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Chapter 18

The Loss from Pandemic Influenza Risk

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INTRODUCTION

The 2014–16 Ebola virus outbreak in West Africa reminded the world that enormous economic and human losses result from the uncontrolled spread of a deadly infection. Less noticed was the likelihood that a pandemic with characteristics similar to the 1918 influenza pandemic would have killed about 10 times as many people in Liberia, Guinea, and Sierra Leone as did Ebola. The global death total from such a pandemic could be 2,500 times higher than the World Health Organization's (WHO) estimate of 11,300 deaths from Ebola through March 16, 2016 (WHO 2016a).

Economic Loss

In addition to the enormous loss in terms of human suffering, an important dimension of loss lies in a pandemic's effect on income. Premature deaths reduce the size of the labor force, illness leads to absenteeism and reduced productivity, resources flow to treatment and control measures, and individual and societal measures to reduce disease spread can seriously disrupt economic activity. The World Bank has generated estimates of these losses (Burns, Mensbrugge, and Timmer 2008; Jonas 2013) and found that a pandemic of the severity of that in 1918 could reduce global gross domestic product (GDP) by about 5 percent and that the disruptive effects of avoiding infection would account for about 60 percent of that total. McKibbin and Sidorenko (2006) examined

the consequences of a range of pandemic severities (mild, moderate, severe, and ultra) and estimated income losses exceeding 12 percent of gross national income (GNI) worldwide and exceeding 50 percent in some low- and middle-income countries (LMICs).

Value of Lives Lost and Illness Suffered

The second major dimension of loss from a pandemic lies in the intrinsic value of lives prematurely lost and of illness suffered. Efforts to measure the dollar value of losses associated with premature mortality and illness remain imperfect. Nevertheless, extensive empirical findings appear in the economics literature, particularly for losses from premature mortality (Hammit and Robinson 2011; Lindhjem and others 2011; Viscusi 2014). Although the valuation of a change in mortality appears most frequently in the environmental economics literature, the report of the *Lancet* Commission on Investing in Health—"Global Health 2035: A World Converging within a Generation," or Global Health 2035—systematically applied these methods to global health (Jamison and others 2013; OECD 2014). This chapter estimates the magnitude of this dimension of loss from pandemic influenza using standard methods.

This chapter assesses the *expected* annual loss from a pandemic with risk r , expressed as a percentage of the annual probability of a pandemic, and severity s , expressed as the fraction of the world population that

dies from the pandemic. It uses the historical and modeling literatures to generate expected values of r and s , and it uses those values to generate estimates of mortality and its associated losses. The estimated loss is relative to the counterfactual of no risk ($r = 0$). Box 18.1 places the results of our research into context.

REVIEW OF HISTORICAL PANDEMIC RISK AND SEVERITY

The literature defines pandemic “severity” in different ways. We define it in terms of mortality only. Paules and Fauci (2017) point to long-term morbidity and disability consequences of a range of potential pandemic pathogens. Global Health 2035 appendix 4 introduced the term *standardized mortality unit* (SMU) in which 1 SMU is 10^{-4} . For example, the pandemic of 1957–58 had a global death rate of 3 SMU (or 0.03 percent of the population).

In the world’s 2015 population of 7.35 billion, 1 SMU corresponds to 735,000 deaths. Seasonal influenza causes about 250,000 to 500,000 deaths per year (WHO 2016b). We define *severe* pandemics as having mortality rates of 10 SMU or greater, and *moderately severe* pandemics as having a severity less than 10 SMU.

The historical record suggests that the 1918 influenza pandemic was an outlier, with unusual circumstances, including the co-occurrence of World War I. No other influenza pandemic had such devastatingly high mortality rates. The 1918 influenza pandemic had an estimated 20 million to 50 million (or more) excess deaths from 1918 to 1920, most of which were concentrated in 1918. In 1918, 20 million deaths would constitute 1.1 percent of the world’s population. In addition to the severe pandemic of 1918, the sparse record suggests that 12 to 17 other pandemics have occurred since 1700. Of these, we identify six as having substantial excess mortality, with mortality rates in the range of 3–8 SMU (table 18.1).

Box 18.1

Research in Context

Evidence before This Study

We searched PubMed and Google Scholar for all studies on influenza epidemics and pandemics. We also searched libraries at Harvard University and the University of Hawai‘i for historical documents and life tables. Studies were restricted to those with abstracts in English.

