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Housing quality improvement is associated with malaria transmission reduction in Costa Rica

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ABSTRACT

Housing quality has been identified as a key factor for malaria transmission risk. Here, we study the macro-ecological association between housing quality, measured by construction materials, and water access with malaria transmission at the county level in Costa Rica. We used SCAN cluster analysis to identify spatio-temporal clusters of malaria transmission using county level annual malaria records from 1976 to 2018. Data on housing materials and water access collected in the 1973, 1984, 2000 and 2011 national population censuses were analyzed using principal component analysis to derive housing quality and water access indices at the county level. Negative binomial rate generalized linear models, and Akaike Information Criterion (AIC) based model selection, were used to study the association between malaria cases and the percent of houses with metallic roofs, housing quality and water access indices. We found that Malaria was clustered in southern Huétar Caribe Region (Relative Risk, RR = 62.61 for 1990–2008), Huétar Norte Region (RR = 13.73, for 1991–2000) and Puntarenas county (RR = 5.77, for 1995–2002). From 1984 to 2011 most of the counties where malaria was clustered were in the lowest 20th percentile of housing quality in Costa Rica. The regression analysis showed that malaria cases significantly decreased with increasing housing quality at rates that accelerated through time. Our results suggest that housing quality improvement is one among several factors that led Costa Rica to the malaria pre-elimination stage. We propose that housing quality improvement should be considered a component of long-term policies aiming to reduce, or eliminate, major vector-borne and other neglected tropical diseases from Costa Rica, regionally in Mesoamerica, and globally elsewhere.

1. Introduction

One of the first malaria transmission eco-epidemiology insights was that disrupting human-vector contact can reduce malaria transmission [1]. This inference led Angelo Celli to propose that housing was a key risk factor driving malaria transmission [2] and to perform some of the first trials showing that simple housing modifications could reduce, or even stop, malaria transmission [3]. Housing improvement was a key sanitary strategy to deal with vector-borne diseases in the Panamá Canal when it was a US colonial possession [4]. Indeed, early epidemiological studies in the Canal Zone showed that malaria was more frequent in people living in the worst quality housing in the area [5,6], where malaria was eliminated using vector control tools for the first time [7]. More recent research from Africa has shown that simple changes in housing design can reduce the exposure to malaria mosquitoes [8], which is associated with malaria transmission and anemia reduction in children [9]. Indeed, the pattern of improved housing reducing malaria transmission has also been observed at the level of individual countries, for example Uganda [10], and regionally, as shown by data from multiple country surveys, in Sub-Saharan African countries [11]. These patterns are not exclusive to Sub-Saharan Africa, as housing design seems critical for malaria vector exposure in Asia, as documented in the Lao PDR [12], and Mesoamerica, where improved housing quality has been associated with reduced malaria cases in Panamá [13]. At a global scale, data has shown that improved housing quality reduces the risk of malaria infection [14], where ecological mechanisms are related with housing entrance by vectors [3,9], vector survival and abundance [15,16], and a potential reduction in parasite fitness [17]. Moreover, it has been increasingly recognized that improved housing quality can reduce the incidence of several tropical diseases [18,19]. This is particularly

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important for diseases where the contact with vectors occurs within the household, as it the case for *Anopheles* spp vectors of malaria [20], including *Anopheles albimanus* Wiedemman the main malaria vector in Mesoamerica [21].

