Published in final edited form as:

Popul Stud (Camb). 2015 July ; 69(2): 201–218. doi:10.1080/00324728.2015.1045546.

The Boundaries of Genocide: Quantifying the Uncertainty of the Death Toll During the Pol Pot Regime (1975-1979)

Patrick Heuveline, PhD

California Center for Population Research, University of California Los Angeles

Abstract

Estimates of excess deaths under Pol Pot's rule of Cambodia (1975-79) range from under one million to over three million. The more plausible among those, methodologically, still vary from one to two million deaths, but this range of independent point estimates has no particular statistical meaning. Stochastically reconstructing population dynamics in Cambodia from extant historical and demographic data yields interpretable distributions of the death toll and other demographic indicators. The resulting 95-percent simulation interval (1.2 to 2.8 million excess deaths) demonstrates substantial uncertainty with regards to the exact scale of mortality, yet still excludes nearly half of the previous death-toll estimates. The 1.5 to 2.25 million interval contains 69 per cent of the simulations for the actual number of excess death, more than the wider (one to two million) range of previous plausible estimates. The median value of 1.9 million excess deaths represents 21 percent of the population at risk.

Keywords

Demographic Accounting; Estimation Techniques; Excess Mortality; Violent Deaths; Cambodia; Stochastic; Uncertainty

From April 1975 to January 1979, the government of Cambodia was officially known as *Democratic Kampuchea*. Today, many people in Cambodia remember its exact duration, “three years, eight months, and twenty days,” and are more likely to refer to this tragic period as “during Pol Pot”—the name taken by its actual leader, who died in 1998. In 2011, the Extraordinary Chambers in the Courts of Cambodia (ECCC) indicted the four highest-ranking surviving former *Democratic Kampuchea* officials. In accordance with the 1948 United Nations Convention on the Prevention and Punishment of the Crime of Genocide (United Nations 1951), the ECCC has focused on executions, deaths from exhaustion or starvation related to forced population movements and forced labour, and the treatment of specific ethnic and religious groups. The ECCC has thus reviewed specific actions and policies which took place in the context of the complete overhaul of Cambodia's political, administrative and social structures and the destruction of much of its infrastructure. Curtailing food production and annihilating disease prevention and treatment capacities in particular, the leadership of the Pol Pot Regime (PPR thereafter) thus contributed to a

general mortality crisis that might have indiscriminately killed more people than any of their more specific, targeted policies.

The scale of a mortality crisis is not among the criteria included in the literal definition of genocide in the 1948 United Nations Convention. Long delayed by domestic and global politics though, the ECCC might not have been constituted to eventually indict the PPR leadership more than three decades after the fall of the regime and more than a decade after the death of Pol Pot himself were it not for the massive death toll. The authoritative historian of Cambodia, Chandler (1991) writes that the PPR left over a million dead, but existing estimates actually range from 741,000 to 3,315 million. To put those in perspective, the number of global war deaths has been estimated to average 378,000 annually during the 1985–94 period (Obermeyer et al. 2008), which on the same annualized basis would amount to 1.4 million excess deaths for the entire duration of the PPR. This figure is well within the range of plausible estimates for the PPR death toll alone, while Cambodia's population size then was about .15 percent of the world population size in 1990.

In this paper, I sought to assess the credibility of previous estimates of the PPR death toll and to determine how reliably we can estimate the actual level of the mortality under the PPR. The next section begins with a review of existing estimates to try and narrow the field to those that are plausible on methodological and empirical grounds. However, we must note that each of these estimates is but a single “best” point estimate, with an inherent unstated uncertainty that cannot be recovered from published materials. In other words, the plausibility of the range of plausible estimates cannot be readily assessed. To provide such an assessment, the rest of the paper presents results of a standard model of population dynamics that incorporates uncertainty in the extant historical and demographic data. In this stochastic framework, the model yields distributions of PPR mortality measures (the death toll, in absolute terms and relative to the population at risk, the number of violent deaths, and life expectancy at birth). As the 1948 United Nations Convention considers genocide as the “acts committed with the intent to destroy, in whole or in part, a national, ethnical, racial or religious group,” killing members of a group as well as “imposing measures intended to prevent births,” distributions are also provided for the birth deficit under the PPR. The final section of the paper discusses the statistical interpretation of these distributions, using them to quantify the likelihood of the estimate range and to compare the plausibility of previous estimates.

Background

Definitions of the death toll

Assessing how many deaths should the PPR be held accountable for involves two distinct types of considerations. The first ones are conceptual: which deaths can be attributed to the PPR? The second ones are methodological: how many of these deaths can be documented? On the conceptual side, the issue concerns possibly non-violent deaths that were nonetheless linked to the PPR policies of population displacement, forced labor, and restricting the availability of food and medicines. If considering only homicides perpetrated by PPR cadres or even other violent deaths (e.g., fatalities or mine-related accidents) seems insufficient, using the total number of deaths is equally unsatisfactory. Few opinions to the contrary

(Seltzer 2008), the general agreement is that no mortality is not a tenable benchmark for assessing a government's responsibility, since deaths remain unavoidable under the best government and circumstances.

The common approach in causal analysis involves comparing the prevailing situation to a counterfactual one; in this case the actual number of deaths to a counterfactual number of deaths had the PPR never taken over. Less straightforward is the definition of the reference period for comparing the actual and the counterfactual numbers of deaths. Should a regime taking over after years of civil war or a government leaving power in the midst of a famine, to which its disastrous resource management contributed, be accountable for some of these war-related or famine deaths? Even though these deaths might occur while the regime is not yet or no longer in power, the answer is probably yes, or at least in part. In practice however, a consensus would seem beyond reach as far as delineating the beginning and end point for this period of accountability, as well as what exact share of these deaths should be attributed to one regime rather than the ones that preceded or followed. In spite of the potential limitations, I followed most previous analysts and focused on the PPR death toll, defined as the difference in the estimated number of deaths between prevailing and counterfactual mortality—that is, “excess” mortality—strictly during the period the PPR was in power. I also sought to estimate the subset of these excess deaths that could be identified as violent deaths.

A typology of estimation approaches

I have reviewed the different approaches developed to estimate the death toll elsewhere (Heuveline 2001) and only briefly describe them below (see online Supplementary Material for further details). For expositional clarity, these approaches can be classified based on the type of evidence they most extensively rely on, even though most combine evidence from more than a single type: verbal (testimonies on the death/survival of relatives), demographic (censuses and surveys), or physical (bone remains). First available chronologically, verbal evidence was collected from refugees who had fled Cambodia toward the end of the PPR (Central Intelligence Agency 1980; Ea 1981) before a few independent researchers were able to collect testimonies in Cambodia as well (Kiernan 1996; Heder 1997). Similar testimonies continued to be collected into the early 1990s, taking advantage of the gradual accessibility of more remote Cambodian provinces (Sliwinski 1995). In the meantime, the post-PPR government had produced its own estimate by attempting to gather an exhaustive testimonial account throughout the country (Gordon 2007).

Even though this first approach may require some demographic data to scale up survival probabilities from the sample to the whole population, the second approach can be characterized by its near-exclusive use of demographic evidence. This approach yields an estimate of excess deaths as a residual (unaccounted for) term in a demographic reconstruction with actual population change, actual fertility and migration, and counterfactual mortality. The residual estimate can be obtained from a simple accounting equation with aggregate numbers of births, counterfactual deaths and migrants, or preferably by performing this accounting for each gender and age groups separately. Whereas samples of testimonies can be collected relatively quickly, however, a scientific population census

takes years to organize, even in peace time. The first aggregate accounting estimates of excess deaths (Vickery 1984), and the first to be disaggregated by gender and age groups (Banister and Johnson 1993) were based on official figures. These were obtained from a simple tally of head counts collected by the local administration in 1980 and updated annually thereafter. Disaggregated accounting was further refined as new demographic data became available. I used in previous work the 1992 electoral rosters assembled by the United Nations (1995) (Heuveline 1998), Neupert and Prum (2005) the first post-PPR General Population Census in 1998 (National Institute of Statistics 1999), and Lognard (2012) the most recent one to date, conducted in 2008 (National Institute of Statistics 2010).

The last type of estimation, based on physical evidence (e.g., bone remains), only concerns violent deaths. Beginning with a full mapping of mass grave pits conducted from satellite imagery, remote sensing, and ground penetrating radars, this approach continues with interviews, and in some cases, forensics to determine the time and cause of each death (Etcheson 2005). Violent deaths had previously been estimated from testimonies using respondents' reported cause of death, and apportioning the number of excess deaths between violent and non-violent (Ea 1981; Sliwinski 1995; Heder 1997). I also used in previous work disaggregated accounting by gender and age group to estimate the number of violent deaths (Heuveline 1998). This estimation requires a comparison with the counterfactual increase in non-violent mortality which can be derived from life tables for high-mortality populations (Preston et al. 1993).