Our review showed a wide range in the estimates of deaths caused by the 1918 influenza pandemic. We found three studies that examined loss in national income from influenza pandemics of varying severity. A substantial literature exists that estimates the monetary value of mortality risk—the value of a statistical life—but we found only one paper in that literature that estimates the loss from elevated mortality associated with pandemics. Integrative estimates of the magnitude of pandemic risk were found in only two sources, both partially proprietary.

Added Value of This Study

This study provides the first assessment of the expected value of losses from pandemic influenza and, specifically, the value of intrinsic losses from

increased mortality. It uses an expected value framework to estimate losses from an uncertain and rare event over time. Past work found that income losses (US\$80 billion per year) are much lower than the losses from increased mortality (US\$490 billion per year). We further analyzed economic losses of national income levels by world regions and conducted sensitivity analyses on the value of a statistical life.

Implications of All of the Available Evidence

Estimates of intrinsic loss substantially exceed previous estimates of income loss. As significant as the direct effect of a pandemic on income appears to be, we conclude that intrinsic losses far exceed the income losses. This finding points to the need for more attention to pandemic risk in public policy and to the value of enhanced understanding of both the magnitude and the consequences of pandemic risk. Low- and middle-income countries would suffer more than high-income countries in mortality losses. Further studies to investigate the potential losses from pandemics from other causes are ongoing.

Table 18.1 Worldwide Mortality from Selected Influenza Pandemics, 1700–2000^a

Year	Estimated worldwide pandemic-related deaths (millions)	Estimated world population (millions)	Severity, <i>s</i> (fraction of world population killed, SMU) ^b
1729 ^c	0.4	720	6
1781–82 ^c	0.7	920	8
1830–33 ^c	0.8	1,150	7
1898–1900 ^c	1.2	1,630	7
1918–20 ^{c,d}	20.0–50.0	1,830	110–270
1957–58 ^c	1.0	2,860	3
1968–69 ^c	1.0–2.0	3,540	3–6

Note: SMU = standardized mortality unit.

a. The table includes pandemics dating from 1700 to 2000 for which severity could be ascertained from the literature. Morens and Fauci (2004) and Morens and Taubenberger (2011) identify 12 to 17 pandemics in the period from 1700 to 2000, but many of those resulted in lower mortality than those in this table (or had mortality levels that could not be ascertained).

b. The SMU represents a 10^{-4} mortality risk and is used to represent small numbers as integers. For example, the 1729 pandemic led to an elevation in mortality of 0.06 percent of the world's population, which is more conveniently expressed as 6 SMU. In the world's 2015 population, 1 SMU corresponds to 735,000 deaths.

c. See Potter (2001).

d. See Beveridge (1991); Ghendon (1994); Johnson and Mueller (2002).

Although the world may be expected to experience moderately severe to severe pandemics several times each century, there is consensus among influenza experts that an event on the very severe scale of the 1918 pandemic may be plausible but remains historically and biologically unpredictable (Taubenberger, Morens, and Fauci 2007). A modeling exercise conducted for the insurance industry concluded that 100 to 200 years would pass before a 1918-type pandemic returned, but the exercise acknowledged major uncertainty (Madhav 2013). Although a biological replica of the 1918 influenza pandemic would result in lower mortality rates than those that occurred in 1918 (Madhav 2013), other studies point to the possibility that exceptionally transmissible and virulent viruses could lead to global death rates substantially higher than in 1918 (McKibbin and Sidorenko 2006; Osterholm 2005).

In general, lower-income areas of the world suffered disproportionately in 1918; in particular, India suffered a major share of global pandemic mortality (Davis 1968). Similarly, Madhav (2013) and Morens and Fauci (2007) argue that a modern epidemic would disproportionately affect poor countries. However, China's mortality rate in 1918 was low, probably because of lower case fatality rates rather than lower incidence rates (Cheng and Leung 2007). This finding points to the possibility of heterogeneity between countries of comparable national income levels in a modern pandemic.

This chapter does not seek to provide a new review of the literature on mortality in previous pandemics but

rather to select plausible values from that literature to define reference cases. With Taubenberger and others (2007), we emphasize the uncertainty inherent both in the history and in projections drawn from it. In light of this literature and its attendant uncertainty, we develop and report results for two representative levels of severity. Table 18.2 defines the severity levels we use and indicates the levels of annual risk assigned to them. Box 18.2 provides the background to the calculation of expected severity that table 18.2 summarizes.