During the global malaria eradication program from the past century, when insecticide residual spraying of houses was the main strategy to reduce human-vector contact in Latin America [22], the malariology division in Venezuela had a branch in charge of rural housing improvement [23] based on the realization that housing was a major risk factor not only for malaria, but also for other vector-borne diseases, e.g., Chagas disease, which was common in inactive and active malarious areas of Venezuela in the 1960s [23]. Housing improvement was seem from inception as a long-term goal to reduce malaria and other vector-borne disease transmission [24] considering the prohibitively large economic burden of quickly transforming housing quality in developing countries [25]. Cost is still a major issue in promoting a more widespread push for housing improvement as a pillar for malaria elimination [26]. However, in Sub-Saharan Africa it has been documented that, through time, housing quality has been improving over recent decades [27], including countries where malaria transmission has declined [28,29] and this pattern raises questions about how globally widespread is the impact of housing quality improvement on malaria transmission decline over relatively long-term time scales. Thus, asking whether housing quality improvement has been a key factor reducing malaria transmission over time in Costa Rica, one of the 21 countries expected to eliminate malaria by 2021 [30,31], is a question that can help to further refine regional plans in Mesoamerica and México to eliminate malaria by setting housing improvement goals, as housing is an often neglected human right key for healthy lives, and a major United Nations Sustainable Development Goal [32]. Therefore, here we study the macroecological association between housing quality, measured by construction materials, and water access with malaria transmission at the county level in Costa Rica. We use long-term annual malaria surveillance records at the county level and data on housing materials and water access from the four most recent population censuses in Costa Rica.

2. Materials and methods

2.1. Data

Annual malaria records were compiled using printed and online reports (available at https://www.ministeriodesalud.go.cr/index.php/biblioteca-de-archivos/centro-de-informacion/material-publicado/boletines-50/boletines-vigilancia-de-la-salud) on infectious diseases from the Costa Rican Ministry of Health. These data included all confirmed malaria cases by blood slide examination collected by the different programs in charge of malaria control and elimination through time. Data for all counties in the country, starting in 1976 and up to 2019, were recovered [33]. During this period the only change in counties was the split of Grecia county into Grecia and Río Cuarto counties in 2017, but for this study we analyzed these two counties as a single unit in 2017 and 2018, thus focusing our analysis on the 81 counties that existed from 1976 to 2016. During the study period over 90% of the malaria cases were due to *Plasmodium vivax* [30]. However, cases by *Plasmodium* species were unavailable at the county level, as this information was only reported at the whole country level [34,35]. The Centro Centroamericano de Población database on Costa Rica national population censuses (available at https://censos.ccp.ucr.ac.cr/) was used to gather county level data on population size and data on housing materials, specifically including data on materials used for roofs, walls and floors, as well as data on water sources and waste water disposal for the 1973, 1984, 2000 and 2011 Costa Rican censuses.

2.2. Statistical analysis

We performed a retrospective space-time cluster analysis with the SCAN statistic, using a discrete Poisson model [36], where the population size of each county for each year was considered when estimating the clusters. Briefly, the SCAN statistic estimates spatio-temporal clusters using an algorithm that detects an excess in cases in a given region assuming cases are generated by an inhomogeneous Poisson point process with an intensity proportional to the population at risk, in other words the model assumes that cases in each county follow the distribution of a Poisson random process whose intensity is proportional to the population size in each county for each year [36]. For the analysis a circular scanning window, whose maximum radius covered up to half of the county centroids, was employed. This means that clusters are searched considering case counts from up to half of the counties and assuming the cases occurred at the centroid of each county [37]. For the inference, a Poisson process null hypothesis was tested through a maximum likelihood ratio test that compared it to an alternative model stating that this assumption was false, and the significance was tested with 999 Monte Carlo randomizations. The population at risk for each county was assumed to be that of the whole county, and data from the 1973, 1984, 2000 and 2011 Costa Rican population censuses were used to interpolate population size between 1976 and 2011, and to extrapolate the population size from 2011 to 2018, using a negative binomial generalized linear model [38] for each one of the country's 81 counties, where census population size was modeled as function of the census year. This modeling strategy is a good approach to predict population size since it assumes population growth is exponential, but with some degree of over-dispersion [39].

