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MASTER THESIS

DO CORAL REEFS MATTER?

AN ANALYSIS OF THE EFFECTS OF CLIMATE INDUCED CORAL BLEACHING ON THE BIOLOGICAL STANDARD OF LIVING IN INDONESIA

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ABSTRACT

In recent years, observations of coral bleaching, which can have devastating effects on coral reefs up to the collapse of entire ecosystems, have become more frequent. This can mainly be attributed to climate change since high sea surface temperatures are widely understood as the trigger of coral bleaching. Since coral reefs are an important income and nutrition source for coastal communities, especially in developing countries, it seems likely that coral bleaching has a negative effect on wellbeing. This paper provides a quantitative analysis of the effects of coral bleaching on the biological standard of living of people in Indonesia, while also considering the role of different channels through which these effects materialize. The results show that being exposed to coral bleaching in the year of birth or at very young age has a causal negative effect on the biological standard of living, which suggests that coral bleaching leads to malnutrition. While both the income channel and the direct nutritional channel through subsistence fishing explain the coral bleaching effect, the results furthermore suggest that the latter might play a bigger role. The results of this work imply that poor coastal communities are highly vulnerable to climate change through coral bleaching, which should be taken into consideration for climate change adaptation and mitigation.

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INTRODUCTION

Coral reefs are among the most biodiverse ecosystems on the planet and although they are mostly known for their incredible beauty, they are furthermore crucial for fisheries, coastal protection and tourism income, especially "in developing countries and island nations where dependence on coral reefs for food and livelihoods is high" (Burke et al. 2011). In recent years, these ecosystems have been under threat from increasing reports of coral bleaching (Oliver et al. 2009), a phenomenon that can cause the death of corals and thereby the collapse of entire ecosystems and has been described as "one of the most striking impacts of climate change that has been observed to date" (Cinner et al. 2013). Ongoing climate change is furthermore "likely to increase the frequency and intensity of bleaching" (Hoegh-Guldberg 1999), which is why some scholars have suggested that "policies that result in [CO2]atm above 500 ppm appear[s] extremely risky for coral reefs and the tens of millions of people who depend on them directly, even under the most optimistic circumstances" (Hoegh-Guldberg et al. 2007). The Intergovernmental Panel on Climate Change predicts in most scenarios that this threshold will be surpassed around the middle of this century (Watson and Albritton 2001).

Since coral reefs are vital for people that depend on them as an income or nutrition source, it is crucial to understand the effects coral bleaching has for their wellbeing. However, despite the role coral reefs play in the public discourse on climate change, there exists very little economic research on the impacts of coral bleaching and although several valuation studies try to estimate the value of coral reef services and thereby assess potential damages from their collapse, the extent to which such events affect the wellbeing of people depending on them is not well established in the literature. The aim of this work is to contribute an assessment of wellbeing effects to the literature by studying the effects of coral bleaching on the biological standard of living, measured in height and height-for-age. Using anthropometric indicators does not only allow the reconstruction of historical data regarding wellbeing and nutrition, it also implies a focus on the poor, since it is to assume that negative shocks from coral bleaching do mostly have a nutritional effect for the poor, while nutrition and height of richer individuals are less affected. This work uses Indonesia as a case study, since it is part of the so-called coral triangle, one of the world's centers of marine biodiversity, and has the "largest reef associated population in the world" (Burke et al. 2011). In the following, an overview over the scientific background of coral bleaching as well as its biological and potential social effects will be provided before methodology and data will be explained. Then the main results will be presented, followed by an analysis of potential channels and a conclusion.

BACKGROUND

Reefs, bleaching and climate change

Coral reefs "appear to be one of the most vulnerable marine ecosystems" (Hoegh-Guldberg, 1999) since they critically depend reef building corals, which create the structure of the reef itself and thereby protect inhabitants from outside influences. Corals are however only able to survive within a very narrow range of temperature, light and water conditions (Speers et al., 2016). Even minor changes to these conditions can therefore have potentially devastating effects on corals and lead to rapid changes in coral reef ecosystems. The effects of such changes are well studied, corals can for example be harmed by storms and freshwater inflows through a decrease in water salinity (McLaughlin et al. 2003; Moberg et al. 1997) or as a consequence of sedimentation (Rogers 1990) as well as by a growing carbon dioxide intake in the ocean causing increased acidity of seawater (Kleypas and Yates 2009; Anthony et al. 2008). Although such influences can harm corals, the literature has highlighted another effect of climate change as crucial, namely rising sea surface temperatures due to their role as "the primary variable triggering coral bleaching" (Hoegh-Guldberg, 1999). They are furthermore "the most common factor believed to be responsible for extensive coral bleaching" (Brown 1997), while changing salinity or increased radiation do not lead to the biological effects observed during mass bleaching events (Hoegh-Guldberg 1999; Lesser 1996; Hoegh-Guldberg and Smith 1989).

In order to understand the role of rising sea surface temperatures and their relationship to the biological process of coral bleaching, the importance of symbiotic relationships within coral reefs is crucial. Since coral reefs are similar to "oases within marine nutrient deserts" (Hoegh-Guldberg, 1999), these symbioses reduce the amount of nutrients lost to the open ocean. This "close association of primary producer and consumer [allows] the tight nutrient recycling that is thought to explain the high productivity of coral reefs" (Hoegh-Guldberg, 1999). Due to the central role of reef building corals, the endosymbiotic relationship, referring to one partner living inside the organism of the other, between them and zooxanthellae, single-celled dinoflagellates, is of highest importance in the context of this work. Zooxanthellae provide their hosts with up to 95% of their photosynthetic production (Muscatine, 1990) and are therefore crucial for the nutrition of corals. In the process of coral bleaching this endosymbiotic relationship is destroyed and the coral starts to expel zooxanthellae as a consequence of thermal stress. Since the coral's nutrition however depends on the symbiosis, this can in severe cases lead to the death of the coral which in turn has negative consequences for the reef ecosystem and makes the structure of the reef vulnerable to erosion.

The name of this process originates from the fact that the zooxanthellae give the otherwise transparent coral organism its color and their expulsion leaves only the transparent coral organism or, in more severe cases, its white skeleton, thereby turning entire reefs white.

Consequences of coral bleaching

Coral bleaching can lead to rapid transformations of coral reefs and to a shift from the domination of coral to a domination of macroalgae (Ostrander et al. 2000), which has both direct and indirect effects on other coral reef organisms. Since the aim of this paper is to analyze effects of coral bleaching on wellbeing, the focus will be on the effects on fish populations and fisheries, since that might lead "to much-reduced yields of protein for dependent human populations" (Hoegh-Guldberg 1999), which is especially relevant since protein malnutrition can have a range of adverse effects on health and can cause stunting (Semba 2016). Direct effects on fish populations stem from the role corals play as part of the ecosystem. Coral-feeding fishes might suffer directly from the loss of coral, while some species use corals as hiding spots from predators and might lose this protection due to erosion after the death of the coral. However, studies show that coral bleaching affects "far more than just coral-feeding or coral-dwelling fishes" (Jones et al. 2004), which indicates that indirect effects might also play an important role. These effects are related to the function of corals as the structural foundation of the ecosystem, which implies that "any reduction in the coral component of the reef community is a threat to the physical structure of the entire reef ecosystem" (Ostrander et al. 2000). This is supported by the more general finding that corals are crucial to the structural complexity of reefs, which in turn is correlated with fish density and biomass (Graham and Nash 2013). Therefore, bleaching can directly and indirectly affect the amount of fishes in a reef and thereby "alter the goods and services that coral reefs provide by reducing reef fisheries productivity" (Cinner et al. 2013). However, the amount of research on bleaching effects on fish populations and fisheries has been limited and while there appears to be a consensus that "coral mortality due to a bleaching event could have a major impact on the fishing yield" (Öhman 1999), scholars disagree about the intensity of the impact and the time at which negative effects materialize. While several studies have shown that a decrease in coral cover can lead to decreased recruitment of young fish (Jones et al. 2004; Graham et al. 2007; Feary et al. 2007), which implies more long-term effects, some also suggest strong effects on current fish populations. Jones et al. (2004) for example found that parallel to a decline in coral cover, "75% of reef fish species declined in abundance, and 50% declined to less than half of their original numbers", while others report falling fishery yield and increased fish prices after a bleaching event (McClanahan et al. 2002).

