Cause of Death Variation under the Shared Socioeconomic Pathways

Samuel Sellers
Center for Health and the Global Environment, University of Washington
22 March 2019

Prepared for Population Association of America Conference, 2019

Abstract

Climate change will create numerous risks for human health, including effects related to temperature extremes, infectious disease, and undernutrition. Such risks, along with other socioeconomic and development trends, will affect cause-of-death patterns experienced in the coming decades. This study explores future mortality trends using the Shared Socioeconomic Pathways (SSP) framework, a widely-utilized series of scenarios for understanding socioeconomic development trends in a world with climate change. Existing projections for GDP, urbanization, and demographic trends based on SSP narratives are incorporated into an integrated assessment model, International Futures (IFs), in order to project causes of death for all countries from 2020-2100. Under more optimistic SSP scenarios, noncommunicable diseases (NCDs) rise as a proportion of all deaths, particularly in low- and middle-income countries, while more pessimistic scenarios suggest a continued high burden of largely preventable communicable diseases. In high-income countries, continuing significant burdens of NCDs are projected for the remainder of the century under all SSPs. Comparisons are also made to recent cause-of-death projections from the Institute for Health Metrics and Evaluation to assess how the IFs and IHME models vary.

Introduction

In recent years, the literature linking global climate change and human health outcomes has developed rapidly. Climate change has a variety of adverse impacts on human health through multiple and complex pathways, including temperature extremes, droughts, impacts of natural disasters, infectious diseases, and undernutrition (Watts et al. 2018). A subset of this literature has focused on the mortality impacts of climate change, with various researchers modeling the projected effects of climate change on mortality through heat-related mechanisms (Hajat et al. 2014; Gasparrini et al. 2015) as well as the effects of natural disasters (Lutz et al. 2014b).

While there is uncertainty regarding the future impacts of climate change, making estimation of health impacts challenging, in general, health harms are likely to be greater at higher levels of warming (Ebi et al. 2018). Although there are numerous and highly visible impacts of climate change in high-income countries, the health effects of climate change will be felt most in low- and middle-income countries that have less capacity to respond to climate-related health hazards (Keim 2008). Factors associated with socioeconomic development, including educational attainment, health system quality, and GDP, are associated with health outcomes (Marmot 2005). In particular, socioeconomic development will have substantial effects on population age structures which in turn significantly affect mortality causes, as infants and children experience different levels of risk for a variety of mortality causes than middle-age adults and elderly populations (KC and Lutz 2017). Thus, both the effects of climate change as well as socioeconomic development characteristics will impact the rates and causes of mortality around the world during this century.

However, while many studies have looked at mortality impacts attributable to specific climate-related causes, less research has explored the aggregate impacts of climate change on mortality. Given growing global attention to the effects of climate change on mortality, it is important to understand how climate change is likely to shape the patterns of mortality worldwide, so that resources can be appropriately mustered and channeled to improve population health outcomes. While the direct effects of climate change on deaths associated with extreme temperatures, infectious disease, undernutrition, etc. often receive the bulk of attention in the climate and health literature, the most substantial effects of climate change are likely to be on shaping patterns of socioeconomic development and policy responses, which will turn have implications on the rates of all causes of mortality. This study aims to fill an important gap in the literature, providing regional estimates of causes of death for 15 cause groupings covering virtually every country under five distinct socioeconomic scenarios in a world with climate change.

Background

Demographic forecasts have been developed to project birth and death rates in order to generate future population compositions by age, sex, country, and most recently, by level of education, allowing for refined analyses of future demographic trends (Lutz and KC 2011; Gerland et al. 2014). Birth and death rates are influenced by myriad factors, including socioeconomic and development indicators. Regarding fertility, educational attainment, as well as access to family planning services, significantly affect desired and achieved fertility outcomes (Lutz and KC 2011; Bongaarts 2011). Additionally, socioeconomic inequalities are closely tied to disparities in health outcomes, including mortality (Marmot 2005). International migration is also affected by socioeconomic disparities, contributing to South-North migration flows (Castles 2013). Thus, socioeconomic indicators are increasingly used to improve and refine demographic forecasts (Lutz et al. 2014a).

Recent research has sought to add further detail to demographic forecasts, in particular, providing estimates of the causes of mortality. Changes in age structures will occur alongside changes in socioeconomic development and technology, which impact mortality rates and causes. Epidemiologists have found that in general, as development levels increase, the causes of mortality shift from communicable to noncommunicable diseases (NCDs), a process often referred to as the epidemiological transition (Orman 2005). This shift has an enormous impact on health systems in terms of what physical infrastructure, knowledge, and services are required in order to keep patients healthy.

While historical cause-of-death data are captured in local and national databases, collating these data across countries has been a considerable research challenge. In recent years, the Institute for Health Metrics and Evaluation (IHME) has made tremendous strides in doing this work through its Global Burden of Disease (GBD) study, most recently producing estimates for over 280 causes of death for every country from 1990-2017 (Roth et al. 2018). GBD has resulted in the centralization of a great deal of knowledge concerning specific risk factors and mortality outcomes, including distal drivers, such as education level or income, as well as proximate drivers, such as smoking or occupational heavy metal exposures (Stanaway et al. 2018). In recent years, GBD has extended its work to include forecasting, using dozens of proximate and distal drivers, although this work has yet to incorporate the effects of climate change (Foreman et al. 2018).

Climate change presents substantial challenges to health forecasting, given its potentially unprecedented effects on a variety of distal and proximate drivers of health, affecting the capacity of individuals and health systems to respond. However, very little research has explored the potential aggregate impacts of climate change on cause of death outcomes. A key exception is a 2014 study projecting impacts from six different causes of mortality: heat, coastal floods, diarrheal disease, malaria, dengue, and undernutrition, finding hundreds of thousands of excess deaths per year worldwide from these causes by the 2030 decade, with impacts worsening by the 2050 decade (Hales et al. 2014). Our study aims to provide cause of death estimates that incorporate the effects of climate change on socioeconomic development trajectories, providing guidance for policymakers and scholars seeking to understand the aggregate effects of climate change on all causes of mortality. In order to derive these estimates, we examined a series of socioeconomic scenarios nested within an integrated assessment model, International Futures (IFs). In addition, we compare these results to those recently obtained by IHME's new forecasting model to illustrate the similarities and differences between IFs and IHME's forecasts. A discussion of the scenarios used and the IFs and IHME models, follows.

Methods

The Shared Socioeconomic Pathways Framework

In recent years, scholars have made advances in scenario development around potential futures in a world where climate change will influence development paradigms. These scenarios can be used to help understand potential mortality trends resulting from these different trajectories. A major framework used to understand different socioeconomic and political responses in a world with climate change is the Shared Socioeconomic Pathways (SSPs). The five SSPs are qualitative narratives that represent different combinations of challenges to climate adaptation and mitigation, which affect socioeconomic development processes (O'Neill et al. 2017). Aspects of these narratives have also been quantitatively modeled, including urbanization (Jiang and O'Neill 2017), GDP (Dellink et al. 2017), and population (KC and Lutz 2017). The SSPs are the most up-to-date and widely used scenarios for understanding the effects of climate change, replacing those presented by the Special Report on Emissions Scenarios (IPCC 2000).

Briefly, SSP1 represents the most optimistic scenario, where challenges to adaptation and mitigation are low, resulting in global gains in socioeconomic development indicators and health system adaptation capacity. SSP3 represents the most pessimistic scenario, where challenges to adaptation and mitigation are high, resulting in considerable challenges to improving health services as a result of resource constraints and the impacts of climate-related disasters on economic growth. SSP2 represents an intermediate scenario between SSP1 and SSP3. SSP4 provides an interesting combination, where challenges to mitigation are low, but adaptation challenges are high, particularly in low- and middle-income countries, resulting in growing global socioeconomic inequality. SSP5 presents the opposite case—a world where adaptation to the effects of climate change is driven by fossil fuel use, resulting in less climate change mitigation, but continued economic growth and improvements in many socioeconomic indicators. Sellers and Ebi (2018) provide further detail on the differences between SSPs in terms of their assumptions and implications for health system responses.

Age structures are expected to change markedly between different SSPs, with SSP1 and SSP5 resulting in a steadily aging world population through lower fertility in low- and middle-income countries, but slightly higher fertility from current levels in many high-income countries. Thus, under these pathways, children as a share of the world's population will decline, while elderly populations will grow. By contrast, SSP3 and SSP4 represent scenarios where the global population will continue to grow substantially through relatively high fertility in low- and middle-income countries, resulting in large numbers of children vulnerable to premature death (KC and Lutz 2017).

By serving as a representation of sustainable development policies in a changing world, scenario modeling using the SSPs provides a platform upon which to understand future changes in mortality. Importantly, however, the SSPs do not specify particular emissions trajectories. In other research, SSPs are complemented by relative concentration pathways (RCPs), which model particular levels of radiative forcing (Van Vuuren et al. 2011). SSPs are designed to be used alone or in combination with the RCPs. For the analysis below, which is focused on socioeconomic responses to the challenges posed by climate change, RCPs are not used. However, previous literature notes that some SSPs and RCPs are incompatible with each other, suggesting that each SSP corresponds to a subset of potential radiative forcing levels (van Vuuren et al. 2014). In other words, some of the SSPs modeled below may not be achievable if emissions levels are too high (or too low).

The International Futures Integrated Assessment Model

To generate mortality estimates, we used the IFs integrated assessment model, which estimates a variety of socioeconomic, environmental, and development outcomes in future world states. IFs contains a health module enabling users to estimate specific mortality causes under different assumptions of socioeconomic development patterns, including those developed through the SSPs. The model allows users to incorporate the projections cited above for population, urbanization, and GDP to model the effect of each SSP on specific health outcomes. IFs is a proven tool in the health literature, and has been used in prior research to project health outcomes under different socioeconomic scenarios (Hughes et al. 2011).

The following description of the IFs health module summarizes a more extensive working paper that interested readers should consult (Hughes et al. 2014). In brief, IFs combines proximate and distal drivers of mortality outcomes in order to assign causes of death to particular age group-sex-country-year categories. Distal drivers include GDP per capita at PPP and years of adult education (among individuals age 25 and above), and in some cases, a measure of smoking impact lagged by 25 years. Proximate drivers include a variety of indicators of risk associated with particular mortality outcomes, such as calories per capita (for communicable diseases associated with undernutrition), indoor solid fuel use (for respiratory diseases), and body mass index (for cardiovascular disease and diabetes). While a general model using the two distal drivers is used to calculate mortality rates for most causes of death (prior to the addition of proximate causes), two causes of death (HIV/AIDS and road traffic deaths) are calculated using specialized submodels. IFs uses sex- and age group-specific coefficients adopted from earlier iterations of mortality projections using the GBD framework for each of the distal drivers in order to assign mortality causes to particular age group-sex-country-year categories (Mathers and Loncar 2006).

IFs generates projections for 15 causes of mortality divided into three cause groups for 1) communicable, maternal, perinatal, and nutritional diseases, 2) non-communicable diseases, and 3) injuries (Table 1). This categorization combines many of the less common causes found in the GBD, allowing for more robust estimates even in countries and age-sex groups where population sizes are low. Projected percentage changes in GDP, population, and educational attainment as projected in the aforementioned SSP research are utilized in the IFs model. These changes in turn affect the calculation of variables endogenous to IFs, which are used to project mortality outcomes. The results below summarize global mortality outcomes under the five SSP scenarios as projected in IFs. Model results are presented at the global level and by region, with countries organized into seven regions, six based on geography, and a single region representing all high-income countries as of 2019 (SI Table 1). These regional groupings were selected to match those used by Hughes et al. (2011).

IHME Forecasts

IHME recently published cause-of-death forecasts through the year 2040; further details about their modeling procedures can be found in the referenced publication (Foreman et al. 2018). We downloaded IHME's point estimates on individual causes of death at year 2040 and compared them to results found in IFs using the SSPs for 2040. Because IHME's forecasts provide estimates for 250 causes of death, each cause was grouped into one of the 15 categories modeled by IFs by matching the ICD-10 codes provided by IHME with those used by Mathers and Loncar (2006) (and adopted by IFs) to facilitate comparability across models. IHME has not made age group- and sex-specific mortality data publicly available, so these are not shown below.

In addition to a reference forecast, IHME generated two scenario forecasts by making different assumptions of the rates of change of distal and proximate predictors of mortality outcomes used in their model. A better health forecast was generated using the 85th percentile of the rate of change from 1990-2016 of predictors used in their model, while a worse health forecast used the 15th percentile of these rates. These scenarios are somewhat analogous to the SSPs, insofar as the SSPs make more or less optimistic assumptions regarding the trajectories of distal and proximate drivers of mortality outcomes. However, unlike the SSPs, the IHME better/worse health scenarios were not developed using any assumptions or narratives regarding the effects of climate change on socioeconomic development.

Results

IFs projects an increase in global mortality in the coming decades, with deaths rising in SSP3 from 67.4 million in 2020 to 109.6 million in 2050, and 146.4 million by 2100. By contrast, overall mortality is expected to rise much more slowly under SSP1 and SSP5, largely because of slower overall population growth as well as longer life expectancies under these pathways. These scenarios are virtually indistinguishable in terms of overall mortality trajectories, with mortality expected to rise from 61.2 million in 2020 to 77.2-77.5 million in 2050, and 104.7-104.9 million by 2100 (Figure 1).

Globally, mortality is expected to remain heavily concentrated in noncommunicable causes of death. However, under SSP3 and SSP4, communicable diseases and injuries will comprise a greater fraction of mortality than under more optimistic scenarios (Figures 2a-2c). Communicable diseases are expected to fall in absolute terms under all SSPs by 2100 (albeit at varying rates), while injury deaths will increase, even under the most optimistic SSPs, largely a reflection of growing automobile use.

The following discussion of mortality in IFs largely centers on five of the 15 causes: cardiovascular disease, diarrheal disease, chronic respiratory disease, cancer, and traffic accidents. These causes were selected because of their high or growing incidence (in the cases of cardiovascular disease and cancer), their linkages with environmental conditions (in the cases of diarrheal and chronic respiratory diseases), or their linkages with socioeconomic development (in the case of traffic accidents). Fraction of overall mortality, rather than absolute number of deaths is used in order to more easily compare the relative burdens of different causes across scenarios and models. The years 2030, 2050, and 2080 are used as markers to illustrate how burdens will change over time. Subsequent to this discussion, IFs data are compared to IHME projections, which are for the year 2040.

Figures 3a-3o display the proportion of all mortality attributable to each cause group by world region/SSP for years 2030, 2050, and 2080. While NCDs will continue to constitute the vast majority of mortality worldwide, patterns will vary by region. In particular, Sub-Saharan Africa will continue to have a disproportionately high burden of communicable diseases into the future, particularly under more pessimistic SSPs. By contrast, the patterns in the Latin America & Caribbean, East Asia & Pacific, and Middle East & North Africa regions appear much more similar to those projected for high-income countries, with relatively low burdens of communicable diseases.

Figures 4a-4o display mortality by individual cause category broken down by world region and SSP for years 2030, 2050, and 2080. Cardiovascular disease is the leading cause of death worldwide, and will constitute over 50% of all deaths in Europe & Central Asia and roughly 40% in the Middle East & North Africa under all SSPs by 2030 (Figure 4a). By contrast, cardiovascular disease will constitute between 13.6% (SSP4) and 21.0% (SSP5) of mortality in that year in sub-Saharan Africa. In future decades, cardiovascular disease burdens will decrease in most world regions as other NCDs become increasingly large causes of mortality. The notable exception is in sub-Saharan Africa, where, due to longer life expectancies and a faster reduction of communicable diseases in more optimistic SSPs, cardiovascular mortality is expected to rise as a share of all mortality by 2050, before falling again by 2080.

Diarrheal disease mortality is heavily concentrated in South Asia and sub-Saharan Africa, and will represent up to 6.5% of all mortality in the latter region in 2030, although deaths from diarrheal diseases as a share of all mortality are expected to fall by the end of the century (Figure 4d). However, the diarrheal model in IFs is sensitive to age structure, acknowledging the fact that diarrheal diseases disproportionately affect the very young and very old. Thus, by 2080, the more optimistic SSPs, SSP1 and SSP5, are actually projected to have a greater share of mortality attributable to diarrheal disease than under SSP2 or SSP3 in part because the age structure under the former scenarios will be older than under the latter.

Chronic respiratory mortality is heavily concentrated in South Asia and East Asia & Pacific, with over 10% of mortality in both regions attributable to chronic respiratory diseases under all SSPs by 2030. These conditions are significantly affected by ambient air pollution concentrations. In future decades, despite increased implementation of pollution controls, GDP growth and aging populations are likely to result in an increased burden associated with chronic respiratory diseases, particularly in these two regions, and particularly under SSP1 and SSP5 which forecast higher rates of economic growth than other SSPs.

Cancer deaths as a proportion of all mortality will remain relatively steady throughout most world regions, with the exception of sub-Saharan Africa, where such deaths are projected to rise from 9.3-12.8%

of deaths in 2030 to between 16.3-26.3% by 2080. Slower growth will occur in South Asia, where as many as 14.7% of deaths may be attributable to cancer by 2080 under SSP5.

Traffic accident deaths are responsible for a substantial proportion of fatalities from injuries (including, as of 2015, a majority of injury fatalities in the Middle East and North Africa), representing a significant public health challenge. Figure 4m displays projected traffic accident fatalities as a share of mortality in 2030, with accidents representing slightly less than 7% of all deaths in the Middle East and North Africa under all SSPs. Projections for sub-Saharan Africa, which under SSP1 and SSP5 depict proportions similar to that of the MENA region, are sensitive to GDP and growth in vehicles per capita, which are expected to be higher under those SSPs. By contrast, proportions are low in North America and Europe, where motor vehicle infrastructure and safety standards are generally improved. In future decades the share of deaths attributable to traffic accidents is expected to skyrocket in sub-Saharan Africa, due to projected increased vehicle use.

We now turn to comparing findings from IFs with those from the recent IHME projections (Figures 5a-5e). Predicted cardiovascular mortality (Figure 5a) is relatively similar across both models, particularly for central projections. For instance, in the region where cardiovascular disease is most prevalent, Europe & Central Asia, SSP2 projects roughly 50.4% of deaths will be attributable to cardiovascular disease in 2040, whereas under the IHME reference projection, 50.3% of deaths in the region will be attributable to cardiovascular disease that year. When the more pessimistic/optimistic scenarios are explored, the gap between the IFs and IHME projections grows. In the same region, under SSP3, 51.1% of deaths are projected due to cardiovascular disease versus 53.6% of deaths under the IHME worse health projection. Broadly similar patterns exist when examining Figure 5d on cancer mortality.

More substantial differences between the models exist for the three other causes of death highlighted. In Figure 5b, South Asia and Sub-Saharan Africa are notable in both models for having elevated shares of mortality for diarrheal disease, even under more optimistic health scenarios. However, the mortality fractions associated with diarrheal disease vary between the models, with IHME being more pessimistic. For instance, in South Asia, IHME's reference projection estimates 4.7% of deaths would be attributable to diarrheal disease in 2040, while the worse health projection estimates 7.2% of deaths attributable to diarrheal disease in the same year. These estimates equate to roughly 792,000 and 1.58 million deaths respectively. By contrast, IFs estimates 4.3% of deaths (roughly 752,000) will be attributable to diarrheal disease under SSP2 in 2040 in South Asia, whereas under SSP4 (the most pessimistic SSP for diarrheal disease), roughly 5.6% (1.15 million deaths) will be attributable to diarrheal disease, a difference of over 400,000 deaths from IHME's model. A disparity also exists between the two models in sub-Saharan Africa, where IHME's reference and worse health projections are much more closely aligned, though it is less stark than in South Asia. These disparities suggest that the more pessimistic scenarios in the two models make differing assumptions for water and sanitation access in many low- and middle-income countries, a key driver of diarrheal disease mortality.

Figure 5c shows differences for chronic respiratory disease, where IFs projects higher proportions and numbers of deaths in the East Asia & Pacific and South Asia regions than IHME. These differences are likely related to differing assumptions about the relationship between GDP growth and air pollution, as well as the effect of air pollution concentrations on mortality outcomes.

Figure 5e reflects the challenges noted above in modeling traffic accident fatalities, with IFs projecting substantially higher fractions and totals of traffic fatalities than IHME. The difference between the models is most clearly seen in sub-Saharan Africa, where there is considerable uncertainty about future vehicle fleet size and where vehicle use has increased substantially in recent decades. Under SSP5, IFs projects in 2040, roughly 10.8% of deaths in sub-Saharan Africa will be attributable to traffic accidents, whereas under IHME's better health scenario, only 3.1% of deaths in the region will be from traffic accidents. There is an important commonality between both models, namely that traffic fatalities as a share of mortality tend to be higher in sub-Saharan Africa under more optimistic scenarios, a reflection of the high burdens of communicable diseases in the region that are unlikely to be reduced in more pessimistic scenarios, lowering the proportion of deaths from traffic accidents.

Finally, we briefly turn to mortality by age group, with a focus on child mortality. As these data are not currently publicly available from IHME, only IFs is discussed here. Young children are especially vulnerable to communicable diseases, though this is particularly true in settings with limited health care capacity. However, the vulnerability of children to communicable diseases will vary considerably throughout the remainder of the century depending on socioeconomic development patterns. In 2030, over seven in ten deaths of children age 0-4 in South Asia and sub-Saharan Africa are projected to be from communicable diseases, under all SSPs (Figure 6a), and this remains true under SSP3 and SSP4 at 2050 (Figure 6c). By 2080, there is greater divergence between the SSPs, where less than 50% of deaths in children age 0-4 in sub-Saharan Africa will result from communicable causes under SSPs 1, 2, and 5, while more than 60% of deaths in that region are projected to be from communicable causes under SSPs 3 and 4 (Figure 6e). In high-income countries, over 40% of deaths in children age 0-4 under all SSPs will be attributable to communicable causes in 2030, though this falls slowly but steadily over the century. As children age, communicable diseases are less significant drivers of the mortality burden. However, there is considerable uncertainty about future burdens, particularly in sub-Saharan Africa, where under SSP3 and SSP4, more than one in four deaths of children age 5-14 will result from communicable causes (Figure 6d) in 2050. Importantly, while the figures shown display share of mortality, the absolute numbers of deaths will vary significantly across SSPs. For instance, in South Asia, 1.30 million children age 0-4 are projected to die (of any cause) under SSP3 in 2050, whereas under SSP5, this number falls to 162,000, a profound example of the divergent mortality outcomes implied by the SSP trajectories.