To estimate a housing quality index we employed data on the percent of houses, at the county level, that used a given material for building walls and floors. Data about roof materials were not included because there was relatively little variability in the materials used for this housing element, which was dominated by metallic roofs throughout the studied censuses. The categories for materials used for building housing units changed through the censuses. For floors all censuses always included data on earthen and wooden floors, and a new category that included all other materials was created (concrete, ceramic, etc). For walls all the censuses included data for walls made with concrete, wood and mud/adobe. The housing quality index was then estimated as the first principal component from a principal components analysis on a variance-covariance matrix [38] that was estimated using data on the percent of houses using each one of the six materials described before at the county level for the 1973, 1984, 2000 and 2011 censuses. We employed the variance-covariance matrix given that we analyzed percentage data, so we could not expect a bias on PCA loadings arising from variables having different magnitudes [38]. A similar methodology was used to estimate the water access index, which considered the percent of houses that obtained water from aqueducts, wells and other sources (for example, rivers or rain), whether houses had a bathroom inside the housing unit, and if the wastewater went to a septic tank and/or sewer.

The association between malaria cases and the percent of houses with metallic roofs, the most common roof material, housing quality index and water access index was studied using negative binomial rate generalized linear models [38]. These rate models consider population size by including an offset of its natural logarithm [38], and we used this method to account for over-dispersion in the number of malaria cases. Since metallic roof, housing quality, water access and malaria data were only available for 1984, 2000 and 2011, data from only those three years were used in this analysis. Because vector-borne disease incidence is highly sensitive to El Niño Southern Oscillation (ENSO) cycles in Mesoamerica [30,37,40–43] malaria case data were smoothed by estimating rates based on 5 year averages, i.e., including data from 2 years before and 2 years after each of the years when the housing data were collected. This smoothing prevents that results are affected by considering data from years belonging to a specific ENSO phase [43]. Then the cumulative sum was averaged by multiplying the population size included in the offset by five. Models were fitted for malaria case number per county as function of the % of metallic roofs, housing quality index and the water access index. Models considering more than one covariate were not fitted given the high positive correlation between the three considered covariates, which was above 0.50 in all cases and could cause parameter unidentifiability [38]. In a first stage a unique slope parameter was fitted for all the censuses. In a second stage, for the best model selected in the first stage, slope parameters were assumed to change through time by including a slope parameter for each census. Models were selected by choosing the model that minimized the Akaike Information Criterion (AIC), a metric that selects models by minimizing the trade-off between parameter number and goodness of fit [38].

2.3. Software

For the SCAN cluster analysis, we used SaTSCAN v.4.9.9 (available at: https://www.satscan.org/). For all other analyses and maps we used R version 3.6.1 (available at: https://cran.r-project.org/). Centroids for each county were estimated using the command 'getSpPPolygonsLabptSlots' from the library 'sp' [44]. PCAs and negative binomial generalized linear models were estimated using, respectively, the 'princomp' and 'glm.nb' from the 'MASS' library [38]. Maps were made employing several commands from the 'OpenStreetMap' and 'GISTools' libraries [44].

3. Results

The SCAN cluster analysis found three significant clusters that increased at least five times the relative risk of malaria cases, when compared with areas outside the clusters, during the study period (Fig. 1). The most important cluster (Log Likelihood Ratio, LLR = 91,160; $P < 0.001$) was found in the southern Huétar Caribe Region, including Matina, Limón and Talamanca counties where the relative risk was 62 between 1990 and 2008. The second most important and significant (LLR = 15,196; $P < 0.001$) cluster included most of the counties in the Huétar Norte Region, including San Carlos, Los Chiles, Guatuso and Upala counties in Northern Costa Rica, on the border with Nicaragua with a relative risk near 14 during 1991–2000 (Fig. 1). A third significant (LLR = 1708; $P < 0.001$) cluster, with a relative risk around 6, was found in Puntarenas county on the Pacific coast, between 1995 and 2002 (Fig. 1).