Generally speaking, the effects seem to vary between locations depending on the locally available fish species (Munday et al. 2008). Another important question concerns the recovery of coral reefs, which is debated in the literature. While some studies find “no indications of recruitment” (Ostrander et al. 2000) and that recovery might take up to 30 years (Hoegh-Guldberg 1999), other results indicate that in some cases, especially in the Indian Ocean, recovery was relatively fast and “detected within as little as 2 years” (Baker et al. 2008), although with a different composition of species and conditional on the stability of the reef structure itself (Pratchett et al. 2008).

This is however only one effect of importance to coastal communities. As the study by Graham and Nash (2013) shows, structural complexity of reefs, which is prone to decline because of coral bleaching, is also very relevant for shoreline protection and tourism revenue. Concerning the first topic, coral reefs serve on one hand to slow down shoreline erosion (Reguero et al. 2018; Sheppard et al. 2005) and furthermore protect shores form severe weather events (Villanoy et al. 2012) which are expected to increase due to climate change (Villanoy et al. 2012). Although it is difficult to assess how much such protection is worth, existing valuation studies suggest a relatively high value of coastal protection by coral reefs. A study for the US Virgin Islands for example suggests an overall value of shoreline protection services of 1.2 Million USD annually (van Zanten et al. 2014).

Concerning the second topic, there exists a considerable valuation literature on coral reef tourism despite the difficulties with such analyses, suggesting a high recreational value of these ecosystems. A meta-analysis by Brander et al. (2007) for example suggests an average value of 184 USD per reef visit although the author himself admits that “the quality of valuation studies for coral reefs seems to be lower” than of comparable studies. A more recent global study of the value of reef-related tourism however underscores its high value, suggesting that reef-related tourism is worth 36 Billion USD per year, equal to more than nine percent of all coastal tourism value in the world's coral reef countries (Spalding et al. 2017).

To sum this up, the literature highlights that coral bleaching can decrease the productivity of fisheries even in the short run and thereby affect both income and subsistence fishing. It can furthermore weaken coastal protection, making communities more vulnerable to severe weather events and decrease important tourism revenue.

Poverty, development and coral bleaching

A question which directly follows from the discussion of potential negative effects of coral bleaching on coral reef services is in how far this might be relevant in the context of development and for the wellbeing of the poor. It has been argued that especially people in developing countries depend heavily on coral reefs for fishery, coastal protection and tourism (Donner and Potere 2007) and that "the benefits of coral reef services are […] a major resource for sustainable development" (Öhman 1999). Regarding fisheries, it has been suggested that "reef fish quantity losses […] are likely to disproportionately reduce the economic well-being of people whose lives and livelihoods depend on reef fish harvests" (Speers et al. 2016) and older studies estimate that coral reefs contribute ca. 25% of the total catch in developing countries (Jameson et al. 1995). Coastal protection is also more important in developing countries, since they can be assumed to have fewer resources for artificial coastal protection, while reef-related tourism revenues contribute up to over 40% of GDP in some small developing island nations like the Maldives (Spalding et al. 2017).

In this context, the question in how far coastal communities can recover is also important and depends not only on the recovery of the reef itself. Since "people dependent on reef goods and services may need to adapt their resource-use patterns to maintain the flow of goods and services" (Cinner et al. 2013) it might also depend on how fast they are able to adjust e.g. fishing techniques or consumption patterns.

The importance of coral reef services for people in developing countries implies that it is crucial to understand the relationships between coral bleaching and wellbeing, especially in the light of ongoing climate change. But although there has been a significant amount of biological research related to coral bleaching, which theoretically describes potential negative effects on wellbeing, quantitative economic analyses have been comparatively scarce. To the authors knowledge, most economic studies until now are either valuation studies focusing on the value of different reef ecosystem services (see e.g. Speers et al. 2016) or meta-analyses of climate change damage using such valuation studies (see e.g. Chen et al. 2015; Cesar et al. 2003). These analyses however do not directly address the effects on the wellbeing of people in developing countries, which is especially important since the theory suggests that these people might suffer most from coral bleaching, especially when they depend on subsistence fishing as a nutrient source. Large-scale valuation studies might therefore not capture all the effects of coral bleaching and might especially overlook short-term effects on the nutrition of directly affected communities.

In order to contribute to the literature assessing the economic impact of coral bleaching, this work will therefore analyze the effect of coral bleaching events on the biological standard of living, measured in height and height-for-age, in Indonesia. The underlying hypothesis for this analysis is that coral bleaching and associated coral mortality cause a reduction in the biological standard of living for people born during or immediately after coral bleaching events. This follows the argument that such people would suffer negatively from direct nutrition shocks, if they depend on subsistence fishing, or from indirect income shocks. Additionally, the analysis will not only investigate whether a causal relationship between bleaching and the biological standard of living exists, but also through which of the channels this effect materializes.

DATA AND METHODOLOGY

Indonesia as a case study

In order to analyze the effects of coral bleaching on wellbeing, Indonesia is the ideal choice since it is the "largest archipelagic country in the world", around 16% of all coral reefs worldwide are located within its borders and it has "the largest reef-associated population of any country in the world" (Burke et al. 2011). The archipelagic nature of the country also allows a more detailed study of the effects of climate-induced bleaching, since this creates a network of geologically separated parts of the sea which leads to considerable variation in the sea surface temperature (Peñaflor et al. 2009) and therefore also to variance in bleaching patterns. Especially the differences between parts of the ocean surrounded by islands and parts which are exposed to the open ocean are crucial in this respect, since the former are naturally protected from warming events (Peñaflor et al. 2009).

Measuring the effect: the biological standard of living

Economists have long been debating about the right measure to use in order to assess the living standard of people and communities and although monetary measurements like GDP or income have been dominant, they have some important shortcomings. These shortcomings materialize especially in the context of developing countries, where income statistics might not be as accurate. Even when they are or when consumption statistics can be used in their place, these measures do allow only limited insights in historic circumstances, since household surveys do in most cases not date far back. Therefore, anthropometric measures, e.g. height, have become more popular in recent years, both in economic history and development economics. Since height depends on conditions an individual grows up in (Baten 2000) and on nutrition during the first five years (Eveleth et al. 1990), it serves as a good measure of wellbeing during these years if taken for a larger population, thereby allowing the recreation of historical data using current survey data. Because “stature is a function of […] determinants such as diet, disease, and work intensity during the growing years” (Steckel 1995), it furthermore reflects more dimensions of wellbeing than income or consumption alone, while it is also not subject to the same data issues as income or consumption because neither recall-related issues nor underreporting are a significant problem. In addition, some scholars have argued that while income or consumption are only indirect measures of wellbeing, health indicators directly measure the outcome of poverty and therefore take into account that poverty is not just a lack of income, but “deprivation of basic capabilities, or the failure of certain basic functioning” (Pradhan et al. 2003). Nevertheless, anthropometric measures have been found to be highly correlated to more traditional measures like real GDP if distribution is accounted for (Baten 2000), which further underlines their validity. In the context of this work, the usage of anthropometric measures is furthermore well suited since they capture potential nutrition effects due to declining subsistence fishery yields more accurately than consumption statistics and also account for income shocks. They furthermore imply a focus on the poor, since it is to assume that the nutrition and therefore the height of richer individuals is not strongly affected by a negative income shock. To conclude, this study will use height and height-for-age z-scores to assess the effect of coral bleaching on the so-called biological standard of living, a term that has been introduced by Komlos (1989) referring to the usage of anthropometric measures to assess wellbeing, in Indonesia.

