chakraborty, 2020). Furthermore, global tropical storm damage is projected to increase by approximately 50% by 2070 (Gottelman et al., 2018). These phenomena will likely have negative impacts on multiple sectors in the coming years (Kunze, 2021). The degree of vulnerability of different economic sectors to the impacts of TC will depend on their unique socioeconomic, cultural, and developmental characteristics (Webersik et al., 2010; Zhou and Zhang, 2021; Roy et al., 2022).

TC are a recurrent hydrometeorological hazard in Costa Rica, causing widespread destruction and economic losses (Hsiang, 2010; Quesada-Román et al., 2022; Krichene et al., 2023). The agricultural sector, one of the main drivers of the region's economy, is particularly vulnerable to the impacts of these events (Shannon and Motha, 2015; Hu et al., 2023). Crops such as coffee, bananas, and sugar cane are highly susceptible to strong winds and heavy continuous rainfall, leading to significant crop loss and reduced yields (Imbach et al., 2017; Juárez-Torres and Puigvert, 2021). The tourism industry, one of the major contributors to the economy of Costa Rica, is also affected by these events as natural attractions and infrastructure are damaged, leading to a decline in visitor numbers (Benavides-Vindas, 2020; Quesada-Román and Pérez-Umaña, 2020). The fishing industry can also suffer because of rough seas and the destruction of coastal habitats (Reyer et al., 2017). The impacts of TC are far-reaching, affecting not only the local economies, but also the well-being of the populations of Costa Rica.

In the past few decades, studies have shown that the frequency and impact of TC in Costa Rica have been on an upward trend (Hidalgo et al., 2020; 2022). However, there is a lack of comprehensive analysis of their differential impact on economic sectors and municipalities. Furthermore, the intrinsic factors that contribute to their risk conditions have yet to be fully understood. Our study is also motivated by climate change scenarios that will impact greater flooding and

landslides in the most important basins of Costa Rica in the coming decades (Hidalgo et al., 2024). This study aims to address these gaps in knowledge by hypothesizing that TC impact differently the economic sectors of the most affected municipalities in Costa Rica, as local government political units. The research will examine the spatiotemporal trends of municipal economic losses by sector due to TC from 1988 to 2020. This study can serve as a valuable example for other countries and regions commonly affected by TC or extraordinary precipitation events, providing insight into the approach and methods used to analyze their impact. Global readers will find this study valuable as it analyzes the economic impacts of TC, relevant to many world regions, addressing current issues such as urban growth and inadequate land use planning crucial for disaster management and climate resilience.

2. Material and methods

2.1. Geographical context

Costa Rica is a country in southern Central America that lies between Nicaragua and Panama, covering a terrestrial area of 51,100 km² and located between 8° and 11° North Latitude and 82° and 86° West Longitude. The country sits on four tectonic plates, namely the Cocos, Nazca, Caribbean, and Panama microplate (Alvarado et al., 2017). Costa Rica's tectonic activity is shaped by various processes, including subduction between the Cocos and Caribbean plates, the arrival of the Cocos volcanic submarine cordillera, the Central Costa Rican Deformed Belt, the Northern and Southern Panama Fault Systems, and local faulting, as stated in a study by Alvarado et al. (2017). Furthermore, the country can be divided into three morphotectonic units, which are the forearc, plutonic/volcanic front, and backarc, as reported by Hidalgo-Leiva et al. (2023). The forearc comprises the Pacific basin, with its rugged topography and catchments controlled by regional faulting, and dates back to the Cretaceous to Quaternary periods (Alvarado and Cárdenes, 2016; Arroyo-Solórzano et al., 2021). The volcanic/plutonic front encompasses the country's mountain and volcanic systems that run primarily from NW to SE and date back to the Tertiary and Quaternary. The backarc, constituting the lowlands of the Caribbean basin, is a result of depositional processes mainly from the Tertiary and Quaternary periods (Quesada-Román and Pérez-Briceño, 2019; Quesada-Román, 2021a).

As reported by Durán-Quesada et al. (2020) and Saenz et al., 2023, Costa Rica is a country located between the Caribbean Sea and the Pacific Ocean, making it highly exposed to various meteorological phenomena, such as the Intertropical Convergence Zone, El Niño Southern Oscillation (ENSO), cold fronts, trade winds, and TC. The dry season on the Pacific coast of the country, as noted by Mendez et al., 2022 and Alfaro (2002), lasts for 3–5 months, starting from the end of the boreal autumn to the beginning of the spring. The Pacific basin generally receives less than 3000 mm of rainfall annually, while the Caribbean basin experiences over 4000 mm annually, according to Birkel et al. (2022).

Costa Rica is comprised of seven provinces and 82 municipalities (see details in [Supplementary Material Table S1](#)). According to [Van Lidth de Jeude et al., 2016](#), Costa Rica has a population of around 5 million people, with the majority (~75%) living in urban areas. The Greater Metropolitan Area (GAM) is home to most of the urban population, accounting for 70% of the total population despite occupying only 14% of the country's territory. The impact of TC, such as landslides and floods, has been assessed and varies across each municipality, resulting in a hazard asymmetry throughout the country ([Quesada-Román, 2021b](#); [Quesada-Román, 2022](#)).