The housing quality index and the water access index explained, respectively, 88.11% and 80.67% of the variability in the data used to estimate them, as assessed by the value of the dominant eigenvalue used to estimate the PCA. The loadings of the PCA used to build the housing quality index indicate that large positive values represent counties where housing walls were dominated by concrete and floors from materials that were not earth nor wood, while large negative values represent counties were housing had earthen and/or wooden floors and wooden walls (Table S1). Meanwhile, the water access index reaches maximum values in counties where baths are located inside the houses, water comes from an aqueduct and waste water goes to a septic tank and/or sewer (Table S2). Through time both housing quality and water access indices increased their values (Fig. 2). For counties were malaria transmission was clustered, with the exception of Puntarenas county through all the censuses and San Carlos county during the 2011 census, housing index estimates were in the lowest quintile (i.e., below the 20th percentile). This is visualized by looking at how points for most of the counties where malaria cases were clustered are to the left of the estimate for the 20th percentile (Fig. 2).

When plotting malaria cases as function of the covariates no clear association with the water access index (Fig. S1) was observed. A similar lack of pattern was observed for the % of houses with metallic roofs (Fig. S2). By contrast, the number of malaria cases clearly decreased as function of housing quality (Fig. 3) in a fashion where housing quality dispersion decreased when comparing the 1984 (Fig. 3A) with the 2000 (Figs. 3B) and 2011 census (Fig. 3C), something not observed for water access (Fig. S1) and % of houses with metallic roofs (Fig. S2). The housing quality model with a unique slope parameter (AIC = 1500) outperformed the water access (AIC = 1504) and the % of houses with metallic roofs (AIC = 1550) models with a unique slope parameter. Meanwhile, the model that assumed changes in the rate at which malaria cases changed with housing quality for each census (AIC = 1482) outperformed the model with a unique slope parameter for all censuses. Parameter estimates for the best model are presented in Table 1, where it can be appreciated that intercepts increased through time. By contrast, proportional rate changes at which malaria case number decreased as function of increasing housing quality, estimated as one minus the exponent of the slope parameter estimates, augmented from 3% by housing quality index unit increase in 1984, to 6% in 2000 and 11% in 2011.

4. Discussion

Housing quality is a major health determinant in both developing

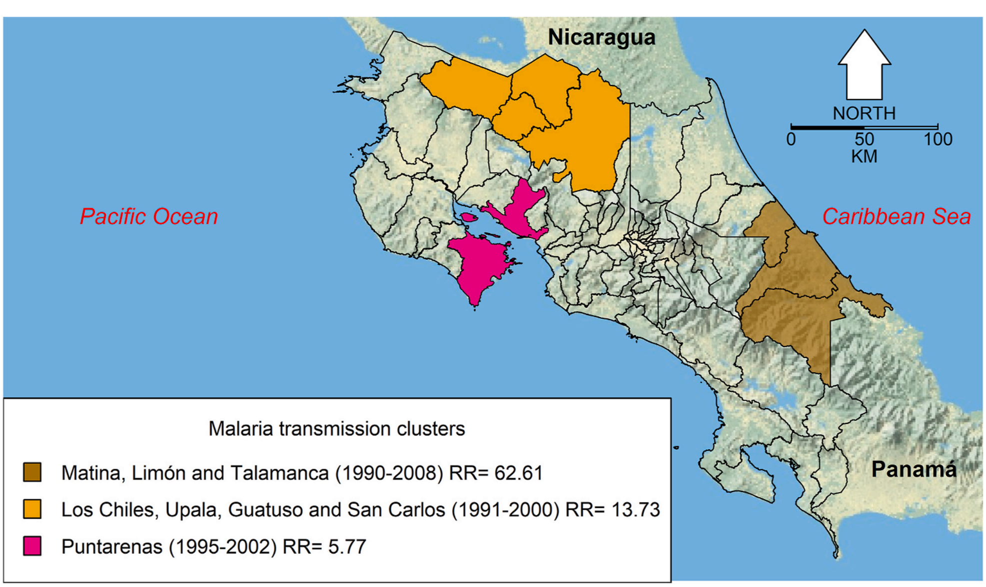

Fig. 1. Map of Costa Rica highlighting the location of the three significant spatio-temporal clusters, at the county scale, found with the SCAN statistic. To ease the understanding of cluster location in space and time a supplementary online only video (Video S1) showing annual choropleth maps for malaria cases by county is available at the journal website. The map was made using a public domain map from the US National Park Service as base (for details see: https://www.nps.gov/hfc/carto/data-sources.cfm).