An assessment of previous estimates

As summarized in Table 1, the seven existing estimates of violent deaths are widely scattered. The lowest three are in the order of 100,000 to 300,000 and the highest two almost identical at 1.1 million. The nine existing estimates of excess deaths range from 741,000 to 3.315 million. The highest figure is the only one based on a direct tally of excess-death reports. This governmental estimate is typically dismissed as propaganda on the ground that no attempt was made to identify multiple counts or to adjust for the differential probabilities of being reported. Likewise, the lowest figure consists of only total accounting, not disaggregated by gender and age groups. These two idiosyncratic estimations aside, the remaining estimates of the PPR death toll range from 1.0 million to 2.1 million.

Coincidentally or not, the one-to-two-million interval appears to be the most often reported range of PPR death toll estimates. The ECCC, historians, and the general public would likely prefer a single estimate, but one could hardly adjudicate between these figures derived with such different methodologies and evidence bases. For each method, a trend toward higher estimates over time can be detected in Table 1, but the later estimates are not necessarily superior to the earlier ones. Collected later, testimonies can originate from a more diverse set of respondents, but this requires respondents to remember more distant events. This longer recall period may reduce data quality. For demographic data, the 1998 census is clearly a more reliable source than previous surveys or administrative counts. To estimate the desired population size at the end of the PPR, however, the reconstruction then requires assumptions about fertility, mortality and migration for nearly two decades after the fall of the PPR (1979–98).

The range of existing estimates is merely a collection of point estimates, each one with its own uncertainty, unstated and unrecoverable ex-post from the published documentation, and is therefore not statistically interpretable. One particular sample-based estimation yielded a 1.843-to-1.869-million interval (Sliwinski 1995) that certainly underestimates the uncertainty inherent to this approach. However, the level of uncertainty is impossible to assess exactly. First, classic sampling designs with readily calculated standard errors cannot be implemented in such crisis settings (Hagan and Palloni 2005). Second, the conditions under which direct mortality estimates from sibling data would be unbiased (Gakidou and King 2003) were not met. As readily anticipated, in particular from the PPR policies of targeting potential enemies along kinship lines (Kiernan 1996; Weitz 2003), mortality clustering within families has been detected (Sliwinski 1995), but available methods to adjust for the differential probabilities of being reported (Trussell and Rodriguez 1990) were not used. Geographical clustering, uncertainty about the total population size to which to prorate estimated survival/death ratios, and uncertainty about baseline mortality add potential biases and uncertainty to the sample-based estimates.

In previous work, I attempted to go beyond the single “best-estimate” approach, by providing a relatively wide range of high/low figures that were based on alternative assumptions with respect to the reconstruction parameters (Heuveline 1998). While the derivation of different, plausible but somewhat extreme scenarios conveys some sense of the outcomes’ uncertainty, Lee (1985, p.234) has long pointed out that any single reconstruction represents but one plausible (e.g., internally consistent) demographic trajectory “among an infinity of different but equally plausible ones.” Each estimate of excess deaths—a residual term in the balancing equation of population change—is then just one of the estimates corresponding to one set of plausible estimates of other parameters in the demographic reconstruction. For the purpose of “quantifying our ignorance” (Lee 2004) regarding future population trends, probabilistic projections can be implemented. A similar approach can be applied to the demographic reconstruction in order to quantify the uncertainty in any outcome of interest.

Methods

Demographic reconstruction and models of population change

Briefly described above, the logic of demographic reconstruction readily emerges from the balancing equation of population change

$$N(t) = N(t-x) + B(t-x, t) - D(t-x, t) + I(t-x, t) - O(t-x, t) \quad (1)$$

where $N(t)$ is the number of persons alive in the population at time t , and $B(t-x, t)$, $D(t-x, t)$, $I(t-x, t)$, and $O(t-x, t)$ are respectively the number of births, deaths, in-migrants, and out-migrants between time $t-x$ and time t (Preston et al. 2001). When only some of the components in Equation 1 are known, the equation can be used to derive the sum of the remaining components. In demography, this is typically used to estimate the net flow of in and out migration, which is often poorly recorded, from the number of births and deaths, which are recorded in vital statistics and population sizes from two population censuses (Shryock and Siegel 1973). This logic can be extended to estimating the number of deaths in

the interval between two population counts with ancillary estimates of the number of births, in-migrants and out-migrants in the same interval. One only needs to further distinguish excess mortality from (counterfactual) baseline mortality to estimate the death toll. Assuming that we can estimate the counterfactual number of deaths corresponding to baseline mortality between time $t-x$ and time t , $\hat{D}^C(t-x, t)$, the number of excess deaths between time $t-x$ and time t , $\hat{D}^E(t-x, t)$, can then be derived as

$$\hat{D}^E(t-x, t) = \hat{N}(t-x) - \hat{N}(t) + \hat{B}(t-x, t) - \hat{D}^C(t-x, t) + \hat{I}(t-x, t) - \hat{O}(t-x, t) \quad (2)$$

To focus on violent mortality only, we need to estimate instead the counterfactual number of non-violent deaths corresponding to the actual increase in non-violent mortality only between time $t-x$ and time t , $\hat{D}^N(t-x, t)$, and derive the number of violent deaths between time $t-x$ and time t , $\hat{D}^V(t-x, t)$, as

$$\hat{D}^V(t-x, t) = \hat{N}(t-x) - \hat{N}(t) + \hat{B}(t-x, t) - \hat{D}^N(t-x, t) + \hat{I}(t-x, t) - \hat{O}(t-x, t) \quad (3)$$

Likewise, this approach can be used to estimate the birth deficit, that is, the gap between the actual number of births and the counterfactual, expected number of births expected had fertility remained at its baseline level. From an estimate of the counterfactual number of births corresponding to baseline fertility between time $t-x$ and time t , $\hat{B}^C(t-x, t)$, the number of missing births between time $t-x$ and time t , $\hat{B}^M(t-x, t)$, can then be derived as

$$\hat{B}^M(t-x, t) = \hat{N}(t-x) - \hat{N}(t) + \hat{B}^C(t-x, t) - \hat{D}(t-x, t) + \hat{I}(t-x, t) - \hat{O}(t-x, t) \quad (4)$$

As shown in Equation 4, the counterfactual number of births is estimated had fertility remained at its baseline level but with prevailing mortality. One could instead estimate the counterfactual number of births had both fertility and mortality remained at their baseline level. While the approach underlying Equation 4 corresponds to a more restrictive definition of the birth deficit, this approach has the advantage of being additive. The estimated birth deficit and the estimated death toll in Equation 2 add up to how much larger the population size would have been with counterfactual fertility and mortality both at baseline.

Like demographic projections, demographic reconstructions are preferably built upon a model of population dynamics disaggregated by gender and age-group rather than from population-level counts. Disaggregation presents at least two advantages. First, this approach uses information on gender and age distribution from census data and takes advantage of the extensive variation in fertility and survival over the life course, the latter embodied in age patterns of mortality models (Heuveline and Clark 2011). Better grounded empirically, the estimation of the counterfactual number of deaths (or births) is improved, and in turn, so is the estimation of excess deaths (or the birth deficit). Second, the breakdown of excess mortality by gender and age group provides useful information in itself. High-mortality model life tables (Preston et al. 1993) provide possible age distributions of deaths resulting from an increase in mortality from natural causes. In turn,

comparison of these with the actual age distribution of excess mortality allows for a decomposition of excess mortality between violent and non-violent mortality (Heuveline 1998).

The cohort-component model of population change (CCMPC thereafter) is by far the most commonly used model of population dynamics (Preston et al. 2001). In this model, the number of persons alive in the population at time t , $N(t)$, is broken down by gender and age groups of the same length x , except for the oldest persons of each gender, who are grouped in open-ended age intervals. The CCMPC can more compactly be written in matrix notation as

$$N(t) = [L(F(t-x, t), \beta(t-x, t), S(t-x, t)) * \{N(t-x) + (\alpha(t-x, t) \cdot \Delta(t-x, t))\}] + [(1 - \alpha(t-x, t)) \cdot \Delta(t-x, t)] \quad (5)$$

where $N(t)$ is the vector of gender and age-groups at time t , $(t-x, t)$ is the vector of differences between the number of in- and out-migrants between times $t-x$ and t by gender and age-group, and $L(F(t-x, t), \beta(t-x, t), S(t-x, t))$ is a matrix function of the vector of female age-specific fertility, $F(t-x, t)$, the sex-ratio at birth scalar, $\beta(t-x, t)$, and the vector of age-specific survival ratios, $S(t-x, t)$, all of them between times $t-x$ and t as well. The value of parameter $\alpha(t-x, t)$ can be chosen between 0 and 1 depending on the flow of migration between times $t-x$ and t , with .5 representing an even flow (constant number of migrants per unit of time) and 1 representing an “instantaneous” migration concentrated at time $t-x$. Implicit in Equation 5 is the common assumption that once they enter the population, immigrants survive to time t and bear children at the same rates as people already in the population at time $t-x$.

