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Future impacts of environmental factors on achieving the SDG target on child mortality – a synergistic assessment

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Abstract

An estimated 26% of current global child deaths is attributable to diverse and modifiable environmental factors, addressed under multiple Sustainable Development Goals (SDGs). This study assesses future child mortality reductions from achieving environment-focused SDG targets. It uses projections of environmental health-risk factors from the IMAGE 3.0 Integrated Assessment Model, based on the Shared Socioeconomic Pathways (SSPs), linked to a standard multi-state health model (GISMO), distinguishing risk factors, disease occurrence and cause-specific death. The analysis concludes that the SDG target on child mortality is not achieved in any of the three SSP scenarios analyzed, mainly due to persistent high mortality rates in Sub-Saharan Africa and South Asia. By 2030, environmental health risk factors are still relevant, being responsible for 10-19% of total global child death. Under the middle-of-the-road SSP2 baseline scenario, achieving the health-related SDG targets on child nutrition, access to clean water and sanitation and access to modern energy, can avoid globally 433 thousand child deaths in 2030. Also including quality aspects of access to water and energy, universal female education and advanced malaria control, a total of 733 thousand child deaths can be avoided, reducing global child mortality in 2030 to 39 deaths per 1000 births. Overall, around 20% of the required reduction in child mortality outcomes to achieve the related SDG target in Sub-Saharan Africa could be addressed by policies in other domains such as food, water and energy. This requires integrated and intersectoral approaches to environmental health.

Keywords: Sustainable Development Goals; child mortality; integrated analysis; environmental risk

1 Introduction

Child mortality is an important indicator of human development, with high levels of child mortality generally associated with low development levels and vice versa. This is also recognized in the 2030 Agenda for Sustainable Development and its 17 Sustainable Development Goals (SDGs) (UN, 2015). The SDGs not only address the eradication of extreme poverty and its symptoms (including health impacts), but, among many other areas, also the underlying dynamics of human, environmental and economic developments. The SDGs thus reframe health from poverty reduction to an integral part of sustainable development (Hill et al., 2014; WHO, 2016). SDG3 is about human health, with Target 3.2 aiming to reduce under-five mortality to at least as low as 25 per 1,000 live births in all countries by 2030. About 60% of 188 countries currently have higher child mortality rates, partly due to persistent and sometimes even increasing environmental risk factors in low- and middle-income countries (Lim et al., 2016).

An estimated 26% of the total global child deaths can be attributed to environmental factors that can be influenced by human activity, contributing to the occurrence of infectious and parasitic diseases, neonatal and nutritional diseases and injuries (Prüss-Ustün et al., 2016; UNEP, 2016). Major infectious diseases are pneumonia, diarrhea and malaria, responsible for around 16%, 9% and 5% of global child mortality in 2015, respectively (Liu et al., 2016). Pneumonia is associated to exposure to carbon monoxide and fine particles emissions, caused by the use of traditional biomass on open fires or traditional stoves (Dherani et al., 2008). Diarrhea is strongly associated to the exposure to micro-pathogens, caused by unsafe drinking water sources and sanitation and the lack of hygiene (Wolf et al., 2014). Malaria is closely associated to environmental factors as the mosquitoes spreading the infection can only survive in suitable climates with high average temperatures, no frost and enough humidity and precipitation, while climate change can expand the areas suitable for malaria transmission (Martens et al., 1995). Finally, child underweight was related to about 15% of total child death in 2011 (Black et al., 2013). It directly contributes to child death via nutritional diseases, and indirectly as an underlying risk factor for pneumonia, diarrhea and malaria, increasing both disease incidence and mortality. Therefore, to achieve SDG target 3.2 on child mortality, achieving SDG targets with respect to eradicating hunger (SDG2), universal access to water and sanitation (SDG6) and universal access to modern sources of energy (SDG7) is also important. This integrated nature of the SDGs calls for a systematic analysis of the many trade-offs and synergies between achieving the broad range of goals and targets simultaneously (Le Blanc, 2015; Nilsson et al., 2016; Niessen et al., Accepted).

Projecting long-term developments in human health using integrated models helps to understand the links between health and other markers of human progress and provides insight into key leverage points for future improvements (Hughes et al., 2011). For example, integrated modelling has been used to estimate avoidable burden of disease related to specific risk factors (Kuhn et al., 2016) or the cost-effectiveness of different types of health interventions (Niessen et al., 2009; Van Ekdom et al., 2011). Different studies have projected child mortality towards 2030 (and beyond). Liu et al. (2015) and You et al. (2015) applied trend extrapolation, assuming that trends in cause-specific mortality between 2000 and 2013 would continue until 2030. Mathers and Loncar (2006) applied a regression model of sex and age specific mortality with indirect, or distal, determinants of health, for ten major-cause clusters. These studies do not take account of changes in the underlying health risk factors and thereby do not allow for a synergistic analysis. Some studies do include underlying health risks. Hughes et al. (2011) expanded the projections by Mathers and Loncar (2006), integrating the baseline estimates and formulations into the International Futures (IFs) integrated modelling framework and incorporating proximate health drivers and structural representations of some important health issues. The model allows to assess potential benefits of health policy intervention on socio-economic development. Hilderink and Lucas (2008) developed a multi-state health model (GISMO), that links socio-economic and environmental risk factors to disease incidence and death. Linking the model to the integrated assessment modelling framework IMAGE3.0 (Stehfest et al., 2014) allows to assess the role of environmental risk factors in long-term developments in child mortality, including food availability, access to safe drinking water, improved sanitation and modern sources of energy, and climate change (Hilderink et al., 2009; Van Vuuren et al., 2015).

The present study describes an actualized GISMO model to assess the role of environmental factors in future trends in child mortality in the context of projected developments in related SDGs. Furthermore, we use the model to address the following research questions:

- Is the world on track to achieve the SDG target on child mortality?
- What is the role of environmental factors in future developments in global child mortality?
- What is the impact on achieving the SDG target on child mortality of achieving environment-focused SDG targets?

We project future developments in child mortality and attributable death related to a range of environmental health risk factors. These projections build on the IMAGE implementation of the Shared Socioeconomic Pathways (SSPs), i.e. a set of five storylines on possible trajectories for human development and global environmental change during the 21st century (Riahi et al., 2017; Van Vuuren et al., 2017a). The analysis responds to the call to specifically incorporate human health indicators in the SSPs (Ebi, 2014; Van Ruijven et al., 2014). Our analysis goes beyond existing studies, by addressing cross-sectoral relations between different SDGs. In addition to projecting future developments in child mortality, we assess the child mortality implications of achieving a range of environment-focused SDG targets, including the eradication of hunger, providing universal access to clean water, sanitation and energy, and climate change mitigation.

2 Methods

We use a tested and widely published long-term integrated assessment model (IMAGE) linked to an actualized population health model (GISMO) to assess future developments and attributable child mortality to a selection of environmental health-risk factors. The integrated assessment model provides a structural representation of environmental health-risk factors. The population health model describes the causal chains between these risk factors and attributable child death, using relative risk ratios from the literature. Three distinct scenario storylines, describing the future evolution of key aspects of society, are used to quantify the underlying drivers. Projections of regional child mortality are based on the demographic projections of KC and Lutz (2017). Attributable child death, as well as reductions in child mortality as the result of achieving a range of, mostly environment-focused, SDG targets, are determined using the population health model. Here, we describe the GISMO health model, the environmental health-risk factors included and how they are linked to the IMAGE integrated assessment model, and the different scenarios with their underlying assumptions.

2.1 The GISMO health model

The GISMO health model describes the causal chain between health-risk factors, morbidity and mortality, based on a multi-state approach, distinguishing risk exposure, disease incidence and death (WHO, 2002; Cairncross and Valdmanis, 2006). Here, the model is used to assess future developments in attributable child mortality. The focus of the analysis is on the most important environmental health risks for children under five that relate to infectious diseases (pneumonia, diarrhea and malaria) and nutritional deficiencies. Together, they account for more than 30% of global child death in 2015 (Liu et al., 2016). The multi-state approach is used for malaria, diarrhea and pneumonia. Mortality related to nutritional deficiencies is calculated directly, by scaling base-year nutritional deficiency mortality with future trends in child underweight (see Section 2.2.1). The model is calibrated to data of the Global Burden of Disease Study 2015 (Forouzanfar et al., 2015; GBD collaborators, 2015; Vos et al., 2015).