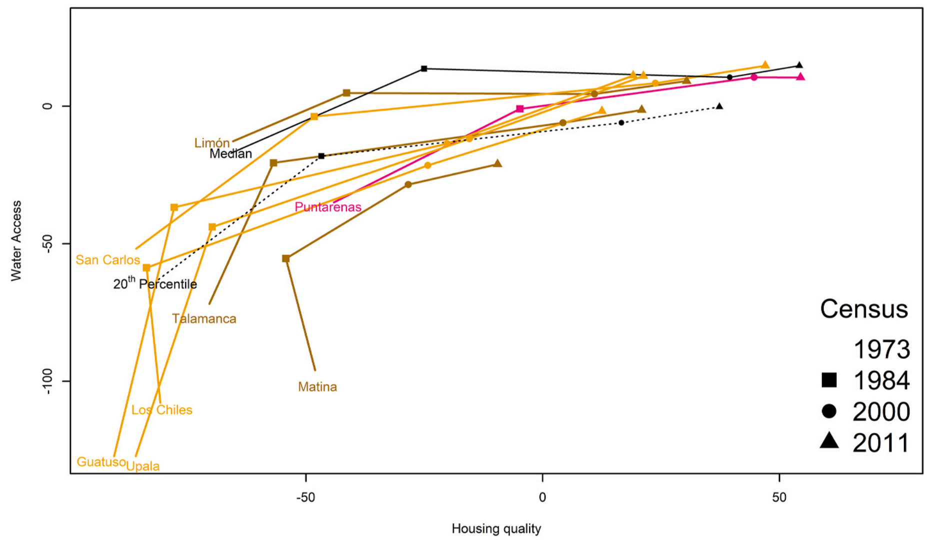

Fig. 2. Evolution of the housing quality and water access indices through time. The individual trajectory of the counties where malaria cases were clustered during the study period is highlighted, as well as, the median and the lowest quintile (or 20th percentile) of the estimated indices. A more dynamic version of the data supporting this plot, including all counties, can be seen in the supplementary online only video (Video S2) available at the journal website.