METHODS

The effort proceeds in two steps. First, information on pandemic severity is used to generate increases in age-specific death rates for the world and for each of the World Bank's four income groups of countries. Second, the literature on valuation of changes in mortality rates is used to generate estimates of the age-specific losses from mortality increase and, by extension, of total loss.

We begin by estimating the change in a population's age-specific mortality rate for the two severity reference cases. Estimates of the age-specific excess mortality rates of different populations from the 1918 pandemic are consistent in their form of a unique inverted U-shaped distribution, whereby adults ages 15 to 60 years experienced elevated rates compared to elderly persons (greater than age 60 years) (Luk, Gross, and Thompson 2001; Murray and others 2006). We use the specific U.S. data for age distribution of excess

Table 18.2 Worldwide Pandemic Risk: Two Representative Scenarios, 2015

Parameter	Moderately severe pandemic (< 10 SMU) ^a	Severe pandemic (≥ 10 SMU) ^b	Any pandemic
1. Annual probability, r^a (%)	2.0	1.6	3.6
2. Return time, $1/r$ (years)	50	63	28
3. Average severity (SMU) ^c	2.5	58	27
4. Expected severity, s^d (SMU)	0.05	0.93	0.98

Note: SMU = standardized mortality unit.

a. The SMU represents a 10^{-4} mortality risk and is used to represent small numbers as integers. For example, the 1729 pandemic led to an elevation in mortality of 0.06 percent of the world's population, which is more conveniently expressed as 6 SMU. In the world's 2015 population, 1 SMU corresponds to 735,000 deaths.

b. These severity states are mutually exclusive. Hence, the annual probability of any pandemic is $[1 - (1 - 0.2)(1 - 0.016)] = 3.6\%$

c. The average severity of a pandemic in a given severity range is the expected value of severity given that a pandemic did in fact occur in that range. For example, 2.5 SMU is the expected severity given that a pandemic of severity $s < 10$ SMU has occurred.

d. "Expected severity" is average severity multiplied by the probability of occurrence [$s = \text{row (3)} \times \text{row (1)}$].

Box 18.2

Estimating Pandemic Severity and Risk

Following its usage in the insurance industry, we define risk, $r(s)$, in terms of "exceedance probability," the annual probability of a pandemic having a severity *exceeding* s . Again following insurance industry usage, the "return time" for s is the expected number of years before a pandemic of at least severity s will occur. If $t(s)$ is the return time, then $t(s) = r(s)^{-1}$. For example, if the annual probability of a pandemic of severity at least s is 1%, then its return time will be 100 years.

If we had access to a function $r(s)$ showing exceedance probability as a function of severity, our analysis could proceed using the expected value of severity of all pandemics. Because $r(s)$ is the complementary cumulative of the density for s , we would have

$$\text{Expected value of } s = \int_0^{\infty} r(s) ds. \quad (\text{B18.2.1})$$

Modeled estimates of the function $r(s)$ are not (publicly) available, so we approximated in two steps. We label pandemics with global $s \geq 10$ SMU as "severe." (As defined in the text, 1 SMU corresponds to a 10^{-4} mortality risk.) We label pandemics with global $s < 10$ as moderately severe. For the first step in our assessment of expected severity, we use recent history as a straightforward guide to frequency and severity

of moderately severe pandemics. In particular, we assume two such pandemics per century in this severity range with the average severity of 2.5 SMU globally. The *expected* annual severity of moderately severe pandemics is $0.02 \times 2.5 = 0.05$ SMU, corresponding to just over 35,000 expected annual deaths worldwide.

We turn next to equation B18.2.2 to estimate the contributions to expected severity from pandemic severity greater than 10 SMU worldwide (or 4 SMU in the United States). Let $s^*(x)$ be the contribution of pandemic severity greater than x to expected pandemic severity. Information available from AIR and its Pandemic Flu Model (AIR Worldwide 2014) allows calibration of $r(s)$ for the United States with $s \geq 4$:

$$s^*(4) = \int_4^{\infty} r(s) ds. \quad (\text{B18.2.2})$$

(Available data allow us to calibrate only an exceedance probability function, $r(s)$, for the United States. Hence, we start with that and translate to world values from severity ratios available in Madhav [2013].) The calibration points to a very fat-tailed distribution. The hyperbolic family of complementary cumulative distributions provides natural candidates for $r(s)$, and we parameterize the hyperbolic in terms of its expectation and the fatness of its tail

box continues next page

Box 18.2 (continued)