The logic used to derive Equations 2 to 4 from Equation 1 is readily repeated to derive excess mortality, violent mortality, or missing births from Equation 5. In the case of excess deaths, they can be estimated from

$$N(t) = [L(F(t-x, t), \beta(t-x, t), S^C(t-x, t)) * \{N(t-x) + (\alpha(t-x, t) \cdot \Delta(t-x, t)) - (\varepsilon(t-x, t) \cdot D^E(t-x, t))\}] + [(1 - \alpha(t-x, t)) \cdot \Delta(t-x, t)] - \{(1 - \varepsilon(t-x, t)) \cdot D^E(t-x, t)\} \quad (6)$$

where $S^C(t-x, t)$ is now the counterfactual survival ratio corresponding to baseline mortality between times $t-x$ and t , $D^E(t-x, t)$ is the vector of excess deaths times $t-x$ and t by gender and age groups, and $\varepsilon(t-x, t)$ is a scalar whose value between 0 and 1 accounts for the timing of excess mortality between times $t-x$ and t . Dropping the cumbersome references to the period $t-x$ to t , the solution now takes the form

$$\hat{D}^E = \varepsilon' \cdot \left[\left\{ \hat{N}(t-x) + (\hat{\alpha} \cdot \hat{\Delta}) \right\} - \left\{ L'(\hat{S}^C) * (\hat{N}(t) - (1 - \hat{\alpha}) \cdot \hat{\Delta}) \right\} \right] + (1 - \varepsilon') \cdot \left[\left\{ L(\hat{F}, \hat{\beta}, \hat{S}^C) * (\hat{N}(t-x) + (\hat{\alpha} \cdot \hat{\Delta})) \right\} - \left\{ \hat{N}(t) - ((1 - \hat{\alpha}) \cdot \hat{\Delta}) \right\} \right] \quad (7)$$

where ε' is a scalar that relates to the scalar ε (a monotonic, strictly positive function thereof—see Appendix for further details on the derivation of Equation 7 from Equation 6).

Equation 7 thus emphasizes the potential impact of the timing of excess mortality through the value of ε' , which act as a weighting function between two terms. These two terms represent the difference between the counterfactual and the actual population size at time $t-x$ and time t respectively, which can be very different when population grows or declines substantially between time $t-x$ and time t .

Defined here as the number of excess deaths during the period the country was ruled by the PPR, the death toll can be estimated from Equation 7 by setting $t-x$ as the onset of the regime, April 17th, 1975, and t as the day it fell, January 7th, 1979. Population counts are not available for these dates, so they must also be derived from population size estimates at the closest available date and estimates of fertility, survival and migration in-between. Formally, Equation 7 must be completed with

$$\hat{N}(t-x) = \left[L(\hat{F}, \hat{\beta}, \hat{S}) * \left\{ \hat{N}(t_1) + (\hat{\alpha} \cdot \hat{\Delta}) \right\} \right] + \left[(1 - \hat{\alpha}) \cdot \hat{\Delta} \right] \quad (8)$$

where all the omitted arguments of the period functions are the interval t_1 to $t-x$. and

$$\hat{N}(t) = \left[L'(\hat{S}) * \left\{ \hat{N}(t_2) - ((1 - \hat{\alpha}) \cdot \hat{\Delta}) \right\} \right] - \left[\hat{\alpha} \cdot \hat{\Delta} \right] \quad (9)$$

where all the omitted arguments of the period functions are the interval t to t_2 . In this case, we can set t_1 as April 18th, 1962, date of the last pre-PPR census, and t_2 as March 2nd, 1998, date of the first post-PPR census.

Instead of an estimate of the total death toll, an estimate of the number of violent deaths is derived by substituting $\hat{S}^N$ for $\hat{S}^C$ in Equation 7, where $\hat{S}^N$ now represents the survival ratios estimated to correspond to a counterfactual increase in only non-violent mortality. Finally, a birth deficit can also be estimated by comparing the actual number of births to a counterfactual number. The actual number, $B(t-x, t)$, is a function of the vector of female age-specific fertility rates, $F(t-x, t)$, and the vector of person-years of exposure in the different age-groups of the female population between times $t-x$ and t , $P(t-x, t)$. With the conventional approximation of person-years (Preston et al. 2001), and the approach discussed with reference to Equation 4, the number of missing births is simply estimated as

$$\hat{B}^M(t-x, t) = \left(\frac{x}{2} \right) * \left\{ \hat{F}^C(t-x, t) - \hat{F}(t-x, t) \right\} * \left\{ \hat{N}(t-x) + \hat{N}(t) \right\} \quad (10)$$

where $\hat{F}^C(t-x, t)$ is the vector of counterfactual fertility rates.

I could have similarly defined the impact of the massive emigration of Cambodian refugees induced by the PPR on population size. However, it is of little interest under the present operative definitions, which limit the estimation of the PPR impact strictly to the PPR era. Leaving Cambodia during the PPR was extremely difficult and the bulk of the Cambodian refugees left either just before the PPR or, in much higher numbers, in the years after the PPR.

A stochastic implementation of the CCMPC

Equations 7 to 10 provide estimates of the number of excess deaths and the number of missing births, from single values (point estimates) of $N(t_1)$, $S(t_1, t-x)$, $F(t_1, t-x)$, $\beta(t_1, t-x)$, $\alpha(t_1, t-x)$, $(t_1, t-x)$, $S^C(t-x, t)$, $F^C(t-x, t)$, $F(t-x, t)$, $\beta(t-x, t)$, $\alpha(t-x, t)$, $(t-x, t)$, $\varepsilon(t-x, t)$, $S(t, t_2)$, $\alpha(t, t_2)$, and (t, t_2) . Uncertainty in any of these point estimates should translate into uncertainty in the estimates of the death toll and the birth deficit. As mentioned above, this uncertainty has long been recognized in population forecasting and several approaches have been developed to provide probabilistic forecasts with probability distributions for the outcome of interest (e.g., Alho and Spencer 1985; Lee and Tuljapurkar 1994; Lutz, Sanderson and Scherbov 1996). In population forecasting, however, the main source of uncertainty typically concerns how different the future will be from the past. In demographic reconstructions, the core uncertainty emerges instead from the past itself (i.e., data quality).

In the interest of clarity, this can be illustrated by returning to the balancing equation of population change (Equation 1) since the logic of the reconstruction is identical in the aggregate and disaggregated forms. If we have independent estimates of

$\hat{N}(t-x)$, $\hat{N}(t)$, $\hat{B}(t-x, t)$, $\hat{D}(t-x, t)$, $\hat{I}(t-x, t)$, and $\hat{O}(t-x, t)$, these estimates might not satisfy Equation 1, a discrepancy known as the “error of closure” (Preston et al. 2001). The discrepancy arises from measurement errors that affect the estimation of the different components of Equation 1, and the error of closure must somehow be “apportioned” to the measurement errors affecting each of the different components. The apportioning process becomes relatively complex in a full CCMPC reconstruction covering a long period, and with data disaggregated by gender and age groups. Wheldon et al. (2013) have developed an elegant solution to the estimation of uncertainty in the demographic reconstruction when the main source of uncertainty is measurement error. The solution depends on the variance structures of the various parameters. Their simplifying assumption of constant variance across age and time for each demographic parameter is plausible for most settings, but doesn't hold here. The PPR period estimates are clearly less certain than those in other periods, and while this particular assumption could be modified, an alternative is not readily defined.

In situations too complex to derive an exact analytical expression, a common alternative to obtain posterior distributions is to use Monte Carlo simulation techniques (Doucet, Freitas and Gordon 2001). In other words, the uncertainty in the reconstruction is formally investigated through a series of simulations that systematically assess the sensitivity of the outputs to uncertainty or measurement error in the input parameters (Iman and Helton 1988). This requires that extant information be used to derive not just point estimates of the scalars and vectors in Equations 7 to 10, as in the deterministic single-scenario approach, but rather to define their full distributions. The elements of the projection matrix are treated as random variables and combined as in the stochastic renewal framework of population forecasting. The key implementation issue is to specify the correlation structure of the renewal matrices' inputs: age correlations (between different values in, say, vector of age-specific fertility rates $\hat{F}(t-x, t)$), time correlation (between values for the same input parameter in two consecutive time periods), and demographic interactions (between, say fertility rates

$\hat{F}(t-x, t)$ and survival ratios $\hat{S}(t-x, t)$). In his review of probabilistic projections, Lee (1998, p.165) concludes that “one can fairly safely assume that forecast errors across age are perfectly correlated, while errors across fertility, mortality and migration are perfectly uncorrelated [...]. By contrast, it is essential that the temporal correlation of errors for fertility, mortality, and migration be carefully estimated.” I thus assumed no correlation between the mortality, fertility and migration parameters. I then assumed that in a given period, there was only uncertainty about fertility levels but not about its age-pattern, and only uncertainty about volume of migration flows, but not about the age-structure of migrants. However, I did allow for some uncertainty about the choice of a mortality model to determine age-specific survival ratios. Mortality models provided survival ratios for 5-year age groups, which were deemed acceptable because mortality varies relatively regularly within 5-year age groups, making the age distribution within 5-year age groups relatively unimportant. (The open-ended age group includes people aged 75 years and over.) The use of these models greatly reduced the dimension of the parameter space by allowing me to project the population backward or forward 5 years at a time. This implicitly assumes that time trends are relatively continuous over 5-year time intervals, which relates to the issue of the temporal correlations.