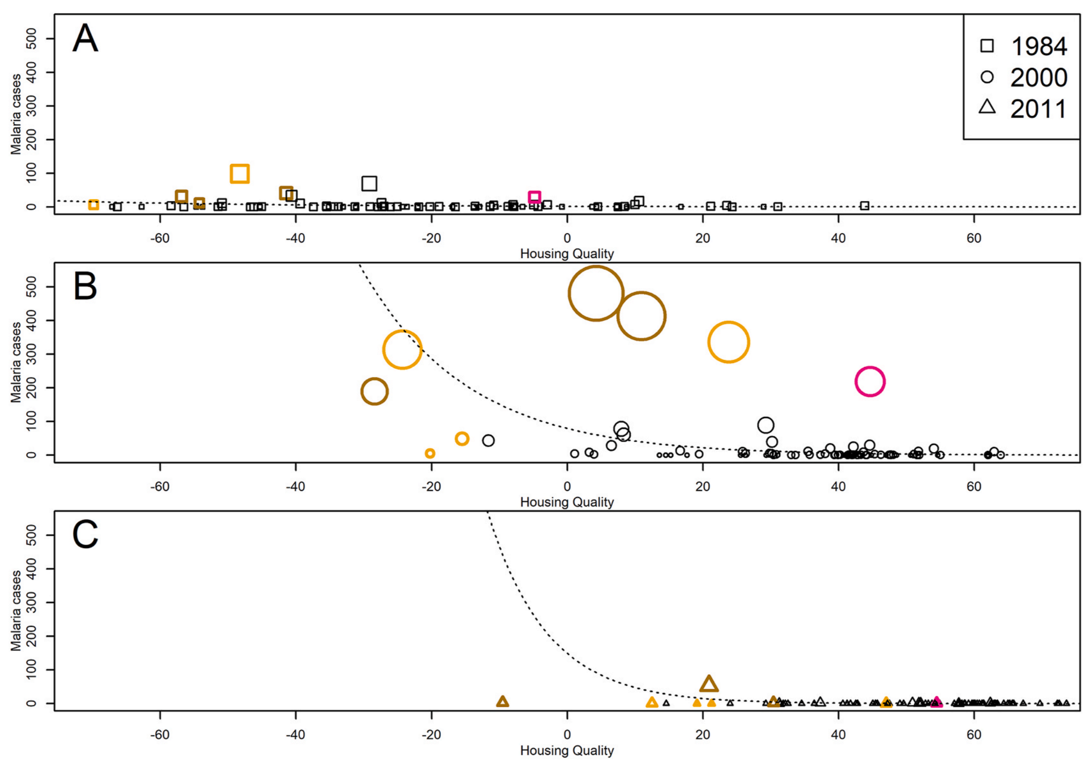

Fig. 3. Malaria cases (5-year smoothed) as function of the housing quality index (A) 1984, (B) 2000 and (C) 2011 census. Each point represents a county during a census. Color indicates the malaria transmission clusters presented in Figs. 1 and 2 and lines represent the model fit based on parameter estimates presented in Table 1. In the panels character size is proportional to the number of cases. To estimate the intercept and slope for 2000 and 2011 "difference" estimates presented in Table 1 were added to the 1984 reference estimates. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

[45] and high income countries [46–48], that can affect the interaction between humans and most kinds of insect vectors [19]. In Costa Rica malaria transmission decreased as housing quality improved, across time and space, and this factor along with improved supervised malaria treatments [30,33,34], which are possible under the relatively strong universal healthcare system of Costa Rica [49], and conventional vector control [35,50] have been major players in leading Costa Rica to a malaria pre-elimination stage [51]. These results highlight the importance of housing quality in scenarios where dominant vectors are mainly zoophilic, exophagic and exophilic, as is the case with *An. albimanus* [52–54], the dominant vector species in Costa Rica and the rest of Mesoamerica, as the probability of occasional infestations is furtherly decreased in high quality housing. For example, traditional Amerindian houses in Panamá frequently get visited by *An. albimanus* [41,55–57]

Table 1
Parameter estimates for the best negative binomial rate model explaining the number of malaria cases (5-year smoothed) as function of the housing quality index (HQ) at the county scale in Costa Rica.

Parameter	Estimate	S. E.	z value	Pr (>|z|)
Intercept-1984	−9.441	0.322	−29.36	<2e-16*
HQ slope-1984	−0.031	0.009	−3.40	0.000679*
Difference for intercept-2000	3.374	0.559	6.03	1.64E-09*
Difference for intercept-2011	3.820	0.899	4.25	2.17E-05*
Difference for HQ slope-2000	−0.033	0.015	−2.19	0.028389*
Difference for HQ slope-2011	−0.083	0.019	−4.41	1.02E-05*
Over-dispersion	0.216	0.023	–	–

*Statistically significant ($P < 0.05$).

and these type of traditional housing is dominant in areas where malaria is geographically clustered in Panamá [13]. However, neither national nor regional efforts are being made in Mesoamerica to improve the design of traditional houses, as currently pursued in Africa [58]. Similarly, despite past experiences that saw rural housing improvement as an integral solution to decrease the transmission of vector-borne diseases in Latin America [23], no regional agendas seeking integral solutions to problems that have poor quality housing as a common ground have been developed. For example, leishmaniasis [59] and Chagas disease [60,61] increase their entomological risk of infection in poor quality housing. This pattern extends to gastro-intestinal pathogens [46,62]. Moreover, research done in Mesoamerica has shown how housing improvement can be done using local materials and low cost technology that can be easily transferred to local communities [61]. Similarly, anthropological research has suggested that using traditional knowledge for housing design might reduce the infestation by insects [63], yet little has been done in the New World to include housing quality improvement in regional agendas to decrease malaria and neglected tropical diseases transmission [64–66], despite the recognition of its importance for malaria transmission in strategic plans for its elimination [67]. In that sense, results from this study call for the establishment of longer-term goals for housing improvement in areas inhabited by vulnerable populations to malaria and similar infectious diseases in Costa Rica, and hopefully, at least, all over Mesoamerica.