(see Jamison and Jamison 2011, table 2, in the formally identical context of discounting). Thus,

$$r(s) = [1 + m(1 - f)s]^{-[1 + 1/(1 - f)]} \quad (\text{B18.2.3})$$

where $1/m$ is the expected value of s , and f indicates the fatness of the tail (smaller values imply a fatter tail). Our calibration yields a value of $m = 1.8$ and $f = -2$. Hence, $s^*(0) = 1/1.8 = 0.56$. $s^*(4)$ is given as

$$s^*(4) = 0.56 - \int_0^4 (1 + 3ms)^{-1.33} ds, \quad (\text{B18.2.4})$$

and the integral is approximately 0.38. (For small values of s , equation B18.2.3 substantially overestimates r when the equation for $r(s)$ has been calibrated to fit larger values of s and thus the need for this two-step procedure.) Hence, $s^*(4) = 0.56 - 0.38 = 0.18$, which is the contribution to expected severity in the United States of severity levels ≥ 4 SMU. We infer global severity from the severity in the United States using the approach described in the main text.

Madhav (2013), using the AIR model, estimates that a 1918-type pandemic would kill 21 million to 33 million people in today's world. She reports a mid-range severity for the United States of such a pandemic of 8.8 SMU with a return time of 100 to 200 years. Equation B18.2.3 predicts that the return time for a pandemic of at least that severity is about 175 years.

Our calibrated value of -2 for f , the tail fatness parameter in equation 2.1.3, suggests that the distribution of exceedance probabilities is very fat tailed indeed. An exponential distribution for $r(s)$ could be considered to be neither fat nor thin tailed.

Calibrating an exponential as we did for the hyperbolic—so that the contribution to expected severity of severity ≥ 4 SMU is equal to 0.18—gives $r(s) = e^{-0.57s}$, and a return time for a 1918-type pandemic of 150 years, quite close to the 175 years of equation B18.2.3. However, for $s = 4$ in the United States (over 7 million deaths worldwide), the exponential gives an unrealistic return time of only 10 years whereas equation B18.2.3 gives 63 years. AIR (AIR Worldwide 2014) estimates that an extreme pandemic with $s = 30$ in the United States (and perhaps 100 million deaths worldwide) has a return time of 1,000 years, and equation 2.1.3 gives 875 years. The exponential would give 27 million years.

Clearly, uncertainty surrounds the numbers we use to reflect the likelihood of pandemics of varying levels of severity. In particular, we point to recent estimates (Madhav and others 2018) of exceedance probability and pandemic risk that use methods similar to those of AIR but come to a substantially smaller number of expected annual deaths. However, our numbers represent conservative choices that are broadly consistent with historical experience and modeling parameters. Substantially greater severities and likelihoods have been discussed by Madhav (2013) and colleagues elsewhere in the literature (Bruine De Bruin and others 2006; McKibbin and Sidorenko 2006; Osterholm 2005). As Morens and Taubenberger (1977, 277) stated, “With human influenza the only certain thing seems to be uncertainty.” We would slightly modify that statement to assert the virtual certainty that, “sooner or later, the world will again suffer a severe pandemic.”

deaths to generate age distributions for the world, adjusting for greater absolute increases elsewhere (Luk, Gross, and Thompson 2001). The fatality rate among young adults, although high in the 1918 influenza pandemic, was relatively low in the 1957 and 1968 epidemics (Simonsen and others 1998). We also use an alternative and more typical distribution of excess mortality, where young children and elderly persons are disproportionately affected, as well as a combination of the two, assuming the same proportional increase in mortality for all age groups. Our final calculations are based on the assumption that moderately severe pandemics will have age distributions like those of the 1957 and 1968 pandemics, whereas severe pandemics will

have age distributions of death like those of the 1918 pandemic.

Using the age distributions of populations and the life tables from the *World Population Prospects* of the United Nations Population Division (2015), we calculate excess deaths and the estimated reduction in life expectancy based on these age-specific mortality rates (Preston, Heuveline, and Guillot 2000). Table 18.3 shows the results for our severity categories. Our *expected* annual pandemic death total across both severities is 720,000 (or 1.2 percent of the number of deaths in 2015), resulting in a decrease in life expectancy at birth by 0.3–0.4 years in low-income countries (LICs) and LMICs.