Because of the discontinuity in demographic trends associated with the March-18th-1970 coup that ushered in a civil war, the forward estimation of the April 17th, 1975 population characteristics from the 1962 census data was thus carried on in three successive intervals: 1962–67, 1967–70 and 1970–75. The backward estimation of the January 7th, 1979 population characteristics from the 1998 census data involved four successive reconstruction intervals: 1993–98, 1988–93, 1983–88 and 1979–83. Within the backward and the forward projections, I assumed temporal correlations in fertility and mortality by selecting the values in intervals other than the first five-year interval as deviations from the values in the previous period.

This specification of age, demographic and temporal correlations led to the identification of 47 critical parameters whose values suffice to determine the renewal matrices in each of the sub-periods (5 years or less) of the entire reconstruction. I thus specified a separate probability distribution for each of these 47 critical parameters of the reconstruction, as shown in Table 2. (See online Supplementary Material for the empirical justification of these distributions; additionally, Table S1 relates these parameters to the inputs of the renewal matrices). Each distribution was set based on a review of data sources that have been available to and used in some or all of the previous estimations, except for only recently available data on fertility during the PPR (Heuveline and Poch 2007). Previous estimations have relied on choosing one source over the others, however, whereas here I was able to consider all these sometimes discordant sources jointly in defining the parametric distributions. Moreover, uniform distributions were chosen when different figures were available, but there was little empirical basis to discriminate between them. Normal distributions were preferred when empirical data seemed to provide a preferable “central” value in the distribution of available figures. Of these 47 parameters, 18 were used for the forward reconstruction from the time of the 1962 census to the time of the 1975 PPR take-over, 24 were used for the backward reconstruction from the time of the 1998 census to the

time of the 1979 PPR fall, and 5 were used to reconstruct the PPR period (by forward and backward iterations).

The Monte Carlo simulations consisted in picking one parameter value at a time, and taking the value that corresponded to a randomly selected percentile in distribution between .5 and 99.5 (with increments of one unit). I then combined the selected parameter values in the CCMPC reconstruction to obtain one set of output values. Each of 100 forward simulations of the 1975 population by age and sex was paired with each of 100 backward simulations of the 1979 population by age and sex, and for each of the 10,000 such pairs, I randomly drew a distinct set of five 1975-79 parameters. From these multiple draws, I recorded the values of the demographic indicators from each reconstruction to obtain frequency distributions, with the usual summary statistics such as the mean, median, standard deviation (SD) and 95 per cent simulations interval (SI). Because making additional draws and simulations was relatively straightforward, I used simple random sampling and a large number of draws rather than alternate sampling designs that might be more efficient but more difficult to implement, e.g., Latin Hypercube sampling based on random sampling without replacement (Handcock 1989).

Results

Figure 1 shows the distribution of estimates of the total population size between the time of the first census ever conducted in Cambodia and the time of the first post-PPR census (1962–98). Uncertainty about the total population size increases from 1962 to 1975, as it compounds uncertainty from the various demographic parameters needed to project the population forward from the time of the 1962 census. This is most noticeable after 1970, as parameter uncertainty is even greater during the civil war leading to the PPR takeover (1970–75) than in earlier periods. Uncertainty with respect to the total population size peaks at the onset of the PPR, and the range of my 95% SI is over one million, from 7.62 to 8.75 million (median 8.11 million.) Uncertainty also increases as the reconstruction proceeds backward from the 1998 census toward the end of the PPR.

Table 3 focuses on the demographic estimates of the PPR period. The median estimate of the number of violent deaths is 1.09 million, over 80% of these deaths being male (884,000). With a SD of 186,000, the 95% SI spreads from 728,000 to 1.455 million. As regards the total PPR death-toll, the median estimate is 1.90 million excess deaths, two thirds of these excess deaths being male (1.27 million). The corresponding SD is 374,000, and the 95% SI spreads from 1.20 to 2.76 million. Both median values are thus within the range of plausible existing estimates reviewed in Table 1.

The full distribution of death toll estimates is displayed in Figure 2. The “standard” one-to-two-million interval only contains only about 60 per cent of the simulations, with the following breakdown: 12.83% (1.0-1.5 million), 20.43% (1.5-1.75 million), and 26.93% (1.75-2.0 million). As a greater proportion of the simulations is between 2.0 and 2.25 million (21.57%) than between 1.0 and 1.5 million, the 1.5-2.25 million range actually also contains a greater proportion of the simulations (68.93%) than the wider 1.0-2.0 million range.

Estimates of the PPR death toll are often expressed in relative terms, as a ratio to the population size at the outset of the PPR. This ratio is not entirely appropriate as excess deaths include deaths from young children born during the PPR. Including these PPR births in the denominator, I find that the number of excess deaths represents 21.0% of the population at risk (median value, Table 3, 90% SI: 14.7% to 27.6%). Another way to capture the dramatic increase in mortality during the PPR is to consider life expectancy at birth. Trending upward until the late 1960s, life expectancy at birth for both males and females probably edged over 50 years, but only to fall back slightly below that threshold during the civil war. By contrast, the estimate of life expectancy at birth during the PPR drops to as low as 16.7 years for females (median, 90% SI: 10.3 to 28.5 years) and only 8.1 years for males (median, 90% SI: 5.6 to 12.1 years). Finally, I also estimate a concomitant decline in total fertility down to 4.21 children per woman, corresponding to a PPR deficit of 358,000 births (median, 90% SI: 251,000 to 481,000 births).

Discussion

A review of existing PPR-mortality estimates suggests that the most plausible among these estimates range from 720,000 to 1.1 million violent deaths and from 1.0 to 2.1 million excess deaths. However, each of these figures is a point estimate with some unknown uncertainty. As shown in Figure 1, the levels of uncertainty regarding demographic trends make the production of point estimates relatively uninformative. This does not only apply to estimations from demographic evidence, but also to estimations based on samples of survivors' testimonies which rest on an estimate of the 1975 total population size. In relative terms, estimations based primarily on verbal evidence cannot be more precise than the 1975 population size estimate.

To quantify our knowledge of PPR mortality and fertility, I use the demographic relationships embodied in the CCMPC and our extant knowledge of other demographic parameters between 1962 and 1998, which was incorporated in the selected parameter distributions. The distributions represent potential measurement errors and also expert disagreement about the reliability of available data. Obviously, a different representation of the current consensus about those would yield different frequency distributions for PPR mortality and fertility indicators. In other words, the part of the overall uncertainty that is most difficult to assess is between-analyst uncertainty. In defining the parameter distributions presented here, the aim was that they contain the central values other experts have offered, as long as those were based on some empirical data. However, it remains that other analysts would not have summarized the current knowledge basis with the exact same parameter distributions.

One way to consider the importance of the issue is to conduct a sensitivity analysis, and in particular to determine if disagreement about a particular parameter might have a particular influence on overall uncertainty. The uncertainty analysis conducted for this purpose did not suggest such influential parameters. Table 4 ranks the parameters from the most to the least influential parameters (i.e., from the smallest to the largest SD when the corresponding parameter is held constant at mean value.) Overall, however, the resulting SD are within a relatively narrow range of 320 to 390 thousands. (For some parameters, the SD is larger than

shown in Table 3 for the full model due to the smaller number of runs for each of the simulations holding a single parameter constant, 100, compared to the full model's 10,000.)

Another issue is whether the model implementation then appropriately derives the PPR mortality and fertility distributions from the selected distributions. Ideally, the joint distribution of all the mortality, fertility and migration parameters involved in this reconstruction would have been specified. To simplify this complex issue, I followed the common practices in population forecasting summarized by Lee (1998:165). I took most care in specifying temporal correlations between 5-year intervals, or less when political events suggested discontinuities within 5-year periods. I assumed perfect age correlations by adopting fixed age pattern of fertility and migration and using existing age models of mortality. Finally, I ignored interactions between fertility, mortality, and migration. This choice was driven in part by the relative paucity of demographic theory with respect to the inter-relationships between demographic variables (Cleland 2001). An assumption of independence between the fertility, mortality and migration parameters is thus more easily defensible than any alternate specification. Whether this approach understates or overstates the level of uncertainty depends on the direction of the correlations (here assumed to be zero) between the demographic components. Recent work on the demographic transition, population momentum and homeostasis indicates possible correlations between mortality, fertility and migration (Heuveline 1999; Blue and Espenshade 2011; Billari and Dalla-Zuana 2013) in a direction that reduce overall uncertainty. On period lengths such as those used here (13 years for the forward projection and 18 years for the backward projection), however, these correlations are likely to have but a very minor impact on population dynamics.

As for the underlying demographic model itself, the CCPMC makes only a few, reasonable assumptions and none that should have much impact on the output frequency distributions. More caution is in order regarding the decomposition of causes-of-death based on mortality models. The extraction of non-violent deaths from excess deaths depends on the ability of a high-mortality model to capture the age pattern of these non-violent deaths. To compensate for the possibility that some non-violent deaths could remain among the residual deaths “unexplained” by this model, the level of non-violent mortality was set to the highest plausible level, namely, the level that accounted for all excess deaths in one of the female age group. This unrealistic working assumption arguably entails some over-compensation and the resulting distribution of violent female deaths (with only 11,000 as a lower-bound of my 95% SI) indicates a possible underestimation of violent mortality.