Discussion

Mortality outcomes in the 21st century may take a wide range of forms depending on the trajectories of climate change impacts and socioeconomic development and the relationship between these trends with health care delivery and risk factors. Understanding possible mortality burdens in future decades can facilitate the efficient allocation of health care resources to treat the greatest population health risks. The substantial variation in death estimates, particularly for communicable diseases, suggests that strong public health efforts to reduce exposure to risk factors and improve health care delivery in low- and middle-income countries can change mortality trajectories, in particular, reducing the burden of communicable disease on young children. This is particularly necessary in sub-Saharan Africa and South Asia, where communicable disease burdens are substantial under more pessimistic SSPs, even towards the end of the century. Additionally, the substantial health burdens attributable to pollution in these regions, most clearly seen in the relationship between ambient air pollution and chronic respiratory diseases, should motivate a stronger focus on reducing pollution loads (Landrigan et al. 2018).

Demographic changes, in particular, aging populations, will likely affect continued vulnerability to communicable diseases. As noted above, IFs projections suggest elevated rates of death from diarrheal diseases under SSP1 and SSP5 in South Asia and sub-Saharan Africa in 2080, reflecting the heightened vulnerability of elderly populations to these diseases. Increased rates of growth in access to safe water and sanitation, beyond those calculated under SSP1 and SSP5 will likely be needed in order to attenuate the relationship between population aging and diarrheal disease mortality.

By contrast, high-income countries have largely completed the epidemiological transition and are projected to have relatively low burdens of communicable diseases and injuries for the remainder of the century, even under more pessimistic SSPs. This reflects both advancements in health service delivery as well as the greater resources at the disposal of high-income countries to adapt to the health effects of climate change. Even as populations age, high levels of development will insulate countries from significant growth in communicable disease burdens.

Comparing the results of IFs and IHME projections in year 2040 found more similarities than differences across models. In particular, the trends outlined above with reference to the NCD burdens in high-income countries and continued communicable disease burdens in low- and middle-income countries were common across both models, although slight variation in the levels of burdens were found, reflecting different assumptions about population structure and risk-outcome relationships.

The biggest area of divergence between the models was found when modeling traffic accident mortality, where there were substantial differences, particularly in sub-Saharan Africa. This divergence suggests advances are needed with regard to modeling mortality from traffic accidents, which is a key area of uncertainty due to both data limitations on vehicle numbers and road safety in low- and middle-income countries, as well as in future vehicle safety technologies that may reduce fatalities. In this instance, divergent findings were likely due in part to different procedures and assumptions between the two models in calculating the number of vehicles per capita, which is an essential element of both traffic accident models. IFs estimates number of vehicles per capita using formulas generated by Dargay et al. (2007), based on 1960-2002 vehicle data from 45 mostly high-income countries, and then estimating the number of fatalities using this fleet size estimate along with population estimates. IHME estimates this value using a weighted annualized rate of change model using estimated vehicle data from 1990-2016 (Foreman et al. 2018 Supplementary Appendix 1). As the time series of vehicle data used in each model varies, it is understandable that mortality estimates vary as well.

Generating mortality estimates in a world with climate change will continue to be a challenging exercise for the foreseeable future due to the tremendous uncertainty future decades hold. On the one hand, the development of new cures or treatments for leading causes of death such as AIDS may result in longer life expectancies than currently projected and reduced (or eliminated) mortality burdens from specific causes. Moreover, a reduction in exposure to major risk factors, such as air pollution or contaminated water supplies, may allow low- and middle-income countries to proceed through the epidemiological transition more rapidly than projected. On the other hand, stronger-than-predicted impacts climate change on mortality, particularly in vulnerable regions, may result in shorter life expectancies and less rapid improvement in health outcomes than predicted. Given continued difficulty in mustering global action to mitigate climate change, as well as the lack of financial and human capital in low- and middle-income countries for adaptation activities, SSP3 is looking like an increasingly probable trajectory for much of the world, an extremely troubling development for population health outcomes.

As socioeconomic and health data become more widely available and more accurate around the world, continued iteration of these projections and model refinement based on the most recent trends is essential. Moreover, as the effects of climate change become clearer, iterative scenario development, including for the SSPs, will be necessary in order to more accurately reflect the range of possible health outcomes in future decades. For the demography community, a more comprehensive exploration of the relationship between diminished health states and population change is likely to be a key area of research in the coming years that can advance scenario modeling. Much as scholars have relatively recently developed demographic data sets disaggregated by educational attainment, setting a goal of developing similar data sets disaggregated by health status is likely to provide useful insights into population health outcomes, and improve predictions regarding causes of death.

References

Bongaarts J (2011) Can family planning programs reduce high desired family size in Sub-Saharan Africa? Int Perspect Sex Reprod Health 37:209–16. doi: 10.1363/3720911

Castles S (2013) The Forces Driving Global Migration. Journal of Intercultural Studies 34:122–140. doi: 10.1080/07256868.2013.781916

Dargay J, Gately D, Sommer M (2007) Vehicle Ownership and Income Growth, Worldwide: 1960-2030. The Energy Journal 28:143–170

Dellink R, Chateau J, Lanzi E, Magné B (2017) Long-term economic growth projections in the Shared Socioeconomic Pathways. Global Environmental Change 42:200–214. doi: 10.1016/j.gloenvcha.2015.06.004

Ebi KL, Hasegawa T, Hayes K, et al (2018) Health risks of warming of 1.5° C, 2° C, and higher, above pre-industrial temperatures. Environmental Research Letters 13:063007

Foreman KJ, Marquez N, Dolgert A, et al (2018) Forecasting life expectancy, years of life lost, and all-cause and cause-specific mortality for 250 causes of death: reference and alternative scenarios for 2016–40 for 195 countries and territories. The Lancet 392:2052–2090

Gasparrini A, Guo Y, Hashizume M, et al (2015) Mortality risk attributable to high and low ambient temperature: a multicountry observational study. The Lancet 386:369–375

Gerland P, Raftery AE, Ševčíková H, et al (2014) World population stabilization unlikely this century. Science 346:234. doi: 10.1126/science.1257469

Hajat S, Vardoulakis S, Heaviside C, Eggen B (2014) Climate change effects on human health: projections of temperature-related mortality for the UK during the 2020s, 2050s and 2080s. J Epidemiol Community Health 68:641–648

Hales S, Kovats S, Lloyd SJ, Campbell-Lendrum D (2014) Quantitative risk assessment of the effects of climate change on selected causes of death, 2030s and 2050s. WHO Press, Geneva

Hughes B, Kuhn R, Peterson CM, et al (2011) Projections of global health outcomes from 2005 to 2060 using the International Futures integrated forecasting model. Bulletin of the World Health Organization 89:478–486

Hughes B, Peterson CM, Rothman DS, Solorzano JR (2014) IFs Health Model Documentation. Pardee Center for International Futures, Denver

IPCC (2000) Special Report on Emissions Scenarios. Cambridge University Press, Cambridge

Jiang L, O'Neill BC (2017) Global urbanization projections for the Shared Socioeconomic Pathways. Global Environmental Change 42:193–199. doi: 10.1016/j.gloenvcha.2015.03.008

KC S, Lutz W (2017) The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100. Global Environmental Change 42:181–192. doi: 10.1016/j.gloenvcha.2014.06.004

Keim ME (2008) Building human resilience: the role of public health preparedness and response as an adaptation to climate change. American Journal of Preventive Medicine 35:508–516

Landrigan PJ, Fuller R, Acosta NJR, et al (2018) The Lancet Commission on pollution and health. The Lancet 391:462–512. doi: 10.1016/S0140-6736(17)32345-0

Lutz W, Butz WP, KC S (eds) (2014a) World Population and Human Capital in the Twenty-First Century. Oxford University Press, Oxford, UK

Lutz W, KC S (2011) World Population and Human Capital in the Twenty-First Century. Science 333:587–592. doi: 10.1126/science.1206964

Lutz W, Muttarak R, Striessnig E (2014b) Universal education is key to enhanced climate adaptation. Science 346:1061–1062

Marmot M (2005) Social determinants of health inequalities. The Lancet 365:1099–1104. doi: 10.1016/S0140-6736(05)71146-6

Mathers CD, Loncar D (2006) Projections of global mortality and burden of disease from 2002 to 2030. PLoS Medicine 3:e442

O'Neill BC, Kriegler E, Ebi KL, et al (2017) The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. Global Environmental Change 42:169–180. doi: 10.1016/j.gloenvcha.2015.01.004

Orman AR (2005) The Epidemiologic Transition: A Theory of the Epidemiology of Population Change. The Milbank Quarterly 83:731–757. doi: 10.1111/j.1468-0009.2005.00398.x

Roth GA, Abate D, Abate KH, et al (2018) Global, regional, and national age-sex-specific mortality for 282 causes of death in 195 countries and territories, 1980–2017: a systematic analysis for the Global Burden of Disease Study 2017. The Lancet 392:1736–1788. doi: 10.1016/S0140-6736(18)32203-7

Sellers S, Ebi KL (2018) Climate change and health under the Shared Socioeconomic Pathway framework. International Journal of Environmental Research and Public Health 15:3

Stanaway JD, Afshin A, Gakidou E, et al (2018) Global, regional, and national comparative risk assessment of 84 behavioural, environmental and occupational, and metabolic risks or clusters of risks for 195 countries and territories, 1990–2017: a systematic analysis for the Global Burden of Disease Study 2017. The Lancet 392:1923–1994. doi: 10.1016/S0140-6736(18)32225-6

Van Vuuren DP, Edmonds J, Kainuma M, et al (2011) The representative concentration pathways: an overview. Climatic change 109:5–31

van Vuuren DP, Kriegler E, O'Neill BC, et al (2014) A new scenario framework for Climate Change Research: scenario matrix architecture. Climatic Change 122:373–386. doi: 10.1007/s10584-013-0906-1

Watts N, Amann M, Arnell N, et al (2018) The 2018 report of the Lancet Countdown on health and climate change: shaping the health of nations for centuries to come. The Lancet 392:2479–2514. doi: 10.1016/S0140-6736(18)32594-7

Tables

Table 1 List of IFs causes of death by cause group

Group I Causes (Communicable Diseases)	**Group II Causes (Non-Communicable Diseases)**	**Group III Causes (Injuries)**
Diarrheal diseases	Malignant neoplasms	Road traffic accidents
Malaria	Cardiovascular diseases	Other unintentional injuries
Respiratory infections	Digestive diseases	Intentional injuries
HIV/AIDS	Chronic respiratory diseases	
Other Group I causes	Diabetes	
	Mental health	
	Other Group II causes	