2.2. Tropical cyclones affecting Costa Rica

TC can have significant impacts on the people and economy of Costa Rica ([Alfaro et al., 2010](#); [Alfaro & Quesada, 2010](#); [Hidalgo et al., 2020](#)). As shown in [Fig. 1](#), TC generally originate over the tropical North Atlantic Ocean or the Caribbean Sea before moving towards Central America. Some TC also occur in the Eastern Tropical Pacific. The period between August and October experiences a higher occurrence of TC in the Caribbean Sea near Central America ([Alfaro et al. 2010](#); [Alfaro and Quesada 2010](#)) and is also the quarter in which more reports of impacts due to TC are reported on the Costa Rican Pacific Slope ([Alfaro and Pérez Briceño, 2014](#)). Once they reach the coast, they can bring strong winds, heavy rainfall, and dangerous storm surges that can cause flooding

and landslides ([Hidalgo et al., 2022](#)). In some cases, TC can cause widespread damage and disrupt essential infrastructure, such as roads, bridges, and power networks ([Quesada-Román, 2023](#)). In terms of climatology, the Pacific basin of Costa Rica is more prone to TC impacts compared to the Caribbean side of the country. When TC occur in the Caribbean or Atlantic basin, a critical configuration near the Gulf of Honduras can increase the probability of extreme precipitation and indirect effects in the southern countries of the isthmus, namely Costa Rica and Panama ([Hidalgo et al., 2020](#)). According to [Hidalgo et al. \(2022\)](#), it is possible that the transportation of humidity via induced air circulation over the isthmus is the primary factor responsible for the high likelihood of extreme precipitation on the Pacific slope of Central America. This process is similar to the mechanism described by [Durán-Quesada et al. \(2017\)](#). The local term for low level westerly winds is “synoptic westerlies” or “oestes sinópticos” in Spanish, as noted by [Muñoz et al. \(2002\)](#). These winds are associated with the occurrence of “temporales” which are defined as periods of continuous stratiform rainfall lasting one or several days, according to [Amador et al. \(2006\)](#). The Eastern Tropical Pacific region experiences a high level of atmospheric instability and oceanic heat content, which can contribute to the formation of TC ([Mendez et al., 2020](#)) that can also cause indirect effects over the Costa Rican Pacific slope ([Hidalgo et al. 2022](#)).

In the 1980s, Hurricane Joan, which formed over the Atlantic Ocean in 1988, made landfall in Nicaragua and

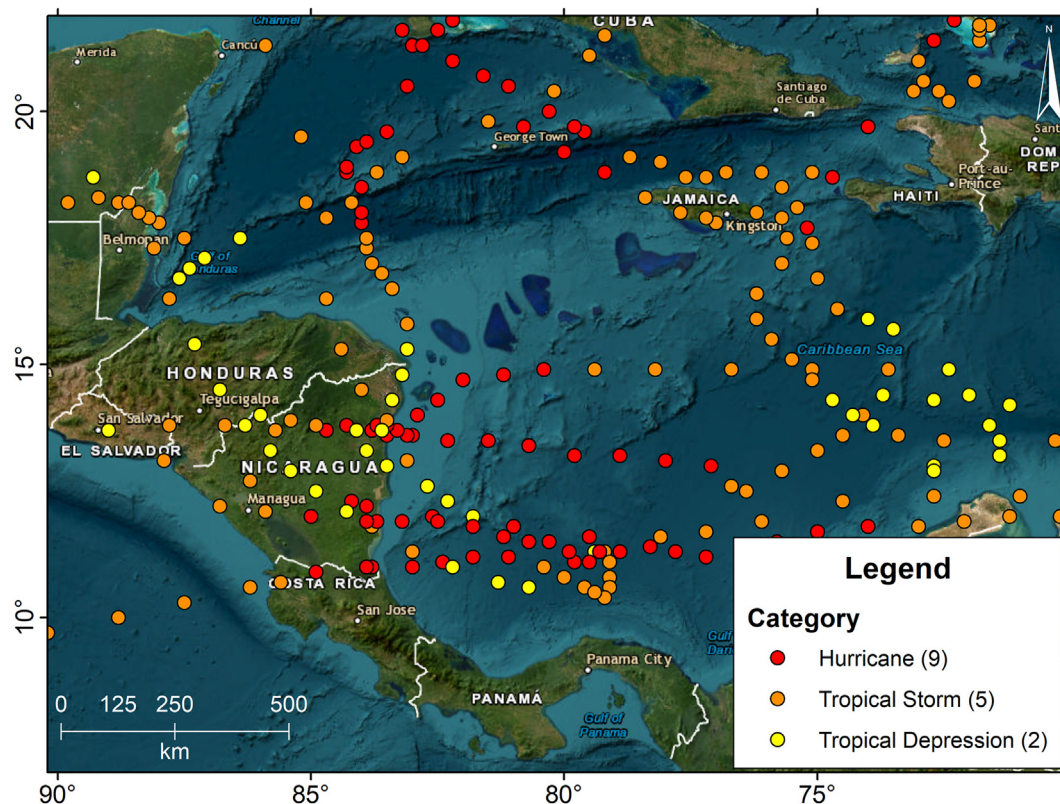


Fig. 1. Reported TC categories which mainly affected Costa Rica between 1988 and 2020, in parenthesis the number of hurricanes, tropical storms, and tropical depressions (HURDAT NOAA: https://www.aoml.noaa.gov/hrd/hurdat/Data_Storm.html).