The main conclusion remains that the uncertainty surrounding PPR death toll estimates is substantial. While the current range of death-toll estimates can be narrowed to 1.0 to 2.1 million excess deaths after ruling out a couple of less methodologically sound estimates, the 95% SI derived here is about 50% wider, stretching from 1.201 to 2.757 million excess deaths. The 95% SI is 728,000 to 1.455 million for violent deaths alone, nearly twice as wide as the range of existing estimates. Wide intervals are to be expected in such contexts: a survey of 1955-2002 war mortality in 13 countries yielded a 95% confidence interval ranging from 3.0 to 8.7-million deaths (Obermeyer et al. 2008).

Moreover, this assessment provides a better basis for comparing previous estimates than a review of the published information on their approach and data alone. This review suggested that recent estimates tended to be higher than earlier estimates, but could not readily determine whether recent ones were actually more reliable. For those derived from demographic evidence, the results shed light on the trade-off between benefitting from recent, more reliable data and requiring a longer reconstruction period that must guide the choice of a post-PPR data point to anchor the reconstruction. The 95% SI derived here for the total population size at the end of the PPR (6.10 to 6.64 million) compares with the 6.40 million figure from the first governmental estimate in 1980 (Banister and Johnson 1993). Another post-PPR data point that has been used to anchor the backward reconstruction is the number of people aged 20 and over documented in the United Nations roster at the end of 1992 (Heuveline 1998). Given the electoral eligibility criteria that excluded some of the de facto population, the inability to conduct registration in some still disputed areas, and the 96% estimated registration coverage elsewhere (United Nations 1995), the 95% SI (4.69 to 4.80 million) also seems compatible with the 4.28 million aged 20 and over appearing in the electoral rosters. The spreads of the SI even seem narrower than what could reasonably be derived from a careful review of these data. This implies that choosing the 1998 Census data over earlier data sources to anchor the backward reconstruction eventually yields narrower SI on demographic indicators of the PPR period as well, and in this sense, later estimates seem superior to earlier ones. The latest, deterministic reconstruction (Lognard 2012) even uses the 2008 census. A replication in a stochastic framework would be required to determine whether a 10-year backward projection from the 2008 census data would similarly yield less uncertainty about the 1998 population than the 1998 census itself, but the relatively small uncertainty about the 1998 figure makes this seem somewhat unlikely.

Finally, a striking finding is that even as wide as the 95% SI derived here may appear, they only cover four of the seven extent estimates of violent mortality and five of the nine existing estimates of the death toll. The lowest three of the seven existing estimates of violent mortality appear most unlikely, all three being even below the lowest value derived in my 10,000 simulations (377,000). As regards the death toll, the reservations expressed on methodological grounds in the review herein with respect to the lowest (741,000 deaths) and the highest (3.315 million deaths) estimates can now be substantiated. The distribution obtained here indicates that excess deaths were over 3 million in only 0.58 percent of the simulations and that they were under 1 million in only 0.52 per cent of the simulations. I find that two of the remaining seven seemingly plausible estimates in the one to two million death interval also fall outside the 95% SI. Overall, the often-cited interval of one to two million excess deaths only contains 60.19 percent of the simulated values, less than the narrower 1.5-2.25 million interval (68.93 percent).

In spite of the uncertainty regarding the exact figures, this assessment leaves little doubt that the impact of the PPR on demographic trends was massive. Even considering only violent mortality, the lower bound of the 95% SI indicates violent deaths exceed 728,000 in 97.5 per cent of the simulations. Providing a more comprehensive assessment of the PPR consequences, a death toll upward of 1.20 million is obtained in 97.5 per cent of the simulations, and a birth deficit of 232,000 or more is also obtained in 97.5 per cent of the simulations. This minimum estimate of the death toll would still represent 13.4% of the

population at risk and equate 323,000 deaths annually, almost as many as a median estimate of global war deaths between 1985 and 1994 (378,000, Obermeyer et al. 2008).

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

The author wishes to thank Mark Handcock, Adrian Raftery, Rob Mare, Ron Brookmeyer, Patrick Gerland, Matthew Salganik, and Seth Sanders for their insightful suggestions and Andrew Hicks for implementing model simulations in Stata (release 12). This research made use of the facilities and resources at the California Center for Population Research, UCLA, which is supported by infrastructure grant R24HD041022 from the Eunice Kennedy Shriver National Institute of Child Health & Human Development. The author is solely responsible for the content of this article.

(Funding)

The author has received no research grant to conduct this research.

Appendix: Deriving excess deaths from a cohort-component model of population change

In the cohort-component model of population change, excess deaths must satisfy Equation 6

$$N(t) = \left[L \left(F(t-x, t), \beta(t-x, t), S^C(t-x, t) \right)^* \left\{ N(t-x) + (\alpha(t-x, t) \cdot \Delta(t-x, t)) - (\varepsilon(t-x, t) \cdot D^E(t-x, t)) \right\} \right. \\ \left. + \left\{ (1 - \alpha(t-x, t)) \cdot \Delta(t-x, t) \right\} - \left\{ (1 - \varepsilon(t-x, t)) \cdot D^E(t-x, t) \right\} \right] \quad (6)$$

where $\varepsilon(t-x, t)$ is a scalar whose value between 0 and 1 accounts for the timing of excess mortality between times $t-x$ and t . When $\varepsilon(t-x, t)$ equals 0, all excess deaths are assumed to occur at exact time t , and Equation 6 becomes

$$N(t) = \left[L \left(F(t-x, t), \beta(t-x, t), S^C(t-x, t) \right)^* \left\{ N(t-x) + (\alpha(t-x, t) \cdot \Delta(t-x, t)) \right\} \right. \\ \left. + \left\{ (1 - \alpha(t-x, t)) \cdot \Delta(t-x, t) \right\} - \left\{ D^E(t-x, t) \right\} \right] \quad (6a)$$

The number of excess deaths can then be estimated from estimates of

$$\hat{N}(t-x), \quad \hat{N}(t), \quad \hat{F}(t-x, t), \quad \hat{\beta}(t-x, t), \quad S^C(t-x, t), \quad \hat{\alpha}(t-x, t), \text{ and } \\ \hat{\Delta}(t-x, t), \text{ as}$$

$$\hat{D}^E(t-x, t) \\ = \left\{ L \left(\hat{F}(t-x, t), \hat{\beta}(t-x, t), \hat{S}^C(t-x, t) \right)^* \left(\hat{N}(t-x) + (\hat{\alpha}(t-x, t) \cdot \hat{\Delta}(t-x, t)) \right) \right\} \\ - \left\{ \hat{N}(t) - ((1 - \hat{\alpha}(t-x, t)) \cdot \hat{\Delta}(t-x, t)) \right\} \quad (7a)$$

Similarly, when $\varepsilon(t-x, t)$ equals 1, all excess deaths are assumed to occur at exact time $t-x$, and Equation 6 becomes

$$\begin{aligned} N(t) = & \left[L(F(t-x, t), \beta(t-x, t), S^C(t-x, t))^* \{N(t-x) + (\alpha(t-x, t) \cdot \Delta(t-x, t))\} - D^E(t-x, t) \right] \\ & + [\{(1 - \alpha(t-x, t)) \cdot \Delta(t-x, t)\}] \end{aligned} \quad (6b)$$

In this case, the number of excess deaths can then be estimated from estimates above and

$L'(\hat{S}^C(t-x, t))$ a matrix such that

$$L'(\hat{S}^C(t-x, t)) * L(\hat{F}(t-x, t), \hat{\beta}(t-x, t), \hat{S}^C(t-x, t)) * \hat{N}(t) = \hat{N}(t)$$

Specifically,

$$\begin{aligned} D^E(t-x, t) &= \left\{ \hat{N}(t-x) + (\hat{\alpha}(t-x, t) \cdot \hat{\Delta}(t-x, t)) \right\} \\ &- \left\{ L'(\hat{S}^C(t-x, t)) * (\hat{N}(t) - (1 - \hat{\alpha}(t-x, t)) \cdot \hat{\Delta}(t-x, t)) \right\} \end{aligned} \quad (7b)$$

$L'(\hat{S}^C(t-x, t))$ is not entirely determined because the oldest closed age interval and the open age interval at time $t-x$ both contribute to the closed age interval at time t , and multiple combinations of the survival ratios for these two age groups are possible. An additional

constraint needs to be applied to select a particular $L'(\hat{S}^C)$ (see Lee (1985) for a fuller discussion), but for relatively short reconstruction periods, the results are not too sensitive to this particular step. The particular constraint selected here was to assume the same age-specific growth rate for the last closed age interval and the open-ended age interval. The backward projection only provided the size of the age group 70+ at time $t-x$ from the size of the age groups 70-74 and 75+ at time t . I then used this assumption to separate the age group 70+ into an age group 70-74 and an age group 75+ at time $t-x$.