The mortality rate (*MR*) in year *t*, of a specific disease (*d*) per region (*r*), sex (*s*) and age groups (*a*), is a multiplication of the incidence rate (*IR*), i.e. the number of disease cases per year as fraction of the subpopulation, and the case fatality rate (*CFR*), i.e. the proportion of the subpopulation dying from a specific disease:

$$MR_{t,r,d,s,a} = IR_{t,r,d,s,a} * CFR_{t,r,d,s,a} \tag{1}$$

Future developments in both IR and CFR are determined as a multiplication of three components: 1) base-year risk-free CFR and IR; 2) future developments in risk-free CFR and IR; and 3) increased CFR and IR because of future developments of exposure to specific health-risk factors:

$$IR_{t,r,d,s,a} = \frac{IR_{2010,r,d,s,a}}{RR_{IR,2010,r,d,s,a}} * \frac{a_{IR,d,s,a} * e^{-b_{IR,d,s,a} * GDPpc_{t,r}}}{a_{IR,d,s,a} * e^{-b_{IR,d,s,a} * GDPpc_{2010,r}}} * RR_{IR,t,r,d,s,a} \tag{2a}$$

$$CFR_{t,r,d,s,a} = \frac{CFR_{2010,r,d,s,a}}{RR_{CFR,2010,r,d,s,a}} * \frac{a_{CFR,d,s,a} * e^{-b_{CFR,d,s,a} * GDPpc_{t,r}}}{a_{CFR,d,s,a} * e^{-b_{CFR,d,s,a} * GDPpc_{2010,r}}} * RR_{CFR,t,r,d,s,a} \tag{2b}$$

Exposure (*P*) to health-risk factors (*rf*) and different exposure categories (*i*), expressed as percentage of the population or age-group, is included by using relative risk ratios (*RR*) based on epidemiological studies. RR ratios indicate the increased risk of falling ill or dying while exposed to a certain risk factor, as compared to a situation with no increased risks (RR=1). The RR ratio of total mortality associated with a specific risk factor is interpreted here as a multiplication of the RR of incidence with the RR of case fatality (Niessen, 2002). If exposure to more than one risk factor is related to a certain disease, the total effect of these risk factors is calculated in a multiplicative way:

$$RR_{IR,t,r,d,s,a} = \prod_{rf} \sum_i (RR_{IR,i,rf,d,s,a} * P_{t,r,i,rf,d,s,a}) \tag{3a}$$

$$RR_{CFR,t,r,d,s,a} = \prod_{rf} \sum_i (RR_{CFR,i,rf,d,s,a} * P_{t,r,i,rf,d,s,a}) \tag{3b}$$

The original GISMO health model made the distinction of base rates and excess rates for incidence and case fatality (Niessen and Hilderink, 1997; Hilderink and Lucas, 2008). The base rates reflect minimum levels attained when exposure to all health-risk factors is removed and there is no excess incidence or case fatality. Excess rates occur when interregional variation exists in risk-free rates. By recalibrating the model to data of the Global Burden of Disease Study 2015, it was difficult to obtain good estimates of the base incidence and mortality rates for the diseases included. Furthermore, for the infectious diseases included it can be argued that without risk exposure, related mortality approaches zero. Therefore, in the updated and recalibrated model used here, the base rates and the excess rates are taken together in projecting future health impacts.

Base year (2010) risk-free rates are determined, by dividing historic incidence and case fatality rates from the Global Burden of Disease Study 2015, by base-year (2010) RR ratios. Future developments in risk-free incidence and case fatality rates are determined, considering developments in regional health systems, using the trend of exponential regression of risk-free rates with per capita Gross Domestic Product (*GDPpc*). The disease-specific regression parameters *a* and *b* are estimated separately for the IR and CFR, for males and females, and for children 0-1 and 1-4, using incidence and mortality data from Global Burden of Disease Study 2015 and RR ratios as determined in the model (Formula 3a and 3b), both for 2010. The regression parameters are assumed to be constant over time.

The effect of a single health-risk factor on a specific disease or total attributable mortality is calculated as the Population Attributable Fraction (Ezzati et al., 2002):

$$PAF_{rf,d,s,a} = \frac{\sum_{i=1}^{n} P_{i,rf,d,s,a} RR_{i,rf,d,s,a} - \sum_{i=1}^{n} P'_{i,rf,d,s,a} RR_{i,rf,d,s,a}}{\sum_{i=1}^{n} P_{i,rf,d,s,a} RR_{i,rf,d,s,a}} \tag{4}$$

where P_i is the exposed population fraction and P_i' the exposure distribution that would result in the lowest population risk.

2.2 Environmental health-risk factors

Risk factors are divided according to their direct or indirect contribution to the occurrence of diseases in distal socio-economic causes, proximal causes and patho-physiological causes (Figure 1) (WHO, 2002; Ezzati et al., 2005). Distal risk factors influence proximal risk factors which, in turn, can affect patho-physiological causes of disease and death. A single factor can be influenced by several factors, and multiple factors can be influenced by one factor. To provide for future developments in health risk factors, the GISMO health model is linked to scenario outcomes of the integrated assessment model IMAGE3.0 (Stehfest et al., 2014) and the agro-economic model MAGNET (Woltjer and Kuiper, 2014).

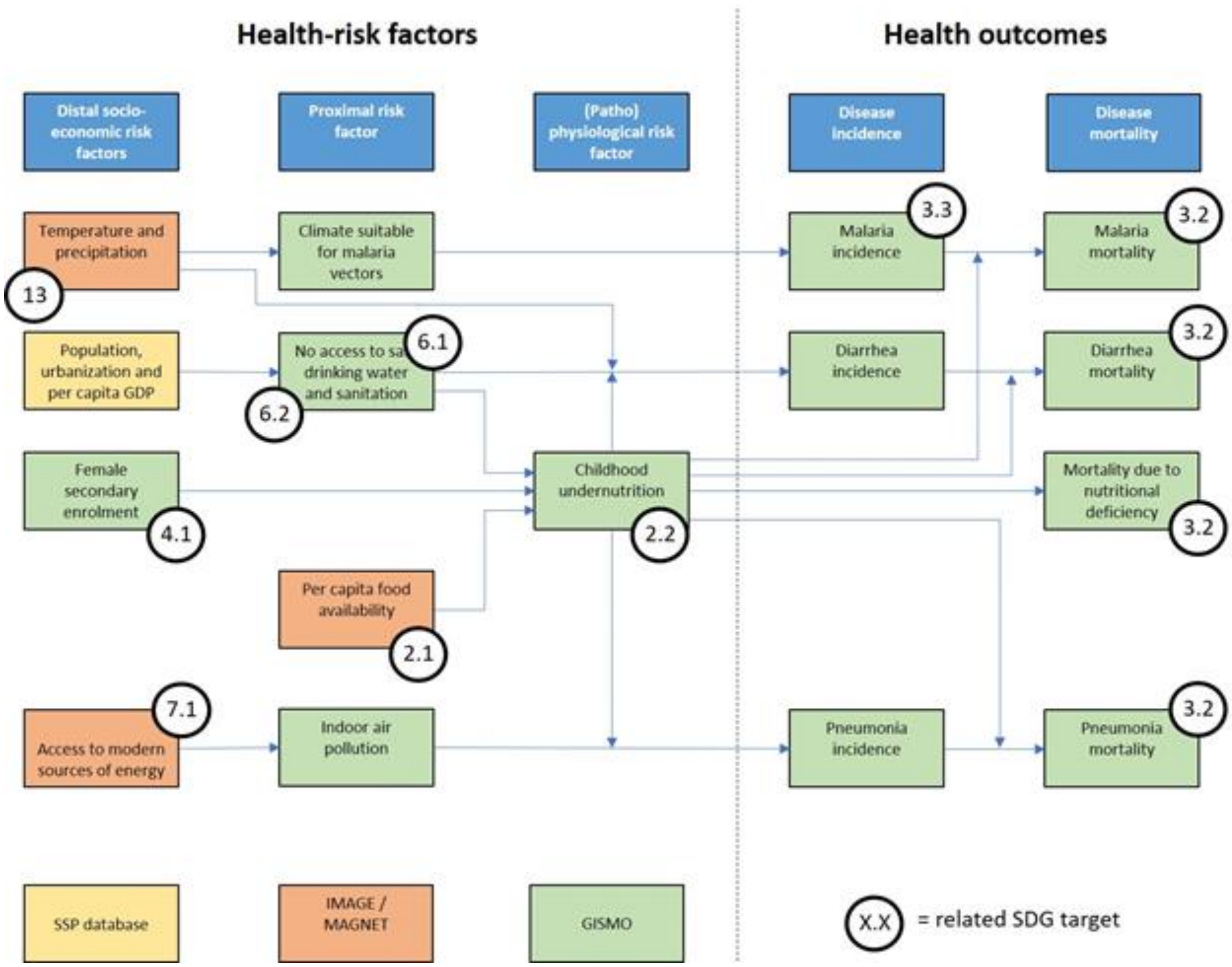

Figure 1: Relations between health risk factors and child mortality outcomes, related SDG targets and databases and models used

IMAGE3.0 is an integrated assessment model framework that simulates global and regional environmental consequences of changes in human activities. The model includes a detailed description of the energy and land-use system and simulates most of the socio-economic parameters for 26 regions and most of the environmental parameters based on a geographical grid of 30’ by 30’ or 5 by 5 minutes (depending on the variable).