traveled through the isthmus, causing widespread damage and flooding totaling 141 US million (Walker et al., 1991). Similarly, in the 1990s, Hurricane Cesar hit Nicaragua in 1996, causing also widespread flooding and mass movements in Costa Rica summing 186 US million (Pasch and Avila, 1999). Hurricane Mitch caused severe floods and landslides in Costa Rica in 1998, leading to deaths and significant economic damage in the agriculture and road infrastructure sectors with 124 US million in losses (Rodriguez and Saenz, 1999). In the 2000s, Hurricane Alma, which formed over the Pacific Ocean, impacted Costa Rica in 2008 causing significant damage and losses of 29 US million (Blake and Pasch, 2009). In recent years, the country has been affected by several significant storms, including Hurricane Otto in 2016 with 331 US million (Maldonado et al., 2020), Tropical Storm Nate in 2017 with 606 US million, and Hurricane Eta in 2020 summing 216 US million (Quesada-Román, 2021c). The socioeconomic impacts of these storms can be severe, causing damage to property and infrastructure, they can also disrupt essential services and commerce (Orozco-Montoya et al., 2022). For example, Hurricane Otto in 2016 resulted in losses estimated at 331 US million (Quesada-Román et al., 2019; Quesada-Román and Villalobos-Chacón, 2020). The recovery costs associated with these storms can be high and can take several years to fully recover.

2.3. Data processing and analysis

This study used official information by MIDEPLAN (Ministry of National Planning and Economic Policy, 2019): <https://www.mideplan.go.cr/>, and an update of the losses of Hurricane Eta in 2020. There were 16 TC that had National Emergency Declaration by the National Commission for Risk Prevention and Emergency Attention (CNE) of Costa Rica and economically affected Costa Rica between 1988 and 2020. In order to analyze the economic impact of TC on municipalities, data on municipal economic losses were extracted for each event. These losses were calculated by MIDEPLAN in colones (Costa Rican currency) and were immediately converted to 2015 US dollars, which is why we used that year. The most affected municipalities were identified based on the severity of the losses incurred. Conditions that make these municipalities more at risk include their location in coastal or flood-prone areas, poor infrastructure, and limited resources to invest in disaster preparedness and response were considered. These factors increased the vulnerability of these municipalities to the impacts of TC, leading to significant economic losses. Understanding the economic impact of TC on specific municipalities can help to inform decision-making regarding disaster risk reduction and preparedness strategies, with the goal of reducing the potential consequences of these events in the future. The used economic sectors were previously categorized by MIDEPLAN. We did not change these sectors and concentrated our analysis in the most influential economic sectors. Finally, the determined economic sectors were sewerage, agriculture, education, river rehabilitation, health, road infrastructure, and housing (Fig. 2). Other economic

sectors included in specific years but which its economic representation was negligible and not included were business, environment (included in river rehabilitation), energy and telecommunications, and emergency attention. The total economic losses by municipality were mapped using ArcGIS 10.3.

2.4. Statistical analysis

We employed a Pearson correlation equation (Wikle et al., 2019) and a Generalized Linear Model (GLM; Dobson and Barnett, 2018) to investigate the relationships between the economic impacts of TC and various environmental and socioeconomic parameters for each municipality. The environmental parameters considered were the percentage of flood-prone hazard areas (FHZ) at a 1:50,000 scale determined by the National Commission for Risk Prevention and Emergency Attention (CNE) of Costa Rica, the municipal slope (SLP), rainfall intensity-duration-frequency curves for every five years (TR5; Rojas-Morales, 2011; Vargas-Valverde, 2017), and the percentage of non-forested areas (NFA). We also included socioeconomic parameters such as 2022 population density projection (PD), mean road density (RD) from the National Territorial Information System (SNIT – Sistema Nacional de Información Territorial, 2023), and the social development index (SDI) from MIDEPLAN (2017) that is composed of 14 variables of economic, public health, educational, security, and civic participation parameters. It is similar but more detailed in spatial resolution than the Human Development Index present worldwide. To evaluate the Total losses by municipality (T) model, we used an Akaike Information Criterion (AIC; Anderson and Burnham, 2004) to perform a backward selection and compare the null hypothesis (i.e., $T \sim 1$) against the full ($T \sim \text{DIS} + \text{PD} + \text{SDI} + \text{SLP} + \text{TR5} + \text{FHZ} + \text{NFA} + \text{RD}$) and