Individual data

Data for anthropometric measures is obtained from the fifth wave of the Indonesian Family Life Survey (IFLS), conducted by the RAND Corporation in 2014/2015 (Strauss et al. 2016). The survey covers 13 of Indonesia’s 27 provinces which represent 83% of the population. The covered provinces are four provinces on Sumatra (North Sumatra, West Sumatra, South Sumatra, and Lampung), five on Java (DKI Jakarta, West Java, Central Java, DI Yogyakarta, and East Java), and four provinces from other islands (Bali, West Nusa Tenggara, South Kalimantan, and South Sulawesi) (Strauss et al. 2016), as seen on Figure 1.

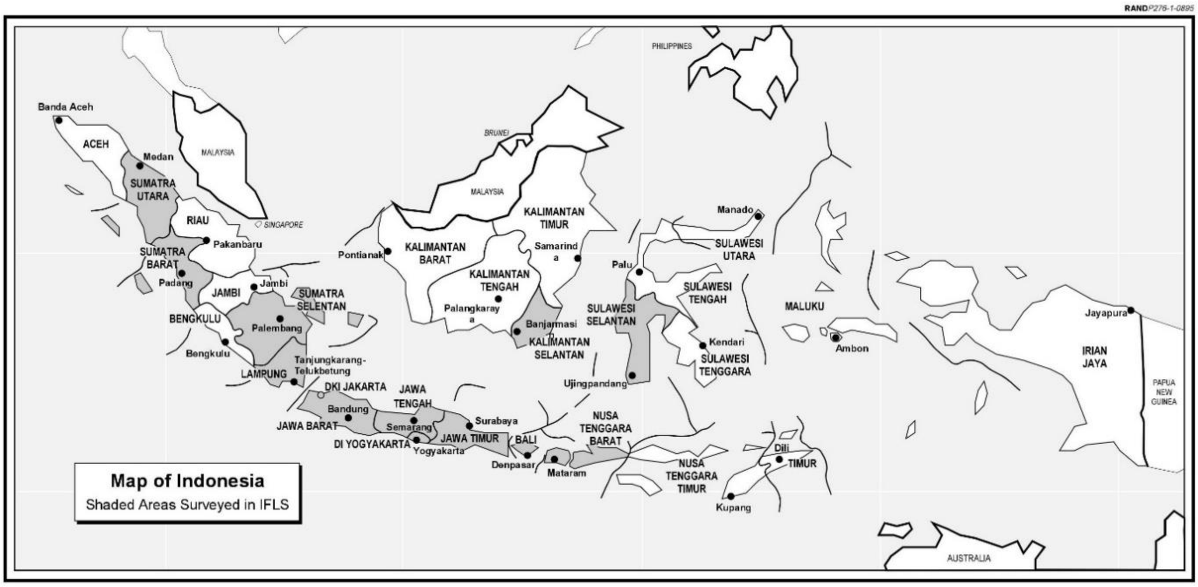

Figure 1 – Map of surveyed provinces in the IFLS. (Frankenberg et al. (1995))

Within the provinces, 321 enumeration areas were randomly selected, although urban areas were oversampled, which is one of the reasons why urban or rural residence is controlled for. Within each enumeration area, 20 (for urban) and 30 (for rural) households were randomly selected, defining a household as a group of people living together and sharing food from the same pot. The analyses focus on individual, not on household level data, which might imply that the individual selection is not entirely random, but since individuals are analyzed by birth year and the amount of people from the same household and with the same year of birth is small, this source of non-randomness should not be a crucial issue.

A more important issue that must be kept in mind for the following analysis is however that not all variables were available for all individuals in the sample, especially height, the main dependent variable. Some individuals could also not be linked to their regencies of birth, which is crucial to link them to bleaching and SST conditions. Therefore, only a subsample of the original IFLS individual dataset could be used, which reduces the overall sample size to roughly 27.800 individuals. Table 1 shows a comparison of individual characteristics of people in the two subsamples. There are some differences in the averages of height, urban/rural composition, education and age of the subpopulations. Height, the main dependent variable used for the analysis differs only slightly between the two populations, although it is only available for a small share of the subsample not used for the analysis. Therefore, the other variables might allow a clearer picture of differences between the two groups. They indicate that the subsample used for the analysis is slightly more rural, but also younger and less educated. While urban/rural differences are also relatively small, the age difference between the two samples is relatively large, which could imply that older populations might be underrepresented. This is however not crucial since the analysis is focused on children, birth-year cohorts are used for the analysis and year fixed effects are included. Furthermore, coral bleaching events are a relatively recent phenomenon (Oliver et al. 2009), which is why underrepresentation of older people will most likely not affect the results much. In addition, there are also strong differences between the years of education of the two subpopulations, which are however most likely a consequence of the age difference.

Table 1 – Comparison of sample averages

	Subsample used in analysis		**Subsample not used in analysis**	
Variable	Average	Number of observations	Average	Number of observations
Height	135,64 (SD 29,30)	27,770	131,65 (SD 35,17)	1.974
Urban/Rural	0,43 (SD 0,5)	27,887	0,39 (SD 0,49)	19,908
Education	3,86 (SD 2,8)	22,355	4,91 (SD 2,74)	17,856
Age	15,58 (SD 10,19)	27,887	21,67 (SD 8,91)	19,908

Bleaching and SST data

The analyses use direct coral bleaching observations and sea surface temperatures in order to estimate the effect of coral bleaching. For the former, the recent Donner et al. (2017) dataset is used, which is more accurate than earlier datasets and combines coral bleaching observations from a range of different sources. This dataset is, to the best of the author’s knowledge, the most comprehensive global coral bleaching dataset available to date and provides detailed information on 52 bleaching events from 1983 to 2010 in Indonesia. The dataset also provides geographical locations, which allows matching the data with both sea surface temperatures and individual-level data.

It is however to assume that, although this dataset is more accurate than earlier sources, it still suffers from considerable bias since it is based on observations from researchers and scuba divers. This makes a range of biases plausible, researchers might for example focus either on very vulnerable or very heathy reefs, while areas with a higher level of economic development might also be favored due to better infrastructure. There could also be a bias towards overreporting sites as bleached even if the situation is not as problematic because researchers and scuba divers might have an interest to promote the protection of coral reefs and therefore to make the situation appear worse. Because of the multitude of these biases, it is furthermore not possible to predict the direction of the bias.

In order to deal with this potential issue, this work does not uniquely rely on bleaching observations but supplements them with data on sea surface temperatures (SST). The temperature data used is satellite-based, has a 1° by 1° latitudinal/longitudinal resolution and is obtained from the US-American National Oceanic and Atmospheric Administration (NOAA ESRL Physical Sciences Division 2019; Reynolds et al. 2002). This data is available in the form of weekly mean values from 1980 to the present for each 1° by 1° latitudinal/longitudinal grid point. For the purpose of this study, time series related to grid points covering a rectangular area around Indonesia were extracted, ranging from the 94th to the 141st degree longitude and from the 11th southern degree to the 6th northern degree latitude. The grid used and its relation to the geographical borders of Indonesia are shown in Figure 2.