MAGNET is a multi-regional, multi-sectoral, applied general equilibrium model, with a focus on agriculture and food markets. It uses information from IMAGE on land availability and suitability, on exogenous developments in crop and livestock production systems, and on changes in crop yields due to agricultural expansion on inhomogeneous land areas.

The following sub-sections describe the calculations of the health-risk factors determined in the GISMO model (green in Figure 1) and their impact on health outcomes, i.e. disease-specific morbidity and mortality.

2.2.1 Childhood undernutrition

Although malnutrition relates to both under- and overnutrition, here we only discuss childhood undernutrition, indicated by child underweight as measured by weight-for-age. Child underweight is modeled by linear regression with average food intake, female enrolment in secondary education and access to clean drinking water (Smith and Haddad, 2000). Base-year (2005) child underweight data is taken from FAO food security indicators (FAO et al., 2015), average food intake (kcal/cap/day) from MAGNET (van Meijl et al., Submitted), and access to clean drinking water and female enrolment in secondary education from calculations within the GISMO model (see Section 2.2.2 and Supplementary Material Chapter S2, respectively).

Based on a normal distribution, the total number of underweight children is divided into a mild, a moderate and a severe underweight group (De Onis and Blossner, 2003). Undernutrition has both a direct and an indirect effect on mortality. The direct effect becomes visible through mortality related to nutritional deficiencies (including protein-energy malnutrition, Iodine deficiency and Iron-deficiency anemia). Child mortality rates due to nutritional deficiencies in the base year are scaled using the projected trend in overall child underweight. Indirectly, undernutrition enhances the incidence of diarrhea and pneumonia, and the case fatality of malaria, diarrhea and pneumonia. The effects are considered distinguishing differential relative risk ratios for both incidence rates and case-fatality rates (Table 1).

Table 1: Relative risk ratios for different underweight levels on the incidence and total mortality of diarrhea, pneumonia and malaria. Source: Edejer et al. (2005) and Fishman et al. (2004).

Disease	Underweight level	RR incidence (95% CI)	RR mortality [a] (95% CI)
Diarrhea	Mild	1	2.32 (1.93, 2.79)
	Moderate	1.23 (1.12, 1.35)	5.39 (3.73, 7.79)
	Severe	1.23 (1.12, 1.35)	12.50 (7.19, 21.73)
Pneumonia	Mild	1	2.01 (1.63, 2.47)
	Moderate	1.86 (1.06, 3.28)	4.03 (2.67, 6.08)
	Severe	1.86 (1.06, 3.28)	8.09 (4.36, 15.01)
Malaria	Mild	-	2.12 (1.48, 3.02)
	Moderate	-	4.48(2.20, 9.15)
	Severe	-	9.49 (3.25, 27.66)

[a] RR case fatality = RR mortality / RR incidence.

2.2.2 Access to safe drinking water and sanitation

The proportion of the population that lacks access to safe drinking water and sanitation is modeled separately for urban and rural populations and different levels of access, i.e. no access, improved access and household connection (Cairncross and Valdmanis, 2006). The last stage is only modeled for drinking water. The access levels are modeled by applying linear regressions with GDP per capita, urbanization rate and population density. Data on access levels is taken from the Joined Monitoring Programme for water and sanitation (WHO/UNICEF, 2015). Developments in drinking water are assumed to be implemented ahead of sanitation. Incidence rate of diarrhea increase dependent on the different access levels to drinking water and sanitation facilities (Table 2), child underweight levels (Table 1) and by temperature increase (McMichael et al., 2004). Temperature increase is calculated as the population weighted average, using gridded population data from Van Vuuren et al. (2007) and gridded temperature data from IMAGE3.0 (Stehfest et al., 2014). The incidence rates and case fatality rates of diarrhea are increased by child underweight levels (Table 1).

Table 2: Determinant-specific relative risk of different exposure categories for the incidence of diarrhea and pneumonia.

Risk factor	Disease	Exposure category	Relative Risk	Source
Drinking water and sanitation	Diarrhea	No improved water supply, no basic sanitation	11.0 (low, high: 6.1, 16.0)	(Prüss-Üstün et al., 2004)
		Improved water supply, no basic sanitation	8.7 (low, high: 4.9, 12.6)	
		Improved water supply, basic sanitation	6.9 (low, high: 3.8, 10.0)	
		Household connection water supply, basic sanitation	2.5 [a]	
Household energy use for cooking and heating	Pneumonia	Modern fuels	1	-
		Traditional biomass and coal on traditional stoves	2.3 (95% CI: 1.9, 2.7)	(Bruce et al., 2006)
		Traditional biomass and coal on improved biomass stoves	0.35 (low, high: 0.1, 0.6) [b]	(Hutton et al., 2006)

[a] Prüss-Üstün et al. (2004) did not conclude low and high estimates for this category**;** [b] Reduction in RR for traditional stoves

2.2.3 Indoor air pollution

Indoor air pollution (i.e. exposure to carbon monoxide and fine particles emissions) is caused by the use of traditional biomass for cooking and heating on open fires or traditional stoves. We distinguish between three types of household energy use: 1) traditional biomass and coal on traditional stoves; 2) traditional biomass and coal on improved stoves; and 3) modern fuels (electricity, natural gas, LPG, kerosene, modern biofuels and solar stoves). For the modern fuels, no distinction in stoves is made. Proportion of the population with different access levels are taken from the IMAGE3.0 model, based on urban and rural household incomes per quintile, fuel prices and potential subsidies on fuels and stoves (Daioglou et al., 2012). Incidence rates of pneumonia are increased due to exposure to indoor air pollution caused by cooking and heating with traditional biomass and coal, with improved stoves reducing the exposure (Table 2). Simultaneously, incidence rates and case fatality rates are associated with child underweight levels (Table 1).

2.2.4 Suitable climate for malaria vectors

Malaria vectors, the mosquitoes spreading the infection, can only survive in suitable climates with high average temperatures, no frost and enough precipitation. The model uses these climatic factors to determine malaria-prone areas (Craig et al., 1999). For each climatic factor (average temperature, frost occurrence, precipitation), a fuzzy suitability index is calculated, with total climatic malaria suitability being determined by the lowest of these three indices. The individual factors are calculated at half-by-half degree grid level, using temperature and precipitation data from IMAGE3.0, specific for each scenario. The regional population at risk of malaria is estimated as the population weighted average over the grid cells, using gridded population data (Van Vuuren et al., 2007). Potential malaria incidence is then determined by multiplying the regional population at risk with a fixed uniform incidence rate for each malaria endemicity category (low and high), separately for urban and rural areas (Table 3). Final incidence rates of malaria are projected using the trend of potential malaria incidence on base year malaria incidence, decreased by the level of insecticide treated bed nets (ITN) and indoor residual spraying (IRS). The case fatality rates are increased by child underweight levels (Table 1).

Table 3: Basic malaria incidence rates, for the absence of malaria control through ITNs and IRS, by world region and endemicity category (Korenromp, 2005).

Region	Malaria endemicity	Rural	Urban
Sub-Saharan Africa (excl. Southern Africa)	High-endemic	1.91	0.6
	Low-endemic	0.5	0.5
Southern Africa	All endemic areas	0.029	0.029
Outside SSA	Hyper-endemic	1.09	0.33
	Meso-endemic	0.45	0.14

2.3 Scenarios

The analyses are based on two sets of scenarios: 1) three explorative scenarios to assess the range in future child mortality and the attributable share related to environmental risk factors; and 2) two normative scenarios to assess reduction in child mortality as the result of achieving a range of, mostly environment-focused, SDG targets. The scenarios build on the IMAGE implementation of the SSPs (Van Vuuren et al., 2017b; Doelman et al., 2018). The SSPs are five distinct global pathways describing the future evolution of key aspects of society that together imply a range of challenges for mitigating and adapting to climate change (Riahi et al., 2017; Van Vuuren et al., 2017a). Each SSPs is described by a quantification of future developments in population (KC and Lutz, 2017), urbanization (Jiang and O'Neill, 2017) and economic development (Dellink et al., 2017), and by a descriptive storyline to guide further model parametrization (O'Neill et al., 2017), including extended storylines that also describe possible consequences for health risks and health systems (Ebi, 2014; Sellers and Ebi, 2018).