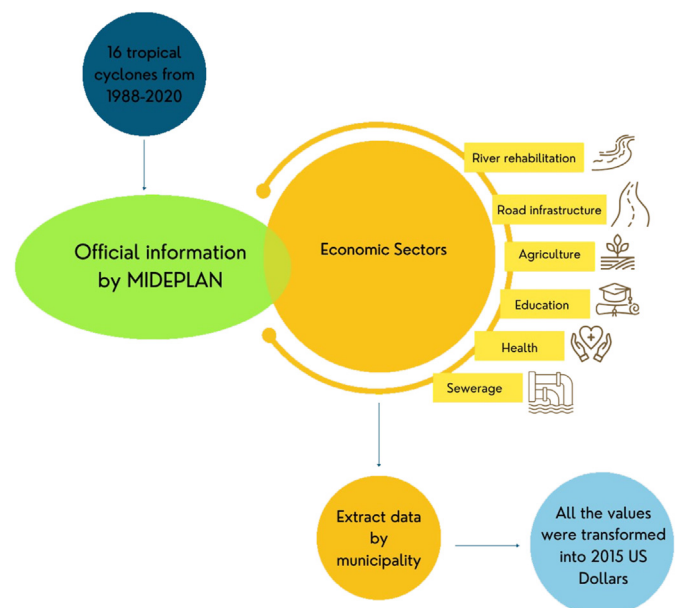


Fig. 2. Data processing and analysis schematic plot.

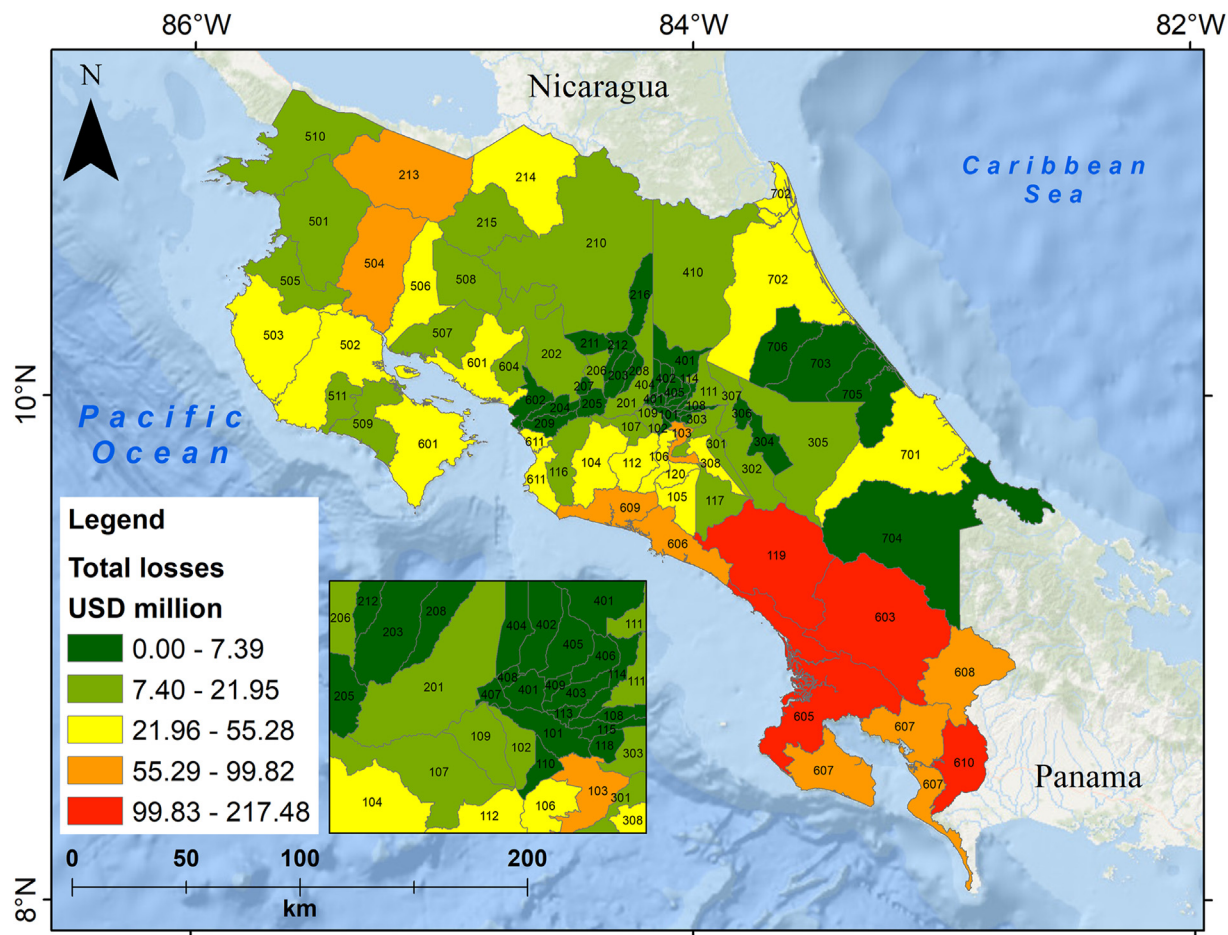


Fig. 3. Total economic losses (2015 USD million) due to TC by municipalities in Costa Rica. To clarify the location of specific municipalities mentioned in the text, see details in Supplementary material (Fig. S2).

alternative ($T \sim DIS + SDI + RD$) models. All covariates were standardized using a z-score.