In a next step, this weekly data was summarized in an annual measure, depending on the threshold at which coral bleaching could be expected to occur. This is however problematic since there is no clear agreement in the literature regarding neither the threshold itself nor how long the temperature has to stay above the threshold. Some scholars even question whether it is possible to define a clear threshold at all (Fitt et al. 2001). While the NOAA uses a threshold of 1°C over the monthly maximum climatological value for its early warning system which has been shown to successfully predict coral bleaching in the great barrier reef (Hoegh-Guldberg 1999), other studies suggest different values, e.g. 30-32°C (Glynn and D'croz 1990; Hoegh-Guldberg and Smith 1989) or 1-2°C over the summer maxima for several weeks (Hoegh-Guldberg et al. 2007). The literature furthermore suggests that these values might depend on local conditions and the species dominating a particular reef. Therefore, this study does not use a predetermined threshold, but different thresholds were tested against the bleaching data. In order to do this, weeks during which the temperature was over a certain threshold for at least two consecutive weeks, which represents a lower boundary for exposure duration, were summed up per grid point and year. These values were then tested empirically against the bleaching data. Simple OLS regressions (see Appendix Table 1) of observed bleaching on these SST values showed that the thresholds of 2°C over the long-term mean value for each year as well as 1 and 2°C over the annual mean were positively correlated with the bleaching observations, which implies that all these thresholds might serve to explain coral bleaching. A selection of the threshold was made based on the main instrumental variables regressions and will be discussed below.

The analysis was furthermore supplemented with a dataset on coral reef locations obtained from ReefBase (ReefBase Project, the World Fish Center 2019). Figure 2 shows both the extent of the grid used for SST data in orange, with land data points not used in the analysis marked in green, as well as the reported locations of coral reefs in blue.

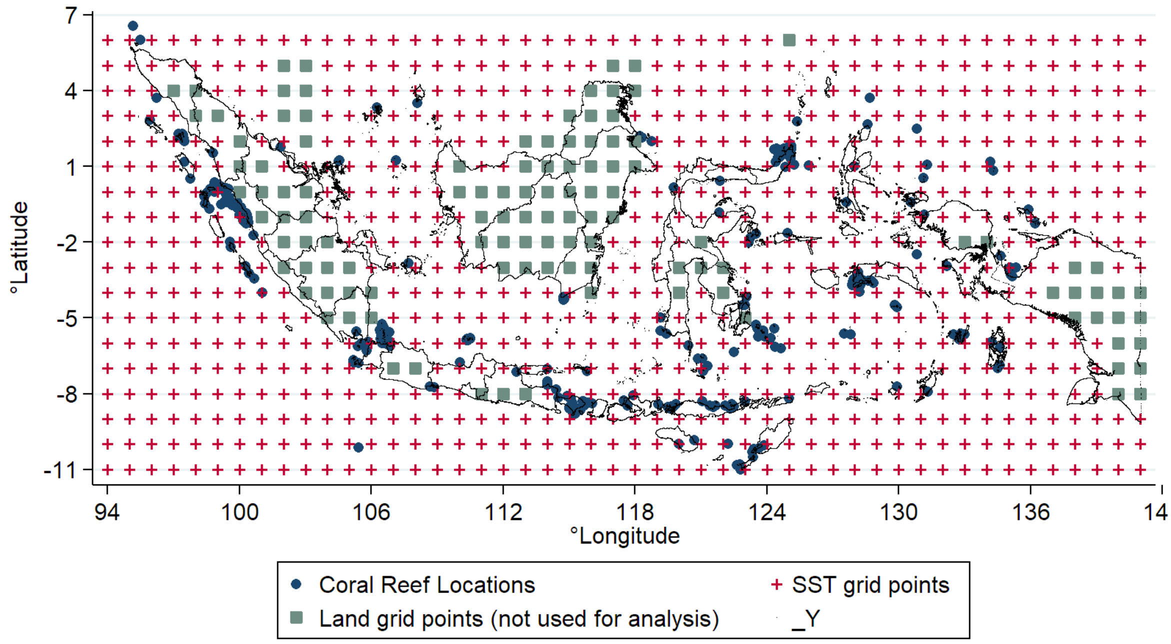

Figure 2 – Map of Indonesia, used grid and coral reef locations (Author based on NOAA ESRL Physical Sciences Division (2019) and ReefBase Project, the World Fish Center (2019))

Linking individual anthropometric data to bleaching and SSTs

One of the crucial methodological questions of this study was how to link individual anthropometric data to bleaching and SST data points. This was in so far difficult, as the exact birth and residence location of each individual were not available, although the current regency[1] of residence was. Furthermore, an additional migration dataset contained migration information for a share of the individuals and indicated a difference between the current regency of residence and the regency of birth for 4.882 individuals. For people without migration data, it was assumed that the regency of their current residence was also the one they were born in. Although this is a bold assumption to make, it can be expected that potential inaccuracies would bias the results downward and decrease significance, which makes potential results even more credible. Since only the regency of birth was known, everyone was assigned the exact location of the capital of their regency, which is a sufficiently accurate approximation for the geographical location of the household since Indonesian regencies are relatively small. The location of the capitals was obtained from a geographical dataset (Centre for Humanitarian Data, OCHA 2013) and in cases in which this dataset did not contain the regency capital, supplemented by data from Google Maps[2]. In doing this, it was assumed that a city sharing the name of the regency was the capital, while in cases where there was no city with the same name, Wikipedia was consulted in order to identify the regency capital.

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[1] Regency (*kabupaten*) is the administrative division below a province in Indonesia, similar to a county in the US
[2] for an overview over the capitals of the regencies used see Figure Annex 1

In the following, SSTs as well as bleaching and reef location data within a radius of 200 km of the respective regency capital were linked to individuals. This distance was chosen to allow for a sufficiently large number of covered grid points. Since between every latitudinal and longitudinal grid point are approximately 111km, this leads to up to 8 covered points per individual. With regards to time, data was linked to the year of birth of the individual, while lagged values were also considered. The details regarding the lag strategy will be provided below.

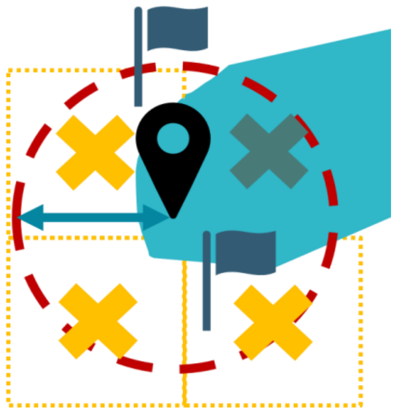

Figure 3 – Example for matching strategy (Author)

Figure 3 provides an example of this matching strategy. The black pin indicates the regency capital and each cross a grid point, while the squares indicate the area which each grid point covers. The red circle indicates the radius in which the data is linked to the individual living in the regency. This implies here that SST data from four grid points are taken into account, while the dark green grid point is coded as land and therefore not used for the analysis. The matching strategy for reef locations and bleaching is the same, with the only difference that the year is considered for bleaching events. In this example, blue flags indicate the bleaching or reef locations; therefore, the sum of reef or bleaching sites within the radius, here two, would be assigned to the regency capital.

Control variables

The control variables used in the analysis originate from different sources. Individual level controls like age or sex are part of the IFLS dataset. Further controls are climatological variables to control for potential correlation of sea surface temperatures and bleaching with land temperatures (in °C) and rainfall (in mm) following Willmott (2000). In addition, each regency's distance to the sea in kilometers following Wessel and Smith (1996) is added as a control, in order to avoid that the coefficient of bleaching also captures the effect of living close to the sea. These geographical variables were obtained from datasets provided by the AidData research lab at William & Mary's Global Research Institute (Goodman et al. 2019).