Figures

Figure 1 Global mortality trajectories under each SSP using IFs, 2020-2100

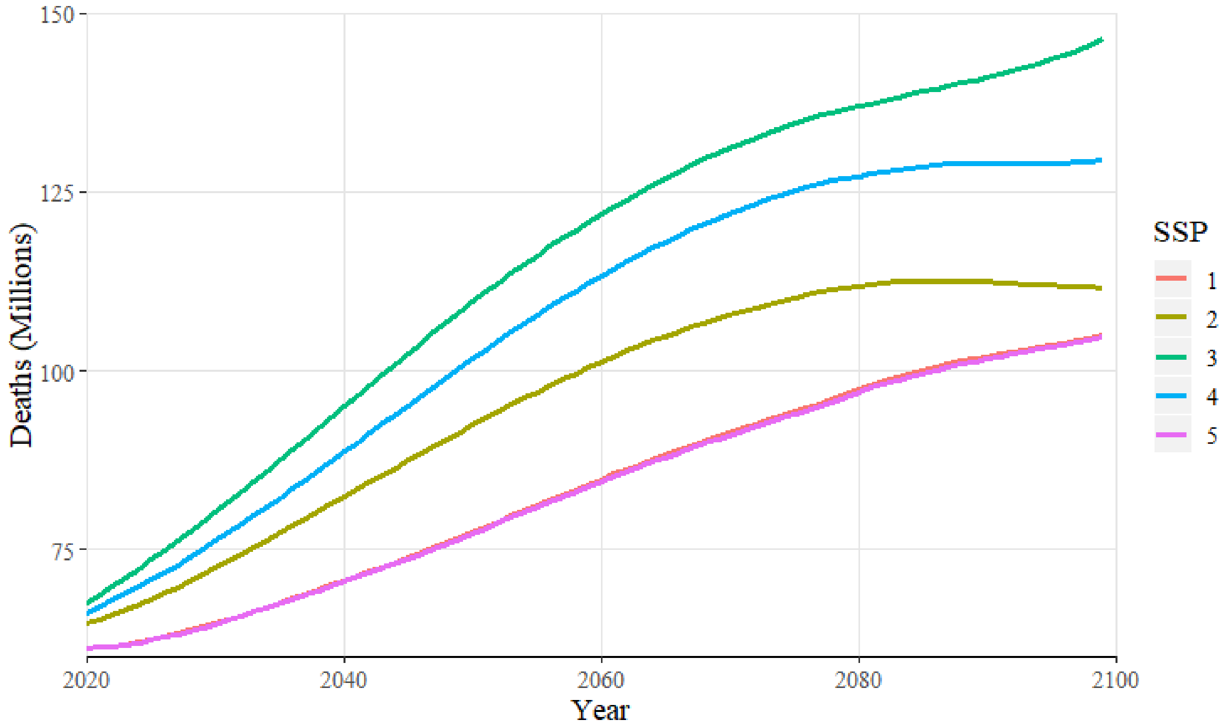


Figure 2a Global communicable deaths by SSP, 2020-2100

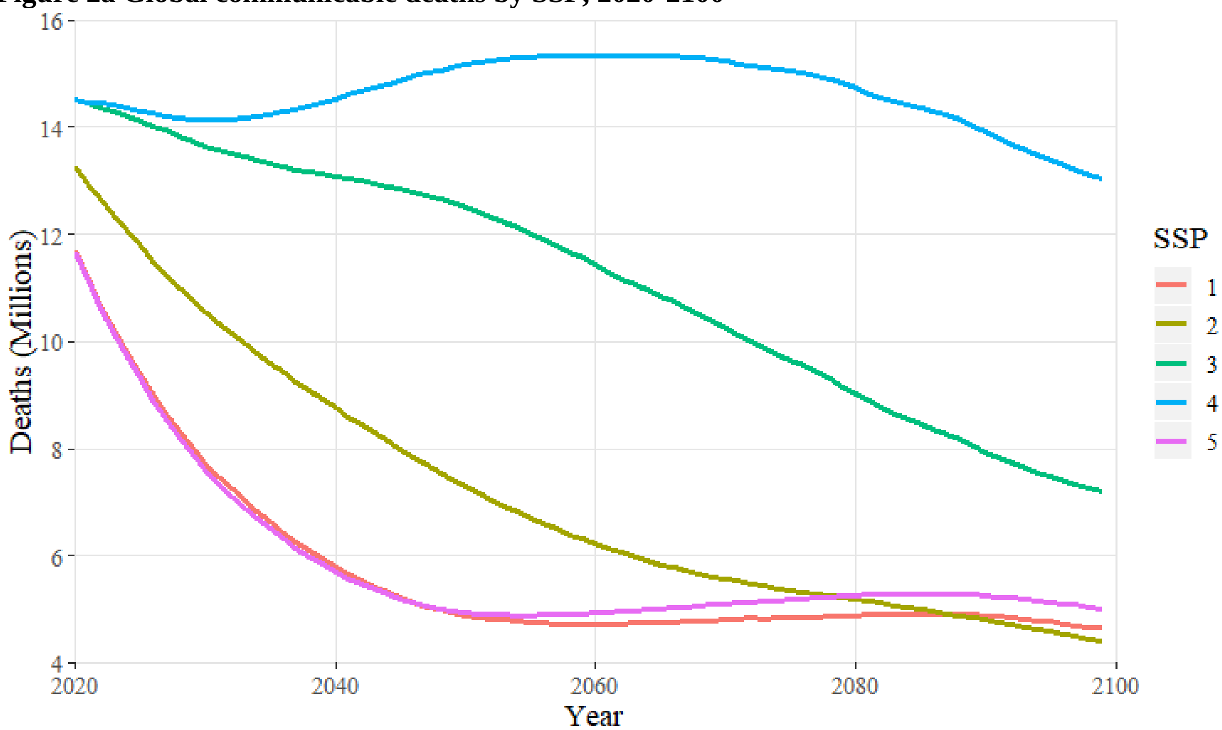


Figure 2b Global noncommunicable deaths by SSP, 2020-2100

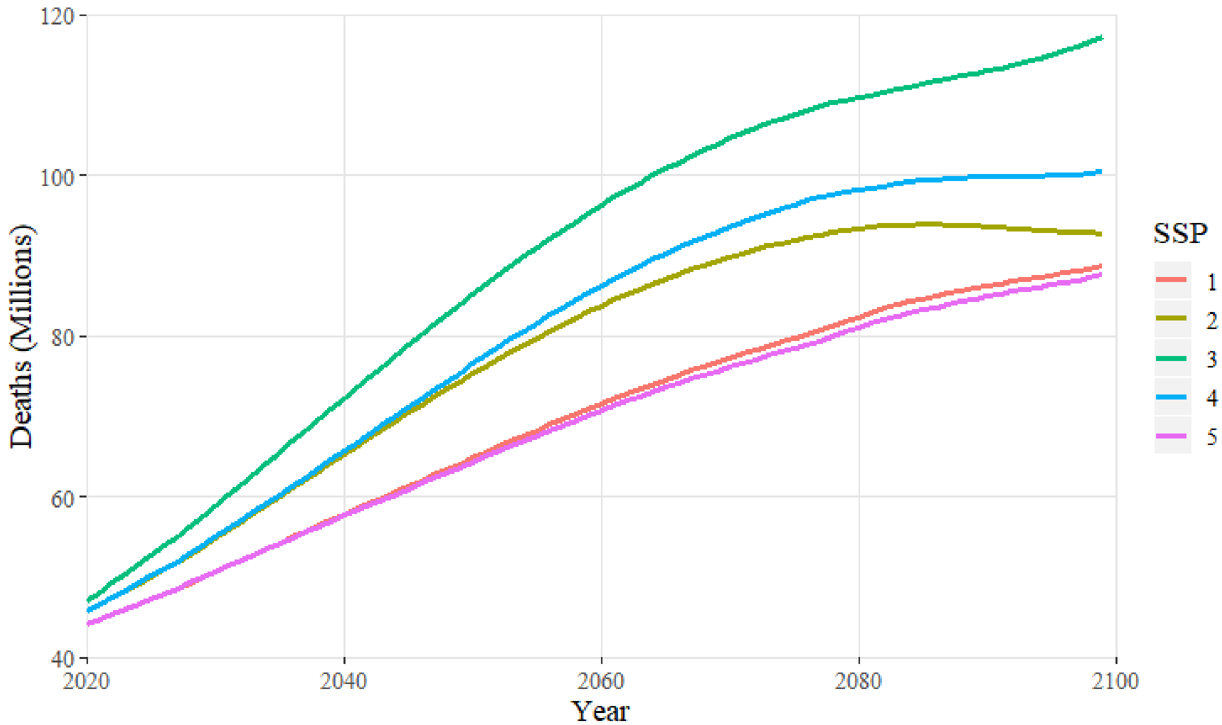


Figure 2c Global injury deaths by SSP, 2020-2100

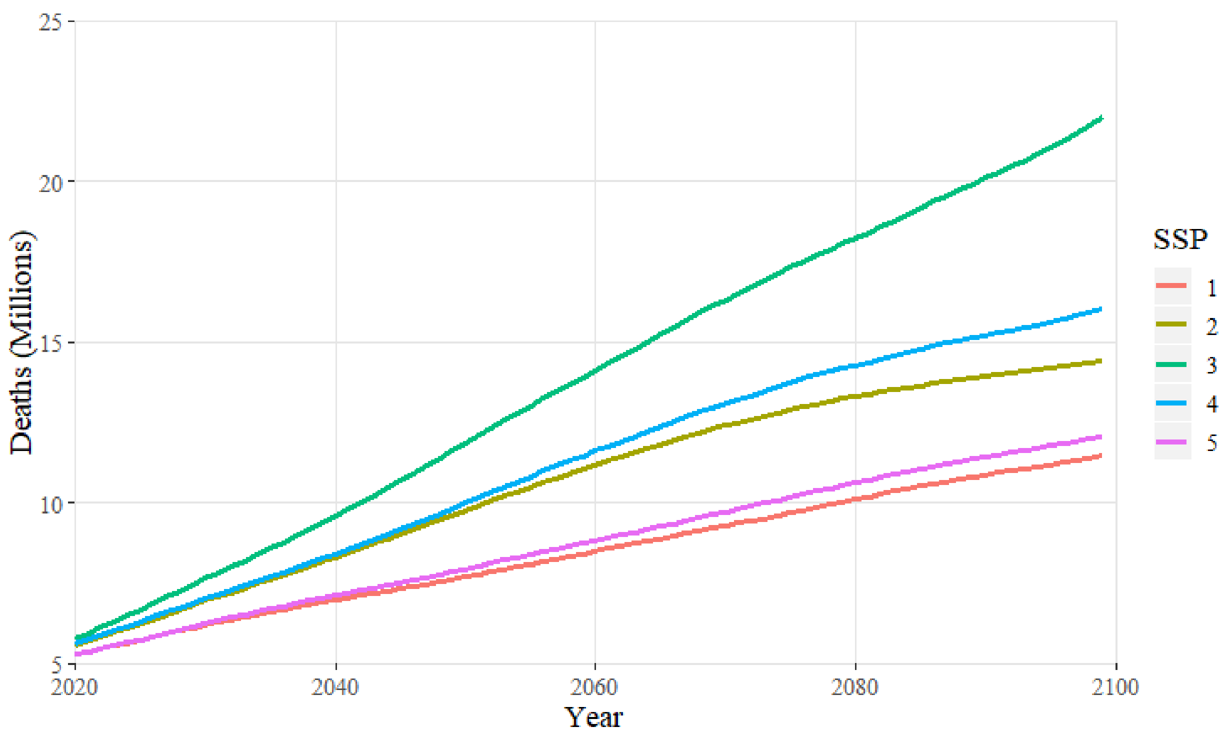


Figure 3a Mortality fraction by cause group & region, SSP1, 2030

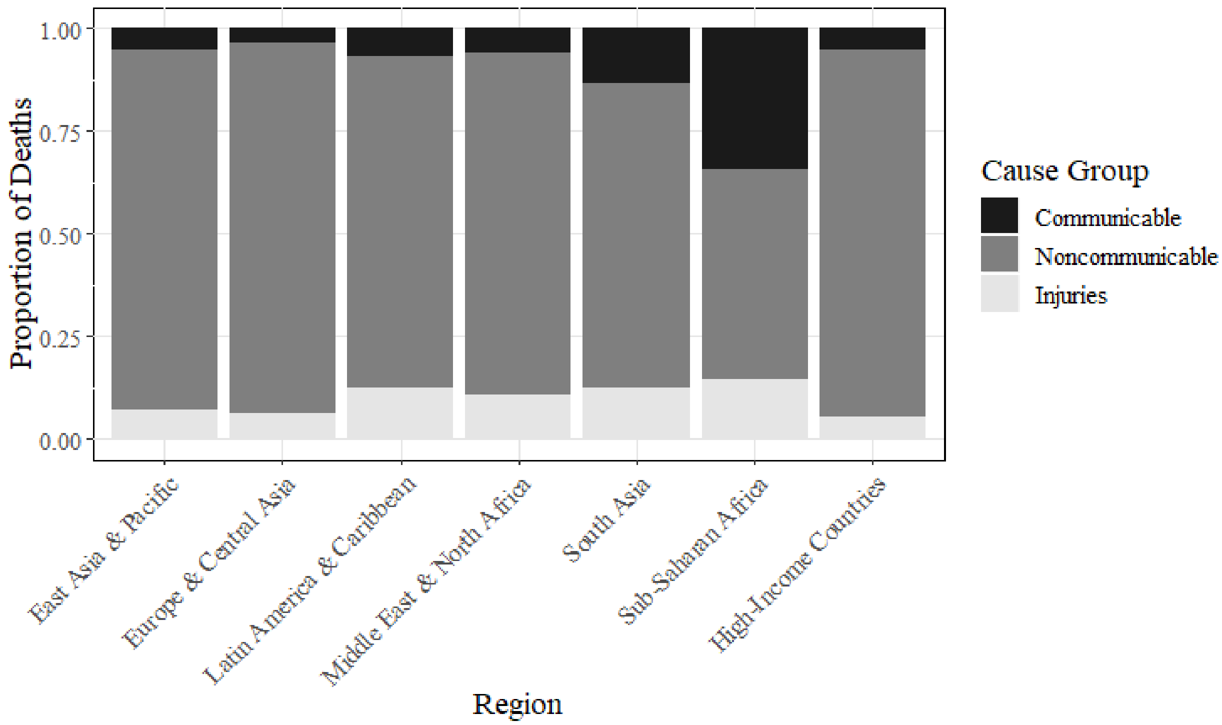


Figure 3b Mortality fraction by cause group & region, SSP2, 2030

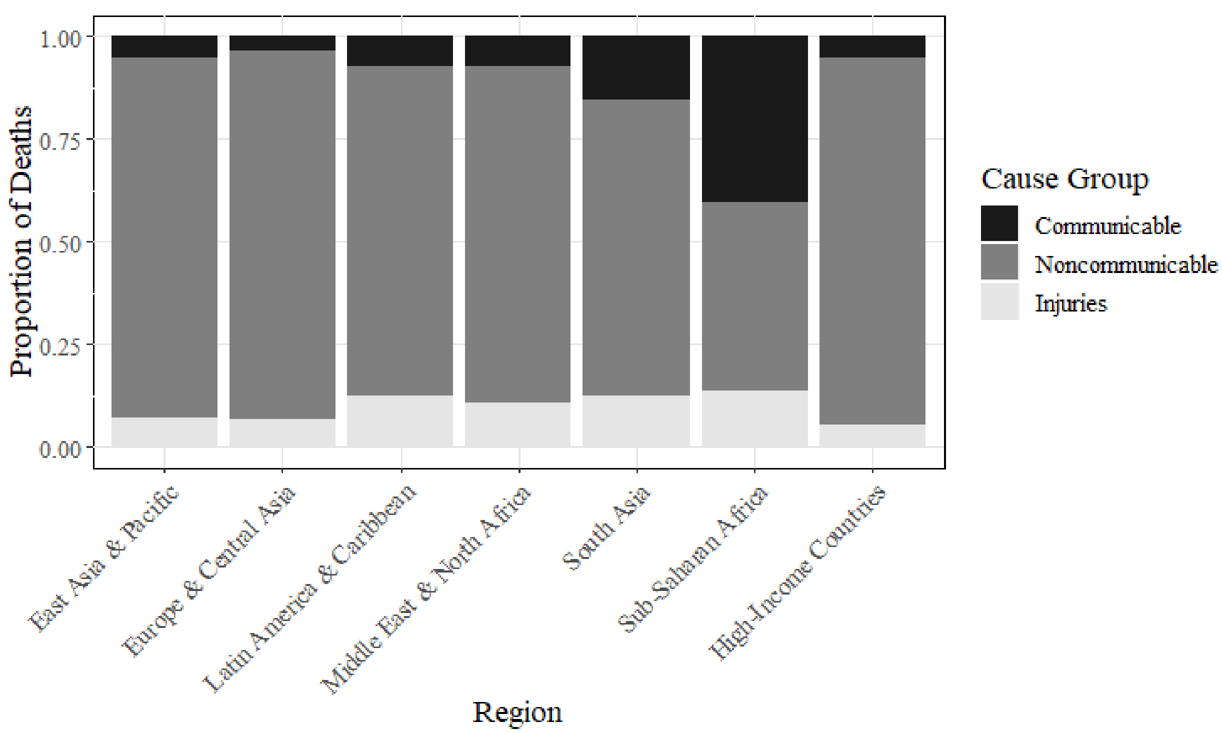


Figure 3c Mortality fraction by cause group & region, SSP3, 2030

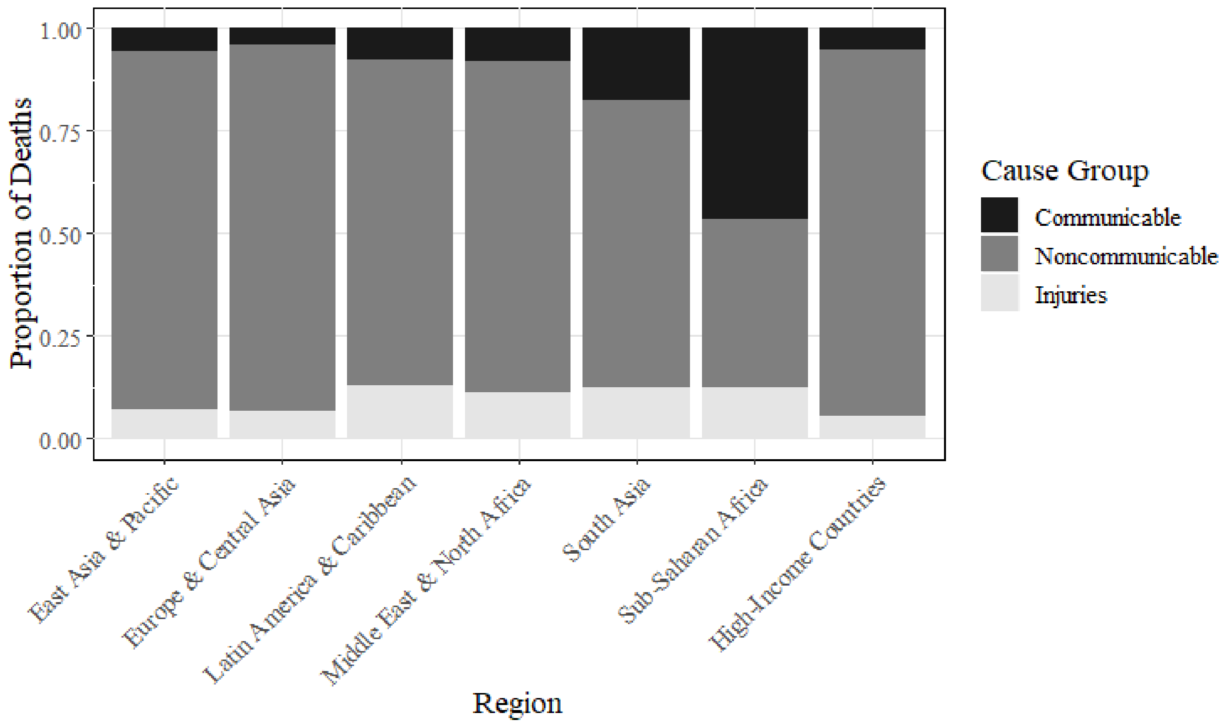


Figure 3d Mortality fraction by cause group & region, SSP4, 2030

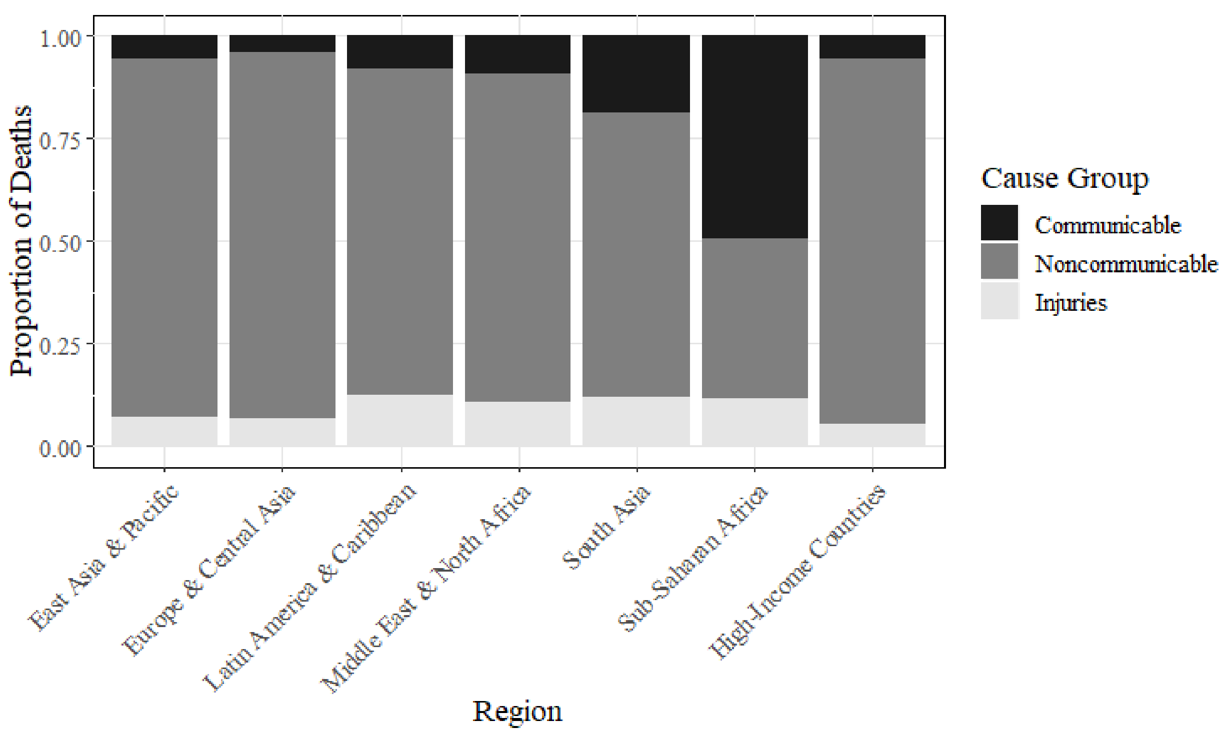


Figure 3e Mortality fraction by cause group & region, SSP5, 2030

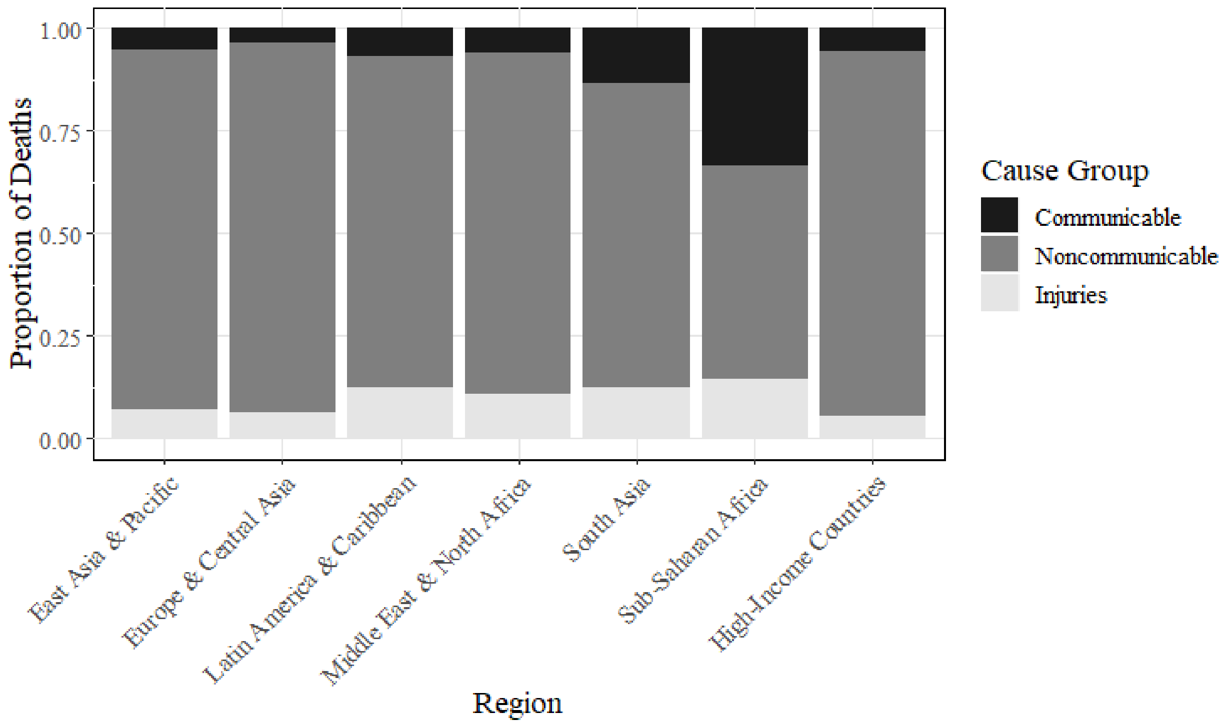


Figure 3f Mortality fraction by cause group & region, SSP1, 2050

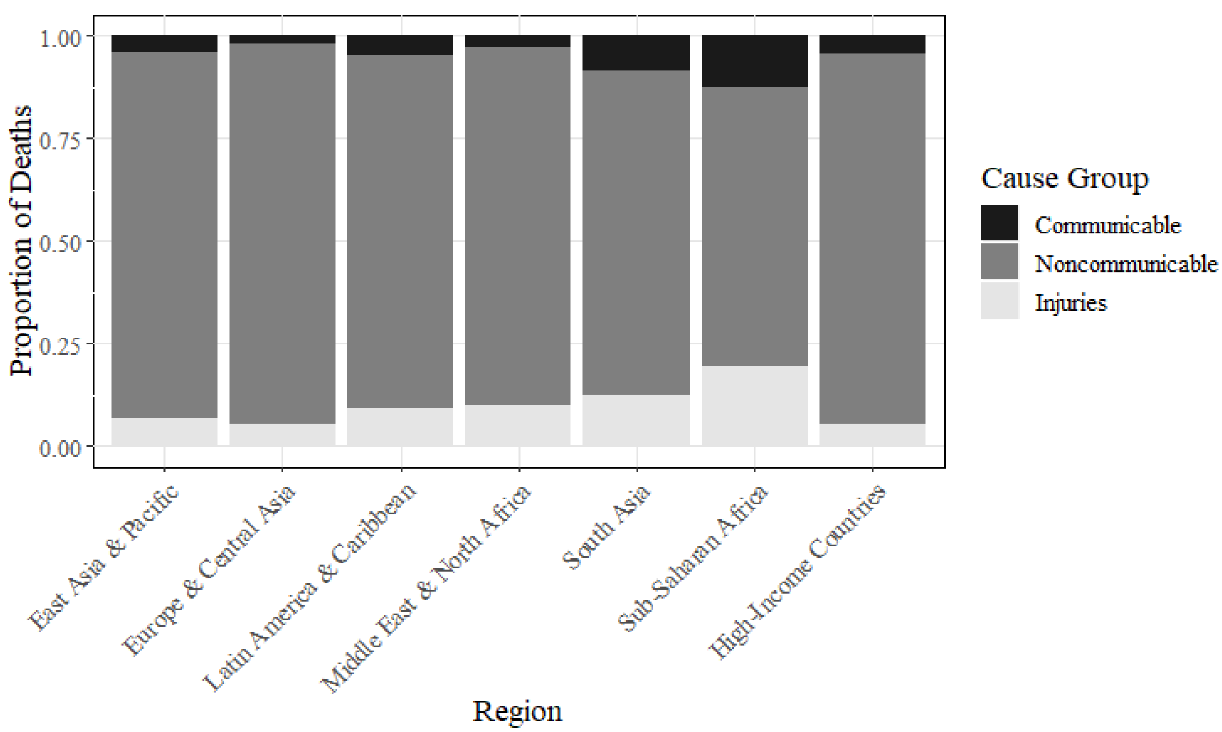


Figure 3g Mortality fraction by cause group & region, SSP2, 2050