Table 18.3 Expected Annual Influenza Pandemic Deaths, by Country Income Group, 2015^a

Parameter	Income level ^b				
	Low	Lower-middle	Upper-middle	High	World
1. Population (millions)	640	2,900	2,400	1,400	7,350
2. Moderately severe pandemics					
2.1. Relative pandemic severity ^c	4	3	2	1	n.a.
2.2. <i>Expected</i> annual pandemic-related mortality rate (SMU)	0.08	0.06	0.04	0.02	0.05
2.3. <i>Expected</i> excess deaths per year [$x = (1) \times (2.2)$]	5,100	18,000	9,600	2,800	37,000
3. Severe pandemics (all severities combined)					
3.1. Relative pandemic severity ^c	10	7	4	1	n.a.
3.2. <i>Expected</i> annual pandemic-related mortality rate (SMU)	1.8	1.26	0.72	0.18	0.93
3.3. <i>Expected</i> excess deaths per year [$x = (1) \times (3.2)$]	120,000	370,000	170,000	25,000	680,000
4. <i>Expected</i> totals					
4.1. <i>Expected</i> mortality rate (SMU)	1.9	1.3	0.76	0.2	0.98
4.2. <i>Expected</i> excess deaths per year [$x = (2.3) + (3.3)$]	125,000	390,000	180,000	28,000	720,000
					(430,000–1,000,000) ^a

Note: n.a. = not applicable. In the “World” column, the rows on pandemic severity are not applicable because this column incorporates all pandemic severities.

a. Very substantial uncertainty adheres to all data in panels 2–4 of this table. We judge that ± 40 percent reasonably reflects this uncertainty. AIR’s (AIR Worldwide 2014) mortality estimates for a 1918-type pandemic occurring today are given ± 22 percent, and we have amplified that somewhat (Madhav 2013). Rather than report a ± 40 percent range, this table reports only our point estimates except for our estimate of total annual expected deaths where we state the range.

b. We use the World Bank’s income level classification of countries (World Bank 2015).

c. Relative severity indicates severity in each income group relative to the high-income group. This ratio is assumed to be different for each level of severity. Our estimates for severe pandemics come from AIR (Madhav 2013). AIR estimates a narrow range of mortality rates across high-income countries (6–11 SMU) for its model of a 1918-type pandemic, and the relative severities we indicate are consistent with the HIC rates and AIR’s estimate of 21 million to 33 million deaths globally in such a pandemic. Evidence for the moderate pandemics of 1957–58 and 1968–69 suggest a more compressed range for these less severe pandemics, and our relative severity numbers in row 2.1 reflect this. Alternative estimates of relative severity in lower-income countries are lower than those for AIR that we use, resulting in a lower estimated global death total.

Next, we place dollar values on the changes in mortality rates. Our specific calculations followed the methods used in *Global Health 2035* (Jamison and others 2013). We defined levels of our valuation metric ν of 0.7, 1.0, 1.3, and 1.6 percent of income per capita per SMU of mortality increase, that is, per 1/10,000 increase in mortality risk for one year for countries in each of the World Bank’s four income groups of countries: 0.7 percent was used for LICs; 1.0 percent for lower-middle-income countries; 1.3 percent for upper-middle-income countries (UMICs); and 1.6 percent for HICs. In calculating the value of change in mortality at age, we used as a reference the literature’s value as a fraction of GNI per capita for age 35 years. This amount was adjusted up or down for ages other than 35 years in proportion to the ratio of life expectancies at those ages to life expectancy at age 35 years. Hence, for a given level of overall mortality, the value of mortality loss will depend on which of the age distributions of excess pandemic mortality described is assumed.

RESULTS

Table 18.4 shows the results of our calculation of the value of intrinsic loss from pandemic risk, using values of ν of 0.7–1.6 percent of GNI per SMU, depending on income category. We stress that these are expected annual values of loss associated with the indicated risks of pandemics in the severity ranges we have chosen. Expected losses from an actual severe pandemic would be about 60 times as large. The World Bank expresses income loss figures as expected annual values but uses different values for annual pandemic risk.

Table 18.4 shows our estimate of the expected annual loss for the world as a whole from the intrinsic loss from pandemic risk to be -0.6 percent of global income or about US\$490 billion per year. Loss varies by income group, from a little over 0.3 percent in HICs to 1.6 percent in lower-middle-income countries.