EMPIRICAL MODEL

The main issue regarding the analysis was that it is not feasible to compare the height of children and adults, because the former have not reached their adult height yet and furthermore display a non-linear age-height relationship. And although year fixed effects, which are part of all following regressions, catch part of this non-linear growth pattern of children, they are insufficient to allow an accurate analysis and lead to indications of omitted variable bias. The intuitive solution to include a more detailed age variable using age in months instead of years also does not solve this issue, and even if age squared, age interacted with sex or other non-linear transformations are included in the regression, some indications of omitted variable bias persist. Therefore, the analysis was split in two parts in order to analyze adults and children, defined as under 18 years of age at the time of the survey, separately. This allowed the usage of height-for-age z-scores following the WHO definition (World Health Organization 2006) instead of height in order to overcome inaccuracies caused by the non-linear growth pattern of children. For an assessment of population data, like in this case, “the z-score is widely recognized as the best system for analysis and presentation of anthropometric data” (Onis et al. 1997) and expresses height as the amount of standard deviations (z-scores) below the value of the reference population. It thereby accounts more accurately for the growth pattern of children and has furthermore the advantage of being a linear measure and independent of sex, which facilitates the analysis. Although this division of the analysis allows a more accurate analysis of children, it leads to problems regarding the adult subsample. Because coral bleaching is a relatively recent phenomenon and reports of it have increased over time (Oliver et al. 2009), the larger share of coral bleaching events in the dataset occurred after 1997, which therefore only matters for people who were children in 2014. For adults the dataset only contains one year with observed coral bleaching, 1983, which leads to a very low number of bleaching observations and therefore makes results obtained for this group problematic. This issue is further aggravated by the fact that 1983 was the first year with recorded coral bleaching in Indonesia, which is why it seems likely that the observations are less exact. Due to these problems, the analysis is focused on more recent birth cohorts, while some regressions concerning adults are also reported, although their results must be seen with caution.

In order to analyze the effect of coral bleaching on the biological standard of living, different regression techniques were used, all with heteroscedasticity-robust standard errors and both for children and adults. First, simple ordinary least squares regressions (OLS) were performed following the model shown below:

$$Y_{i,t} = \beta_0 + \beta_1 bleaching_{i,t} + \beta_2 reef_i + \beta_3 distance_i + \beta_4 rural_{i,t} + \beta_5 male_{i,t} + \beta_{6,r} climate_{r,i,t} + \beta_7 detailedclimate_{i,t} + year_t + province_i + u$$

Y represents the dependent variable, either the height of adult individuals or z-scores for height for age of individuals younger than 18 at the time of the survey (in the following referred to as children) for each regency/individual *i* and year *t*. This analysis is performed both on an individual level and using regency averages, whereby the latter is used to avoid potential overrepresentation of certain regencies.

Regarding the explanatory variables on the right-hand side, *bleaching* is the main variable of interest. In the simple OLS framework, this variable is a dummy indicating whether coral bleaching was observed within 200km of the regency/individual at least once in a given year. The other variables and their respective coefficients stand for additional controls. *Reef* indicates the number of coral reefs within 200km of regency/individual *i*, and *rural* and *male* indicate place of residence and sex of the individual or the respective shares in the regency. In the z-scores regressions, male is not used since sex is already accounted for. *Climate* stands for one of r=3 different climate controls used, the mean and maximal temperature for each regency and year as well as the mean precipitation. Since detailed climate information on the regency level was however not available for each regency, in some cases provincial level data had to be used instead. To account for this, the dummy variable *detailedclimate* was introduced, which takes on a value of one in case regency-level climate data was available. Apart from these controls, year and provincial fixed effects were also used in order to account for differences in economic development across provinces as well as for general time trends and effects of policies on national level. This is furthermore relevant since the data used in this study is effectively a pooled cross section with one cross section each year. This implies a changing composition of the dataset, which has to be accounted for. It is however assumed that the effect of coral bleaching is independent of time, since the associated losses of fish, coastal protection and other reef services should have the same effect independent over time.

Since it is likely that the bleaching observations are not fully exogenous, as mentioned before, a set of two stages least squares instrumental variables regressions (IV) was employed in a second step, using the number of weeks sea surface temperatures were over a given threshold in a given year as an instrument. Since SSTs are the main trigger of coral bleaching the theory suggests that they are relevant to explain coral bleaching, which is also confirmed by regressions of observed bleaching on SSTs showing significant and positive effects (see Appendix Table 1). These results and overidentification tests following the main regressions have shown that the threshold of 2°C above the long-term mean is best suited as an instrument. The temperatures are furthermore the result of large-scale climatological phenomena and can therefore be assumed to be exogenous. Problems may only emerge because of a potential correlation with land temperatures and precipitation, which is why these variables are controlled for. Potential observational biases are not an issue with regard to SSTs, since they are measured using satellites and consequently independent of local circumstances. Due to both relevance and exogeneity, SSTs are therefore valid instruments. In order to improve the explanatory power of the instrumental strategy, the number of coral reefs within the 200km radius was used as an additional instrument, since high SSTs can only influence the biological standard of living through coral bleaching. Since reef locations are geographic, it is safe to assume that they are exogenous and although they could also suffer from an observational bias, there is a much larger number of observations and no clear clustering, as seen in Figure 1. Therefore, and due to the fact that only less than 10% of all regencies in the dataset do not have an observed coral reef within 200km of their capital, exogeneity is in this case a reasonable assumption, while regressions also proved its relevance. The instrumental variable regressions follow the model used in the OLS case with the main explanatory variable being replaced by instrumented observed bleaching. *Reef* is used as an instrument and does not appear as control variable. Since height as a measure of the biological standard of living depends on circumstances during the first five years (Eveleth et al. 1990), using only the year of birth ignores a large part of the story. In order to get further insights, the IV regressions using instrumented coral bleaching were repeated using lags of the main explanatory variable for the first five years of each individual's life. Employing the values for all years at once might however cause biased estimates, since in some cases the timespan between two major bleaching events is less than five years. This means that the estimated coefficient would in some cases only reflect the difference to the effect from the first bleaching event and bias the results. Therefore, the regressions were run separately, using one lag at a time.

Due to difficulties regarding the assessment of the coral bleaching effect for the adult subsample, which are partly caused by there being only one year with observed coral bleaching for adults, a difference-in-difference (DiD) model was additionally used for the years from 1981 to 1988. This model follows the OLS setup without year fixed effects but replaces the main explanatory variable with interactions between a dummy indicating whether an individual's regency was affected by coral bleaching in 1983 and an indicator dummy for the year 1983. Unlike most DiD models, this approach therefore focuses not on years before and after 1983, but only on a comparison between 1983 and all other years.

RESULTS

Children

As mentioned before, the regressions for children, which are the focus of this analysis, were performed using height-for-age z-scores as dependent variables in order to correctly represent the unique growth pattern of children. The results of the children subsample are reported in Table 2, both for OLS and IV regressions and using both individual level data and regency averages.

Table 2 – Regressions for the children subsample (individuals younger than 18 at the time of the survey)
Dependent variable: Height for age z-scores