3. Results

3.1. Major impacted municipalities by tropical cyclones

The most suitable explanation for T is found in the interplay of several factors (Table 1), including disaster events that occurred between 1970 and 2020 (DIS), the social development index (SDI), and the density of roads (RD). TC can have severe impacts on the inhabitants and infrastructure of

municipalities in Costa Rica. The study findings indicates that the most affected municipalities are those with more historical records of disasters, medium-low levels of social development, and medium-high road densities (Fig. 4). These characteristics appear to exacerbate the negative consequences of TC ,

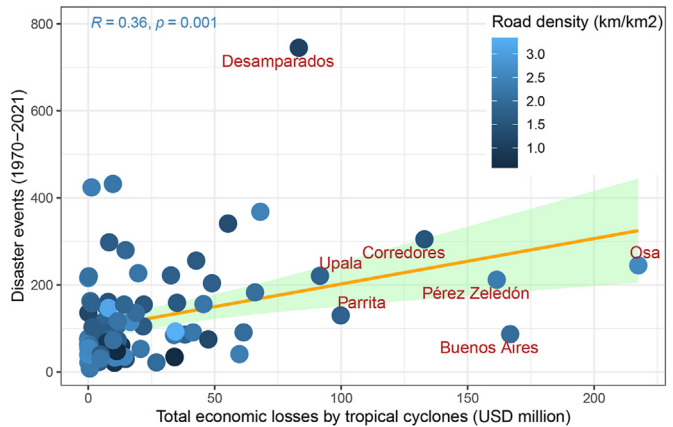


Fig. 4. Relationships between disaster events (1970–2021) and total economic losses by TC (2015 USD million) distributed with road density by municipalities.

Table 1

Parameters used to model the economic impacts of TC by municipality. AIC: 3079.6. $Pr(>|z|)$ is the probable finding of the observed Z-ratio by a critical point of $|z|$ in the normal distribution of Z. Null deviance: 1.3159e+17 on 81 degrees of freedom. Residual deviance: 8.6903e+16 on 78 degrees of freedom. Signif. Codes: 0 '****' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Model terms	Estimate	Std. Error	t value	$Pr(> t)$	
(Intercept)	29,320,694	15,343,192	1.911	0.05968	.
DIS	101,843	31,886	3.194	0.00202	**
SDI	92,551,080	18,608,360	−4.974	3.82e-06	***
RD	63,432,128	28,836,925	2.200	0.03079	*

resulting in increased damage and loss. There is a negative relationship between the Social Development Index and the total economic losses by TC (Fig. 5). The most affected municipalities have medium to high road densities (as an exposure factor) except by Desamparados in the GAM, but they present high vulnerability (low SDI).

Historical disaster records serve as an indicator of the municipality's vulnerability to future events, and the presence of a history of disasters can result in more destruction and loss of life when a new event occurs. These municipalities are mostly urban such as San José, Desamparados, Alajuela, Cartago, Heredia, and other large peri urban and rural municipalities such as San Carlos, Puntarenas, Turrialba, and Pérez Zeledón. On the other hand, low levels of social development, as indicated by the social development index, often result in a lack of resources and preparedness, exacerbating the effects of the disaster. TC can have severe impacts on the inhabitants and infrastructure of municipalities in Costa Rica, particularly in the Pacific basin. In terms of US millions in economic losses from 1988 to 2020, seventeen out of the first twenty most affected municipalities by TC are in the Pacific basin. Moreover, 83% of all the reported economic impacts by TC were in the Pacific basin municipalities. The study findings indicates that the most affected municipalities by these events in the Pacific basin are those with limited economic opportunities, lower levels of development, and poor quality of education. This result is also supported with the findings of Alfaro et al. (2010). Furthermore, these municipalities are often located far from the main cities and opportunities for health, public services, and education in Costa Rica. Municipalities such as Osa, Buenos Aires, Pérez Zeledón, Corredores, Parrita, and Quepos are the most affected units (Fig. 3). The municipality of Upala, located in the Northern Region of Costa Rica, is one of the most affected areas by TC (see also Alfaro et al., 2018). This is due, in part, to the direct impact of Hurricane Otto in 2016 (Maldonado et al. 2020), which caused approximately 75 million US dollars in losses. The effects of this disaster highlight the vulnerability of the region to the impacts of TC.

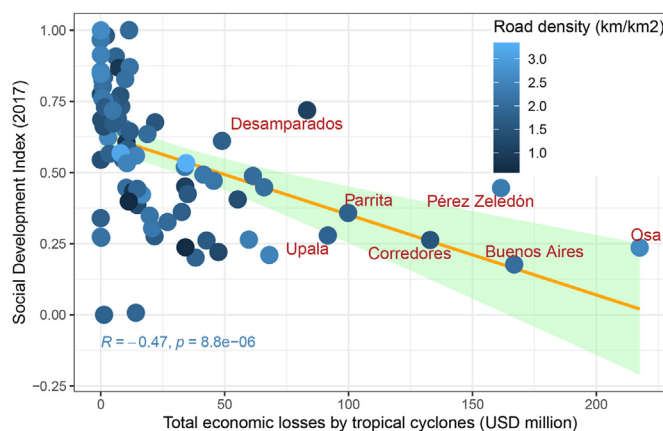


Fig. 5. Relationships between Social Development Index and total economic losses and TC (2015 USD million) distributed with road density by municipalities.