Table 4: Scenario description

	Scenario name	Description
Explorative scenarios	SSP1 (Sustainability)	A world that makes relatively good progress towards sustainability, with sustained efforts to achieve development goals, while reducing resource intensity and fossil fuel dependency. Educational and health investments accelerating the demographic transition, leading to relatively low mortality. Economic development is high and population growth is low.
	SSP2 (Middle of the Road)	A world in which trends typical of recent decades continue (business as usual), with some progress towards achieving development goals, reductions in resource and energy intensity at historic rates, and slowly decreasing fossil fuel dependency. Fertility and mortality are intermediate and also population growth and economic development are intermediate.
	SSP3 (Regional Rivalry)	A world that is fragmented, characterized by extreme poverty, pockets of moderate wealth and a bulk of countries that struggle to maintain living standards for a strongly growing population. The emphasis is on security at the expense of international development. Mortality is high everywhere, while fertility is low in rich OECD countries and high in most other countries. Economic development is low and population growth is high.
Normative scenarios	SSP2_FullAccess (Based on SSP2)	A scenario that builds on the SSP2 scenario, but in which, by 2030 the SDG targets on hunger (Target 2.1), access to clean water and sanitation (Target 6.1 and 6.2) and access to clean energy (SDG Target 7.1) are achieved.
	SSP2_QualityAccess (Based on SSP2)	An extension of the *SSP2_FullAccess* scenario, with further measures to improve the quality of access (Target 6.1 and 7.1), behavioral measures (Target 3.3 and 4.1) and climate policy for keeping the increase in the global mean temperature below 2 °C compared to preindustrial levels (SDG13).

For the explorative scenarios, we look at SSP1, SSP2 and SSP3 (see Table 4 and 5). Projections of regional child mortality in the these three scenarios are based on the demographic projections of KC and Lutz (2017). Their mortality projections were made based on global conditional convergence of life expectancy at birth. Over time, country-level life expectancy approaches the life expectancy in regional forerunner countries, which themselves slowly approach the life expectancy of the global forerunner Japan. In SSP2 a constant increase of two years in life expectancy at birth per decade was assumed for Japan. For SSP1 and SSP3 it was assumed that the life expectancy in Japan would increase one year per decade faster or slower than in SSP2, respectively. Corresponding to each life expectancy, life tables were generated by interpolating the life tables from UN's World

Population Prospects 2010 (UN, 2011). In cases where life expectancy was higher than the range in WPP2010, mortality rates above age 60 were extrapolated. Survival ratios were extracted from the resulting life tables and further decomposed into six sets of education specific survival ratios using iterative simulation for assumed mortality differentials at age 15, and mapped to the different SSP scenarios. To estimate under five mortality rates, after applying the survival ratios, an weighted average of the death rate among the newborns and those aged 0-4 years old was used. Projections of attributable child mortality are determined using the GISMO health model in combination with the IMAGE implementation of the three SSPs (see Table 5).

The two normative scenarios – *SSP2_FullAccess* and *SSP2_QualityAccess* – build on the SSP2, middle-of-the-road, scenario (see Table 4 and 5). The policies in these two scenarios are stylized in the sense that they do not consider socio-economic and environmental constraints. With respect to climate policy, temperature and precipitation maps are taken from the IMAGE SSP2 climate mitigation scenario (Van Vuuren et al., 2017b). Overall child mortality as a result of these policies are calculated by subtracting the reductions in attributable mortality, as determined with the GISMO health model, from the overall child mortality in the *SSP2* scenario, as determined using the data of KC and Lutz (2017).

Table 5: Model parametrization of the five scenarios

	SSP1	SSP2	SSP3	SSP2_FullAccess	SSP2_QualityAccess
Socio-economic developments	SSP1	SSP2	SSP3	SSP2	SSP2
Childhood undernutrition	Hunger is ended by 2050	Endogenous trend	Endogenous trend	Hunger is ended by 2030	Similar to *FullAccess*
Access to safe drinking water and sanitation	Universal access to clean water and sanitation by 2050	Endogenous trend	Endogenous trend	Universal access to clean water and sanitation by 2030	Similar to *SSP2_FullAccess*, but with 100% piped water
Indoor air pollution	Universal access to modern fuels by 2050	Endogenous trend	Endogenous trend	Universal access to modern fuels by 2030	Similar to *SSP2_FullAccess*, but without improved stoves
Suitable climate for malaria vectors	Endogenous trend	Endogenous trend	Endogenous trend	Endogenous trend	Full coverage of insecticide treated bed nets and indoor residual spraying
Net female enrolment in secondary education	Fast progress in regression parameters	Intermediate progress in regression parameters	No change in regression parameters	Intermediate progress in regression parameters	All girls are enrolled in secondary education by 2030

Our model-based analysis is subject to a range of uncertainties, including future socio-economic developments and the extent to which health risk factors impact disease incidence and death. The first type of uncertainty is addressed by using the three SSP scenarios, that build on distinct, but internally consistent, storylines. SSP2 describes a continuation of current trends, while SSP1 and SSP3 describe more optimistic and more pessimistic developments, respectively. No uncertainty values are attached to their scenario results with respect to overall child mortality rates, and projections for hunger and access to water, sanitation and energy. Only a range of possible outcomes is presented, with SSP1 and SSP3 at the lower and higher end of that range, respectively.

The second type of uncertainty relates to the relative risk ratios used in the analysis. The assessment of attributable mortality takes this uncertainty into account, using Monte Carlo sampling (N=1000) on the full uncertainty ranges of the different RR values (Table 1-2). For the RR values for malaria of climate suitability on the incidence rate (Table 3) no estimates of uncertainty were available from Korenromp (2005). The ranges indicated in Table 1 and 2 have been interpreted as strict minima and maxima to truncate the lognormal and normal shaped uncertainty distributions, respectively, which have been employed for sampling the RR values. In sampling, the various relative risks were assumed to be uncorrelated. The Monte Carlo sampling concludes a 95% confidence interval (CI) for attributable mortality for the five scenarios, and for the child mortality rates for the two normative scenarios.

3 Results

3.1 Future developments in child mortality

Figure 2 shows future developments in under-five mortality for the three SSP scenarios. Globally, child mortality is projected to decrease most in SSP1 – and to a lesser extend also in SSP2 – and increase in SSP3, from 59 child deaths per 1000 children born in 2010 (UN, 2011) to 31, 45 and 71 in 2030 and 15, 32 and 70 in 2050, in SSP1, SSP2 and SSP3 respectively. As a result, the 2030 SDG target on child mortality (25 child deaths per 1000 children born) is not met at the global level in any of the three SPP scenarios, mainly due to persistent high levels of child mortality in Sub-Saharan Africa (54-140) and South Asia (39-67). The numbers in between brackets refer to the more optimistic SSP1 scenario and the more pessimistic SSP3 scenario. By 2050, 20 years later than the official SDG target year, the target is only achieved at the global level in SSP1, where even Sub-Sahara Africa comes close to achieving the target. In the other two scenarios, by 2050 the target is still largely out of reach. Lange and Klasen (2017) already concluded that this SDG target is overly ambitious for countries in Sub-Saharan Africa, as it is an absolute target and not a relative one. It should be noted that the SDG target of 25 child deaths per 1000 children born is to be achieved by all countries. As many developed countries have already achieved this target, with child mortality rates far below 10 child deaths per 1000 children born, even in the optimistic SSP1 scenario, many countries will still be off-track in 2050.