Whether the quantity in (7a) is smaller or larger than the quantity in (7b) depends on whether population is growing or declining between time $t-x$ and time t . In the more common case of population growth, the estimate corresponding to deaths exactly at the end of the period will be larger (7a). In either case, however, the number of excess deaths when $\varepsilon(t-x, t)$ equals neither 0 nor 1 will be between the values estimated in (7a) and (7b)

$$\begin{aligned} D^E(t-x, t) = & \varepsilon'(t-x, t) \cdot \left[\left\{ \hat{N}(t-x) + (\hat{\alpha}(t-x, t) \cdot \hat{\Delta}(t-x, t)) \right\} \right. \\ & \left. - \left\{ L'(\hat{S}^C(t-x, t)) * (\hat{N}(t) - (1 - \hat{\alpha}(t-x, t)) \cdot \hat{\Delta}(t-x, t)) \right\} \right] \\ & + (1 - \varepsilon'(t-x, t)) \cdot \left[\left\{ L(\hat{F}(t-x, t), \hat{\beta}(t-x, t), \hat{S}^C(t-x, t)) * (\hat{N}(t-x) + \right. \right. \\ & \left. \left. (\hat{\alpha}(t-x, t) \cdot \hat{\Delta}(t-x, t))) \right\} - \left\{ \hat{N}(t) - ((1 - \hat{\alpha}(t-x, t)) \cdot \hat{\Delta}(t-x, t)) \right\} \right] \end{aligned} \quad (7c)$$

Because the cohort-component model of population change is generally not linear, $\varepsilon'(t-x, t)$ is not exactly equal to $\varepsilon(t-x, t)$, except when the latter equals 0 or 1. However, $\varepsilon'(t-x, t)$ is a monotonic, strictly increasing function of $\varepsilon(t-x, t)$ (the larger $\varepsilon(t-x, t)$ the larger $\varepsilon'(t-x, t)$) so that

$\varepsilon(t-x, t)$ can be recovered from $\varepsilon'(t-x, t)$ computationally by trial and error. In this model of population change for the 1975-79 period for instance, I found that a value of .435 for $\varepsilon'(t-x, t)$ produced an even distribution of excess deaths through the period, that is, $\varepsilon(t-x, t)$ equals to .5.

In any case, dropping the references to the period $t-x$ to t to simplify the notations yields Equation (7)

$$\begin{aligned} \hat{D}^E = \varepsilon' \cdot \left[\left\{ \hat{N}(t-x) + (\hat{\alpha} \cdot \hat{\Delta}) \right\} - \left\{ L'(\hat{S}^C) * (\hat{N}(t) - (1 - \hat{\alpha}) \cdot \hat{\Delta}) \right\} \right] \\ + (1 - \varepsilon') \cdot \left[\left\{ L(\hat{F}, \hat{\beta}, \hat{S}^C) * (\hat{N}(t-x) + (\hat{\alpha} \cdot \hat{\Delta})) \right\} - \left\{ \hat{N}(t) - ((1 - \hat{\alpha}) \cdot \hat{\Delta}) \right\} \right] \end{aligned} \quad (7)$$

References

- Alho, Juha M.; Spencer, Bruce D. Uncertain population forecasting. *Journal of the American Statistical Association*. 1985; 80(390):306–314. [PubMed: 12340317]
- Banister, Judith; Paige Johnson, E. After the nightmare: The population of Cambodia. In: Kiernan, Benedict, editor. *Genocide and Democracy in Cambodia: The Khmer Rouge, the United Nations and the International Community*. Yale University Southeast Asia Studies; New Haven, CT: 1993. p. 65-140.
- Berman, Jennifer S. No place like home: Anti-Vietnamese discrimination and nationality in Cambodia. *California Law Review*. 1986; 84(3):817–874.
- Billari, Francesco C.; Dalla-Zuana, Gianpiero. Cohort replacement and homeostasis in world population, 1950–2100. *Population and Development Review*. 2013; 39(4):563–85.
- Blue, Laura; Espenshade, Thomas. Population momentum across the demographic transition. *Population and Development Review*. 2011; 37(4):721–47. [PubMed: 22319771]
- Central Intelligence Agency. *Kampuchea: A Demographic Catastrophe*. National Foreign Assessment Center; Washington, DC: 1980. Research Paper GC80-10019U
- Chandler, David. *The Tragedy of Cambodian History: Politics, War and Revolution since 1945*. Yale University; New Haven, CT: 1991.
- Cleland, John. *Population and Development Review*. Vol. 27. Global Fertility Transition; 2001. The effects of improved survival on fertility: A reassessment; p. 60-92.
- Coale, Ansley; Demeny, Paul; Vaughan, Barbara. *Regional Model Life Tables and Stable Populations*. Academic Press; New York, NY: 1983.
- Demont, Floriane. *Dynamiques Démographiques et Parcours de Vie au Cambodge, 1998-2008 : Des Trajectoires Individuelles et Familiales à l'Epreuve du Développement*. Université de Genève, Doctoral Thesis; Genève, Switzerland: 2011.
- De Walque, Damien. Selective mortality during the Khmer Rouge period in Cambodia. *Population and Development Review*. 2005; 31(2):351–368.
- Doucet, Arnaud; de Freitas, Nando; Gordon, Neil, editors. *Sequential Monte Carlo Methods in Practice*. Springer Verlag; Berlin: 2001.
- Ea, Meng Try. *Kampuchea: A country adrift*. *Population and Development Review*. 1981; 7(2):209–228.
- Etcheson, Craig. *After the Killing Fields: Lessons from the Cambodian Genocide*. Praeger; Westport, CT: 2005.
- Gakidou, Emmanuella; King, Gary. Death by survey: Estimating adult mortality without selection bias from sibling surviving data. *Demography*. 2003; 43(3):569–585. [PubMed: 17051828]
- Gordon, Amy. *The Renakse petitions: Background and suggestions for future use*, manuscript. Documentation Center of Cambodia; Phnom Penh, Cambodia: 2007.
- Hagan, John; Palloni, Alberto. Death in Darfur. *Science*. 2005; 313:1578–1579. [PubMed: 16973863]

- Handcock, Mark S. IBM Research Report. Thomas J. Watson Research Center; Yorktown Heights, NY: 1989. Latin Hypercube Sampling to Improve the Efficiency of Monte Carlo Simulations: Application to a CSET Logic Circuit with ASTAP. RC 14546
- Heder, Stephen. Personal communication. 1997
- Heuveline, Patrick. 'Between one and three million': Towards the demographic reconstruction of a decade of Cambodian history. *Population Studies*. 1998; 52(1):49–65. [PubMed: 11619945]
- Heuveline, Patrick. The global and regional impact of mortality and fertility transitions, 1950– 2000. *Population and Development Review*. 1999; 25(4):681–702. [PubMed: 22053413]
- Heuveline, Patrick. Daniel Chirot and Martin Seligman (eds), *Ethnopolitical Warfare: Causes, Consequences, and Possible Solutions*. American Psychological Association; Washington, DC: 2001. Approaches to measuring genocide: Excess mortality during the Khmer Rouge period; p. 93–108.
- Heuveline, Patrick; Clark, Samuel J. Model schedules of mortality. In: Rogers, Richard G.; Crimmins, Eileen M., editors. *International Handbook of Adult Mortality*. Springer; New York: 2011. p. 511–532.
- Heuveline, Patrick; Poch, Bunnak. The phoenix population: Demographic crisis and rebound in Cambodia. *Demography*. 2007; 44(2):405–426. [PubMed: 17583312]
- Huguet, Jerrold W.; Chamratrithirong, Apichat; Rama Rao, Nott; Sy Than, San. Results of the 1998 population census in Cambodia. *Asia-Pacific Population Journal*. 2000; 15(3):3–22. [PubMed: 12295994]
- Iman, Ronald L.; Helton, Jon C. An investigation of uncertainty and sensitivity analysis techniques for computer models. *Risk Analysis*. 1988; 8(1):71–90.
- INSERE.. Résultats du Recensement Général de la Population 1962. Ministry of Planning; Phnom Penh, Cambodia: 1966.
- Kiernan, Benedict. *The Pol Pot Regime*. Yale University; New Haven, CT: 1996.
- Kiljunen, Kimmo, editor. *Kampuchea: The Decade of the Genocide, Report of a Finnish Inquiry Commission*. Zed Books; London, U.K.: 1984.
- Lee, Ronald D. Inverse projection and back projection: Comparative results and sensitivity tests for England. *Population Studies*. 1985; 39(2):233–248. [PubMed: 11620664]
- Lee, Ronald D. Probabilistic approaches to population forecasting. In: Lutz, Wolfgang; Vaupel, James; Ahlburg, Dennis, editors. *Frontiers of Population Forecasting, supplement to Population and Development Review 24*. Population Council; New York: 1998. p. 156–190.
- Lee, Ronald D. Linda Waite (ed.) *Aging, Health, and Public Policy: Demographic and Economic Perspectives, Supplement to Population and Development Review 30*. Population Council; New York: 2004. Quantifying Our Ignorance: Stochastic Forecasts of Population and Public Budgets; p. 153–176.
- Lee, Ronald; Tuljapurkar, Shripad. Stochastic population forecasts of the U.S.: Beyond High, Medium, Low. *Journal of the American Statistical Association*. 1994; 89(428):1175–1189.
- Lognard, Marie-Odile. "Conséquences démographiques de la période khmer rouge," [Demographic consequences of the Khmer Rouge period] paper presented at the Chaire Quételet, Impact démographique des conflits. 2012. Last accessed on 12/12/2013 at <http://www.uclouvain.be/cps/ucl/doc/demo/documents/Lognard.pdf>
- Lutz, Wolfgang; Sanderson, Warren; Scherbov, Sergei. Probabilistic population projections based on expert opinion. In: Lutz, Wolfgang, editor. *The Future Population of the World: What Can We Assume Today?*. revised edition. Earthscan Publications; London: 1996.
- Migozzi, Jacques. *Cambodge: Faits et Problèmes de Population*. Editions du Centre National de la Recherche Scientifique; Paris, France: 1973.
- National Committee for Population and Development (NCPD). *Migration and Development in Cambodia*. The Office of the Council of Ministers and United Nations Population Fund; Phnom Penh, Cambodia: 2009.
- National Institute of Statistics. *Demographic Survey of Cambodia*. National Institute of Statistics; Phnom Penh, Cambodia: 1996.
- National Institute of Statistics. *General Population Census of Cambodia 1998: Final Census Results*. National Institute of Statistics, Ministry of Planning; Phnom Penh, Cambodia: 1999.