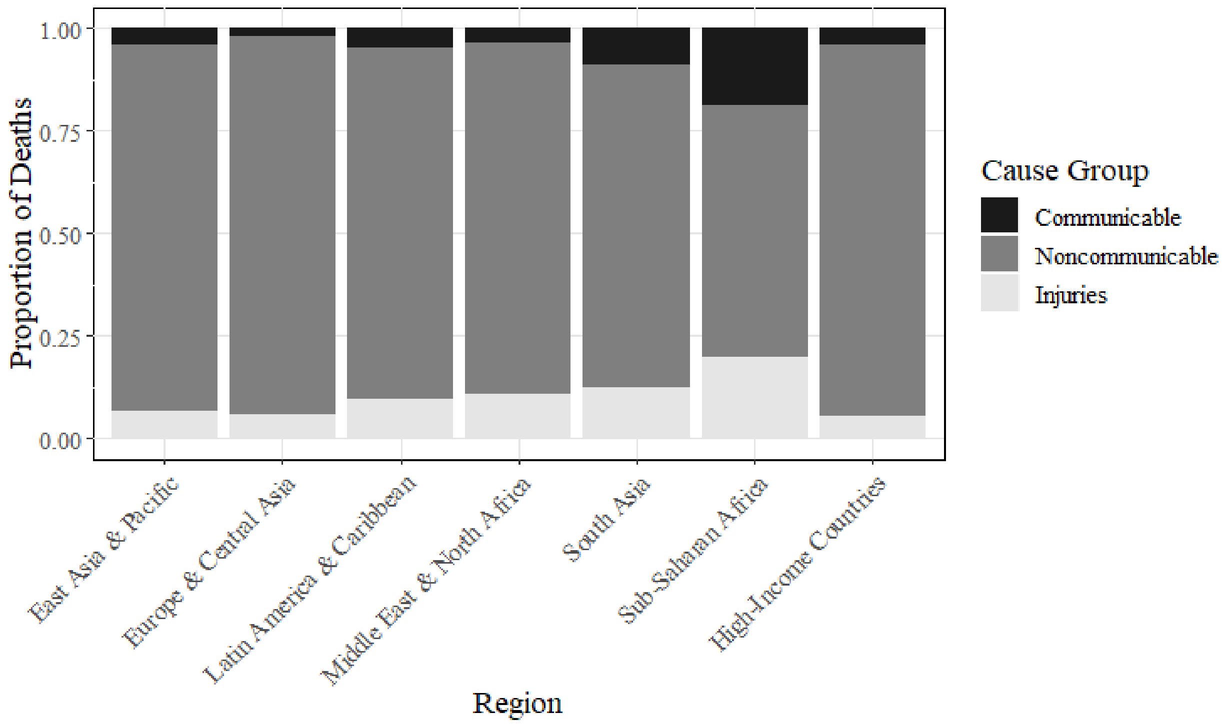


Figure 3h Mortality fraction by cause group & region, SSP3, 2050

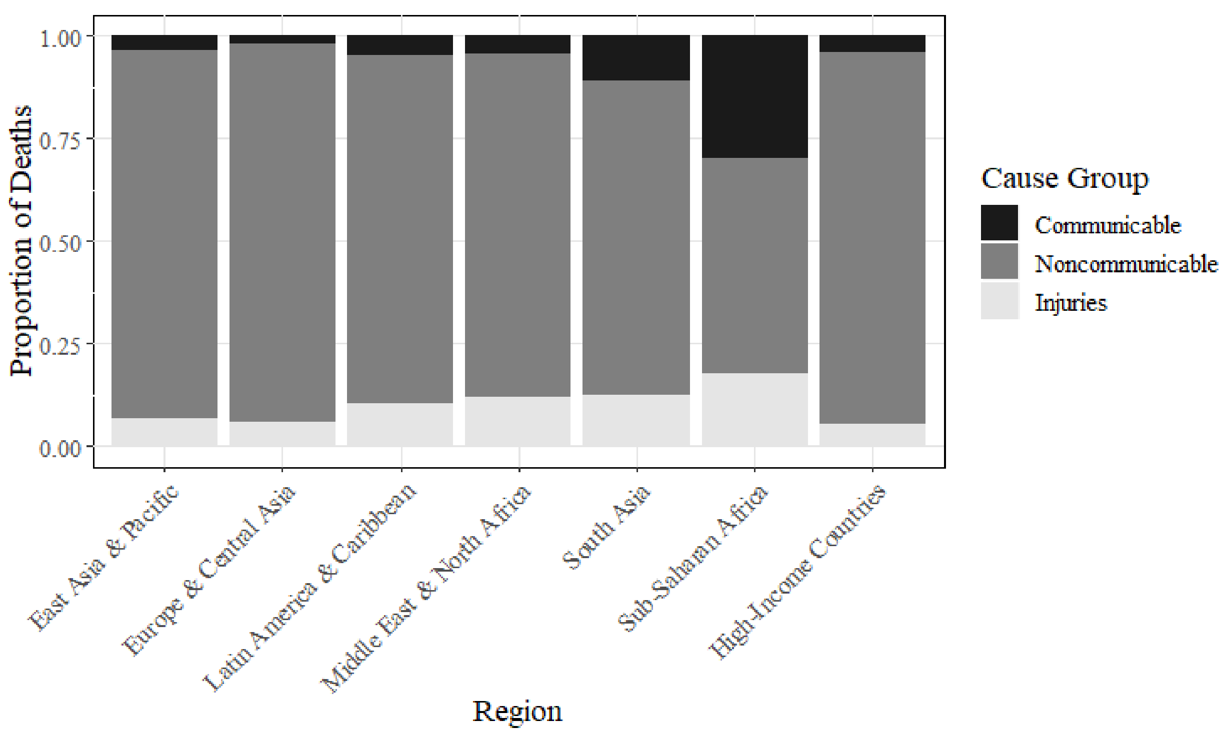


Figure 3i Mortality fraction by cause group & region, SSP4, 2050

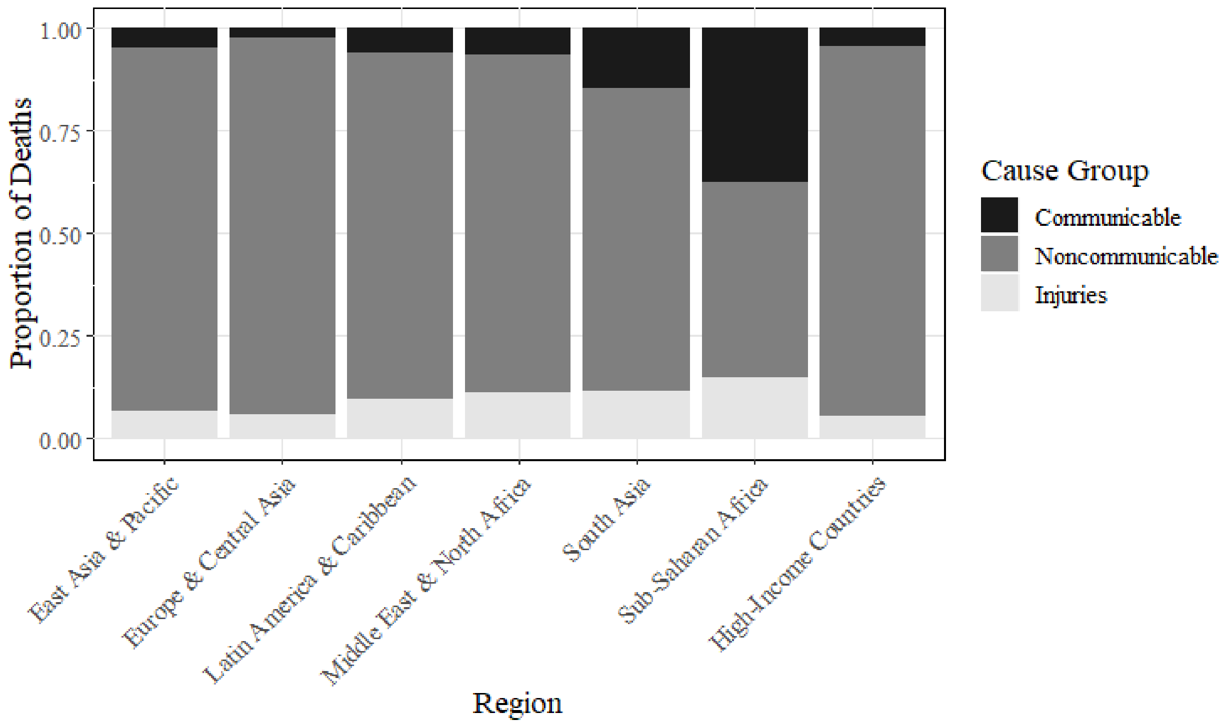


Figure 3j Mortality fraction by cause group & region, SSP5, 2050

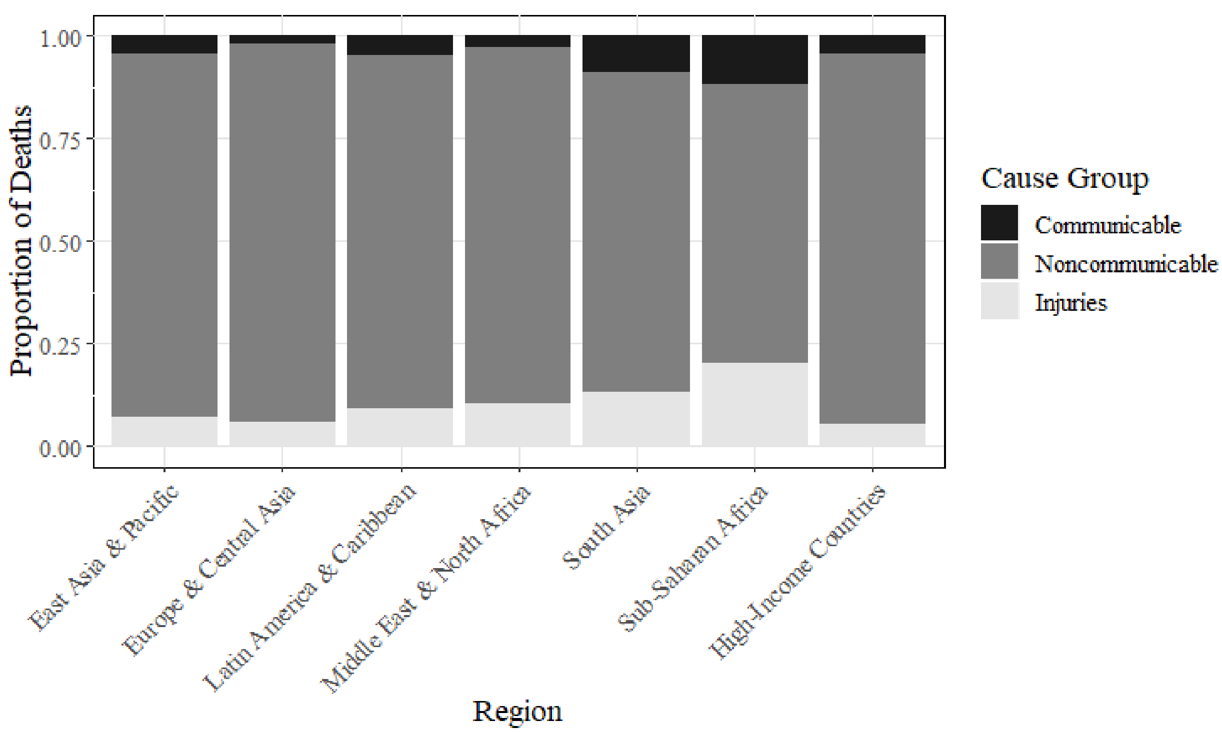


Figure 3k Mortality fraction by cause group & region, SSP1, 2080

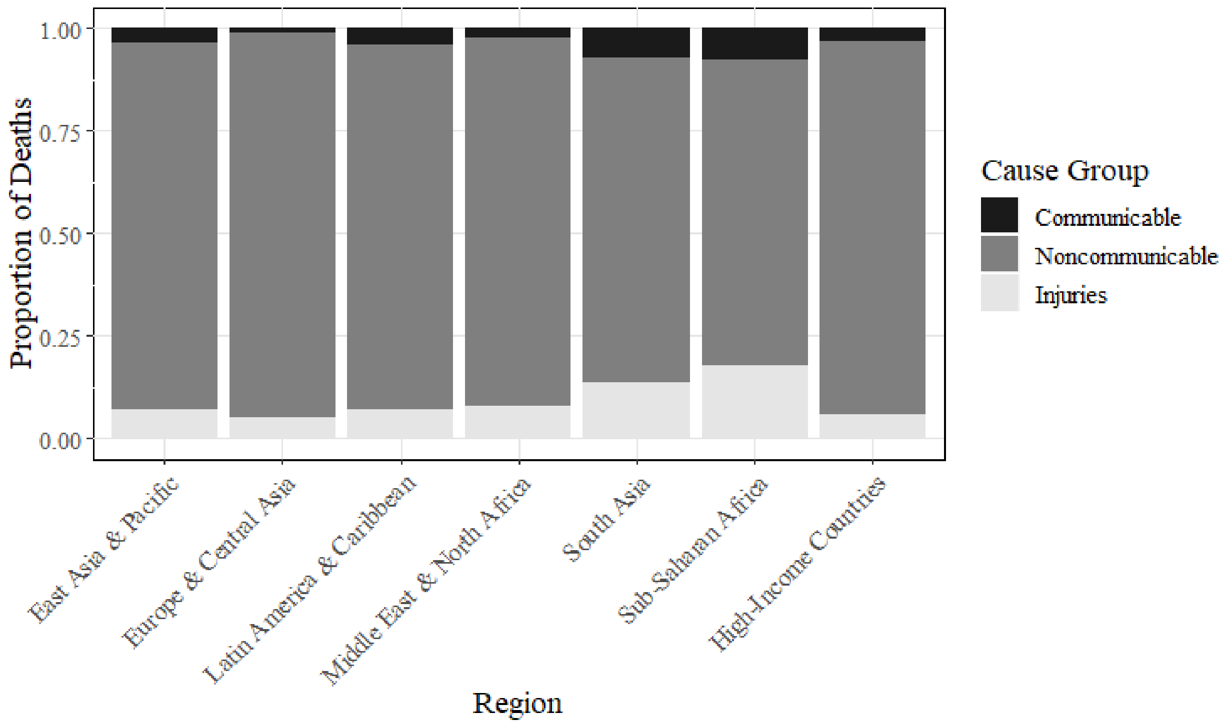


Figure 3l Mortality fraction by cause group & region, SSP2, 2080

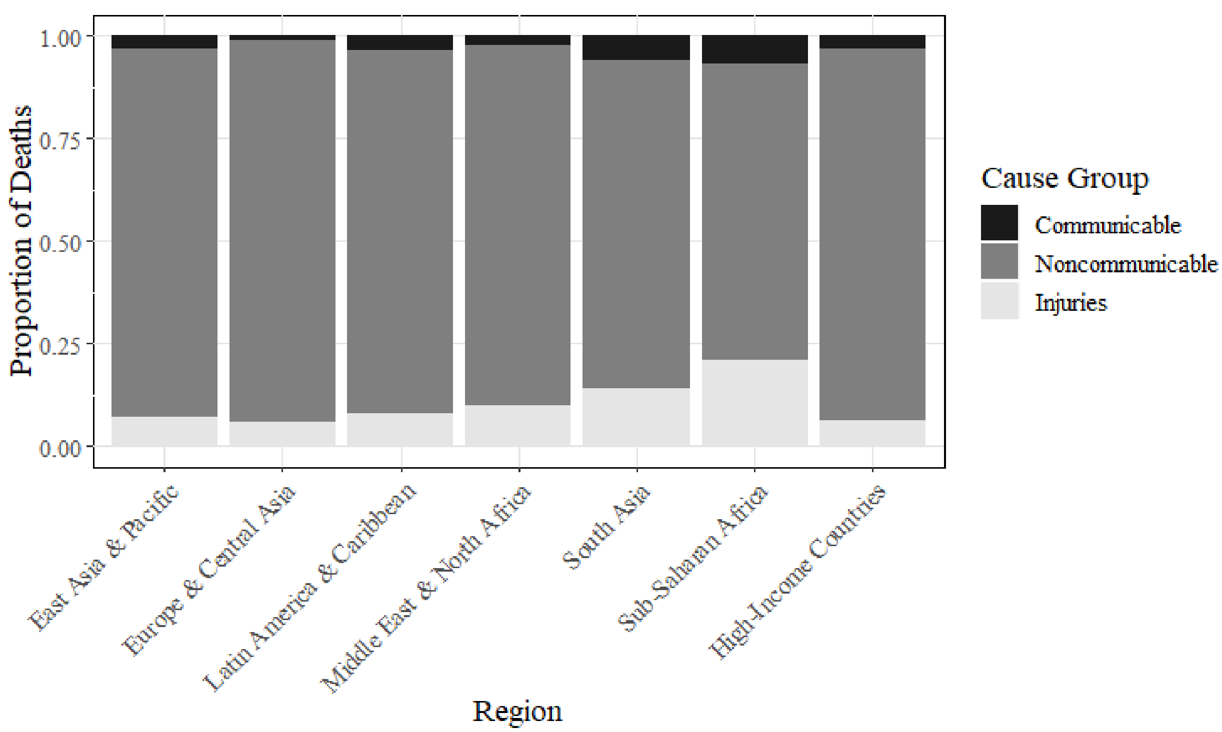


Figure 3m Mortality fraction by cause group & region, SSP3, 2080

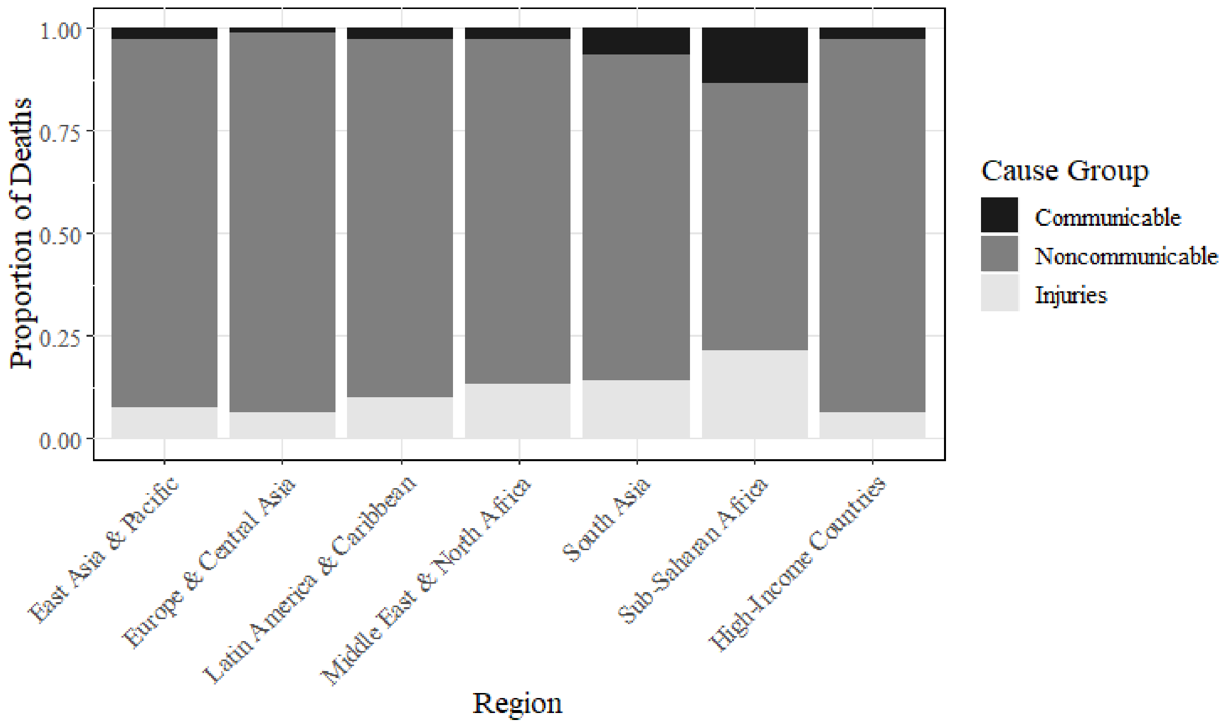


Figure 3n Mortality fraction by cause group & region, SSP4, 2080

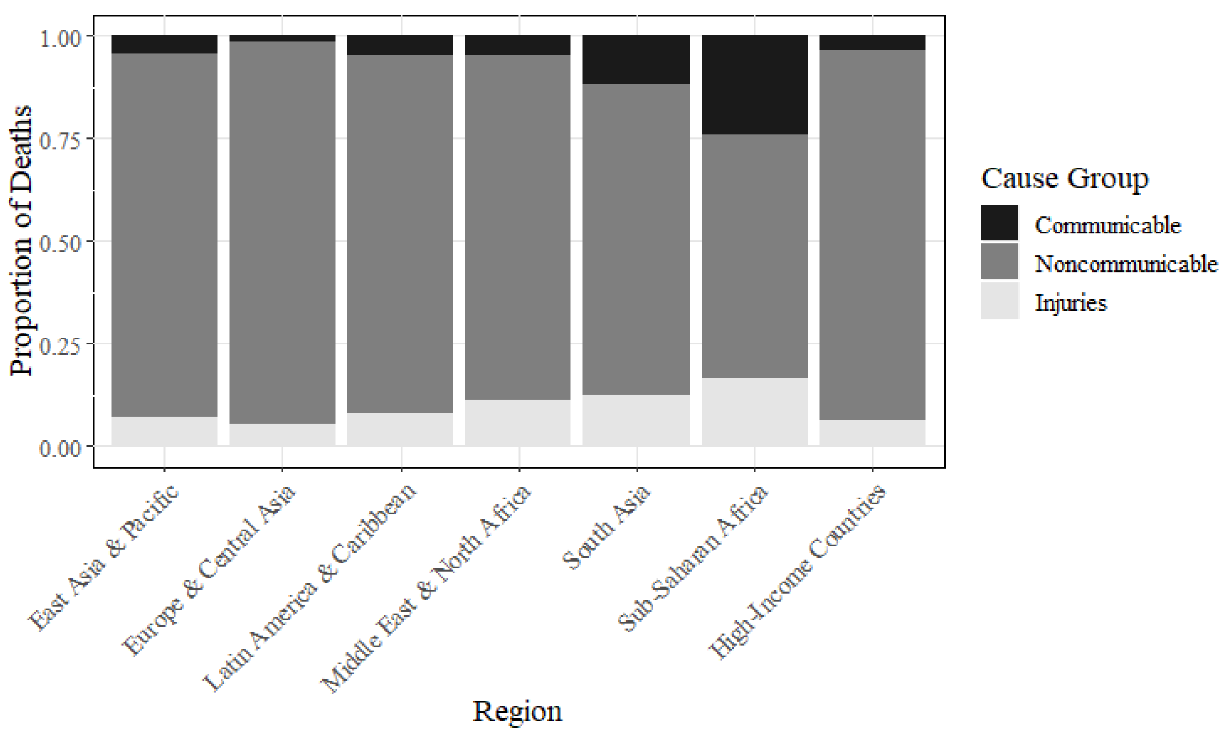


Figure 3o Mortality fraction by cause group & region, SSP5, 2080

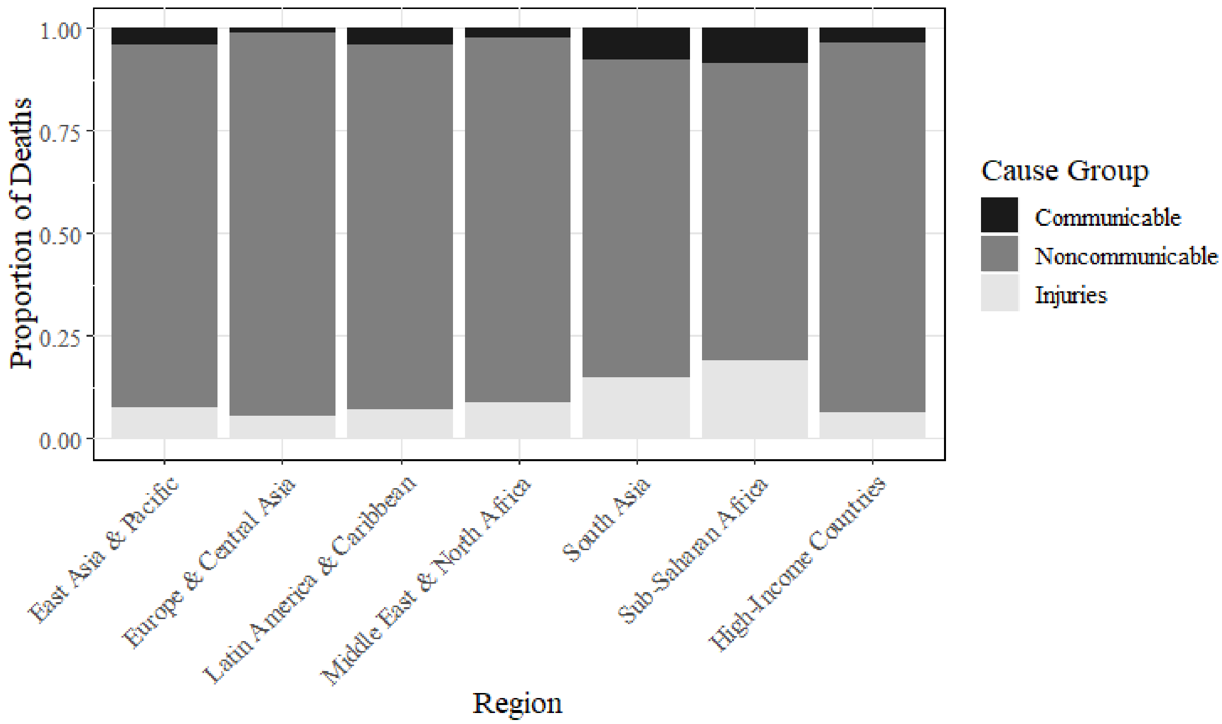

Proportion of Deaths
1.00
0.75
0.50
0.25
0.00
East Asia & Pacific
Europe & Central Asia
Latin America & Caribbean
Middle East & North Africa
South Asia
Sub-Saharan Africa
High-Income Countries
Region
Cause Group
Communicable
Noncommunicable
Injuries