	(1) OLS	(2) OLS	(3) IV	(4) IV
Sum Bleaching	**-0.103**** **(0.023)**	**-0.103** **(0.134)**	**-1.427***** **(0.001)**	**-1.372**** **(0.019)**
Sum Reef	-0.0320*** (0.001)	-0.0283** (0.025)		
Distance to coast (km)	0.00242*** (0.000)	0.00177** (0.048)	0.00207*** (0.001)	0.00172* (0.061)
Rural	-0.273*** (0.000)	-0.372*** (0.000)	-0.277*** (0.000)	-0.365*** (0.000)
Max. Regency temperature	-0.0367*** (0.000)	-0.0227 (0.119)	-0.0325*** (0.001)	-0.0182 (0.211)
Mean. Regency temperature	0.0289*** (0.000)	0.0193* (0.078)	0.0312*** (0.000)	0.0217* (0.053)
Mean. Regency precipitation	-0.000967*** (0.001)	-0.000941** (0.023)	-0.00105*** (0.000)	-0.000985** (0.022)
Detailed Climate	-0.144*** (0.000)	-0.0873** (0.026)	-0.158*** (0.000)	-0.0971** (0.018)
_cons	-0.485* (0.092)	-0.675* (0.095)	-0.410 (0.268)	-0.457 (0.352)
Fixed Effects	Year, Province	Year, Province	Year, Province	Year, Province
Unit of analysis	Individual	Regency	Individual	Regency
N	16698	3692	16698	3692
R^2	0.071	0.150	0.028	0.078

p-values in parentheses
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

The coefficients of the coral bleaching variable have the expected negative sign in all specifications and are significant on the 5% significance level except for the OLS regression on regency level, where the coefficient is only significant on a 14% significance level. The p-values for the individual level regressions are lower in both the OLS and the IV case, which is intuitive considering the higher number of observations. At the same time, the coefficients obtained in the individual and regency regressions are very similar, which shows the robustness of the results and furthermore implies that the insignificance of the regency-level OLS coefficient is of no concern but might only be caused by a low number of observations. All models only explain a relatively small share of the overall variance in the dependent variable, the R square values range from 0.028 to 0.15. This can however be expected since anthropometric data generally exhibits a high variation caused by genetics. Wooldridge's (1995) robust score tests are significant on the 5% level and therefore confirm the usage of IV, while overidentification tests following Sargan (1958) confirm the instruments on a 5% significance level. These findings imply that the IV results are consistent, while there are indeed issues with OLS.

It is striking that the estimates in the IV setting are higher than the OLS results and also show lower p-values for both regency and individual level regressions. This indicates that the OLS regressions underestimate the effect and therefore support the idea that bleaching was overreported in areas with a higher level of development or generally healthier reefs. In order to further investigate this bias, an OLS regression of the long-term average of the SST variable, a dummy indicating whether there was bleaching close to a regency in the past and some controls was performed (see Appendix Table 2). Although this shows only correlations and is restricted to a small share of the dataset, it indicates that regencies closer to the coast and with more coral reefs have a lower average income than others, mirroring the results obtained above. The same holds for regencies with more weeks of SSTs over the threshold. Bleaching observations and income are however positively correlated, which is at odds with the other results and therefore strengthens the idea that bleaching observations are biased towards areas with a higher level of development. Furthermore, the finding that the number of reefs is negatively correlated with income, just as the inverse distance to the coast, indicates that the reef observations are not biased towards more well-off areas and therefore underlines the validity of the number of reefs as an instrument.

The magnitude of the VI coefficients indicates furthermore that the effect of coral bleaching is not only significant and negative, but also relevant since the estimates are in both cases higher than one standard deviation of z-scores in the regency sample (.84). This implies that a coral bleaching event in the radius of 200km of a given regency decreases the average height-for-age z-score of people born in the same year by approximately 1.6 times the standard deviation, ceteris paribus. The findings thereby confirm the hypothesis of this work that climate-induced coral bleaching causes a significant and relevant decrease in the biological standard of living. These results are furthermore robust, since they are similar in all four specifications, although more robustness checks were also performed and are reported below.

Most of the control variables enter with the expected sign and the estimated coefficients are robust across all four specifications, although there are some changes in the significance levels. Generally, most coefficients are significant on one of the usual significance levels and enter with the expected sign. The rural dummy, maximal temperature and precipitation as well as the dummy indicating detailed climate data enter with negative signs, while the mean temperature enters with a positive sign. The coefficients regarding distance to the coast and the number of coral reefs however are striking, since they indicate on a 5% significance level that the biological standard of living of people living closer to the coast or in proximity to more coral reefs is lower. Although analyzing these interesting results in more detail is beyond the scope of this work, it appears as a topic worth investigating further.

In addition to the OLS and IV results, IV regressions using lagged main explanatory variables, indicating whether there was bleaching in the years after the birth of an individual, were also employed in order to analyze whether coral bleaching had an effect on people during the first five years after birth. Since using all lags at once would bias the results, the regressions were run separately, using one lag at a time, while the model specifications are the same as in the IV regressions before. The results of these regressions are displayed in Table 3, but since the estimated coefficients of the control variables largely follow the pattern in the main regressions, only the estimated coefficients associated with the main variable of interest are reported. Just as before, overidentification tests showed that the instruments are valid on the 5% significance level for all regressions, with the only exception being the regression using the second lag and individual level data. The coefficients associated with the lags are in both, the individual and the regency level regressions, significant on the 5% significance level and negative. The estimated coefficients do not decrease over time, but remain at similar levels, which shows that coral bleaching does indeed have negative effects on people during all of the first five years of their life. The significance as well as the share of the variance explained by the model does however decline over time, which implies that the importance of coral bleaching for height decreases with exposure age.

Table 3 – IV Regressions using lagged main explanatory variables for children
Dependent variable: Height/Height for age z-scores on regency level

	Regency level					**Individual level**				
	(26)	(27)	(28)	(29)	(30)	(31)	(32)	(33)	(34)	(35)
	IV lag1	IV lag2	IV lag3	IV lag4	IV lag5	IV lag1	IV lag2	IV lag3	IV lag4	IV lag5
Bleached (lagged)	-0.802** (0.010)	-0.762** (0.014)	-1.013** (0.024)	-1.345** (0.030)	-1.248** (0.028)	-0.584*** (0.000)	-0.401** (0.030)	-1.143*** (0.001)	-1.291*** (0.001)	-1.180*** (0.000)
Controls	sum reef, distance to coast, rural, male, max. regency temperature, mean regency temperature, mean regency precipitation, detailed climate, _cons; year and province fixed effects									
N	3692	3692	3692	3692	3692	16698	16698	16698	16698	16698
R^2	0.027	0.038	0.026	.	0.019	0.033	0.049	.	.	.

p-values in parentheses
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Adults

For the adult subsample, the same regression analyses were performed as for the children, with the number of grid points with SSTs over the threshold being added as an instrument. The usage of IV regressions is confirmed by a significant endogeneity test on the 5% significance level and a test of overidentifying restrictions confirms that the instruments are valid on a 1% level. It has however to be mentioned that the results obtained in these regressions are not as reliable and are therefore only reported to show robustness. The individual level results for adults are reported in Table 4.

Both in the OLS and IV regressions, the sign of the estimated coefficient of the main explanatory variable is negative. The OLS coefficient is almost significant on the 10% level, the IV coefficient on the 1% level. While the OLS estimate indicates that being born in a year with coral bleaching reduces the average height by ca. 6mm, ceteris paribus, the estimated coefficient of the IV regression is unreasonably high, which most likely results from the biases discussed before. Another problem might be the fact that bleaching was only observed in 1983, a concern that is underlined by a high estimate for the year fixed effect of 1983. In order to address this, a difference-in-difference model was applied additionally using interaction terms between a dummy indicating whether the regency was affected by coral bleaching in 1983 and an indicator dummy for 1983. This approach results in a negative and significant estimate for the DiD estimator, showing that people born in affected regencies in the year of the bleaching event were on average 1.2 cm shorter, ceteris paribus. Adding more years after the bleaching event to the latter dummy decreased the significance with each added year, which indicates fast recovery after the event. These results add robustness to the overall result that climate-induced coral bleaching has a significant negative effect on the biological standard of living. The estimated coefficients for the control variables, have, just as in the lagged regressions, the same signs, the same order of magnitude and a similar significance pattern as in the first set of regressions.