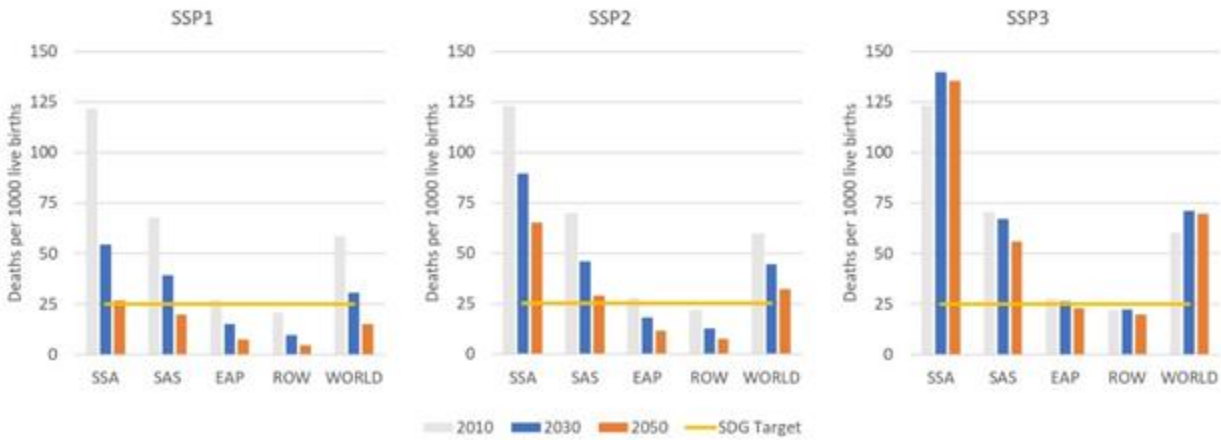

Figure 2: Under-five mortality rate in the three SSP scenarios (SSA = Sub-Saharan Africa; SAS = South Asia; EAS = East Asia Pacific; ROW = Rest of the World)

3.2 The role of environmental factors

Figure 3 shows future developments in total children being underweight (SDG Target 2.2) and children not having access to improved drinking water (SDG Target 6.1), basic sanitation (SDG Target 6.2) and modern sources of energy (SDG Target 7.1) in the three SSP scenarios. Overall, children without adequate access to food, water and energy decrease significantly in relative terms. In absolute terms, however, by 2030 still many children live without adequate access, mainly in Sub-Saharan Africa and South Asia, but to a lesser extend also in East Asia Pacific. The related SDG targets of eradicating hunger and achieving universal access to clean water, sanitation and energy are not achieved.

By 2030, depending on the SSP scenario, 48-108 million children are projected to being underweight, 18-44 million children do not have access to safe drinking water, 80-201 million children do not have access to basic sanitation and 30-226 million children live without access to modern sources of energy for cooking and heating. Child underweight is projected to remain a problem especially in South Asia, while not having access to safe drinking water further concentrates in Sub-Saharan Africa. Access to improved sanitation and modern sources of energy for cooking remains a problem in both South Asia and Sub-Saharan Africa, and to a lesser extend also in East Asia Pacific. This is in line with current regional shares in environmental deprivation. Large improvements in absolute numbers are projected in SSP1 in all regions, while almost no improvements are projected in SSP3, with even a deterioration with respect to access to modern sources of energy. The latter is the result of high population growth, slow economic development and persistent inequality.

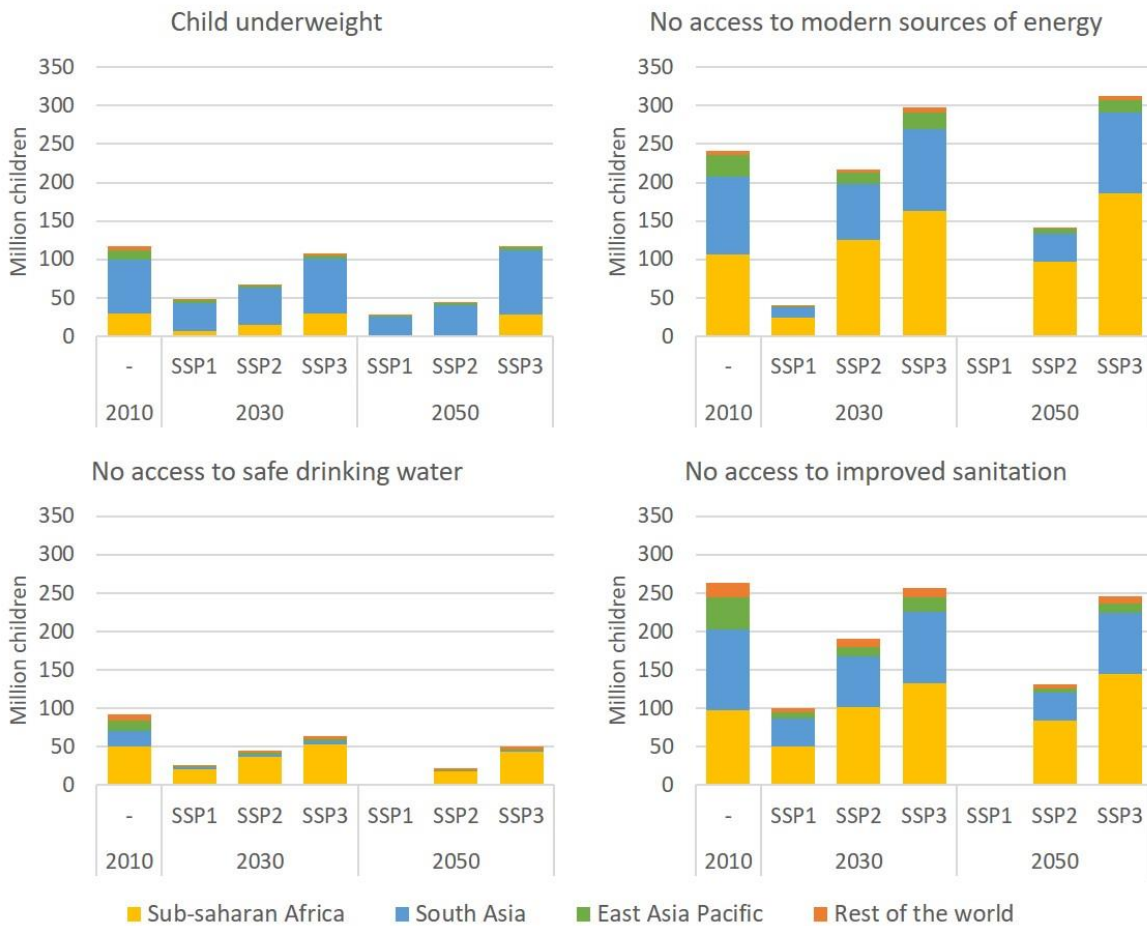

Figure 3: Children without adequate access to food (underweight), safe drinking water, improved sanitation, and an improved energy source for cooking and heating, in the three SSP scenarios.

Figure 4 shows developments in attributable mortality in the three SSP scenarios, related to the selected environmental health risks, i.e. not having access to drinking water and sanitation, not having access to modern sources of energy, malaria vectors and child underweight (nutritional deficiencies and underweight-related mortality that does not overlap with attributable mortality related to malaria and not having access to drinking water, sanitation and modern sources of energy). As a result of projected improved access, as well as improved overall development levels, attributable mortality to the selected environmental factors decreases. For East Asia pacific and the Rest of the World, attributable mortality decreases fast and, except for SSP3, is almost completely eliminated by 2050. Also in Sub-Saharan Arica and South Asia strong reductions are projected. Assuming nominal values for the RR ratios, globally, the share of the included environmental risk factors decreases from 27% in 2010 to 10-19% in 2030 and 1-14% in 2050. In 2030, child underweight is projected to be responsible for 5-12% of total global child deaths, the lack of safe drinking water and improved sanitation for 3-4%, indoor air pollution for 1-3% and exposure to malaria vectors for 4-7%. This concludes that the selected environmental health risk factors are still significant in 2030.