Figure 4a Share of deaths from cardiovascular disease by world region & SSP, 2030

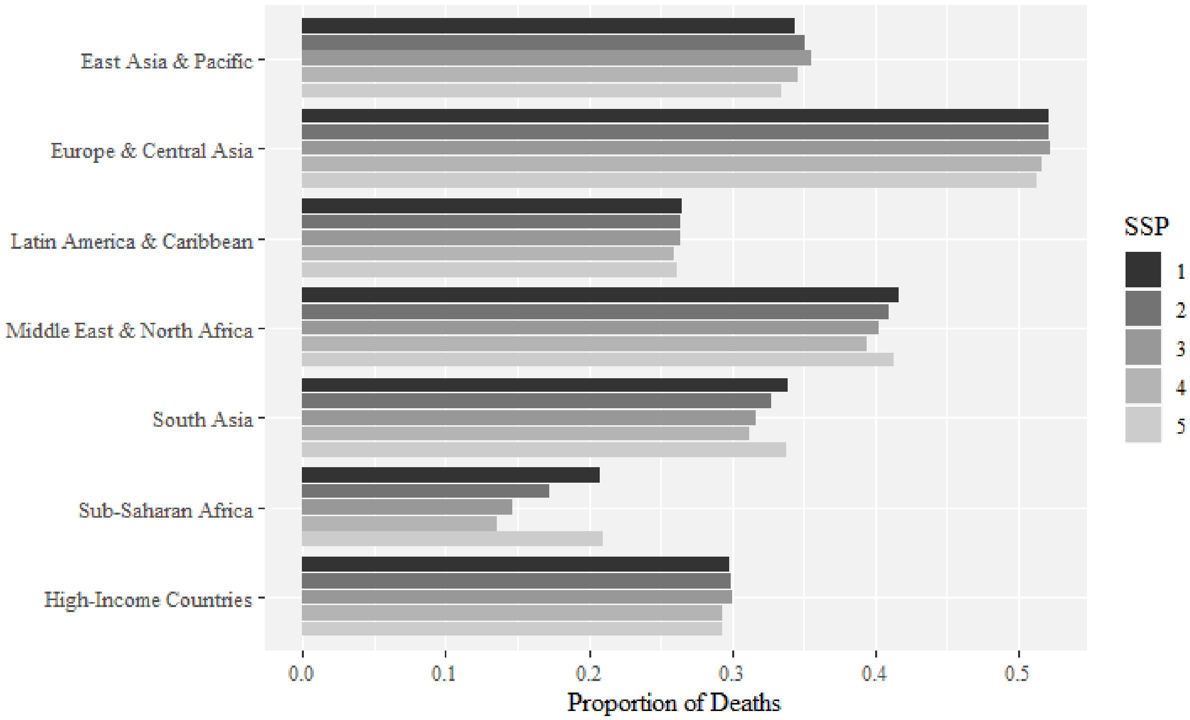


Figure 4b Share of deaths from cardiovascular disease by world region & SSP, 2050

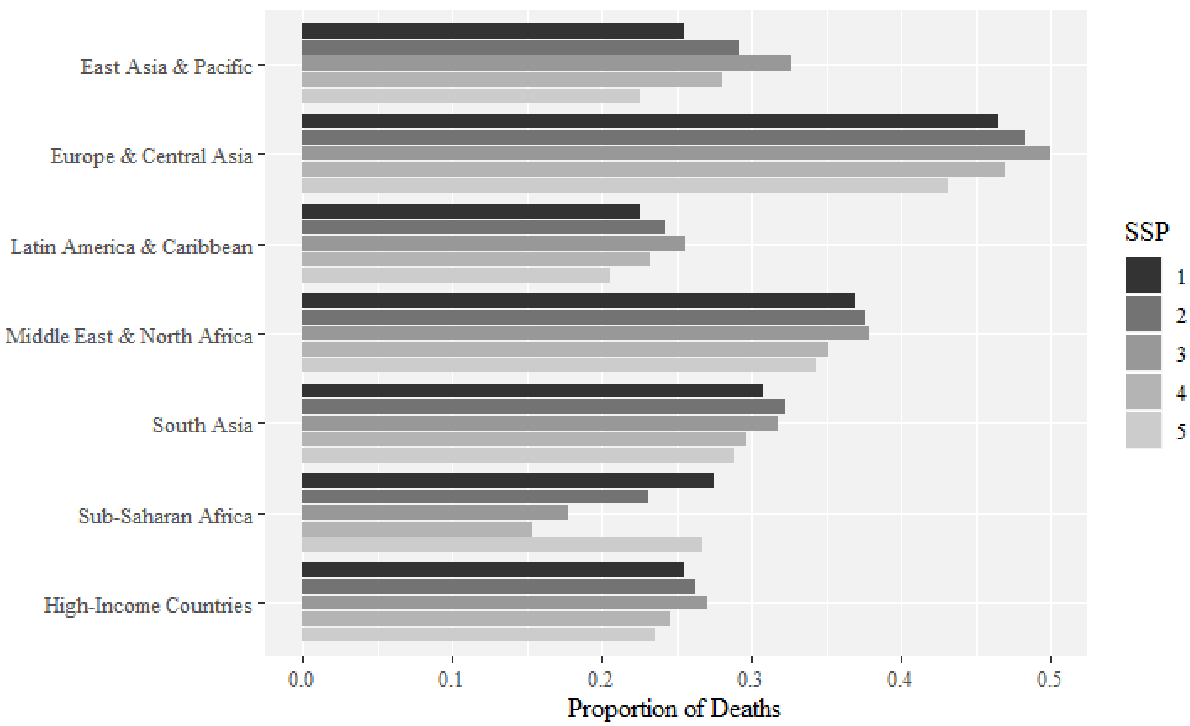


Figure 4c Share of deaths from cardiovascular disease by world region & SSP, 2080

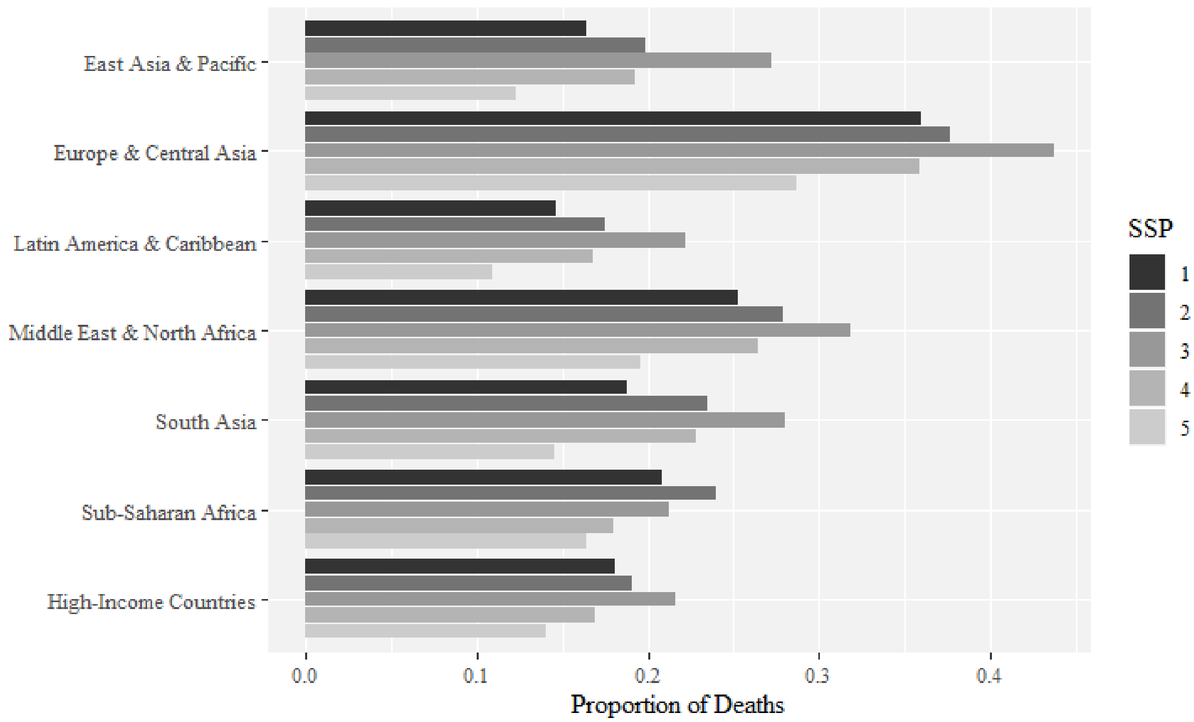


Figure 4d Share of deaths from diarrheal disease by world region & SSP, 2030

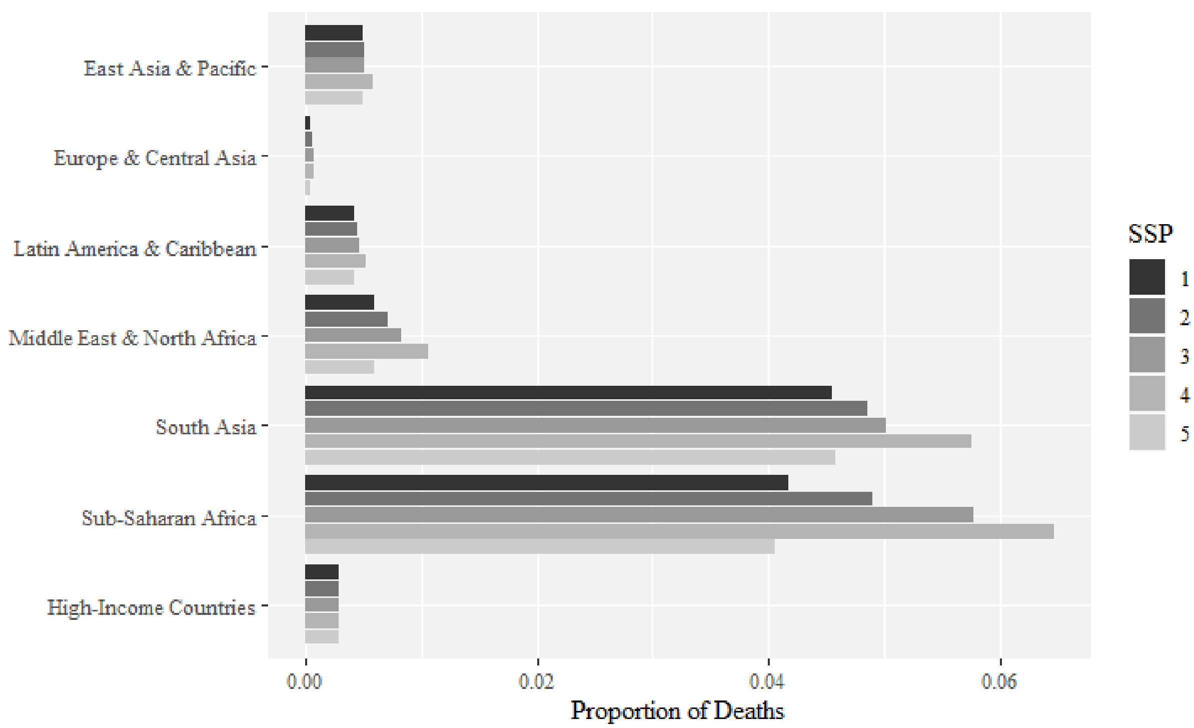


Figure 4e Share of deaths from diarrheal disease by world region & SSP, 2050

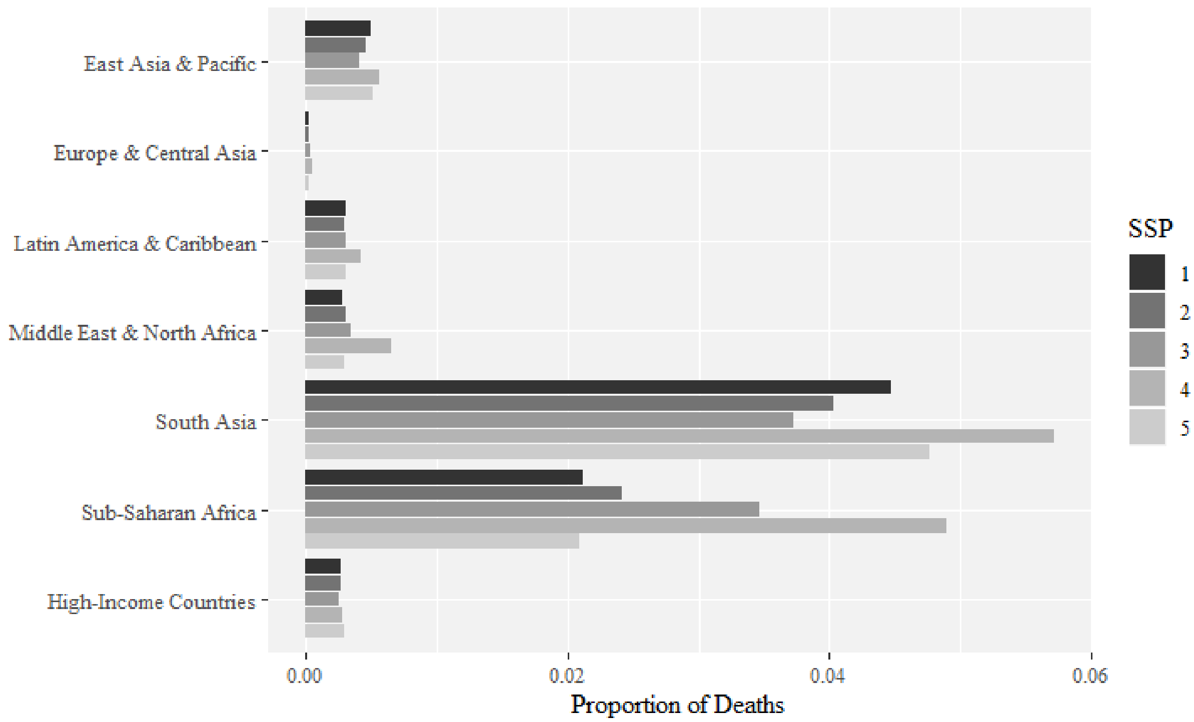


Figure 4f Share of deaths from diarrheal disease by world region & SSP, 2080

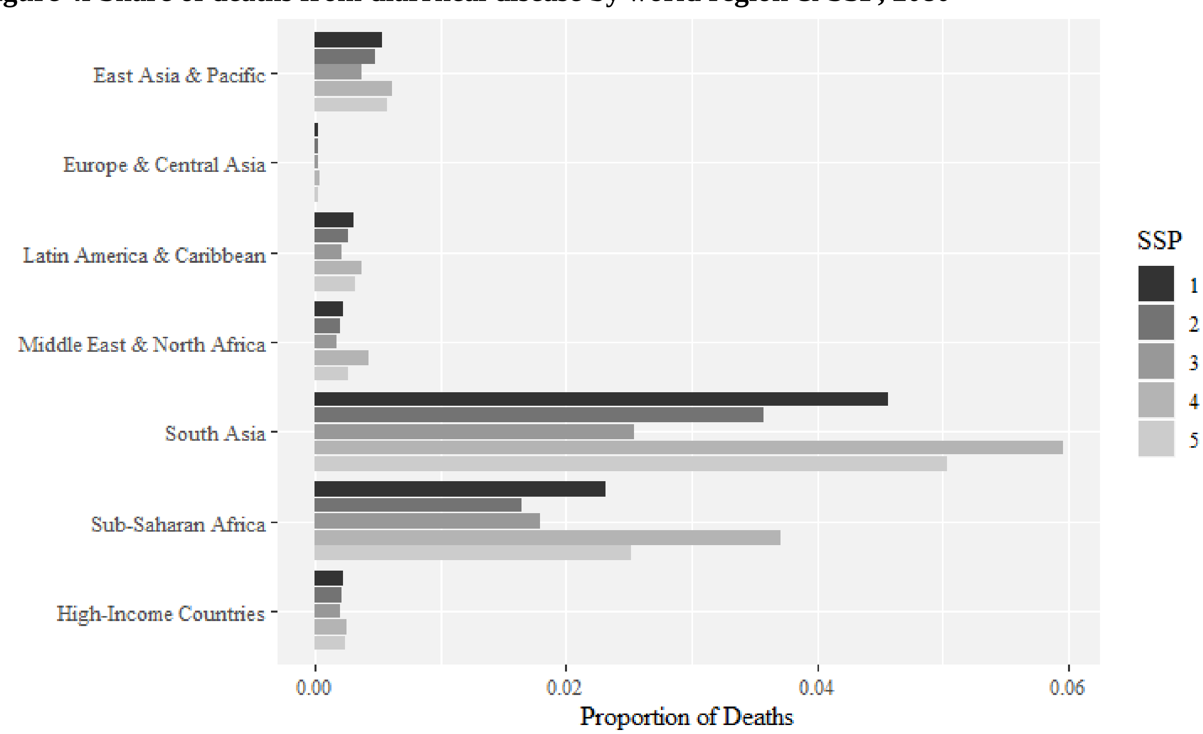


Figure 4g Share of deaths from chronic respiratory disease by world region & SSP, 2030

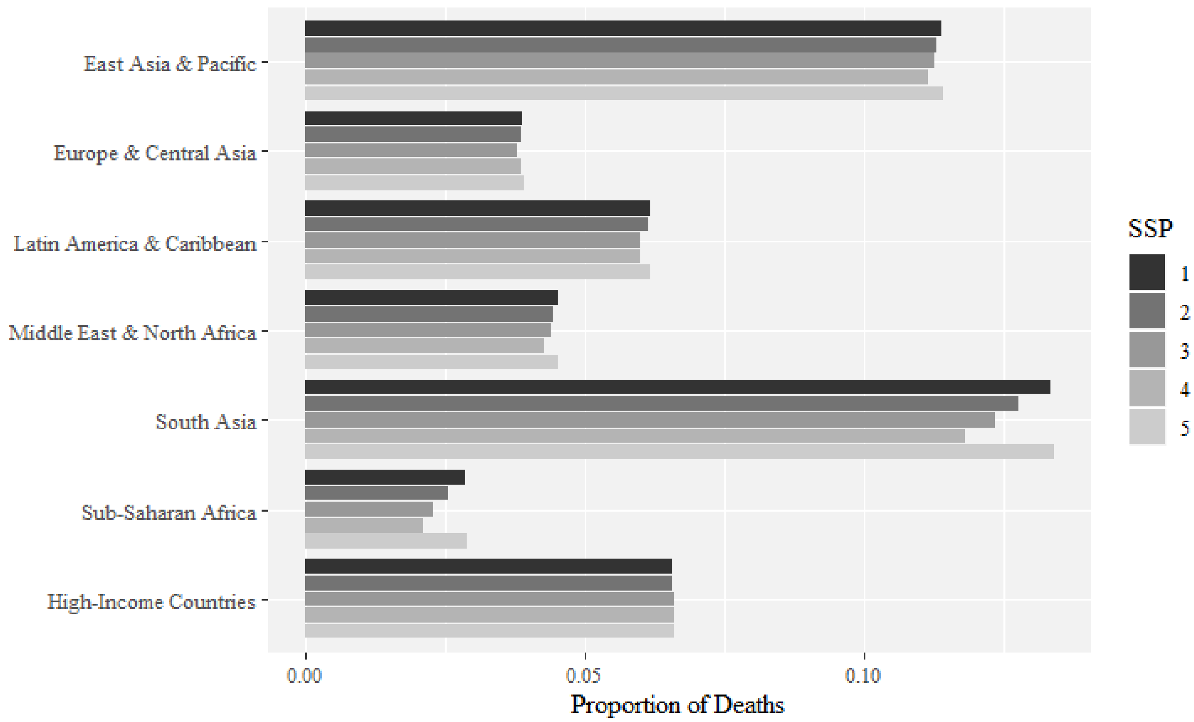


Figure 4h Share of deaths from chronic respiratory disease by world region & SSP, 2050