Desamparados, a municipality located in the Greater Metropolitan Area of Costa Rica, is one of the most affected urban areas by TC, previously identified also by Alfaro et al. (2010). This is due to its high road and population densities, as well as its lower levels of social development compared to surrounding municipalities. The high population density in Desamparados and other urban areas can increase the disaster risk and limit the ability of residents to evacuate in a timely manner. Additionally, the high road density can cause significant damage to transportation infrastructure, hindering recovery efforts and exacerbating the economic impacts of the disaster.

3.2. Main affected economic sectors by tropical cyclones

TC and hurricanes have had a significant impact on the economy of Costa Rica, affecting different economic sectors to varying degrees. According to this analysis, the main sectors affected by TC in the country are road infrastructure, river rehabilitation, agriculture, housing, and health (Table 2; Fig. 6). Road infrastructure has been the most affected sector, accounting for 58.56% of the total economic losses caused by TC. This can be attributed to the damage caused to roads, bridges, and other transportation systems, leading to disruptions in transportation and commerce. The rehabilitation of rivers has been another significant impact, with 14.83% of total losses. TC often result in severe flooding and landslides, leading to riverbank erosion and the need for river rehabilitation. An interesting result of Table 1 is that indirect tropical cycle effects account for an important quantity of the damage costs, associated with the persistent continuous stratiform rainfall of *temporales* on the Pacific slope, induced by the low-pressure system in the Caribbean Sea.

Agriculture has also been affected, accounting for 10.61% of total losses. This is due to the loss of crops, infrastructure damage, and soil degradation caused by floods and landslides. The housing sector has been impacted as well, accounting for 6% of total losses. This can be attributed to the damage caused to homes, displacement of residents, and the need for temporary or permanent housing solutions. Health sector accounted for 5.63% of total losses, this is due to the disruption of health services, the need for emergency response, and the risk of disease outbreaks. Other minor affected sectors are infrastructure, education, and sewerage, accounting for 0.82%, 1.31%, and 2.22% of total losses, respectively.

4. Discussion

4.1. Local and regional socioeconomic impacts

Southern Pacific Region is the most affected area of Costa Rica, comprising Osa, Buenos Aires, Pérez Zeledón, and Corredores municipalities. The following affected region is the Central Pacific with Parrita and Quepos municipalities. These local governments have several socioeconomic disparities (Royo, 2009; Hunt et al., 2014; Hunt et al., 2015). These economic limitations can exacerbate the negative consequences of

Table 2

Amounts of the economic sectors impacts in 2015 USD million by TC affecting Costa Rica between 1988 and 2020. Red values indicate the most affected economic sector according to each TC.

Year	Cyclone	Health	Infrastructure	Education	Sewerage	Agricultural	Rivers	Road Infrastructure	Housing	Total (USD million)	Percentage
1988	Joan	54.77	0.00	0.67	0.00	6.50	0.00	26.53	11.53	141.36	6.82
1993	Gert	2.67	0.00	0.00	0.00	35.73	0.00	55.09	6.51	8.5	0.41
1996	Cesar	11.64	0.31	5.08	1.44	5.63	9.54	60.25	6.11	186.26	8.99
1998	Mitch	12.21	0.00	0.72	1.90	38.81	1.63	36.57	8.17	124.75	6.02
2001	Michelle	0.00	0.00	1.26	1.29	9.77	0.00	87.68	0.00	25.28	1.22
2002	Lili	0.00	0.00	0.00	2.38	0.00	3.53	78.99	15.09	19.22	0.93
2005	Rita	0.00	0.00	0.00	0.00	16.18	28.70	38.00	17.11	25.5	1.23
2008	Alma	0.00	5.38	0.12	0.40	1.98	16.01	76.08	0.03	29.63	1.43
2008	DT16	0.00	0.00	0.00	0.00	46.98	0.58	52.44	0.00	35.06	1.69
2008	Hannah	0.00	0.00	0.77	0.00	88.86	0.00	9.90	0.46	16.04	0.77
2010	Nicole	0.00	0.00	0.00	0.00	0.00	1.02	98.98	0.00	17.05	0.82
2010	Thomas	0.14	0.67	1.84	3.47	8.62	24.24	50.11	10.89	278.88	13.46
2011	DT12	0.00	0.00	0.00	11.60	0.45	4.53	73.46	9.96	9.64	0.47
2016	Otto	0.00	3.65	0.72	2.52	14.72	17.45	59.86	1.08	331.64	16.01
2017	Nate	0.29	0.14	1.29	3.11	6.25	12.10	71.88	4.94	606.53	29.27
2020	Eta	0.00	0.02	0.00	0.99	0.00	34.63	57.99	6.38	216.6	10.45
Total (USD million)		81.74	10.18	12.48	29.09	280.50	153.96	933.80	98.26	2071.94	100.00
Percentage		5.63	0.82	1.31	2.22	10.61	14.83	58.56	6.01	100.00	100.00

TC, resulting in increased damage and loss (Quesada-Román et al., 2021). For instance, a lack of job options can reduce the ability of communities to recover from the disaster and rebuild their homes and livelihoods (Abarca-Jiménez, 2016). Furthermore, less development and poor quality of education can limit the resources and capacities available to municipalities to respond to disaster events. In addition, being located far from the main cities can create further challenges for these municipalities, such as limited access to healthcare, public services, and educational opportunities. These limitations can also impact the overall quality of life for inhabitants, making them more vulnerable to the impacts of TC. It is important to consider the unique challenges faced by the municipalities in the Pacific basin when developing strategies to mitigate the effects of TC in Costa Rica (Quesada-Román et al., 2023a). These communities need access to the resources and capacities necessary to prepare for, respond to, and recover from disaster events, such as TC. Addressing these economic limitations and providing support and opportunities can improve the resilience of these communities and enhance their ability to withstand future events.