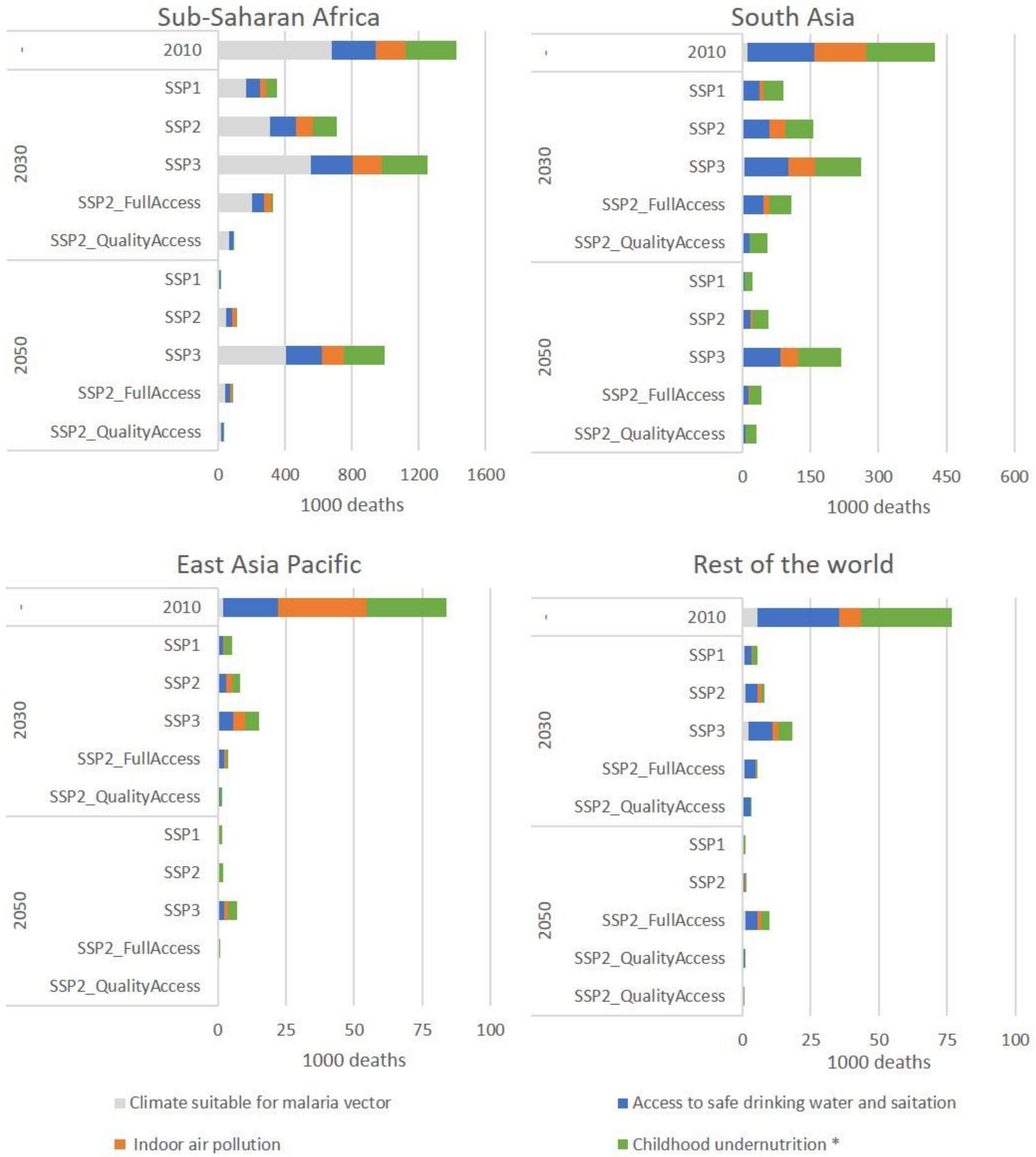

Figure 4: Attributable child death to the four risk factors included in the five scenarios, assuming nominal values for the RR ratios (* excludes cross effect with malaria, access to drinking water and sanitation and indoor air pollution)

Table 6: Global attributable child mortality and global under-five mortality rate, in 2030

	Suitable climate for malaria vectors (x1000 deaths) (95% CI)	Access to safe drinking water and sanitation (x1000 deaths) (95% CI)	Indoor air pollution (x1000 deaths) (95% CI)	Childhood undernutrition [a] (x1000 deaths) (95% CI)	Total attributable child death (x1000 deaths) (95% CI)	Under-five mortality rate (deaths / 1000 live births) (95% CI)
SSP1	168 (148, 197)	122 (78, 155)	47 (33, 64)	230 (204, 271)	448 [363, 538]	30.6
SSP2	314 (267, 384)	217 (164, 277)	142 (105, 184)	488 (430, 581)	878 [729, 1071]	44.6
SSP3	561 (443, 693)	363 (255, 436)	237 (178, 312)	961 (816, 1135)	1545 [1235, 1863]	71.1
SSP2_FullAccess	205 (198, 215)	122 (75, 172)	54 (34, 78)	123 (107, 147)	445 [366, 537]	41.2 (40.8, 41.7)
SSP2_QualityAccess	66 (66, 66)	37 (36, 39)	0 (0, 0)	50 (46, 57)	145 [141, 105]	38.9 (38.8, 38.9)

[a] Child underweight includes total child mortality attributable to child underweight, including the increased effects on incidence and case fatality for malaria, diarrhea and pneumonia. Attributable deaths can thus not simply be summed.

3.3 Gains in child mortality from achieving specific SDG targets

In the *SSP2_FullAccess* scenario, bringing the prevalence of undernourishment to zero, decreases mortality attributable to child underweight by 75% in 2030, compared to the *SSP2* scenario (Table 6). Remaining underweight can largely be attributed to the way food is utilized, in our modelling framework linked to female education levels (Smith and Haddad, 2000; Marmot, 2010). Universal access to safe drinking water and improved sanitation reduces attributable mortality with 44% in 2030, with further mortality reductions possible through hygiene measures and replacing public standpipes and boreholes by household connections for drinking water (Prüss-Üstün et al., 2009). Universal access to modern energy sources decreases attributable mortality with 62% in 2030, with further mortality reductions possible through increased ventilation and a complete transition to modern fuels as electricity and LPG, also replacing improved biomass stoves (Hutton et al., 2006). Finally, malaria mortality reduces with 35% as result of significant reductions in child underweight, with further improvements possible by combatting the malaria mosquitoes with insecticide treated bed nets and indoor residual spraying (Morel et al., 2005).

Achieving the SDG targets with respect to hunger elimination and universal access to clean water, sanitation and energy reduces global child mortality with around 433 thousand child deaths in 2030 compared to the SSP2 scenario, with by far the largest share in Sub-Saharan Africa (see Table S1-S4). In 2050, the improvement is much smaller, only around 45 thousand child deaths, as access levels in the SSP2 scenario in 2050 are already relatively high, and thus attributable mortality is low. Overall, global child mortality in 2030 is reduced with around 8%, from 45 child deaths per 1000 children born in SSP2 to 41 in the *SSP2_FullAccess* scenario.

In the *SSP2_QualityAccess* scenario, remaining environmental health risk exposure is almost eliminated, reducing global child mortality further with in total around 733 thousand child deaths in 2030 and 110 thousand in 2050, as compared to the SSP2 scenario. Compared to the *SSP2_FullAccess* scenario, global child mortality is reduced further. Overall, global child mortality in 2030 is 13% lower than the reference scenario, reducing it further to 39 child deaths per 1000 children born, in 2030. Again, Sub-Saharan Africa takes the lion share of avoided child deaths in 2030 (see Table S1-S4). Removing health risks due to further improved energy and water services eliminates most of the attributable mortality. Furthermore, targeting female education significantly improves the utilization of food – reducing child underweight due to better nutrition – especially in Sub-Saharan Africa where secondary school enrolment for girls in SSP2 is projected to be around 60% in 2030. Reduced climate change decreases the extension of the malaria-prone areas and reduces the risk of diarrhea incidence. It should however be noted that the effects of climate change are still small in 2030 and their impacts are more significant in the second half of this century. Finally, insecticide treated bed nets and indoor residual spraying to combat malaria can reduce malaria incidence with around 75% (Morel et al., 2005).

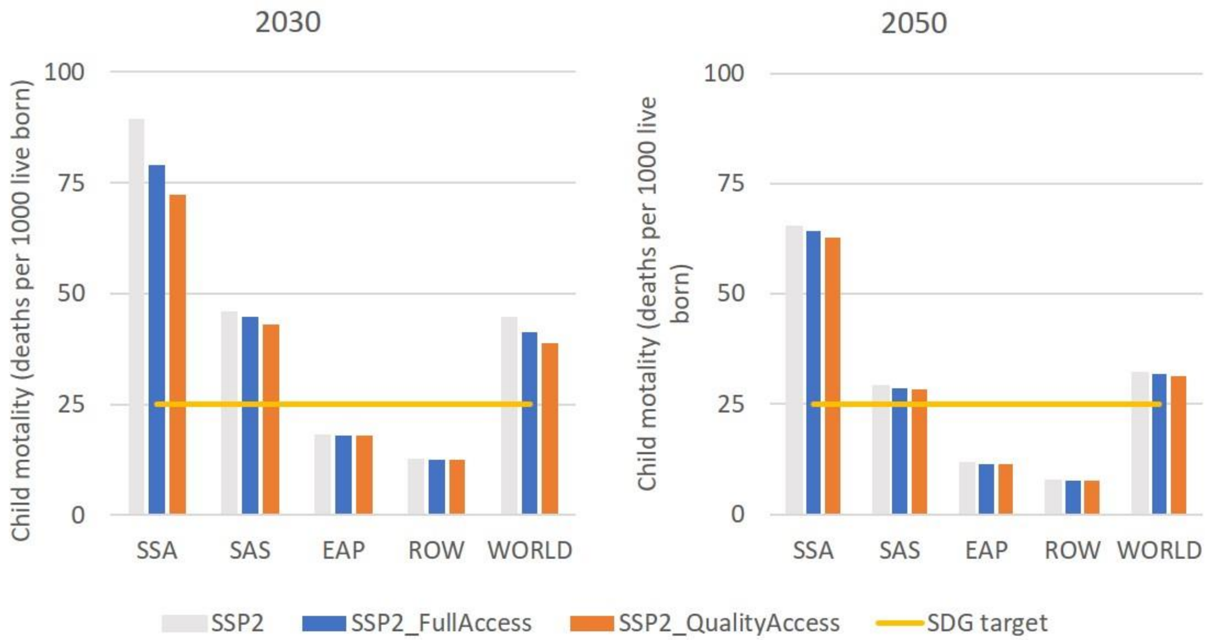

Figure 5: Under-five mortality rate in the SSP2, *SSP2_FullAccess* and *SSP2_QualityAccess* scenarios, assuming nominal values for the RR ratios (SSA = Sub-Saharan Africa; SAS = South Asia; EAS = East Asia Pacific; ROW = Rest of the World)

4 Discussion

The analysis concludes the SDG target on child mortality is not achieved in any of the three SSP scenarios analyzed, with environmental health risk factors being still relevant in 2030. Furthermore, a significant proportion of the required reduction in child mortality outcomes to achieve the 2030 SDG target could be addressed by achieving SDG targets on child nutrition, access to clean water and sanitation, access to modern energy and advanced malaria control.