- National Institute of Statistics. Cambodia Demographic and Health Survey 2000. National Institute of Statistics and Directorate General for Health; ORC Macro; Phnom Penh, Cambodia: Calverton, MD: 2001.
- National Institute of Statistics. Cambodia Demographic and Health Survey 2005. National Institute of Statistics and Directorate General for Health; ORC Macro; Phnom Penh, Cambodia: Calverton, MD: 2006.
- National Institute of Statistics. General Population Census of Cambodia 2008: Final Census Results. Ministry of Planning; Phnom Penh, Cambodia: 2010.
- Neupert, Ricardo F.; Prum, Virak. Cambodia: Reconstructing the demographic stab of the past and forecasting the demographic scar of the future. *European Journal of Population*. 2005; 21(2/3): 217–243.
- Obermeyer, Ziad; Murray, Christopher J. L.; Gakidou, Emmanuella. Fifty years of violent war deaths from Vietnam to Bosnia: Analysis of data from World Health Survey Programme. *British Medical Journal*. 2008; 336(7659):1482–1486. [PubMed: 18566045]
- Owen, Taylor; Kiernan, Benedict. Bombs over Cambodia. *The Walrus*. Oct.2006 2006 :62–69.
- Preston, Samuel H.; McDaniel, Antonio; Grushka, Carlos. New model life tables for high-mortality populations. *Historical Methods*. 1993; 26(4):149–59.
- Preston, Samuel H.; Heuveline, Patrick; Guillot, Michel. *Demography: Measuring and Modeling Population Processes*. Blackwell; Malden, MA: 2001.
- Seltzer, William. Exploring the limits of demography: The use of “excess mortality” to estimate genocide mortality. Fordham University; 2008. manuscript
- Shryock, Henry S.; Siegel, Jacob S. *The Methods and Materials of Demography*. U.S. Department of Commerce; Washington, DC: 1973.
- Siampos, Georges. The population of Cambodia 1945–1980. *Milbank Memorial Fund Quarterly*. 1970; 48(3):317–360. [PubMed: 5512712]
- Sliwinski, Marek. *Le génocide Khmer Rouge: Une analyse démographique*. L'Harmattan; Paris: 1995. [The Khmer Rouge Genocide: A Demographic Analysis.]
- Trussell, John; Rodriguez, German. A note on the sisterhood estimator of maternal mortality. *Studies in Family Planning*. 1990; 21(6):344–346. [PubMed: 2075625]
- United Nations. Convention on the prevention and punishment of the crime of Genocide. Adopted by the General Assembly of the United Nations on 9 December 1948. *Treaty Series*. 1951; 78-I-1021:277–322.
- United Nations. *Model Life Tables for Developing Countries*. United Nations; New York, NY: 1982.
- United Nations. *The United Nations and Cambodia, 1991–1995*. United Nations; New York, NY: 1995. The Blue Book Series
- Vickery, Michael. *Cambodia 1975–1982*. South End Press; Boston, MA: 1984.
- Weitz, Eric D. *A Century of Genocide*. Princeton University; Princeton, NJ: 2003.
- Wheldon, Mark C.; Raftery, Adrian E.; Clark, Samuel J.; Gerland, Patrick. Reconstructing past populations with uncertainty from fragmentary data. *Journal of the American Statistical Association*. 2013; 108(501):96–110. [PubMed: 23579202]

Figure 1.
Total population size estimates, Cambodia, 1962 to 1998, median and 95% simulation interval (in millions)

Pol Pot regime's death toll, estimates' density distribution (number of excess deaths, in thousands)
Note: Numbers between the vertical lines indicate the density between the corresponding points in the distribution

Figure 2.

Model estimates' density distribution, total number of excess deaths, Cambodia, April 17th, 1975 to January 7th, 1979 (in thousands)

Note: Numbers between the vertical lines indicate the density between the corresponding points in the distribution

Table 1Existing mortality estimates, Cambodia, April 17th, 1975 to January 7th, 1979 (in thousands)

Main evidence type	Methodology	Data (year & origin)	Estimates		
			Violent Deaths	Excess Deaths	Other
Verbal (survivors' testimonies on kin survival/death)	Sample probabilities of death applied to subpopulation totals	<1980, refugees abroad	50 to 100 (executions)	n/a	Population decline, 1975-79: 1,200 to 1,800
			100 to 120	1,000 to 1,200	
		1979-80, Thailand & France	n/a	1,671	
		1980-81, Cambodia & Thailand	750	1,500	
		1989-91, Cambodia, Thailand & France	720 to 840	1,843 to 1,869	
		Sum of death reports	n/a	3,315	
		Total accounting			
		1981 population estimate	300	741	
		1980 population estimate	n/a	1,050	Excess deaths, 1970-79: 1,300
		1992 electoral rosters	1,100	1,500 to 2,000	Excess deaths among cohorts born before 1970, 1970-79: 2,520
Demographic (census and national surveys)	Demographic reconstruction by age and sex	1998 population census	n/a	n/a	Excess deaths, 1970-79: 1,953
		2008 population census	n/a	2,095	
Physical (bone remains)	Inventory of mass graves	1995-2004, Cambodia	1,113	n/a	

Sources: Banister & Johnson (1993), Central Intelligence Agency (1980), Ea (1981), Etcheson (2005), Gordon (2007), Heder (1997), Heuveline (1998), Kiernan (1996), Lognard (2012), Neupert & Prum (2005), Sliwinski (1995), Vickery (1984).

Table 2

Variable parameters of the demographic reconstruction, Cambodia, 1962-98

Description	Distribution
Forward Projection (1962-75)	
Initial total population size, 4/17/1962: Undercount in the 1962-Census official total (%)	N(3.2,1)
Initial sex and age structure, 4/17/1962: Weighting function between the official (when weight=-1) and Siampos' 1962-Census adjustment (when weight=+1)	N(0,1)
Mortality age pattern, 1962-67: Weighting function between UNSA (when weight=0) and CDW (when weight=1) mortality patterns	U(0,1)
Initial mortality level reference date: Shift in reference date for the first male and female life expectancy estimates (years)	N(0,2)
Male mortality level, 1962-67: Average annual gain in male life expectancy at birth (years)	N(.5,.1)
Female mortality level, 1962-67: Female v. male difference in average annual gain in life expectancy at birth (years)	N(.1,.1)
Mortality age pattern, 1967-70: Convergence toward CDW between 1962-67 & 1967-70 (with no change from 1962-67 when weight=0 and CDW when weight=1)	U(0,1)
Male mortality level, 1967-70: 1962-67 v. 1967-70 difference in average annual gain in male life expectancy at birth (years)	N(.1,.05)
Female mortality level, 1967-70: Male v. female difference in 1962-67 v. 1967-70 difference in average annual gain in life expectancy at birth (years)	N(.05,.05)
Fertility level, 1962-67: Correction factor to the 1962-Census TFR estimate by Siampos	N(-.2,.2)
Fertility level, 1967-70: Annual change in TFR between 1962-67 & 1967-70	N(-.1,.1)
International migration, 1962-70: Emigrants during the first 8 months of 1970 (thousands)	U(150,300)
Counterfactual male mortality level, 1970-75: Ratio of average annual life expectancy change in baseline mortality between 1970-75 & 1967-70 to average annual life expectancy change in total mortality between 1967-70 & 1962-67 (years)	U(-1,1)
Counterfactual female mortality level, 1970-75: Female to male relative ratio of average annual life expectancy change in baseline mortality between 1970-75 & 1967-70 to average annual life expectancy change in total mortality between 1967-70 & 1962-67 (years)	U(0,1)
Excess mortality, 1970-75: Number of excess deaths from bombing, civil-war and pogroms (thousands)	U(50,250)
Domestic fertility level, 1970-75: Relative change in TFR between 1967-70 & 1970-75	U(-.1,0)
Expatriate fertility level, 1970-75: Ratio of change in TFR between 1967-70 & 1970-75 to change between 1962-67 & 1967-70	N(0,1)
International migration, 1970-75: Number of emigrants (thousands)	U(75,175)
Backward Projection	
Initial total population size, 3/2/1998: Undercount in the 1998-Census official total (%)	N(3.2,1)
Initial sex and age structure, 3/2/1998: Inverse of the fraction of each five-year age group shifted to the next, younger five-year age group in the official 1998-Census distribution	N(30,10)
Mortality age pattern, 1993-98: Weighting function between CDN (when weight=0) and CDW (when weight=1) mortality patterns	U(0,1)
Mortality level, 1993-98: Correction to the 1998-Census estimate of life expectancy at birth for both sexes (years)	N(0,1.5)
Gender gap in mortality levels, 1993-98: Female v. male difference in life expectancy at birth (years)	N(4,1)
International migration, 1993-1998: In v. out difference in number of international migrants (thousands)	N(75,25)
International migration, 1993: Number of refugees returning from camps, late 1992 to early 1993 (thousands)	N(400,25)
Mortality age pattern, 1988-93: Convergence toward CDN between 1993-98 & 1988-93 (with no change from 1993-98 when weight=0 and CDN when weight=1)	U(0,1)
Male mortality level, 1988-93: Average annual gain in male life expectancy at birth between 1988-93 & 1993-98 (years)	N(.3,.1)
Female mortality level, 1988-93: Female v. male difference in average annual gain in life expectancy at birth between 1988-93 & 1993-98 (years)	N(.1,.1)
International migration, Vietnam, 1979-1993: Number of immigrants (including return migrants) from Vietnam between mid-1979 & March 1993 (thousands)	N(350,75)
International migration, 1988-1993: Proportion of the number of immigrants from Vietnam between mid-1979 & March 1993 occurring in 1988-93	N(.25,.05)