Table 4 – Regressions for the adult subsample Dependent variable: Height in cm			
	(1) OLS	(2) IV	(3) Diff-in-Diff
Sum Bleaching	**-0.634** **(0.106)**	**-20.04***** **(0.005)**	
Sum Reef	-0.254*** (0.000)		
0.affected#1.year1983			-0.224 (0.381)
1.affected#0.year1983			-0.170 (0.679)
1.affected#1.year1983			**-1.195**** **(0.033)**
Distance to coast (km)	-0.000423 (0.906)	0.000148 (0.970)	0.00100 (0.824)
Rural	-1.111*** (0.000)	-1.130*** (0.000)	-0.937*** (0.000)
Male	12.27*** (0.000)	12.31*** (0.000)	12.15*** (0.000)
Max. Regency temperature	-0.261*** (0.000)	-0.184*** (0.009)	-0.251*** (0.001)
Mean. Regency temperature	0.173*** (0.000)	0.0775 (0.217)	0.170*** (0.005)
Mean. Regency precipitation	-0.00473*** (0.006)	-0.00722*** (0.001)	-0.00278 (0.166)
Detailed Climate	-0.739*** (0.000)	-0.743*** (0.000)	-0.718*** (0.001)
_cons	161.7*** (0.000)	159.4*** (0.000)	161.0*** (0.000)
Fixed Effects (coeff. not reported)	Year, Province	Year, Province	Province
Unit of analysis	Individual	Individual	Individual
N	10304	10304	6431
R^2	0.558	0.462	0.532

p-values in parentheses
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Robustness checks

Apart from the endogeneity of the bleaching observation data, which were addressed by using instrumental variables, there are some other concerns which might shed doubt on the results and are therefore addressed in the following. The first concern relates to the role of outliers. Especially since in some cases the number of bleaching observations in a given year is relatively low, it is a plausible concern that some outliers might drive the results. This is however not the case, there are very few outliers and manually deleting outliers does not fundamentally change the results.

A second concern might be spatial autocorrelation. Since coral bleaching is triggered by high sea surface temperatures, which are the results of large-scale climatological patterns, it is highly likely that the values are spatially autocorrelated. In order to detect spatial autocorrelation, individual Moran I tests were performed by year for both SST and bleaching data. The tests showed clear indication for spatial autocorrelation on all usual significance levels in both cases, which implies a potential bias in the results.

One way to account for this is to think of provinces as spatial clusters and to use clustered standard errors on provincial level in the regressions. This does not impact the estimates themselves but might indicate too high p-values. It indeed decreases significance levels and three of the four coefficients estimated in Table 2 are only significant on an unusually high 15% significance level when clustered standard errors are used (see Appendix Table 3). This does however not invalidate the results, especially keeping in mind that this approach is overly simplified.

The ideal way to solve this issue would be the usage of spatial regression techniques. Running the models used in the main part of the analysis using such techniques was however infeasible due to the high computational demands of such regressions and the problem that there exists very little literature concerning the usage of spatial regression models in the context of cross sections and using instrumental variables. Therefore, for each year with coral bleaching a simplified spatial regression analysis was performed using the children subsample and following the OLS setup. This approach does not allow an estimation of the size of the bias and most likely suffers from a lack of accuracy but can give indications whether spatial autocorrelation invalidates the results. As seen in Table 5, this is not the case. All coefficients enter as negative and two of them are significant on the 10% significance level, while the coefficient for 2010 is significant on the 15% significance level. These results are not troubling, especially since the separation by years leads to a reduction in the number of observations and thereby most likely also to a decrease in significance.

Table 5 – Spatial lag regressions by year for the children subsample
Dependent variable: Height for age z-scores

	(26)	(27)	(28)	(29)
	1998	2002	2009	2010
Bleached	-0.04 (0.763)	-0.557** (0.023)	-0.419* (0.052)	-0.231 (0.150)
Controls	sum reef, distance to coast, rural, male, max. regency temperature, mean regency temperature, mean regency precipitation, detailed climate, _cons; province fixed effects			
N	662	824	955	1011

p-values in parentheses
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

CHANNELS

After the analysis has shown that coral bleaching has a significant, relevant and negative effect on the biological standard of living in Indonesia, the question remains through which of the channels discussed this effect materializes. In order to answer this question, this paper follows a setup used by Beck et al. (2002), namely the usage of bleaching as an instrument for variables indicating the channels, which are in turn used to explain the outcome, here the biological standard of living. This allows on the one hand insights into whether the parts of the channel indicators explained by bleaching explain the biological standard of living and on the other hand whether bleaching does explain the biological standard of living only through the channel in question. The first question can be answered by the second stage in this setup, while the answer to the second question can be derived from overidentification (OIR) tests indicating the quality of the instruments used. The setup looks as follows:

First Stage: $Channel\ Indicator = \alpha\ bleaching + \beta\ controls + v$

Second Stage: $Height\ for\ age = \gamma[Channel\ Indicator] + \delta\ controls + u$

In order to perform this analysis, household data from the IFLS was used. The dataset does however not allow an exact calculation of the household size, which is why the household's consumption of rice is included, assuming that household size is correlated with the consumption of such a basic staple. Since the number of observations with reported income is very low, the overall expenditure on bought protein (meat, chicken, fish) was used as a measure for the income channel, which is plausible since this measure is correlated with income and protein is furthermore especially important for child growth (Semba 2016). The overall home production of fish was used as a measure of the direct channel. All regressions were, as in the Beck et al. paper, performed once using only the channel indicator in order to allow a clear interpretation of the OIR test and once using the same controls as in the main IV regressions. The results are displayed in Table 6.

Table 6 – IV regressions for channels using the children subsample

Dependent variable: Height for age z-scores, Instruments: Sum Bleached; Sum Bleached*Distance

	(1) I	(2) IV	(3) IV	(4) IV
Fish produced (in mio Rp p.a.)	0.932*** (0.000)	0.445* (0.085)		
Meat, Fish bought (in mio Rp p.a.)			0.083** (0.034)	0.106** (0.038)
Controls used	No	Yes	No	Yes
Controls	rice consumed, distance to coast, rural, max. regency temperature, mean regency temperature, mean regency precipitation, detailed climate, _cons; province and year fixed effects			
N	11254	6649	1392	731
OIR test	**p = 0.528**	**p = 0.441**	**p = 0.021**	**p = 0.609**
First stage F test	p=0.000	p=0.000	p=0.000	p=0.000

p-values in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

The estimated coefficients are significant and positive in all four specifications, which implies that the part of the channel variables explained by coral bleaching does explain z-scores. The regressions themselves therefore confirm both, the income and the direct channel, although it must be mentioned that the results indicate only correlations. The null hypothesis of the OIR tests in the regressions without controls is that bleaching, the only instrument in these cases, is not correlated with the error term. A rejection of the test therefore implies that bleaching impacts the biological standard of living not only through the channel in question. This is the case for the income variable, for which the OIR test is rejected on a 5% significance level. Interestingly, the OIR test for the direct channel does not reject the H0 on any usual significance level. Although both, the income and the direct channel, serve as potential explanations, these results therefore suggest that the main channel goes directly through fishing. This result is in so far as expected as an analysis of anthropometric data necessarily focuses on the poor part of a society, where people in this case depend more on subsistence fishing. This is further underlined by the finding that individuals living in a household that at least partly lives from fishing have a significantly lower biological standard of living (see Appendix Table 4).

CONCLUSION

Coral bleaching, which has been described as "one of the most striking impacts of climate change that has been observed to date" (Cinner et al. 2013), and its effects have long been discussed in the biological literature. But although theory suggests that coral bleaching has adverse economic and social consequences, e.g. through reduced fishery yields, decreased tourism income and weakened coastal protection, the topic has not been extensively studied in the economic development literature. To contribute to this literature, this paper analyzed the hypothesis that coral bleaching has a negative effect on the biological standard of living, measured in height and height-for-age z-scores, in Indonesia. The presented analyses have confirmed this hypothesis and shown that climate induced coral bleaching causes a significant and relevant decrease in the biological standard of living of children exposed to a coral bleaching event in their year of birth or during the first five years of their life. Similar results were also obtained for people born in the year of the first recorded coral bleaching event in Indonesia, 1983, which adds robustness to the results. In a second step, the study also analyzed through which channel coral bleaching affects the biological standard of living. The results showed that both channels put forward in the literature, the direct channel through subsistence fishing as well as the income channel are valid but suggested that the main effect goes directly through subsistence fishing, which is most likely due to the bigger role it plays for poor households.