In Costa Rica most housing developments are funded by loans from private and public banks, with market based interest rates and conditions, often outside the means of most of the population [68]. Meanwhile social housing programs, which have been increasingly insufficient since the mid 1980s [69], are managed through publicly funded institutions that offer reduced and fixed interest loans to build or improve homes [70] and through grants for families living in extreme poverty or affected by natural catastrophes [71], a strategy that has not shown the best outcomes. The latter is illustrated by the resurgence of malaria in the Huétar Caribe region of Costa Rica in the 1990s, which followed a major infrastructure collapse triggered by the 1991 Limón earthquake [72]. A relative worsening of the housing quality conditions in Limón county, which had almost no malaria transmission before the earthquake [35] and whose housing quality was above the median up to the 1984 census (Fig. 2) was followed by a sharp increase in malaria transmission that corresponds to the 1990–2008 malaria transmission cluster in the southern Huétar Caribe Region (Fig. 1), a time when Limón county went from being above the median to being in the lowest quintile of housing quality (Fig. 2). In that regard, results from this study suggest that policies for granting access to housing should not be mainly driven by offer/demand market dynamics, especially as socio-economic inequities have been growing since the last two decades of the 20th century in Costa Rica [73,74] a scenario where access to high quality housing can be limited by a market not able to affordably cover housing needs for most of the Costa Rican population [70].

An interesting aspect of housing materials in Costa Rica is that since the 1970s metallic roofs are the most common across the country, a factor shaped by guidelines for housing design and construction that encourage the use of low weight roofs because of frequent earthquakes [75]. In that respect, at least at the macroecological scale of this study, it can be affirmed that metallic roofs do not seem to have had a major impact in malaria transmission, as they are suspected to have had in Africa [16]. The studied data did not reveal an impact of water access in malaria transmission, and this probably reflects the biology of the dominant vector, *An. albimanus*, which breeds in natural sunlit aquatic habitats near houses [40,55,56,76] being autonomous of water issues important for other mosquito vectors, like water supply/storage [77] and waste water management [78]. More generally, it is interesting to see that through time housing quality kept improving and reducing its variability (Fig. 3) in opposition to what was observed for water access (Fig. S1) and metallic roofs (Fig. S2) which kept a similar range through the study period. In that regard, the association between housing quality and malaria transmission is something that could be expected according to Schmalhausen's law, the biological principle stating that biological systems are more sensitive to more unpredictable variables around their mean values [37,79,80]. This type of variability is measured by the kurtosis of a distribution, where platykurtic (a.k.a., low kurtosis distributions) are less likely to have a near constant mean value, as opposed to what is observed in leptokurtic (high kurtosis distributions) where values near the mean are less variable or closer to a constant [17,81–83].

Finally, results from this study highlight the need to consider access to high quality housing, a sustainable development goal [32], as a major component of long-term policies aiming to reduce, and eventually eliminate, vector-borne and other neglected tropical diseases in Costa Rica and elsewhere.

CRediT authorship contribution statement

Luis Fernando Chaves: Conceptualization, Methodology, Data analysis, Funding acquisition, Original draft preparation. **Melissa Ramírez Rojas:** Data curation, Reviewing and Editing. **Sandra Delgado Jiménez:** Data curation, Reviewing and Editing. **Monica Prado:** Funding acquisition, Data analysis, Reviewing and Editing. **Rodrigo Marín Rodríguez:** Conceptualization, Funding acquisition, Reviewing and Editing.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.seps.2020.100951.

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