Our projections of global child mortality are broadly in line with earlier studies that assumed that trends in cause-specific mortality between 2000 and 2013 would continue until 2030 (Liu et al., 2015; You et al., 2015; GBD 2016 SDG Collaborators, 2017). Their 2030 projections range between 23 and 32 child deaths per 1000 children born, which is at the lower end of our range, close to the scenario with sustained efforts to achieve development goals (SSP1). Part of this difference can be explained by a much faster reduction in under-five mortality between 2000 and 2010 than was anticipated in the SSP projections. The latest child mortality estimate for 2010 is 52 child deaths per 1000 children born (UN, 2017) compared to 59 (UN, 2011) used for constructing the SSP scenarios used in our study. Nevertheless, the rates of improvement in our child mortality projections and the conclusion that the world is not on track for achieving the SDG target on child mortality, is in line with the earlier studies listed above.

The relative differences between the three SSP projections, as well as the trends in attributable mortality, are in line with the qualitative discussion of potential SSP outcomes regarding human health of Sellers and Ebi (2018). They argue that the SDG target on child mortality is achievable under SSP1, as health systems are likely to deliver higher-quality and more equitable service and fewer deaths will be associated with preventable causes, such as undernutrition, malaria, and diarrheal diseases. On the contrary, for SSP3 they argue that the mortality transition stalls nearly completely, with undernutrition, malaria, and diarrheal diseases continuing to serve as major causes of death, particularly among young children.

There are some limitation to our study. The assessment of attributable mortality assumes an independent occurrence of the risk factors included. This does not completely reflect reality as very often these risk factors are related with, for example, poverty, and therefore might cluster in the poor population groups. However, data on how these factors correlate is lacking. Furthermore, this study does not account for competing mortality risks, i.e. elimination of a single risk could cause an increase in mortality risks related to other risk factors. This might result in a small overestimation of the effect of specific interventions. Finally, several risk factors are only included indirectly or largely aggregated. For example, access to clean cooking is used as a binary parameter (yes or no), while the related smoke, i.e. the $PM_{2.5}$ concentration, which in turn depends on the type of fuel, the cook stove used, and the way the cook stove is used, determines the overall impact at the household level.

5 Conclusions

This study examined the role of environmental risk factors in future developments in global child mortality, by addressing cross-sectoral relations between different SDGs. By linking a multi-state health model, distinguishing risk exposure, disease and death, to an integrated assessment model, that addresses future developments in drivers and impacts of global environmental change, key insights on synergies between environment-focused SDG targets and the SDG target on child mortality were provided. By including mortality related to nutritional deficiencies, pneumonia, diarrhea and malaria, around 36% of 2013 global child death is covered (GBD collaborators, 2015), with around two-third directly linked to environmental factors.

The analysis shows that the SDG target of all countries reducing global child death to at least as low as 25 per 1,000 live births, by 2030, is not achieved in any of the three SSP scenarios analyzed, mainly due to persistent high mortality rates in Sub-Saharan Africa and South Asia. Global child mortality is projected to reduce from 59 deaths per 1000 births in 2010 to 45 in 2030 in SSP2 (and to 31 and 71 in SSP1 and SSP3, respectively). Only in SSP1, a scenario with sustained efforts to achieve development goals, the target is achieved globally before 2050, while SSP3, a scenario with increasing differences between rich and poor, shows a deterioration in child mortality.

The SDG targets on hunger and access to clean water, sanitation and energy are also not achieved in any the three SSP scenarios. Although large improvements in relative terms are projected, childhood undernutrition, inadequate access to clean water and modern energy, and malaria exposure remain relevant health risk factors in 2030, accounting for 10-19% of total child mortality. In general, these environmental health risks are avoidable. Developed countries have already shown that with the right policies and investments they can be almost completely eradicated and even in developing countries there are many examples of countries fighting these risks with success.

Under SSP2, reducing health-risk exposure by achieving specific environment-focused SDG targets – i.e. eradicating hunger and achieving universal access to clean water, sanitation and energy – results in a reduction in global child death with 433 thousand in 2030, or 8% of total mortality. Furthermore, by also taking the broader socio-economic context into account – including higher standards of access to clean water and energy, female education and advanced malaria control – global child mortality can be reduced further, avoiding 733 thousand child deaths in 2030, or around 13% of total mortality, with by far most of these mortality gains achieved in Sub-Saharan Africa. As a result, taking away these environmental health risks reduces global child mortality in 2030 from 45 child deaths per 1000 children born to 39. To further reduce child mortality, next to risk-factor reduction and broader prevention measures, also health promotion and treatment needs to be addressed. Their impact is not assessed in our analysis.

Overall, the analysis concludes that a significant proportion of the required reduction in child mortality outcomes to achieve the related SDG target could be addressed by policies in other domains such as food, water and energy sectors. For example, one fifth of the targeted child mortality reductions in Sub-Saharan Africa can be addressed through SDG-related policies on food, water and energy. This requires shifts towards fully integrated approaches to health that include these sectors (Whitmee et al., 2015; Queenan et al., 2017). The SDGs offer a framework and unique opportunity to do so.

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Supplementary Material

S1 Regional attributable child mortality and under-five mortality rate

Table S1: Attributable child mortality and under-five mortality rate for Sub-Saharan Africa, in 2030

	Suitable climate for malaria vectors (x1000 deaths) (95% CI)	Access to safe drinking water and sanitation (x1000 deaths) (95% CI)	Indoor air pollution (x1000 deaths) (95% CI)	Childhood undernutrition [a] (x1000 deaths) (95% CI)	Under-five mortality rate (death / 1000 live births) (95% CI)
SSP1	166 [146, 195]	82 [62, 103]	36 [26, 49]	153 [131, 185]	54.4
SSP2	311 [264, 380]	151 [114, 194]	105 [78, 135]	363 [311, 441]	89.4
SSP3	554 [454, 710]	252 [187, 326]	170 [129, 222]	741 [633, 919]	139.6
FullAccess	202 [195, 211]	73 [43, 103]	39 [24, 55]	40 [33, 51]	79.0 [78.1, 80.0]
QualityAccess	65 [65, 65]	20 [20, 20]	0 [0, 0]	0 [0, 0]	72.3 [72.3, 72.3]

[a] Child underweight includes total child mortality attributable to child underweight, including the increased effects on incidence and case fatality for malaria, diarrhea and pneumonia. There is thus some overlap and attributable deaths can thus not simply be summed.

Table S2: Attributable child mortality and under-five mortality rate for South Asia, in 2030

	Suitable climate for malaria vectors (x1000 deaths) (95% CI)	Access to safe drinking water and sanitation (x1000 deaths) (95% CI)	Indoor air pollution (x1000 deaths) (95% CI)	Childhood undernutrition [a] (x1000 deaths) (95% CI)	Under-five mortality rate (death / 1000 live births) (95% CI)
SSP1	1 [1, 2]	36 [26, 48]	10 [7, 14]	71 [64, 85]	39.2
SSP2	2 [2, 3]	58 [43, 77]	33 [25, 44]	119 [104, 144]	46.0
SSP3	4 [3, 7]	97 [70, 131]	60 [44, 82]	204 [178, 250]	67.0
FullAccess	2 [2, 3]	44 [27, 62]	14 [9, 21]	81 [70, 98]	44.6 [44.2, 45.3]
QualityAccess	1 [1, 1]	14 [12, 16]	0 [0, 0]	49 [45, 55]	43.1 [43.0, 43.3]

[a] Child underweight includes total child mortality attributable to child underweight, including the increased effects on incidence and case fatality for malaria, diarrhea and pneumonia. There is thus some overlap and attributable deaths can thus not simply be summed.