Although the direct effect of a pandemic on income appears to be significant, we conclude that intrinsic losses

Table 18.4 Value of Mortality Losses from Pandemic Risk, by Country Income Group, 2015
(age-dependent VSMU)

Parameter	Income level ^a				
	Low	Lower-middle	Upper-middle	High	World
1. Economic parameters					
1.1 Income, Y (trillions of 2013 US\$)	0.7	6.0	20.0	54.0	80.0
1.2 Per person income, y (2013 US\$)	780	2,300	8,200	41,000	11,000
1.3 v (%) ^b	0.7	1.0	1.3	1.6	n.a.
2. Losses from pandemic ^c					
2.1 <i>Expected</i> annual value of mortality loss, C (billions of 2013 US\$) ^d	-7	-100	-200	-180	-490 (-290 to -690)
2.2 Annual mortality loss, c [as % of income = (2.1) ÷ (1.1)]	-1.1	-1.6	-1.0	-0.34	-0.62 (-0.37 to -0.87)

Note: n.a. = not applicable; VSMU = value of a standardized mortality unit. In the "World" column, row 1.3 on pandemic severity is not applicable because this column incorporates all pandemic severities.

a. We use the World Bank's income data and income level classification of countries (World Bank 2015).

b. We use " v " to denote the value of a 1-in-10,000 risk of death, expressed as a percentage of per capita GNI. The dominant position in the literature is that lower-income countries should have lower values for v (Hammit and Robinson 2011). The literature provides weak quantitative guidance on how v should vary with y , if at all, and the numbers we have chosen should be viewed as reasonable assumptions within the spirit of the literature.

c. Very substantial uncertainty adheres to these cost estimates (see note a, table 18.3). We judge that ± 40 percent reasonably reflects this uncertainty but report that range for our estimates of worldwide costs only.

d. For any given value of s , our calculation of the value of intrinsic loss from a pandemic depends on the age distribution of deaths from the pandemic, and the calculations reported here use different age distributions for pandemics of different severities. In particular, for moderately severe pandemics, we assume an older age distribution of deaths, typical of such pandemics. For severe pandemics, we assume the younger age distribution of deaths that characterized the 1918 pandemic.

far exceed the loss from lost income. We referred to estimates in the literature of the income loss from pandemics of differing levels of severity (Burns, Mensbrugge, and Timmer 2008; Jonas 2013; McDonald and others 2008; McKibbin and Sidorenko 2006). Though our severity categories differ from theirs, the values of 1 percent of global income from a moderately severe pandemic and 4 percent from a severe pandemic are consistent with estimates in the literature. Using our estimates of the annual probabilities of such pandemics (table 18.2), we find expected annual income losses globally of US\$16 billion for moderately severe pandemics and US\$64 billion for severe pandemics, for a cost of approximately US\$80 billion per year. Table 18.4 shows an expected annual value of mortality loss from pandemics of US\$490 billion, of which 95 percent is from severe pandemics. (See annex 18A for further details on research methods.)

DISCUSSION

Expected annual pandemic losses appear substantial. Comparing the loss from pandemic risk with losses from climate change is instructive. As with pandemic risk, much uncertainty is attached both to the magnitude of future climate change and to the possible losses

(Moore and Diaz 2015). In contrast to the modest number of studies on potential pandemic loss, there are hundreds of studies on the cost of climate change and the social cost of carbon (Pizer and others 2014; Tol 2013). Global carbon dioxide emissions were on the order of 36,000 million tons in 2013, containing 6,200 million tons of carbon (Global Carbon Project 2015). Estimates of the social cost of carbon vary widely, but if it were around US\$120 per ton, then the cost of carbon dioxide emissions in 2013 would be about 1 percent of world income; US\$120 per ton is within the range of available estimates (Nordhaus 2010; Tol 2013). One must add the losses from carbon in carbon dioxide to the losses from methane, which are likely to be substantial (Smith and others 2013). The synthesis of the 2014 report of the Intergovernmental Panel on Climate Change (IPCC) assessed the literature and estimated that global economic losses for warming of 2.5°C higher than pre-industrial levels range from 0.2 to 2.0 percent of income (Pachauri and others 2014). In comparison, our expected annual intrinsic loss from pandemic risk (at 0.7 percent of global income) lies 25 percent higher than the low end of the range of the IPCC's estimated range for global warming.