In the Caribbean basin, the most affected municipalities by TC are Upala, Los Chiles, El Guarco, Guatuso, Turrialba, San Carlos, and Sarapiquí. Upala, Los Chiles, Guatuso, and San Carlos are particularly susceptible to the impacts of these

events due to their geographic location and their level of development. They are large, mostly flat terrains, where their land uses have been intensively changed in the last decades from extensive lowland evergreen forest to pastures and agriculture, the latter especially to pineapple (Fagan et al., 2013). For example, the region is prone to flooding and landslides, which can cause significant damage to homes and infrastructure (Quesada-Román et al., 2019; Quesada-Román and Villalobos-Chacón, 2020). Furthermore, the region may have limited resources and capacities to respond to disaster events, exacerbating their negative impacts. Turrialba is a municipality surrounded by volcanic mountains with a marked change to transition floodplains where landslides and floods are common (Garro-Quesada et al., 2023). Normally, its disasters are not related to TC but due to their location, geomorphological dynamics, and high exposure especially in its principal city with the same name, its impacts will increase in the following decades (Quesada-Román, 2024). El Guarco, although it is a small municipality in the GAM, it is located on the Caribbean slope. Its rapid population growth and limited land use planning increase its exposure and potential impacts from TC.

TC in urban contexts of Costa Rica can cause flooding, landslides, and property damage, affecting the local economy and increasing the risk of public health issues. Desamparados is the second municipality in Costa Rica, after San José, with the

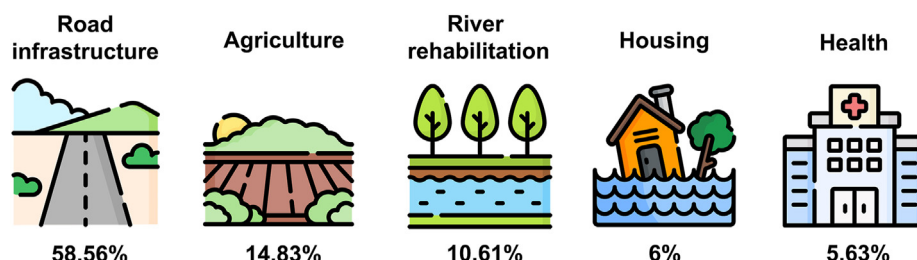


Fig. 6. Main economic sectors affected by TC in Costa Rica summing a 95.64% of the total losses between 1988 and 2020. Icons by Freepik.

highest number of informal settlements (Quesada-Román and Calderón-Ramírez, 2018). This fact makes it highly vulnerable to disaster events, such as those caused by TC, due to the lack of basic services and infrastructure in these settlements. The high concentration of informal settlements in Desamparados increases the exposure of damage to property and loss of life during disaster events (Quesada-Román, 2022b). It is crucial to consider the unique challenges faced by Desamparados and other urban municipalities when developing strategies to reduce the impacts of TC. This may include investing in infrastructure improvements to increase the resilience of buildings and transportation systems, as well as increasing community engagement and preparedness efforts to help residents respond to disaster events. By addressing the specific challenges faced by urban municipalities, it may be possible to reduce the negative impacts of TC and increase the resilience of these communities.

It is important for the government and other organizations to develop comprehensive plans to prepare for and respond to TC (Hoque et al., 2017a). This may include investing in infrastructure improvements, strengthening disaster response capabilities, and increasing community engagement and preparedness efforts. By taking proactive measures, it may be possible to reduce the negative impacts of these storms and help communities recover more quickly following a disaster.

According with Quesada-Román and Campos-Durán (2022) Quesada-Román and Campos-Durán, 2023, TC frequently impact the region of Central America, especially in their road infrastructure and agriculture sectors. Central American countries, such as Guatemala, Honduras, and Nicaragua, face significant poverty rates, which makes their populations particularly vulnerable to the impacts of disasters (Brockett, 2019). Limited access to resources and support exacerbates this vulnerability, increasing its negative consequences during times of need. Mountain topography of mainly urban areas of Costa Rica coupled with urban disorganized growth challenge the territorial planning and disaster risk reduction (Quesada-Román et al., 2021). Mountain areas are becoming more populated and affected by hydrometeorological hazards (Pinos and Timbe, 2020). A recent study has demonstrated the critical roles that population density and road density play in elucidating the transmission of COVID-19 from 2020 to 2022. Moreover, population density, coupled with the social development index, can offer valuable perspectives on the impact of past disaster events at the municipal level in Costa Rica (Quesada-Román et al., 2023b). It is imperative to consider these factors when developing strategies to mitigate the effects of TC in Costa Rica. The information gathered through this research can aid in the development of targeted and effective preparedness and response plans that prioritize the most hazardous municipalities and improve the resilience of communities.