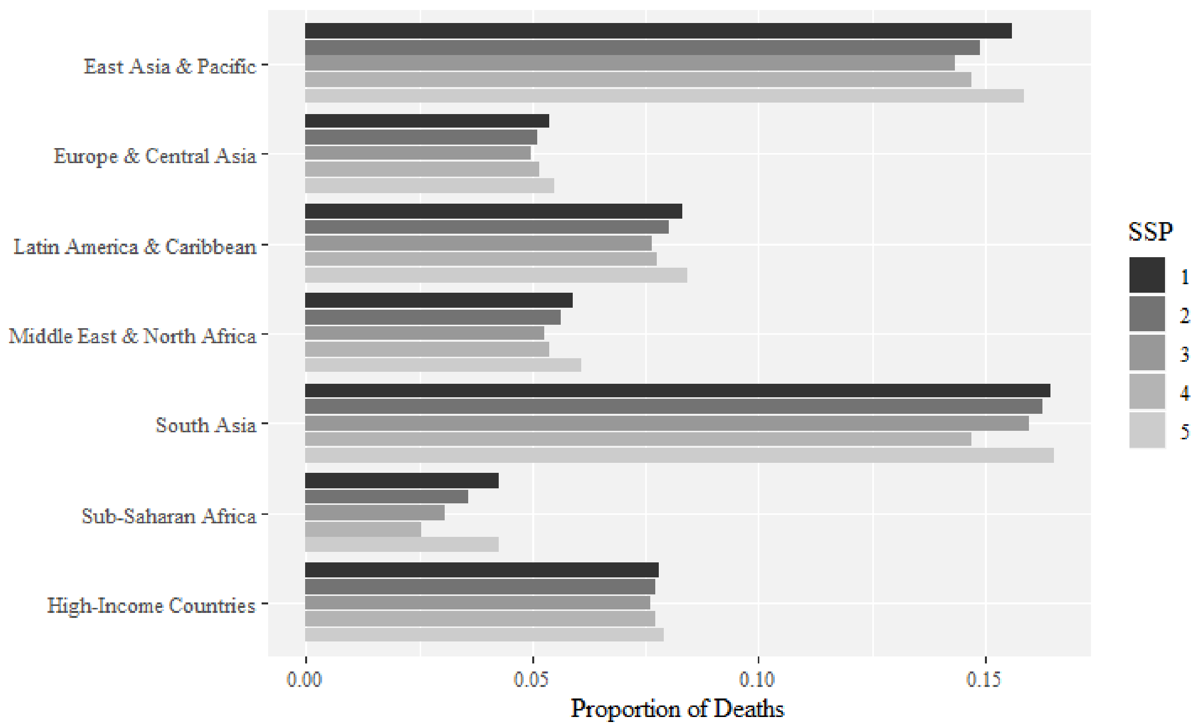


Figure 4i Share of deaths from chronic respiratory disease by world region & SSP, 2080

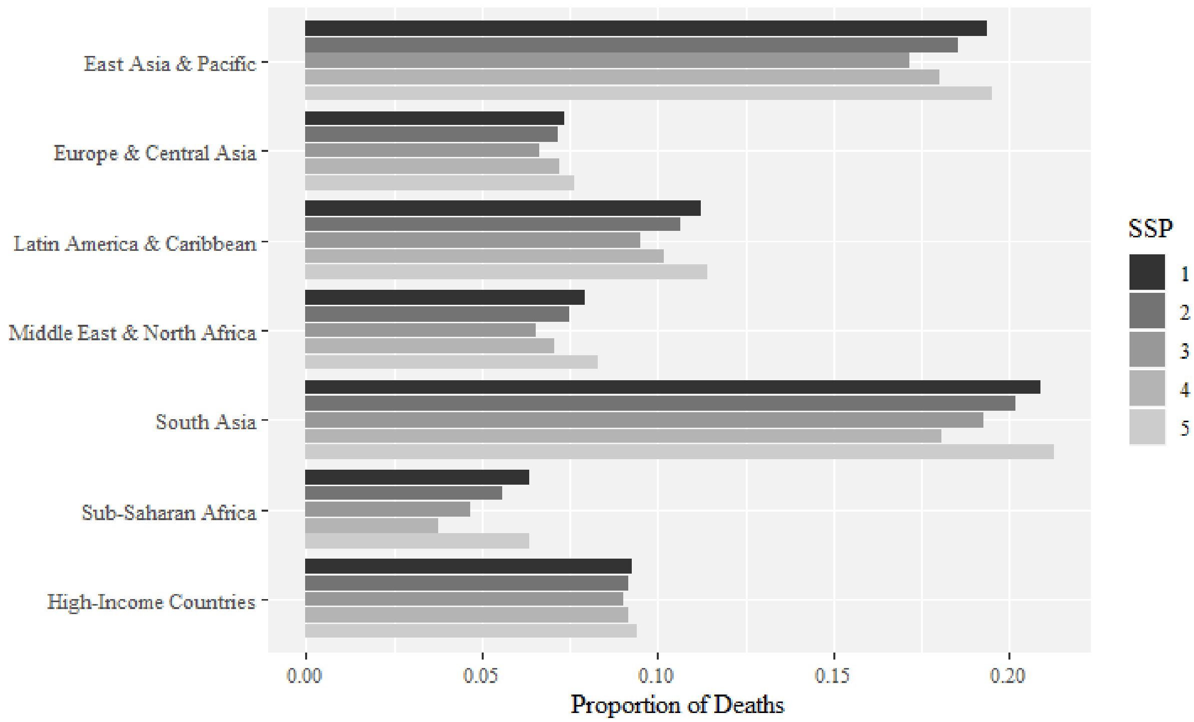


Figure 4j Share of deaths from cancer by world region & SSP, 2030

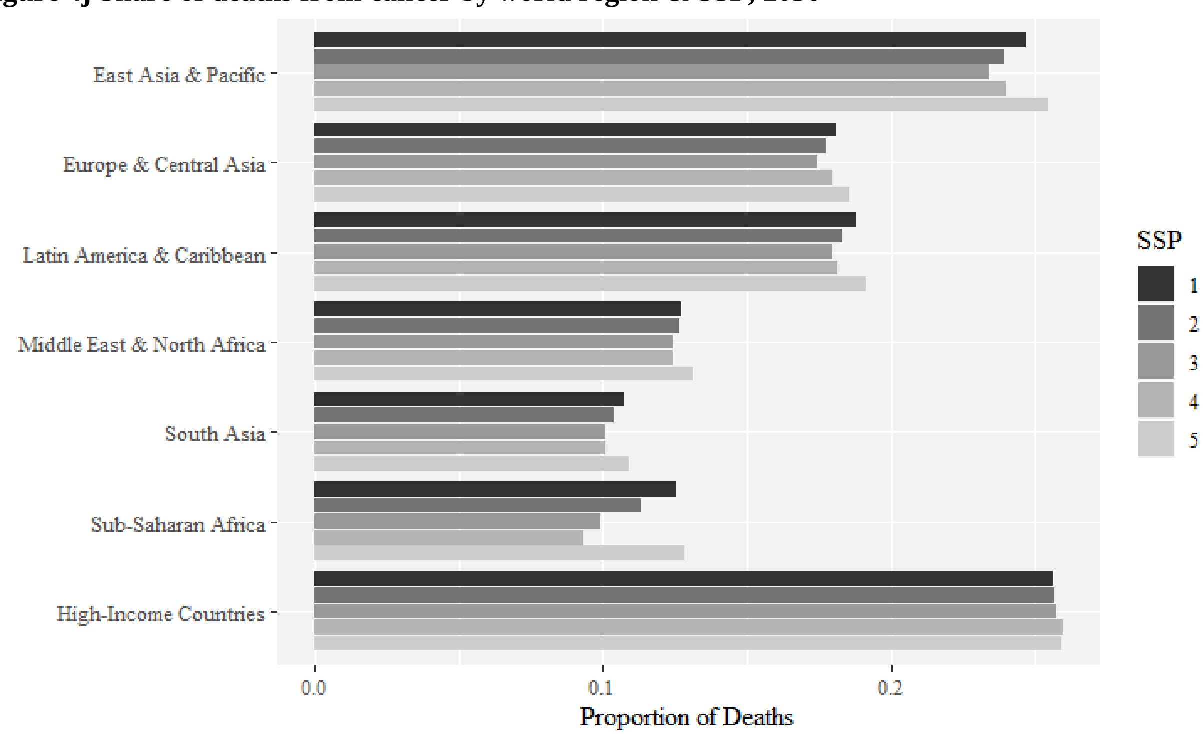


Figure 4k Share of deaths from cancer by world region & SSP, 2050

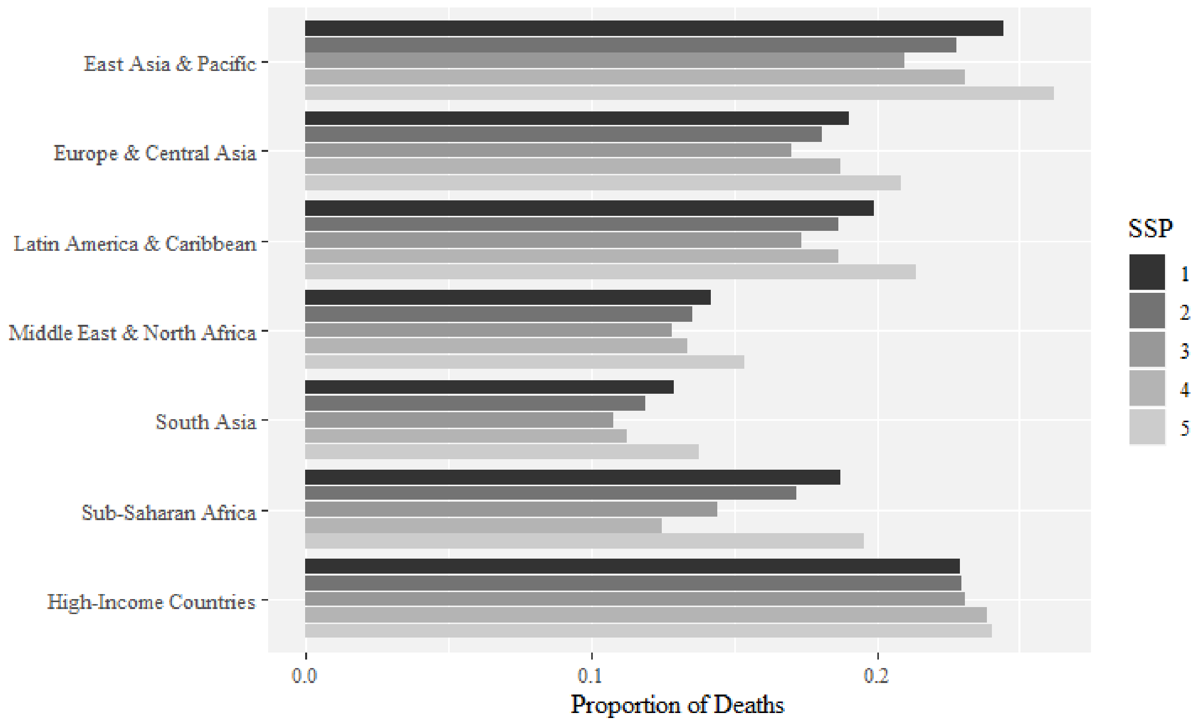


Figure 4l Share of deaths from cancer by world region & SSP, 2080

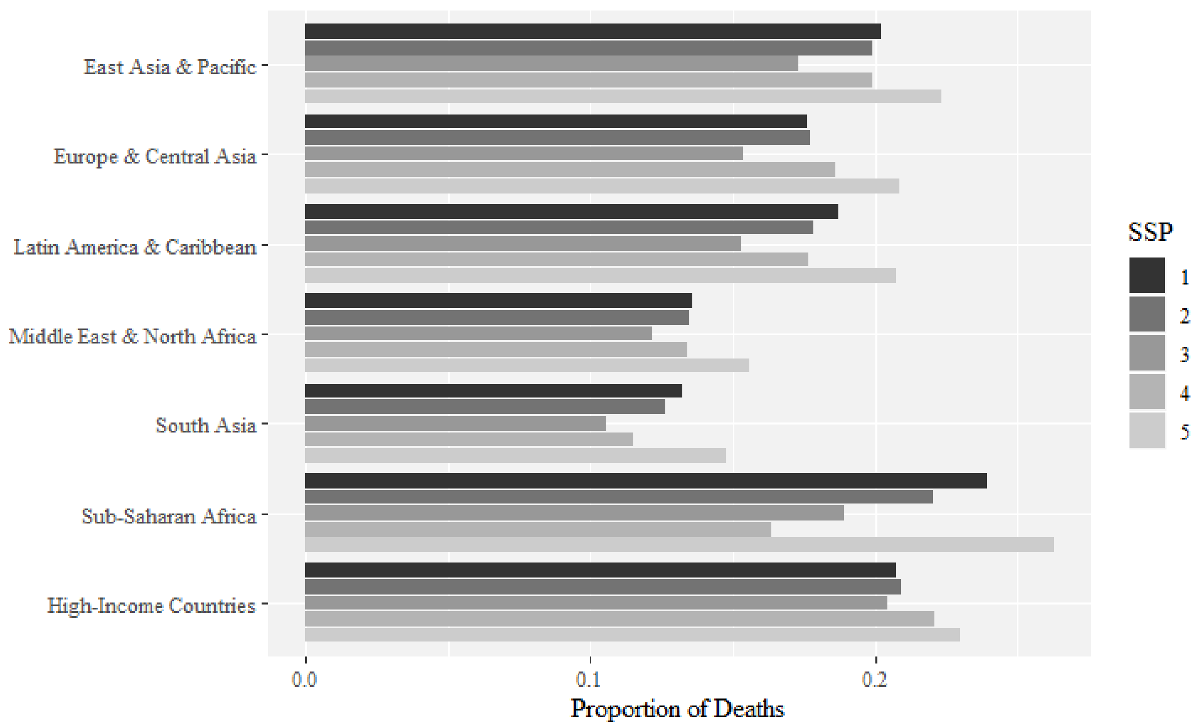


Figure 4m Share of deaths from traffic accidents by world region & SSP, 2030

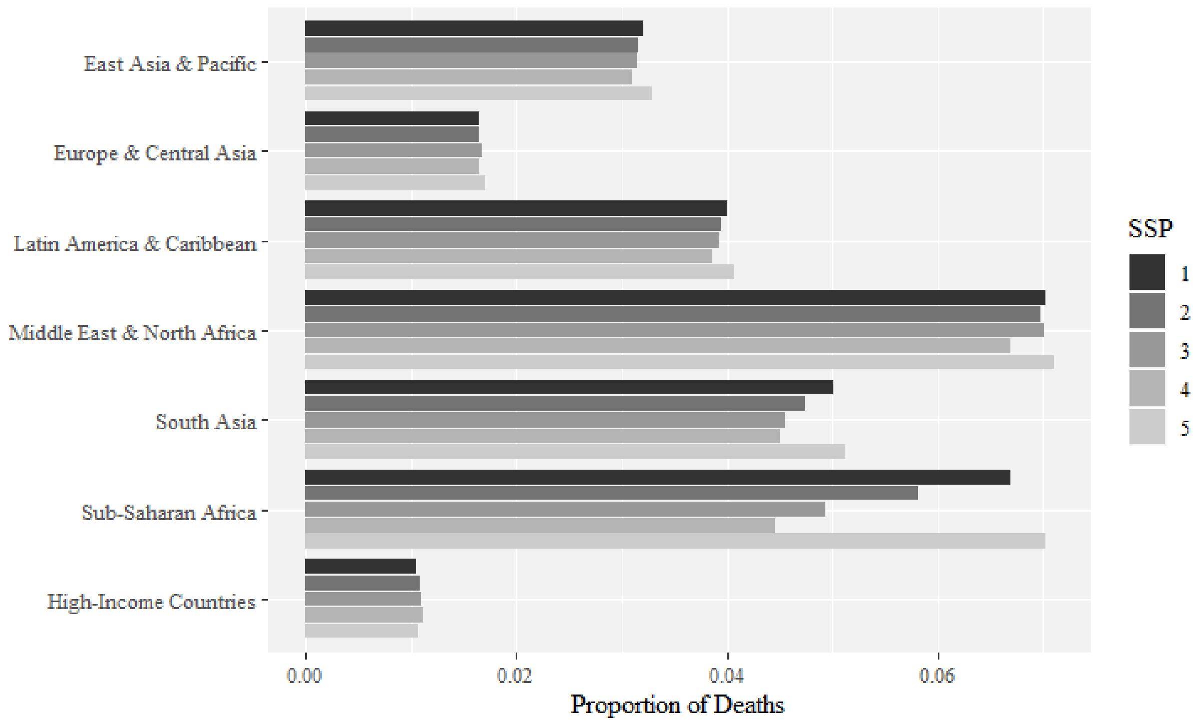


Figure 4n Share of deaths from traffic accidents by world region & SSP, 2050

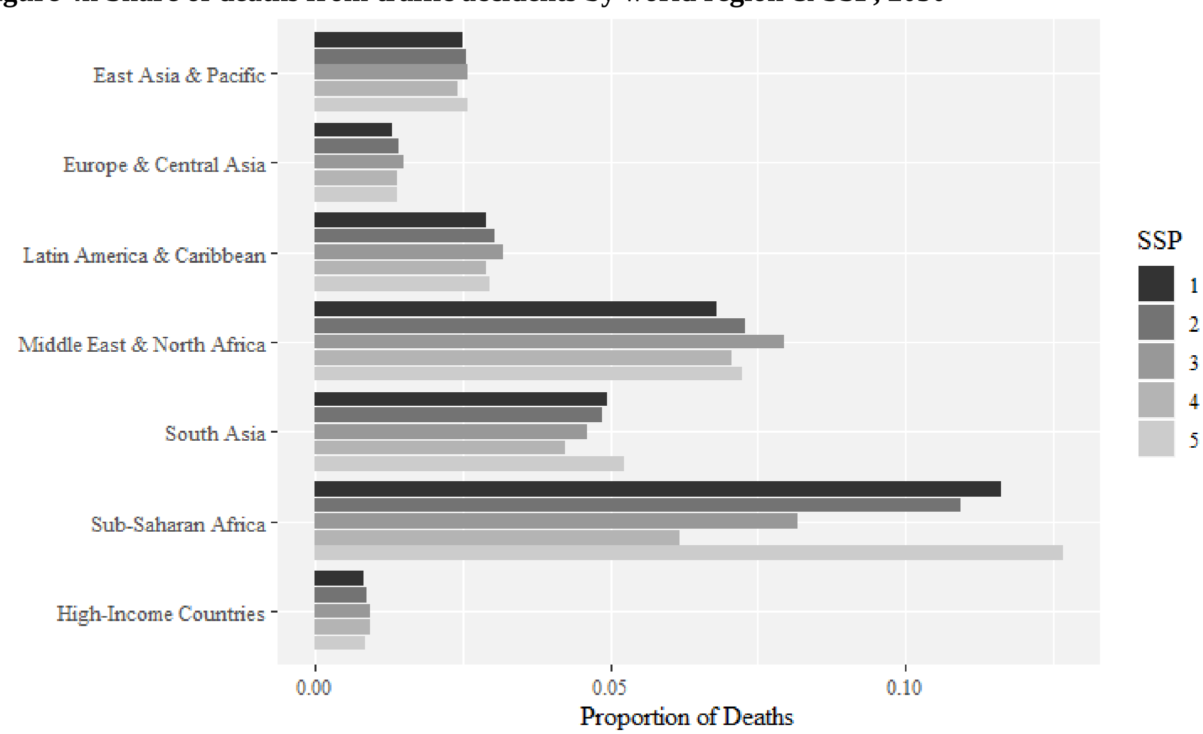


Figure 4o Share of deaths from traffic accidents by world region & SSP, 2080

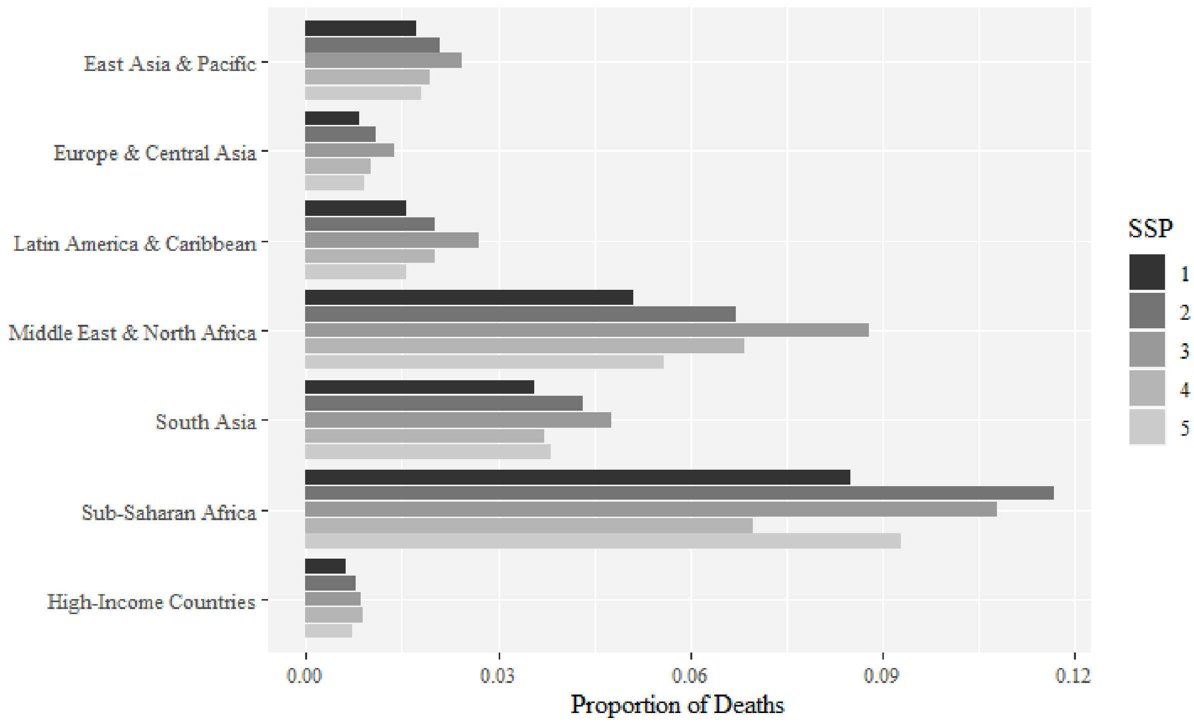
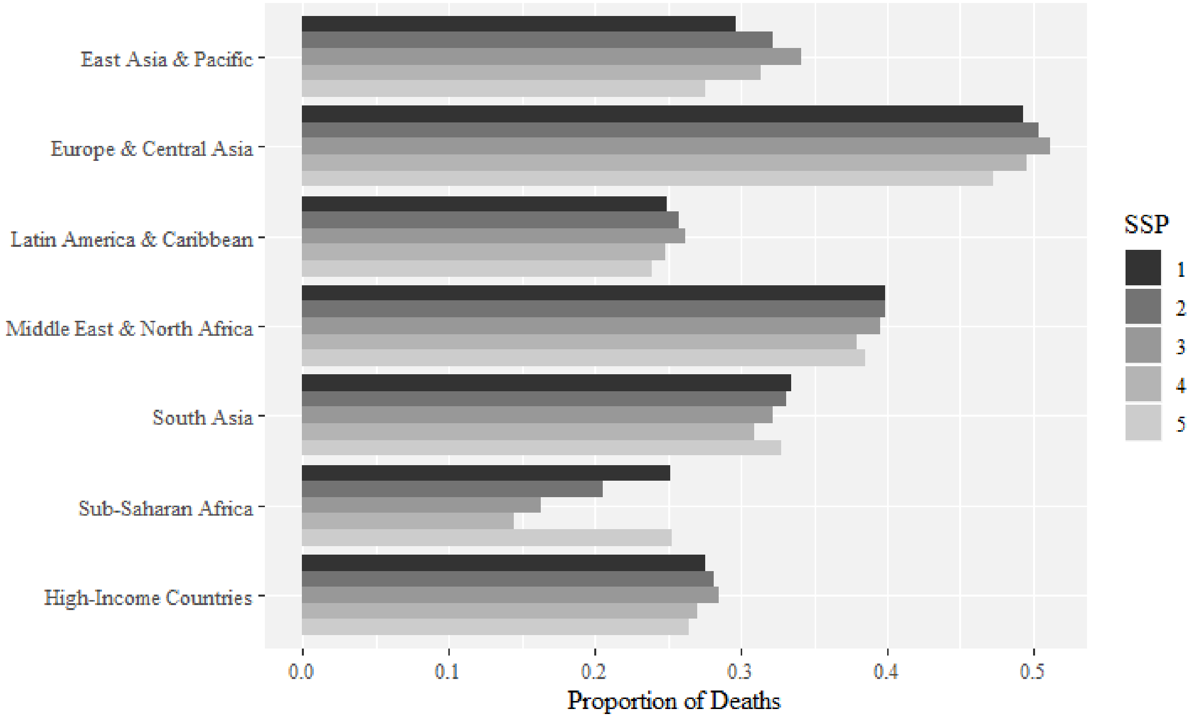