Table S3: Attributable child mortality and under-five mortality rate for East Asia Pacific, in 2030

	Suitable climate for malaria vectors (x1000 deaths) (95% CI)	Access to safe drinking water and sanitation (x1000 deaths) (95% CI)	Indoor air pollution (x1000 deaths) (95% CI)	Childhood undernutrition [a] (x1000 deaths) (95% CI)	Under-five mortality rate (death / 1000 live births) (95% CI)
SSP1	0 [0, 0]	2 [1, 2]	1 [0, 1]	4 [3, 4]	15.0
SSP2	0 [0, 0]	3 [2, 4]	2 [2, 3]	5 [4, 5]	18.2
SSP3	0 [0, 1]	5 [4, 7]	4 [3, 6]	9 [8, 11]	26.2
FullAccess	0 [0, 0]	2 [1, 3]	1 [0, 1]	1 [1, 2]	18.0 [17.9, 18.0]
QualityAccess	0 [0, 0]	1 [1, 1]	0 [0, 0]	1 [1, 1]	17.9 [17.9, 17.9]

[a] Child underweight includes total child mortality attributable to child underweight, including the increased effects on incidence and case fatality for malaria, diarrhea and pneumonia. There is thus some overlap and attributable deaths can thus not simply be summed.

Table S4: Attributable child mortality and under-five mortality rate for Rest of the World, in 2030

	Suitable climate for malaria vectors (x1000 deaths) (95% CI)	Access to safe drinking water and sanitation (x1000 deaths) (95% CI)	Indoor air pollution (x1000 deaths) (95% CI)	Childhood undernutrition [a] (x1000 deaths) (95% CI)	Under-five mortality rate (death / 1000 live births) (95% CI)
SSP1	1 [1, 1]	3 [2, 3]	0 [0, 1]	2 [2, 2]	9.5
SSP2	1 [1, 1]	5 [4, 5]	1 [1, 2]	2 [2, 2]	12.6
SSP3	2 [2, 2]	9 [8, 10]	2 [2, 3]	7 [7, 8]	22.3
FullAccess	1 [1, 1]	4 [3, 4]	1 [0, 1]	0 [0, 0]	12.5 [12.5, 12.6]
QualityAccess	0 [0, 0]	3 [3, 3]	0 [0, 0]	0 [0, 0]	12.5 [12.5, 12.5]

[a] Child underweight includes total child mortality attributable to child underweight, including the increased effects on incidence and case fatality for malaria, diarrhea and pneumonia. There is thus some overlap and attributable deaths can thus not simply be summed.

S2 Female secondary school enrolment

The population projections of KC and Lutz (2017) used in this study are based on future projections on educational attainment. Preferably we had used these education projections for our scenario analysis. However, as they are difficult to translate to enrolment ratios, we used a simplified education model that start from enrolment (see also Hilderink and Lucas, 2008).

The education model describes future development in school enrolment at three levels of education: primary, secondary and tertiary. The model uses logarithmic regression of net enrollment with per capita GDP (PPP), based on historic country-level enrollment ratios from Lee and Lee (2016) and country-level GDP data from Dellink et al. (2017):

$$Enrollment_{r,i,t} = a_{i,t} * \ln(GDPpc\_ppp_{r,t}) + b_{i,t} \quad \text{(S1)}$$

where *r* is the region, *i* the level of education (primary, secondary and tertiary) and *t* the year. Countries with per capita GDP levels above USD 35,000 were excluded from the regression analysis.

The regression analysis reveals both increasing enrolment ratios with increasing per capita income, as well as over time (Figure S1 and Table S1). For future projections, the regression parameters evolve over time, based on 1990-2010 trend, using linear regression. Furthermore, we added an extra parameter to tune the speed of improvement, dependent on the scenario storyline. For SSP2 we did not tune the speed of improvement, for SSP1 we increase the yearly improvement with 50%, and for SSP3 we keep the regression parameters at 2010 levels. These assumptions are in line with the SSP scenario assumption of KC and Lutz (2017) for educational achievement.

Table S5 Regression parameters and R2 for net primary, secondary and tertiary enrollment ratios

	Primary enrollment			Secondary enrollment			Tertiary enrollment		
	a	b	R^2	a	b	R^2	a	b	R^2
1970	15.05	-50.27	0.45	15.64	-96.25	0.55	4.57	-29.60	0.39
1980	11.80	-19.50	0.45	17.30	-101.8	0.59	6.60	-43.16	0.50
1990	10.40	-5.27	0.43	18.59	-107.0	0.71	9.56	-62.93	0.51
2000	7.10	30.52	0.32	18.79	-97.50	0.74	13.14	-86.34	0.64
2010	2.46	75.07	0.15	17.13	-77.24	0.79	18.74	-124.9	0.68

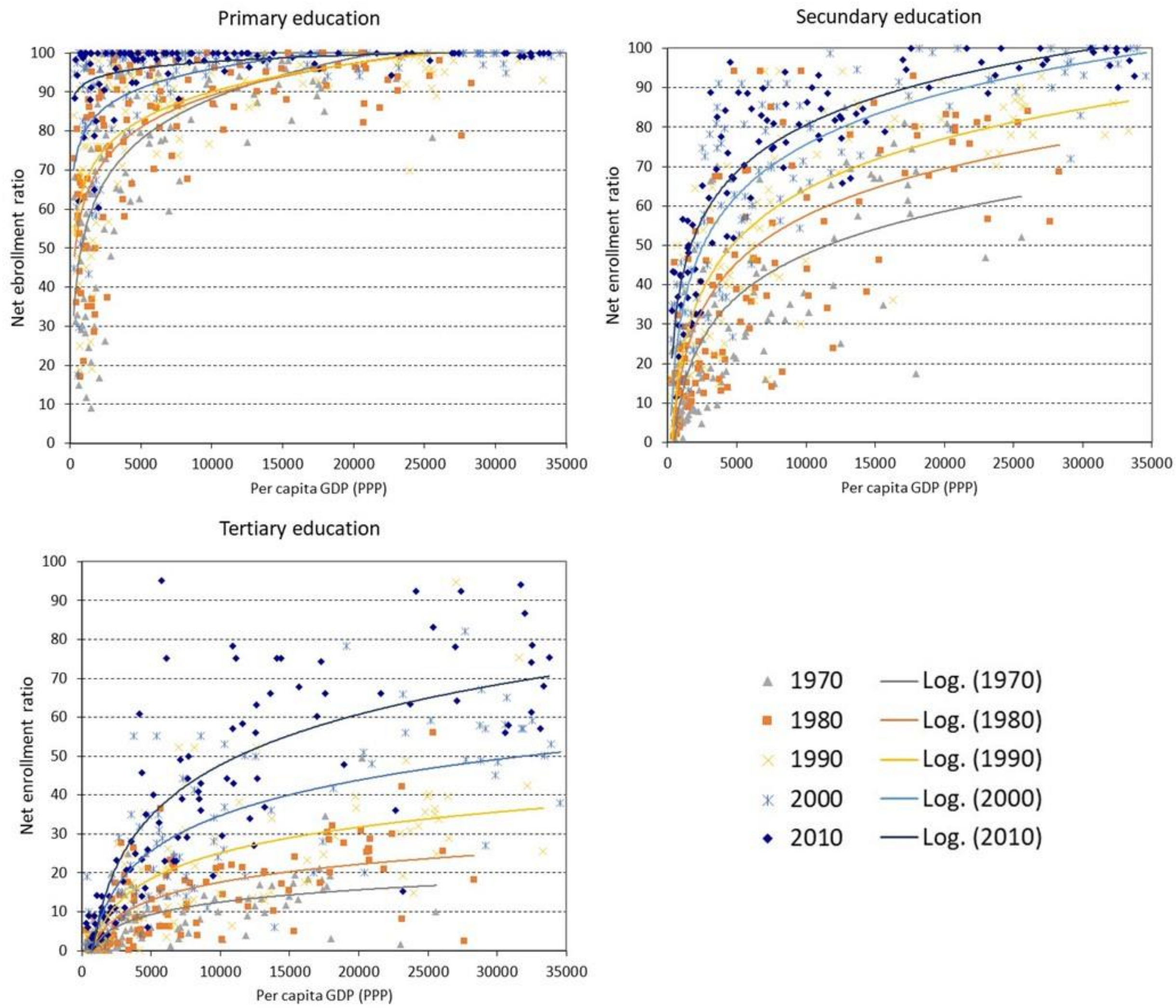

Figure S1: Country level net enrollment ratios versus per capita GDP (PPP)