4.2. Worldwide affected economic sectors by tropical cyclones

TC are intense weather phenomena that can affect various regions worldwide (Kunze, 2021). Coastal areas are typically

the most affected due to the cyclones' landfall, which can cause severe flooding, strong winds, and storm surges (Woodruff et al., 2013). Indirect impacts carry immense weight in Costa Rica, particularly for the municipalities situated along the Pacific slope, where they can potentially cause significant damage (Hidalgo et al., 2020). Studies indicate that countries located in the western Pacific Ocean and the North Atlantic Ocean are among the most affected areas (Knutson et al., 2010; Mendelsohn et al., 2012). These regions include the Philippines, Japan, the United States, and China. In terms of economic sectors, agriculture and tourism are among the most affected by TC. Cyclones can lead to significant agricultural losses due to crop damage, soil erosion, and contamination of water resources (Ortiz et al., 2023). Similarly, tourism can suffer from cyclones due to the destruction of infrastructures and natural resources, leading to a decline in tourism activities in affected areas (Alvarez and Huang, 2021). The consequences of TC can have long-term impacts on the economy, environment, and social welfare of the affected regions.

TC can cause severe damage to both infrastructure and natural resources in affected regions, leading to significant economic, environmental, and social impacts. Therefore, it is crucial to take action to reduce the potential consequences of these events. Mitigation strategies can include implementing early warning systems, increasing public awareness of risks, and strengthening building codes to ensure structures can withstand high winds and flooding (Swain, 2022). Additionally, proper land use planning and management can help to reduce the potential for landslides and flooding (Hoque et al., 2017a). Restoration of natural habitats, such as mangroves and wetlands, can also help to reduce the impact of storm surges and flooding, as these ecosystems can act as a buffer against these phenomena (Sun and Carson, 2020). Moreover, investment in disaster risk reduction and preparedness can help to mitigate the impacts of TC by improving the capacity to respond to and recover from these events (Hoque et al., 2017b).

Under-developed countries can set up early warning systems that provide timely information about approaching TC (Kuleshov et al., 2020). This information can help people living in vulnerable areas to evacuate to safer places. Policy gaps can be identified, and a novel framework can be developed to address regional challenges posed by tropical cyclones. This approach will enhance targeted policies to mitigate economic impacts and improve resilience in vulnerable areas (Islam et al., 2023). Moreover, it is key to invest in infrastructure improvements such as building flood barriers, improving drainage systems, and constructing better roads and bridges that are more resilient to flooding (Adhikari et al., 2021). Governments can implement effective land use planning to prevent people from building in areas that are prone to flooding. This can include zoning regulations and building codes that require new construction to be elevated above flood levels (Yin et al., 2020). The identification of return periods is compulsory in dynamic catchments using different paleogeographic methods (Wilhelm et al., 2022). Therefore, the continued monitoring of riverbeds using high-resolution remote sensing and fieldwork is key reducing the impact of

floods in rural and urban areas (Granados-Bolaños et al., 2021; Rabanaque et al., 2022).

Deforestation has been linked to increased flooding in tropical regions. Under-developed countries can work to reverse this trend by implementing reforestation programs that help to retain water in the soil and reduce the impact of floods (Vu et al., 2017; Friess et al., 2020). The implementation of different nature-based solutions in hazardous areas triggered by TC (e.g., coasts, lowlands, hillslopes, and floodplains) is a novel and practical approach reducing these natural hazards (Lallemant et al., 2021). In addition, countries and their most affected regions or municipalities can work with international organizations and nations to share knowledge and resources to better prepare for and respond to TC (Kuleshov, 2020). This may encompass a range of actions, such as sharing best practices, extending financial aid, and fostering collaboration in the research and development of novel technologies.

Our study's limitations include reliance on historical economic data, which may miss losses in the informal sector and indirect costs. Additionally, the focus is primarily on economic impacts, without addressing social and environmental consequences. Future research should incorporate diverse data sources, include long-term socio-economic effects, and compare results with other regions. Exploring the influence of climate change on tropical cyclone patterns and impacts could further enhance resilience strategies worldwide.

5. Conclusions

This study demonstrates the persistent hazard that TC pose to Costa Rica, particularly due to increasing population in urban areas and inefficient land use planning. Employing the baseline information of the Ministry of National Planning and Economic Policy of Costa Rica, this extensive examination accentuates the economic consequences of TC on the nation during the last thirty years. The analysis recognizes road infrastructure, agriculture, sewerage systems, and housing as the sectors that have sustained the most severe impacts. Furthermore, this study provides valuable insights into the most vulnerable municipalities and economic sectors in Costa Rica, with Pacific basin municipalities found to be particularly susceptible due to the indirect effects of TC. The replicable approach used in this study can provide useful guidance for other countries and regions affected by similar phenomena in the tropics. These findings underscore the importance of proactive measures and effective responses to reduce the impact of TC on vulnerable communities and promote more resilient societies.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.tcr.2024.08.001>.

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