Although most studies of the cost of climate change fail to include the intrinsic loss of increased mortality

risk, the effect of doing so may be modest. The IPCC report anticipates increased risks, with very high confidence, of ill health owing to heat waves and fires, undernutrition from diminished food production in poor regions, and increased foodborne and waterborne diseases and some vectorborne and infectious diseases (Pachauri and others 2014). Modest reductions in cold-related mortality and morbidity will be offset by the magnitude and severity of the increased risks. Although the IPCC presents scenarios of health risks, the aggregate effect of climate change on mortality was not summarized. However, the gradual nature of warming allows time for costly adaptations that could be expected to reduce the mortality consequences. A recent paper points to potentially important mortality reductions in the United States resulting from efforts to keep U.S. emissions consistent with global warming of 2°C (Shindell, Lee, and Faluvegi 2016). These benefits appear to flow almost entirely from reduced pollution rather than slower atmospheric warming. Most health losses from climate change are then likely to be included in the income losses from adaptation rather than included separately.

Another useful comparator for pandemic risk lies in deaths from selected alternative causes. The expected annual number of pandemic influenza deaths for 2015 in our reference cases is 720,000 (table 18.3). One might reasonably add 300,000 deaths per year from seasonal influenza to this number for a total of over 1 million deaths (WHO 2016b). In comparison, Mathers (2018) reports new WHO estimates for the diseases of comparable magnitude for 2015 (table 18.5).

Earlier studies have estimated losses from disease that included valuation of mortality consequences. Ozawa and others (2011), for example, estimated the losses from vaccine-preventable diseases, and Watkins and Daskalakis (2015) estimated burdens from rheumatic

heart disease using methods closely related to ours. Far more studies assess the losses from specific environmental risk factors (OECD 2014).

SENSITIVITY TESTS AND LIMITATIONS

Sensitivity to Assumptions

The methods used to value mortality risk have limitations. The valuation of health risks—including fatalities, illness, and injuries—is inherently difficult because money is often an ineffective substitute for dimensions of human well-being. In practice, however, these estimates are obtained from ex post observations of the labor market and reflect the way people differentially value and trade off very small fatality risks for income. Substantial variation exists both in the estimated value of a small mortality risk at a given age in the United States and in the way the valuation (v) should vary across ages and countries (Hammit and Robinson 2011; Lindhjem and others 2011). Our calculations to test the sensitivity of our results to this alternative assumption found a change of only about 5 percent in our headline number of US\$490 billion.

Hammit and Robinson (2011) have assembled the evidence that the value of mortality risk as a percentage of income in LICs may be less than for HICs. Global Health 2035 did not include this potential effect in its calculations (Jamison and others 2013). This chapter does include an adjustment for this effect, which leaves estimates of losses in HICs unchanged but reduces our estimated cost for the world as a whole. We assessed the sensitivity of our results to alternative assumptions on this point and others and concluded our main findings to be robust to the specific assumptions made.

Limitations

A key limitation of this study is its use of historical mortality estimates and modeled estimates from various sources to estimate pandemic risk. As we have noted throughout, the estimates we use for pandemic risk, r , and severity, s , remain subject to substantial inherent uncertainty. Although the AIR modeling efforts (Madhav 2013) on which we rely explicitly account for potentially increased risks associated with increased air travel and mobility of persons and goods, as well as increased urbanization, we lacked access to the full results of that study. Similarly, whereas AIR attempted to account for decreased risks associated with increased incomes, schooling, and access to health care services—including vaccination, antiviral medications, improved infection control, increased surveillance, and real-time communications—we could use that information only indirectly.

Table 18.5 Causes of Death with Magnitude Comparable to Expected Deaths from Pandemic Influenza, 2015

Cause of death	Magnitude of deaths
Tuberculosis	1.4 million
HIV/AIDS	1.1 million
Maternal mortality	0.3 million
Cancers	8.8 million
Ischemic heart disease	7.9 million
Stroke	6.2 million

Source: Mathers 2018.

Note: HIV/AIDS = human immunodeficiency virus/acquired immune deficiency syndrome.