East Asia & Pacific
Europe & Central Asia
Latin America & Caribbean
Middle East & North Africa
South Asia
Sub-Saharan Africa
High-Income Countries
0.00
0.03
0.06
0.09
0.12
Proportion of Deaths
SSP
1
2
3
4
5

Figure 5a Comparison of IFs (top) and IHME (bottom) findings on share of deaths from cardiovascular diseases by world region, 2040



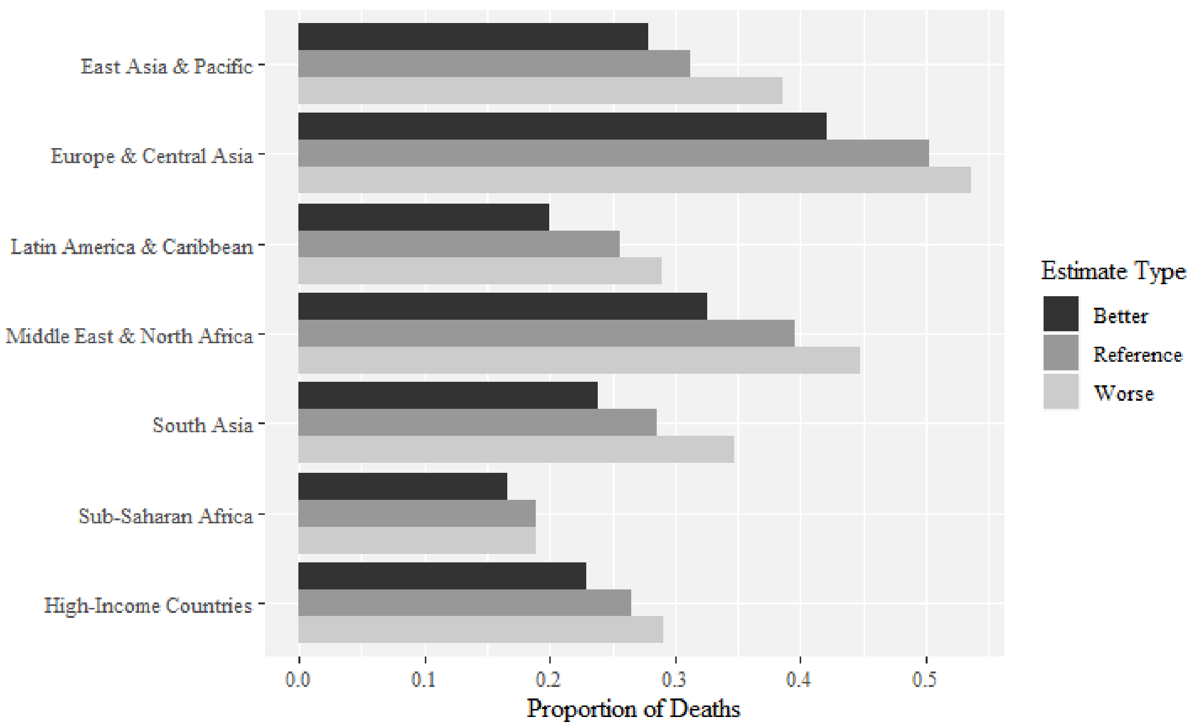


Figure 5b Comparison of IFs (top) and IHME (bottom) findings on share of deaths from diarrheal disease by world region, 2040

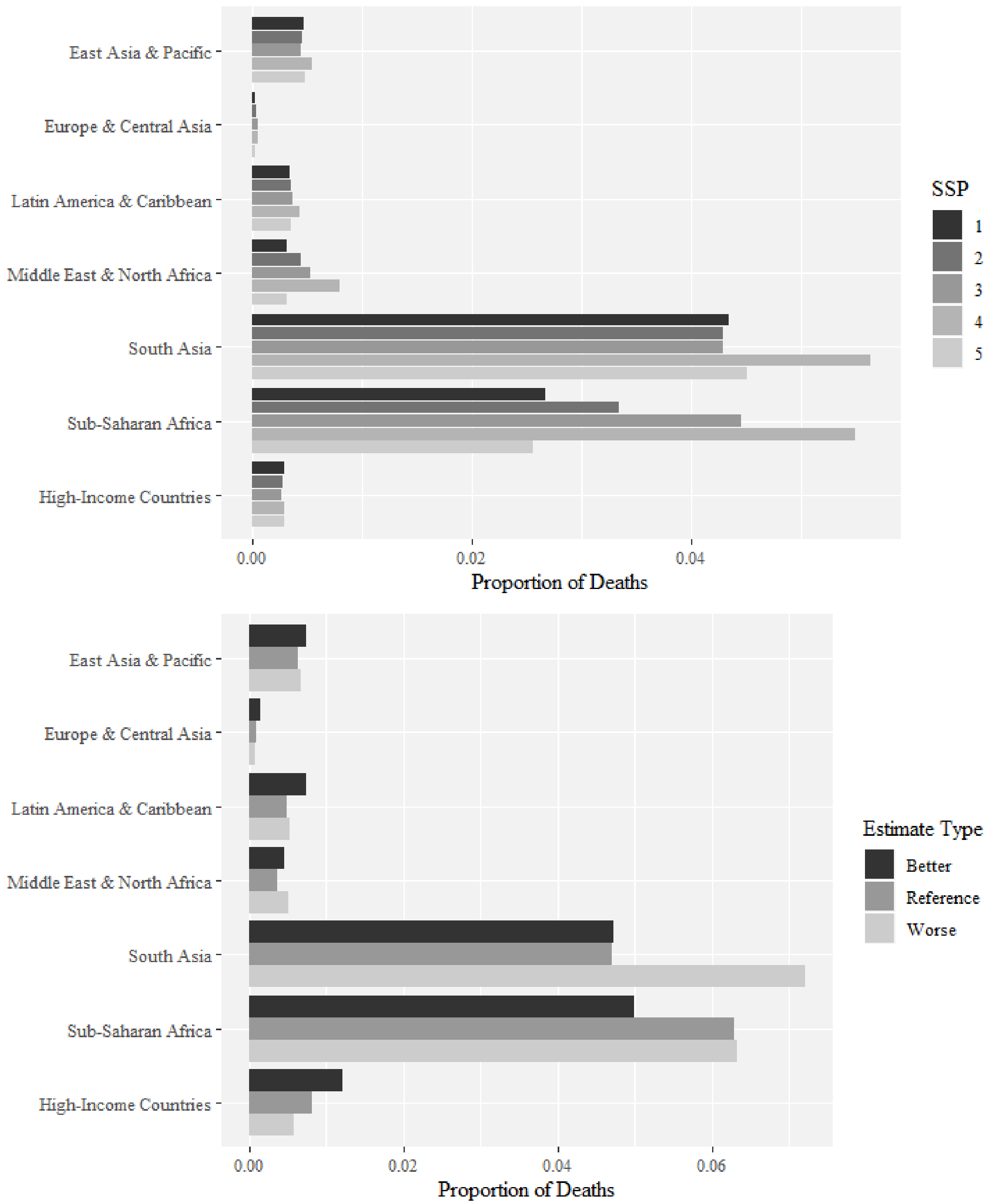


Figure 5c Comparison of IFs (top) and IHME (bottom) findings on share of deaths from chronic respiratory disease by world region, 2040

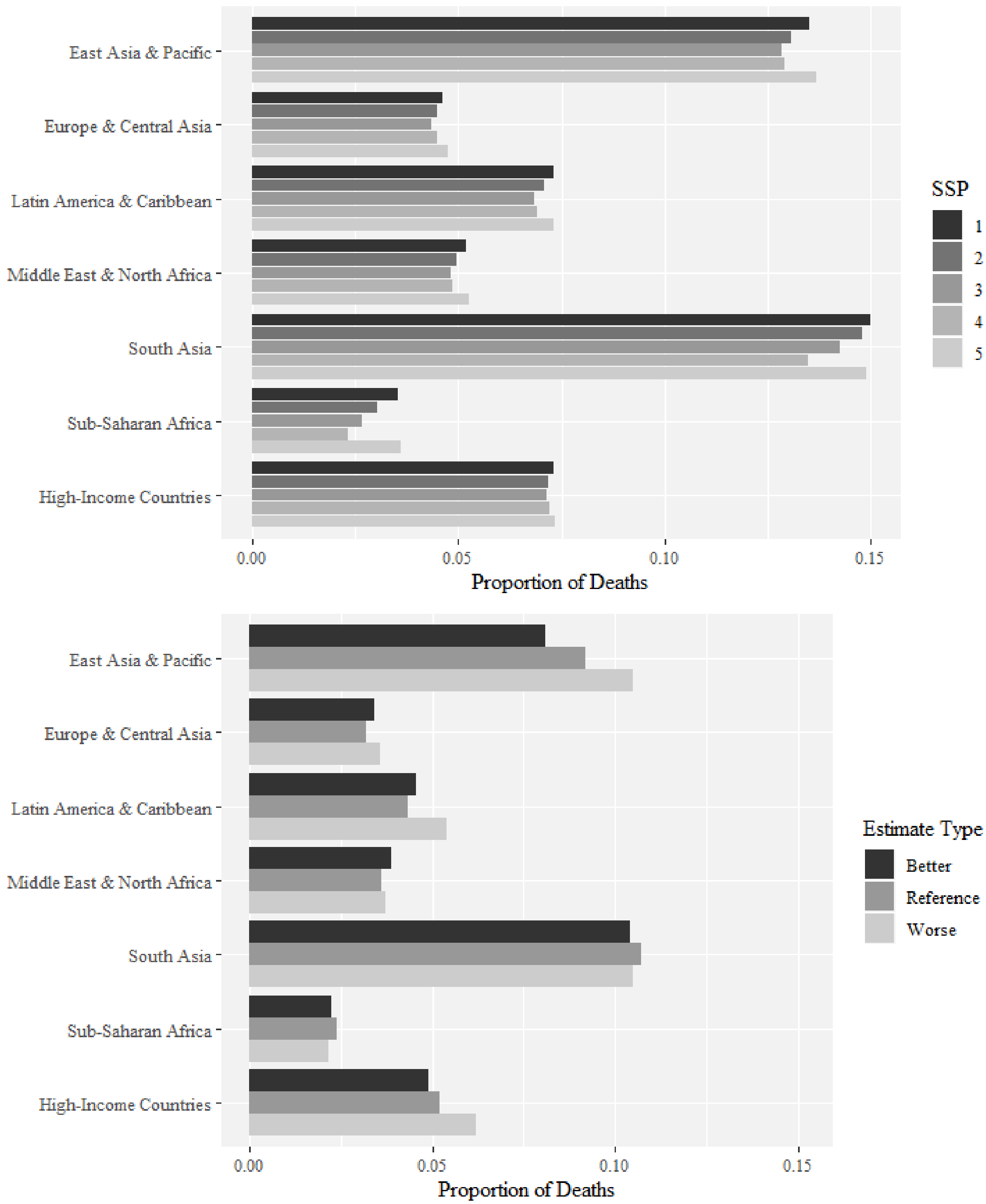


Figure 5d Comparison of IFs (top) and IHME (bottom) findings on share of deaths from cancer by world region, 2040

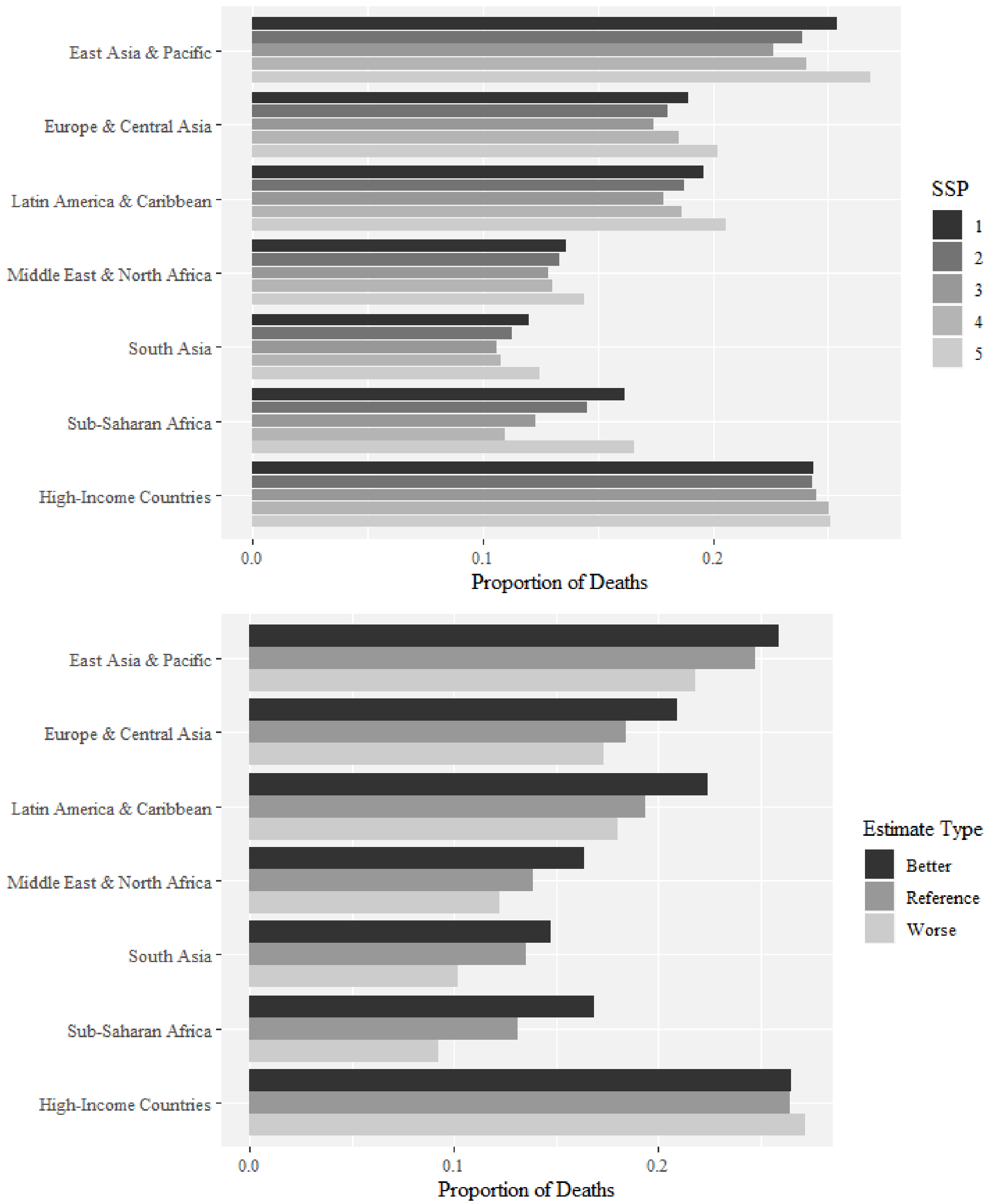
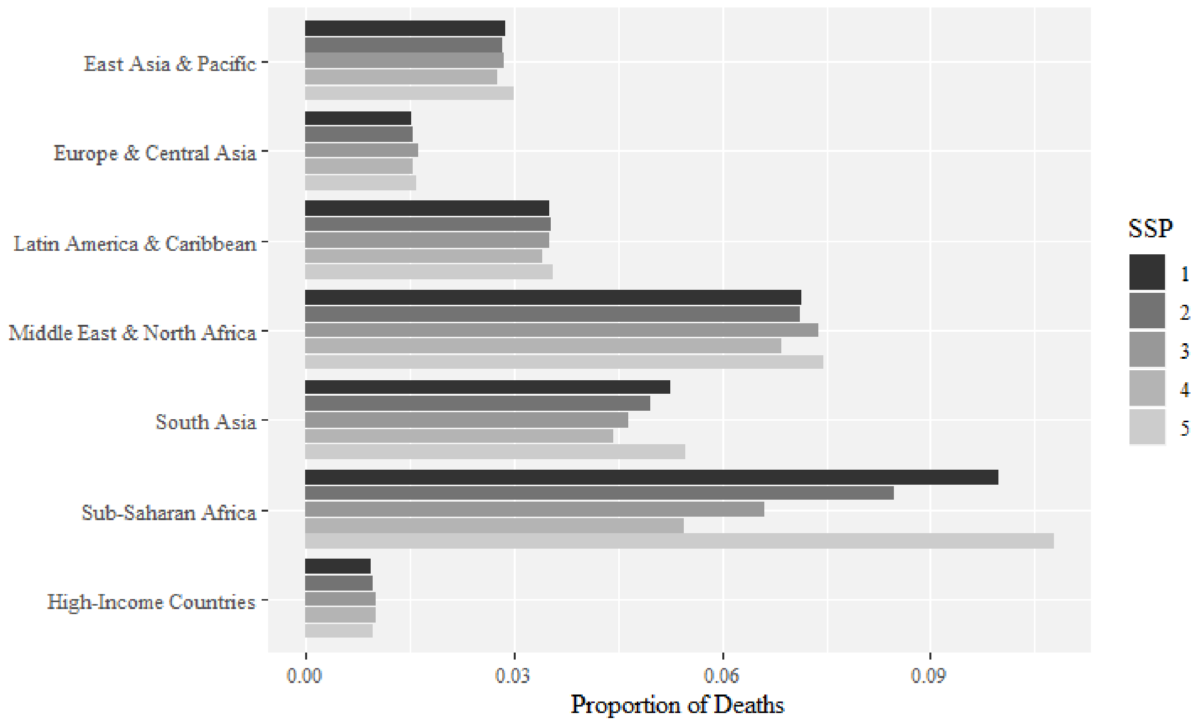


Figure 5e Comparison of IFs (top) and IHME (bottom) findings on share of deaths from traffic accidents by world region, 2040


East Asia & Pacific
Europe & Central Asia
Latin America & Caribbean
Middle East & North Africa
South Asia
Sub-Saharan Africa
High-Income Countries
0.00
0.03
0.06
0.09
Proportion of Deaths
SSP
1
2
3
4
5