Although the results in this paper are obtained for Indonesia, it can be assumed that they are to a degree generalizable to other developing island nations, since the effect on fisheries can be expected to be similar. Since the composition of reefs, the species living in them and the climate tolerance of different corals are however different, the biological and therefore also the economic effects will nevertheless differ between world regions. These results show that especially poor people living with and from the sea are vulnerable to climate change through coral bleaching. They furthermore prove that the consequences of climate change will not only materialize at some point in the future, but already impact the wellbeing of vulnerable groups today. This has two policy implications, the first one being that international efforts to limit global warming must be invigorated. The second implication is that people living from coral reefs must be considered in efforts regarding the adaptation to climate change and must be supported during large-scale bleaching events in order to avoid malnutrition and negative effects on their biological standard of living in the future.

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APPENDIX

Appendix Table 1 – OLS regressions regarding the relevance of the instruments used
Dependent variable: Bleached (dummy indicating bleaching in a given year)

	(1) ols2ovm	(2) ols1ovm	(3) ols2ovlm	(4) ols1ovlm	(5) olsreef	(6) olscount
2° over mean	0.0117^{***} (0.000)					
1° over mean		0.00112^{***} (0.000)				
2° over long term mean			**0.00181^{***}** **(0.000)**			
1° over long term mean				0.000000161 (0.996)		
Sum Reef					**0.0146^{***}** **(0.000)**	
Number of weeks above 2° over long term mean						0.0367^{***} (0.000)
_cons	0.0393^{***} (0.000)	0.0185^{***} (0.000)	0.0454^{***} (0.000)	0.0470^{***} (0.000)	-0.000596 (0.812)	0.0365^{***} (0.000)
N	27004	27004	27004	27004	27004	27004
R^2	0.023	0.026	0.001	0.000	0.018	0.033

p-values in parentheses
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Appendix Table 2 – OLS regression indicating correlation between income and other variables
Dependent variable: Income of household member

	(1) OLS
BleachedDiff (dummy indicating whether there was coral bleaching at any point)	1546385.6** (0.044)
OverTemp (mean of weeks over the threshold per year during the whole period)	-752794.8 (0.598)
Sum Reef	-12913.9 (0.944)
Distance to coast (km)	47.52*** (0.003)
Rural	-6988838.4*** (0.000)
Male	6364804.8*** (0.000)
Child	-3206330.0* (0.055)
Age in years	812660.4*** (0.000)
_cons	-5357944.2* (0.081)
N	5779
R2	0.058

p-values in parentheses
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Appendix Table 3 – Regressions for the children subsample with cluster-robust standard errors
Dependent variable: Height for age z-scores

	(1) OLS	(2) OLS	(3) IV	(4) IV
Sum Bleaching	-0.103 (0.115)	-0.103** (0.029)	-1.237 (0.152)	-1.372 (0.153)
Sum Reef	-0.0320 (0.177)	-0.0283 (0.265)		
Distance to coast (km)	0.00242* (0.097)	0.00177 (0.123)	0.00212 (0.110)	0.00172* (0.081)
Rural	-0.273*** (0.000)	-0.372*** (0.000)	-0.275*** (0.000)	-0.365*** (0.000)
Max. Regency temperature	-0.0367*** (0.002)	-0.0227 (0.130)	-0.0325*** (0.002)	-0.0182 (0.229)
Mean. Regency temperature	0.0289*** (0.008)	0.0193* (0.089)	0.0306*** (0.005)	0.0217** (0.026)
Mean. Regency precipitation	-0.000967** (0.013)	-0.000941* (0.084)	-0.00103*** (0.005)	-0.000985** (0.026)
Detailed Climate	-0.144*** (0.004)	-0.0873* (0.093)	-0.157*** (0.001)	-0.0971** (0.049)
_cons	-0.485 (0.194)	-0.675 (0.219)	-0.295 (0.655)	-0.457 (0.423)
Fixed Effects	Year, Province	Year, Province	Year, Province	Year, Province
Unit of analysis	Individual	Regency	Individual	Regency
N	16698	3692	16698	3692
R^2	0.071	0.150	0.040	0.078

p-values in parentheses
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Appendix Table 4 – Regression indicating correlation between different variables and z-scores
Dependent variable: Height for age z-scores

	(1) OLS
Fishing	-0.192*** (0.000)
Distance to coast (km)	0.00205*** (0.001)
Rural	-0.235*** (0.000)
Max. Regency temperature	-0.0339*** (0.001)
Mean. Regency temperature	0.0222*** (0.007)
Mean. Regency precipitation	-0.00117*** (0.000)
_cons	-0.651** (0.026)
Fixed Effects	Year, Province
N	11907
R2	0.067

p-values in parentheses
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

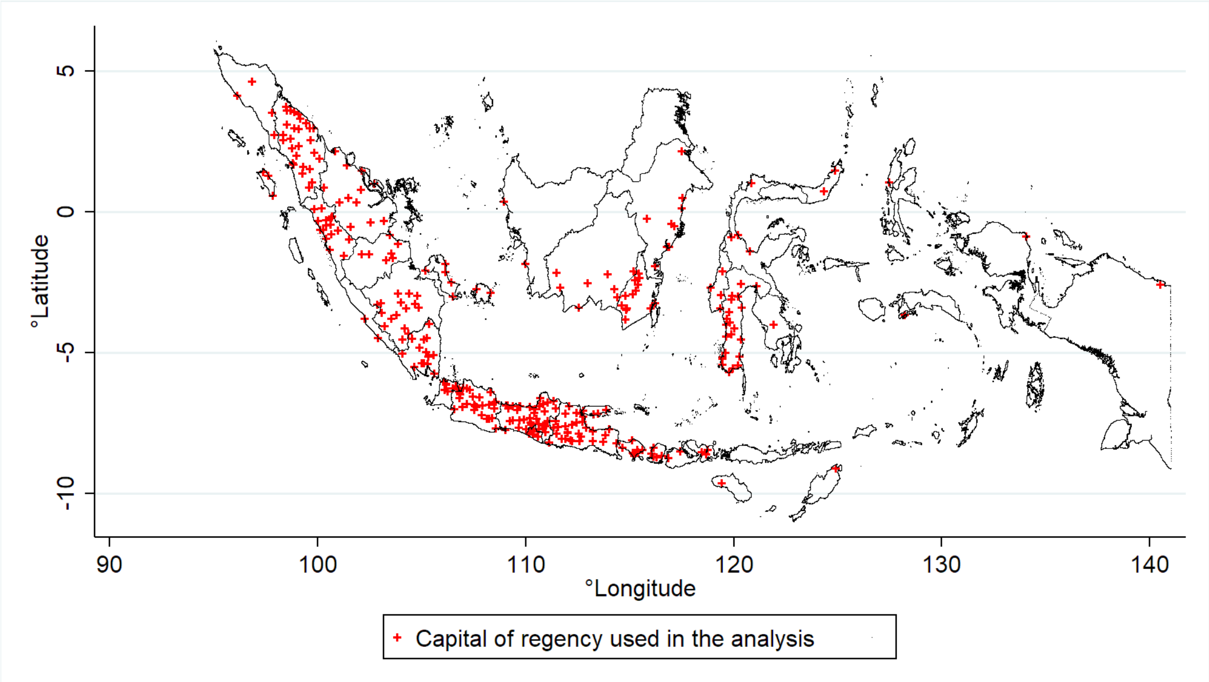

Figure Annex 1 – Overview over regencies used in the analysis (Author, based on Strauss et al. (2016))