A modeling effort separate from that by AIR uses similar methods but different assumptions, resulting in a smaller expected annual mortality, although in the same broad range (Madhav and others 2018). In contrast to the robustness of our conclusions with respect to how to value mortality risk, our findings respond sensitively to how we model r and s . Increased global temperature may reduce the case fatality rates of influenza, but it may also increase the transmissibility of the virus. Population-level immunity against a particular influenza strain likely varies by region and by age distribution, although the extent of that variation is not known. In 1918, a few countries did not experience the typical inverted U-shaped distribution of excess age-specific mortality from influenza. In Mexico, elderly persons were not spared from excess mortality in contrast to those in the United States, although its working-age population suffered as significantly as those in other regions. (Chowell and others 2010). In China, mortality rates were low at all ages. The characteristics of new pandemic viral strains depend on poorly understood patterns of immunity and the complex and poorly understood process of viral evolution and genetic re-assortment in dynamic ecosystems (Morens, Folkers, and Fauci 2004).

An additional limitation of this study is its omission of an estimated value of the intrinsic undesirability of non-fatal illness or of pandemic fear—significant characteristics of population response to SARS (severe acute respiratory syndrome) in Taiwan, China (Liu and others 2005). The high media salience and associated fear may also lead populations to overreact to mild pandemics, increasing the effect beyond what might be considered optimal (Brahmbhatt and Dutta 2008). The economics literature currently provides value estimates almost entirely for mortality risk. However, when appropriate valuations of illness and fear become available, our results may be shown to be underestimates for this reason.

A final limitation of this study is its estimation of losses from only pandemic influenza risk. Further work should extend this analysis to at least 11 additional pathogens that the WHO regards as known potential causes of pandemics or epidemics (Brende and others 2017). Including most other known pathogens may increase the risk to about 50 percent over that from influenza alone (personal communication, J. Douglas Fullam).

CONCLUSIONS

World Bank studies estimate approximately 5 percent of global income as the probable income loss from a pandemic as severe as that of 1918. This chapter estimates the value of intrinsic loss from the excess deaths from potential pandemics. Our estimate of the expected number of

pandemic deaths per year is 720,000. The expected annual intrinsic cost that results for the world is US\$490 billion, or 0.6 percent of global income. In comparison, the IPCC estimates that the likely cost of global warming falls in the range 0.2 to 2.0 percent of global income annually.

Posner (2004) has argued that economics and the social sciences generally fail to pay adequate attention to potentially catastrophic events, although literature is emerging (Barro and Jin 2011; Pike and others 2014; Pindyck and Wang 2013). Concluding that the academic and policy attention provided to pandemic risk falls well short of a sensibly estimated comparison of that risk with its consequences is reasonable. However, recent trends are encouraging. As he prepared to host the G-7 (Group of Seven) in 2016, Japanese Prime Minister Shinzo Abe placed high priority on dealing with health crises (Abe 2015). German Prime Minister Angela Merkel, as host for the meeting of the G-20 (Group of Twenty) in Hamburg in June 2017, maintained this high-level interest by including specific attention to pandemic preparedness. Hosted for the WHO and the World Bank by the U.S. National Academy of Medicine, a recent Commission on a Global Health Risk Framework for the Future pointed to practical and significant financial and organizational steps to improve pandemic preparedness and response (GHRF Commission 2016; Sands and others 2016). Despite these encouraging indicators, Moon and others (2017) have concluded that inadequate action followed the warning from the Ebola virus in West Africa.

In chapter 17 of this volume, Madhav and others (2018) assess the costs and probable effects of investments to reduce the likelihood or potential severity of a pandemic. These investments could range from research and development to a universal influenza vaccine to much-enhanced surveillance to pre-investment in manufacturing capacity for drugs and vaccines (Varney and others 2017). Important investments along these lines are indeed being made. Given this chapter's estimate of the intrinsic expected loss from pandemic risk, the economic benefits of further investments are likely to substantially exceed their cost.

ANNEX

The annex in this chapter is as follows. It is available at <http://www.dcp-3.org/DCP>.

- Annex 18.A. Materials and Methods

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NOTE

World Bank Income Classifications as of July 2014 are as follows, based on estimates of gross national income (GNI) per capita for 2013:

- Low-income countries (LICs) = US\$1,045 or less
- Middle-income countries (MICs) are subdivided:
 - (a) lower-middle-income = US\$1,046 to US\$4,125
 - (b) upper-middle-income (UMICs) = US\$4,126 to US\$12,745
- High-income countries (HICs) = US\$12,746 or more.

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