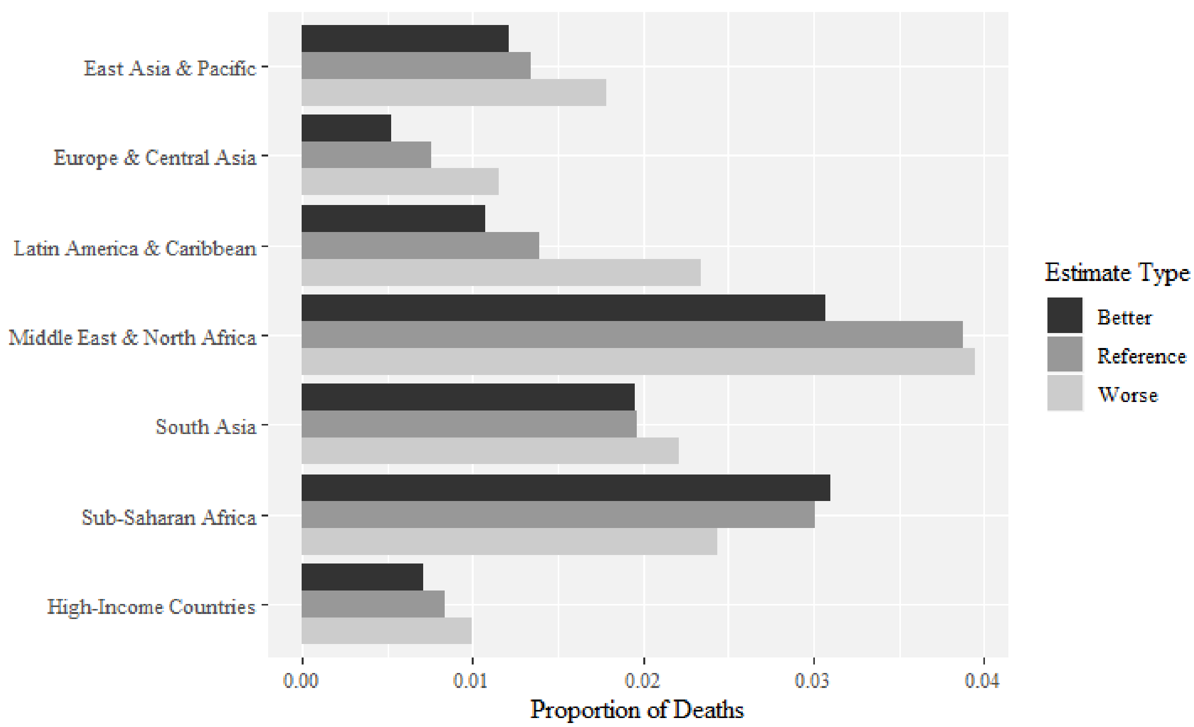

East Asia & Pacific
Europe & Central Asia
Latin America & Caribbean
Middle East & North Africa
South Asia
Sub-Saharan Africa
High-Income Countries
0.00
0.01
0.02
0.03
0.04
Proportion of Deaths
Estimate Type
Better
Reference
Worse

Figure 6a Proportion of age 0-4 mortality attributable to communicable diseases, 2030

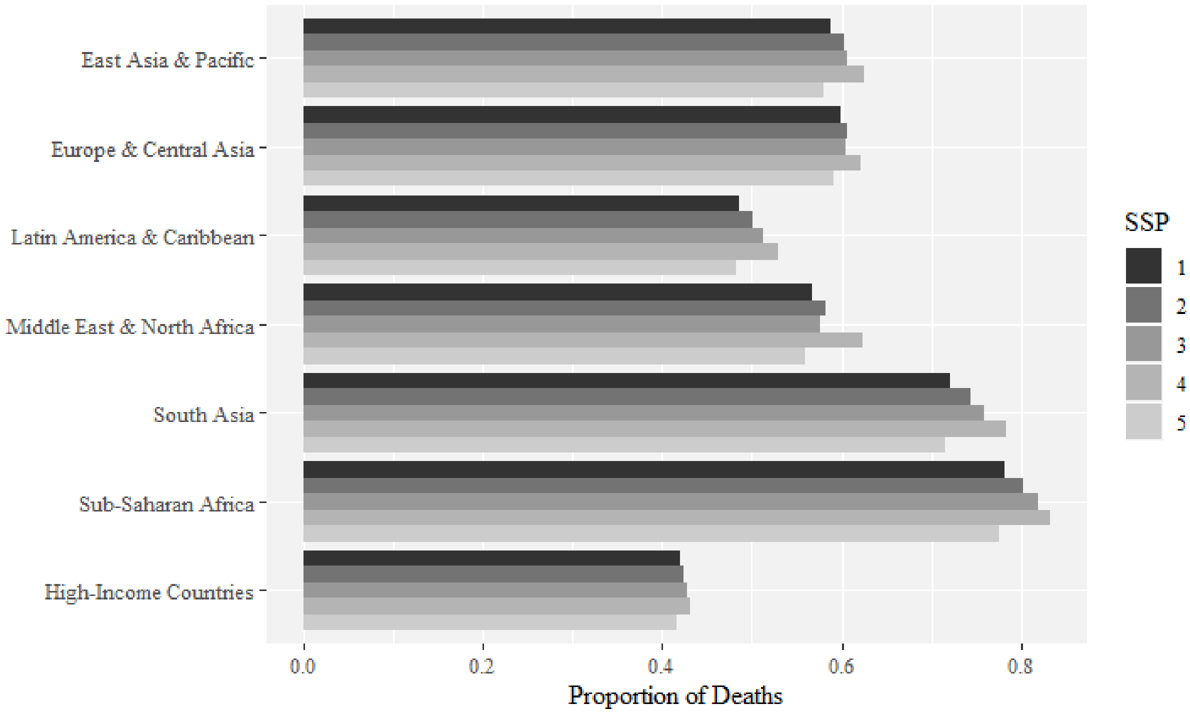


Figure 6b Proportion of age 5-14 mortality attributable to communicable diseases, 2030

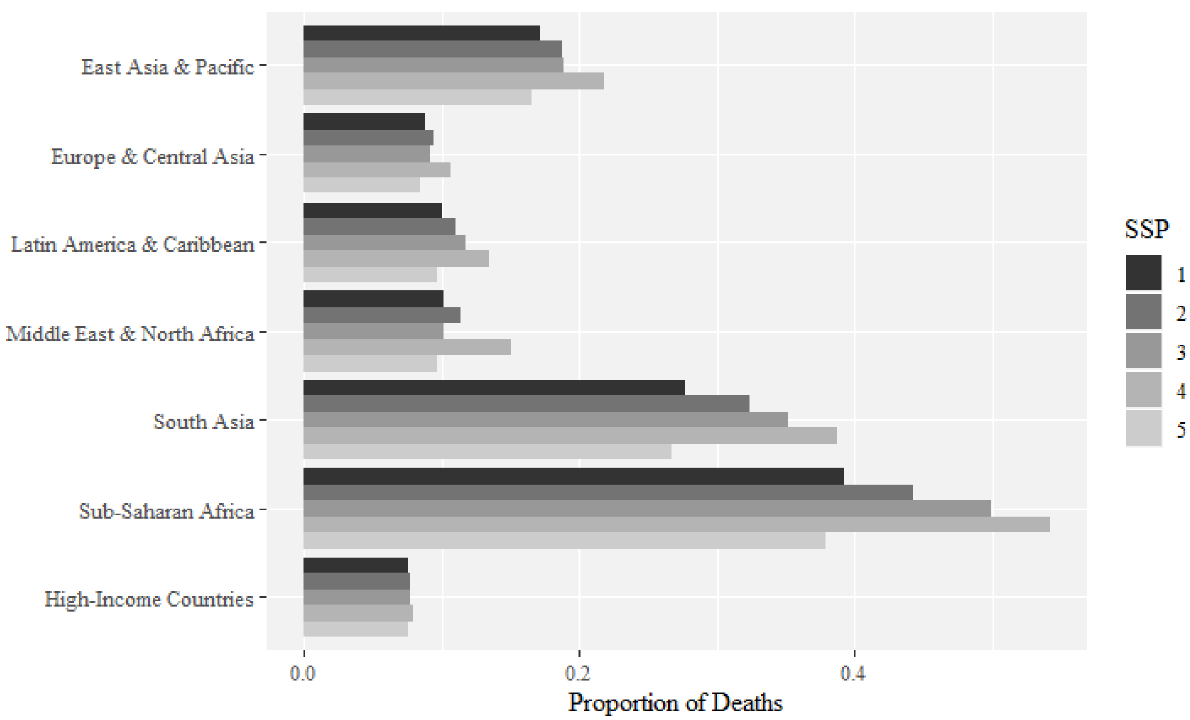


Figure 6c Proportion of age 0-4 mortality attributable to communicable diseases, 2050

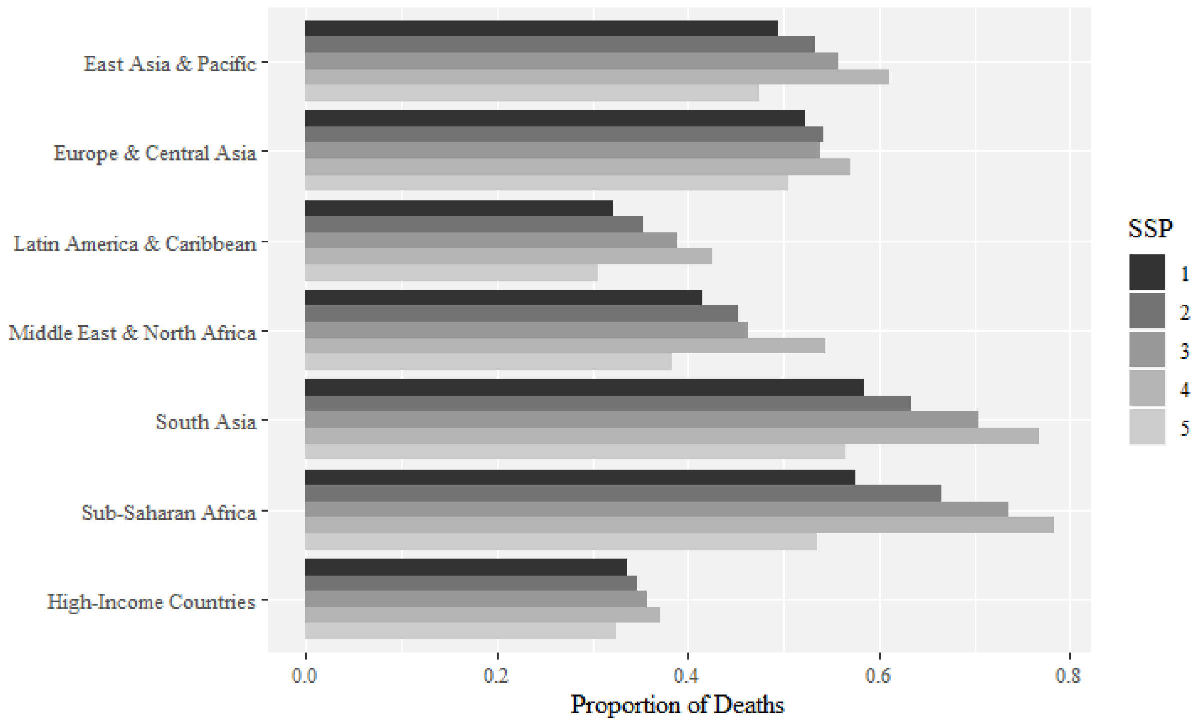


Figure 6d Proportion of age 5-14 mortality attributable to communicable diseases, 2050

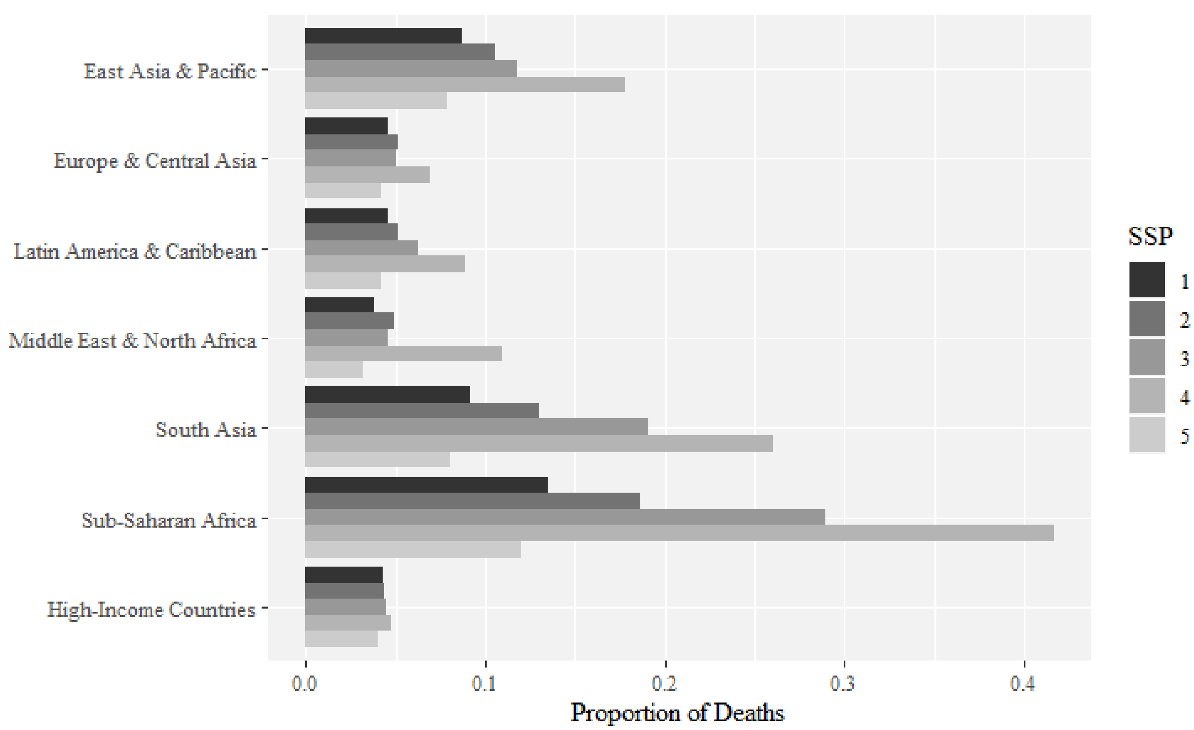


Figure 6e Proportion of age 0-4 mortality attributable to communicable diseases, 2080

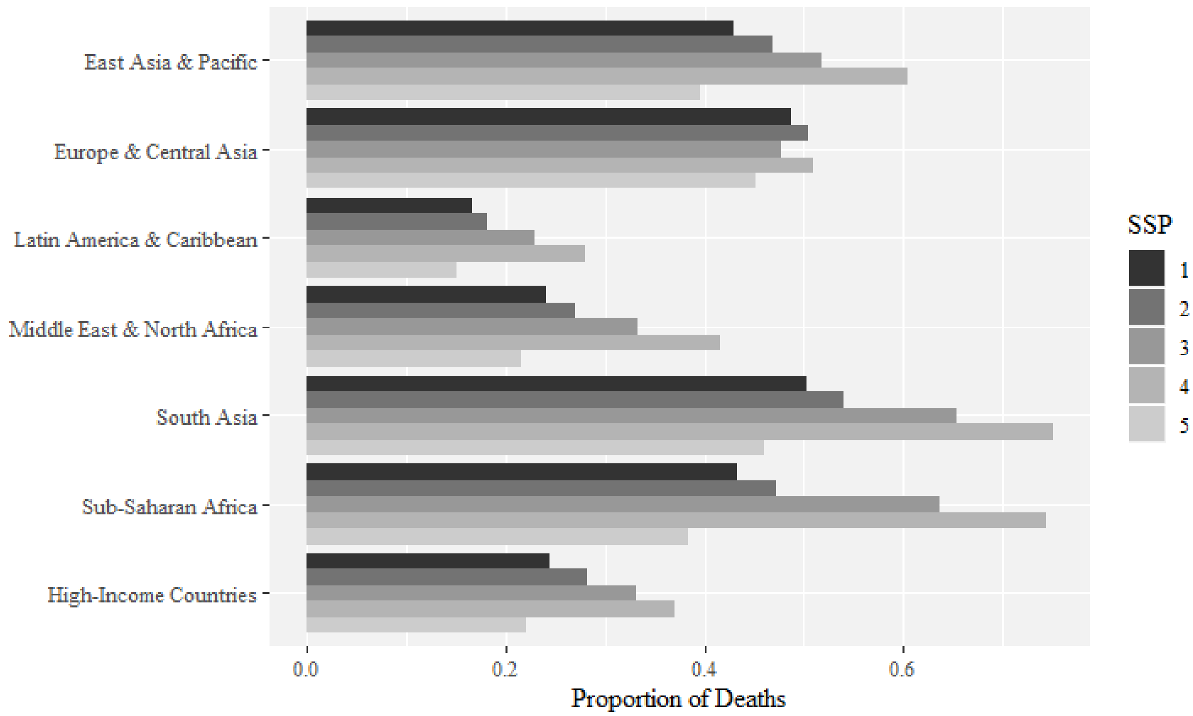
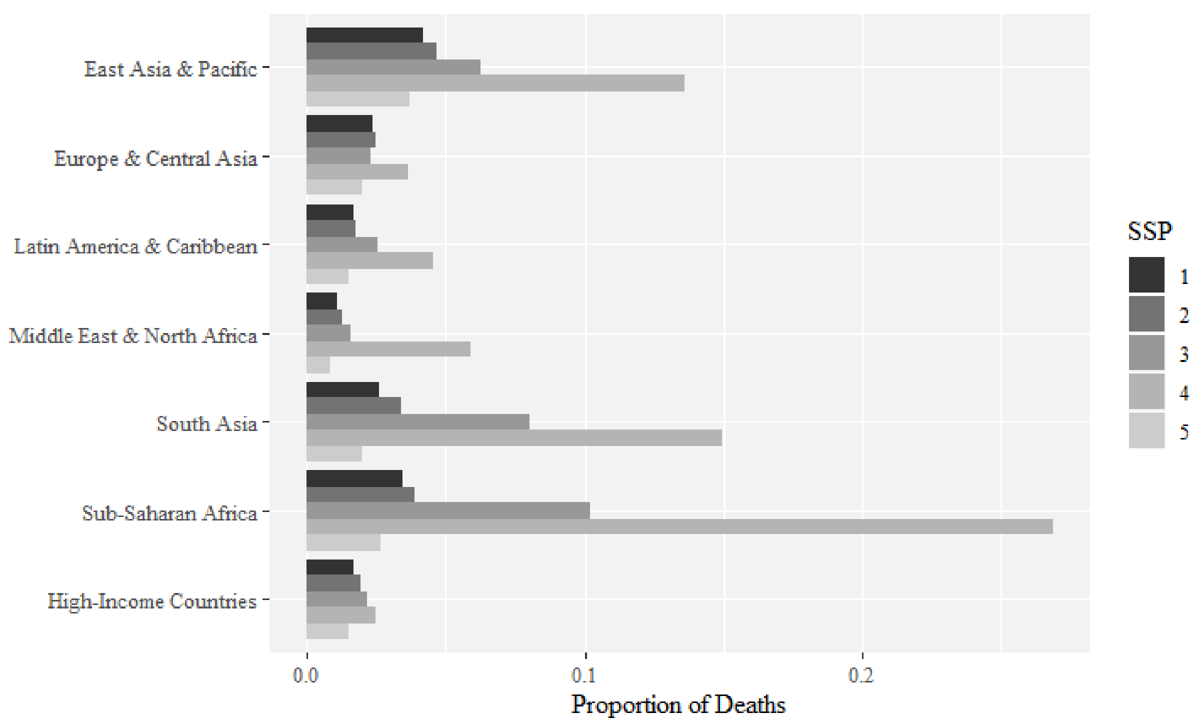


Figure 6f Proportion of age 5-14 mortality attributable to communicable diseases, 2080



Supplementary Appendix 1: List of Regional Groupings (based on World Bank 2019 classifications)

East Asia & Pacific		
Cambodia	Mongolia	Thailand
China	Myanmar	Timor-Leste
Fiji	North Korea	Tonga
Indonesia	Papua New Guinea	Vanuatu
Laos	Philippines	Vietnam
Malaysia	Samoa	
Micronesia; Federated States of	Solomon Islands	
Europe & Central Asia		
Albania	Kazakhstan	Russia
Armenia	Kosovo	Serbia
Azerbaijan	Kyrgyzstan	Tajikistan
Belarus	Macedonia	Turkey
Bosnia and Herzegovina	Moldovia	Turkmenistan
Bulgaria	Montenegro	Ukraine
Georgia	Romania	Uzbekistan
Latin America & Caribbean		
Belize	El Salvador	Nicaragua
Bolivia	Grenada	Paraguay
Brazil	Guatemala	Peru
Colombia	Guyana	St. Lucia
Costa Rica	Haiti	St. Vincent and the Grenadines
Cuba	Honduras	Suriname
Dominican Republic	Jamaica	Venezuela
Ecuador	Mexico	
Middle East & North Africa		
Algeria	Jordan	Palestine
Djibouti	Lebanon	Syria
Egypt	Libya	Tunisia
Iran	Morocco	Yemen
Iraq	Oman	
South Asia		
Afghanistan	India	Pakistan

Bangladesh	Maldives	Sri Lanka
Bhutan	Nepal	
Sub-Saharan Africa		
Angola	The Gambia	Rwanda
Benin	Ghana	Sao Tome and Principe
Botswana	Guinea	Senegal
Burkina Faso	Guinea-Bissau	Sierra Leone
Burundi	Kenya	Somalia
Cape Verde	Lesotho	South Africa
Central African Republic	Liberia	South Sudan
Chad	Madagascar	Sudan
Comoros	Malawi	Swaziland
Congo Republic	Mali	Tanzania
Cote d'Ivoire	Mauritania	Togo
DRC	Mauritius	Uganda
Equatorial Guinea	Mozambique	Zambia
Eritrea	Namibia	Zimbabwe
Ethiopia	Niger	
Gabon	Nigeria	
High-Income Countries		
Argentina	Hong Kong	Puerto Rico
Australia	Hungary	Qatar
Austria	Iceland	Saudi Arabia
The Bahamas	Ireland	Seychelles
Bahrain	Israel	Singapore
Barbados	Italy	Slovakia
Belgium	Japan	Slovenia
Brunei	Kuwait	South Korea
Canada	Latvia	Spain
Chile	Lithuania	Sweden
Croatia	Luxembourg	Switzerland
Cyprus	Malta	Taiwan
Czech Republic	Netherlands	Trinidad and Tobago
Denmark	New Zealand	United Arab Emirates
Estonia	Norway	United Kingdom
Finland	Oman	United States of America
France	Panama	Uruguay
Germany	Poland	

Greece	Portugal	

Note: Jurisdictions not included in the above table are not modeled in IFs.