Description	Distribution
Mortality age pattern, 1983-88: Convergence toward CDN between 1988-93& 1983-88 (with no change from 1988-93 when weight=0 and CDN when weight=1)	U(0,1)
Male mortality level, 1983-88: Average annual gain in male life expectancy at birth between 1983-88 & 1988-93(years)	N(.4,.1)
Female mortality level, 1983-88: Female v. Male difference in average annual gain in life expectancy at birth between 1983-88 & 1988-93 (years)	N(.1,.1)
Immigration, 1983-1988: Proportion of the number of immigrants from Vietnam between mid-1979 & March 1993 occurring in 1983-88	N(.35,.05)
Emigration, 1983-1988: Number of emigrants to Thailand (thousands)	N(300,50)
Counterfactual mortality age pattern, 1979-83: Convergence toward CDN between 1983-88 & 1979-83 in baseline mortality (with no change from 1983-88 when weight=0 and CDW when weight=1)	U(0,1)
Counterfactual male mortality level, 1979-83: Average annual life expectancy gain in baseline male mortality between 1979-83 & 1983-88 (years)	N(.4,.1)
Counterfactual female mortality level, 1979-83: Female v. male difference in average annual life expectancy gain in baseline mortality between 1979-83 and 1983-88 (years)	N(.1,.1)
Immigration, 1979-1983: Proportion of the number of immigrants from Vietnam between mid-1979 and March 1993 occurring in 1979-83	N(.4,.05)
Emigration, 1979-1983: Number of emigrants to Thailand (thousands)	N(50,15)
Excess mortality, 1979-80: Number of deaths from famine in late 1979 to early 1980 (thousands)	N(150,50)
International migration, 1979: Number of immigrants from Vietnam, first months of 1979 (thousands)	N(100,25)
1975-79 Reconciliation	
Domestic fertility level, 1975-79: Relative change in TFR between 1970-75 & 1975-79	N(.3,.05)
Expatriate fertility level, 1975-79: Ratio of change in TFR between 1970-75 & 1975-79 relative to change in TFR between 1967-70 & 1970-75	N(0,1)
International migration, 1975-78: Number of emigrants (thousands)	U(100,300)
International migration, 1978-79: Number of emigrants, ca. January 1979 (thousands)	N(150,25)
Excess mortality timing, 1975-79: fraction of the difference in 1979 population by sex and age between the counterfactual and the backward projections in 1979 that are attributed to excess deaths in the second half of the PPR	U(.5,1)
Sources: Berman (1986), Demont (2011), De Walque (2005), Hugué et al. (2000), INSERE (1966), Kiljunen (1984), Migozzi (1973), National Committee for Population and Development (2009), National Institute of Statistics (1996; 2001; 2006), Owen and Kiernan (2006), Siampos (1970)	
Notes: $N(m,s)$ refers to a normal distribution of mean m and standard deviation s . $U(a,b)$ refers to a uniform distribution between extreme values a and b .	
UNSA, CDW and CDN model patterns refer to the United Nations' (1982) South Asian and to Coale and Demeny's (1983) West and North model life tables.	

Table 3Model estimates of mortality and fertility indicators, Cambodia, April 17th, 1975 to January 7th, 1979

	Median	Average	Std Dev.	90% SI		95% SI	
Violent deaths (in thousands)							
Total males	884	884	93	729	1,037	703	1,066
Total females	205	204	99	41	368	11	398
Total	1,090	1,088	186	783	1,398	728	1,455
Excess deaths (in thousands)							
Total males	1,270	1,275	186	978	1,610	919	1,696
Total females	631	633	193	326	951	275	1,058
Total	1,902	1,908	374	1,317	2,548	1,201	2,757
Excess deaths relative to population at risk (in percent)	21.0	21.0	3.9	14.7	27.6	13.4	29.8
Life expectancy at birth (in years)							
Male	8.1	8.4	2.1	5.6	12.1	5.2	13.2
Female	16.7	17.8	5.8	10.3	28.5	9.3	31.6
Total fertility rate (children per woman)	4.21	4.22	0.48	3.46	5.03	3.32	5.19
Birth deficit (in thousands)	358	360	69	251	481	232	504

Table 4

Simulated mean values and standard deviations with one parameter held at mean value, total number of excess deaths, Cambodia, April 17th, 1975 to January 7th, 1979 (in thousands)

Parameter held at mean value	Mean	St. Dev
Fertility decline, 1967-70	1911.51	321.51
Excess mortality, 1970-75	1997.67	322.34
Mortality gains for males, 1979-83	2021.75	326.43
Female mortality gain over males, up to 1967	1934.75	330.31
Gender gap in mortality, 1993-98	1965.19	333.05
Fertility level, 1962	2046.11	335.06
Weighting function of the 1975 and 1979 estimates	1913.51	335.20
Famine deaths, 1979-80	1988.67	340.39
Multiplicative mortality weight for female domestic population, 1970-75	1979.79	342.44
Mortality gains for males, 1988-93	1933.68	343.17
Change in mortality gender gap, 1983-88	1959.49	345.22
Age pattern of mortality, 1962-67	1932.99	345.40
Percent undercount on 3/2/1998	2008.98	348.06
Migration from VN, 1993-98	1930.02	351.78
Migration, 1975-78	1926.15	352.44
Migration from VN, 1988-93 (share of 1979-83)	1955.79	352.65
Fertility decline, 1970-75, over 1967-70 (domestic)	1953.47	355.65
Mortality weight for domestic male population, 1970-75	1958.83	359.43
Migration, 1978-79	1964.42	360.19
Fertility trend, 1975-80, over 1970-75 (domestic)	2006.73	362.69
Migration from VN in 1979	1996.51	363.35
Fertility trend, 1975-80, over 1970-75 (expatriates)	1903.93	363.73
Change in mortality gender gap, 1988-93	1921.12	363.81
Mortality level, 1993-98	1918.35	364.20
Fertility trend, 1970-75, over 1967-70 (expatriates)	1897.76	364.79
Percent undercount on 4/17/1962	1924.73	366.25
Age structure adjustment on 3/2/1998 (percent shifted to younger age group)	1963.07	368.07
Migration, 1970 (in thou, first 9 months)	1949.84	369.18
Total migration from VN, 1979-93	1972.34	369.25
Convergence toward West model, 1988-93	1940.54	369.58
Migration to Thailand, 1983-1988	1969.63	370.81
Mortality gain slowdown, females, 1967-70	1896.78	372.07
Mortality gains for males, 1983-88	1905.53	372.48
Convergence toward West model, 1979-83	1870.38	375.00
Convergence toward West model, 1983-88	1957.44	376.11
Convergence toward West model, 1967-70	1944.32	377.87
Migration from VN, 1979-1983 (share of 1979-93)	1971.04	379.19
Change in mortality gender gap, 1979-83	1895.81	379.52

Parameter held at mean value	Mean	St. Dev
Age structure of on 4/17/1962	2002.39	380.06
Migration from camps, 1992-93	2009.71	380.13
Migration to Thailand, 1979-1983	1993.88	382.55
Mortality gain for males, up to 1967	1980.96	382.84
Mortality gain slowdown, males, 1967-70	1915.04	385.10
Mortality level, 1962	2043.32	386.18
Migration, 1971-1975	1960.37	386.36
Migration from VN, 1983-88 (share of 1979-93)	1968.17	388.02
Mortality model age pattern, 1993-98	1933.43	389.12

Note: The table is ranked from the smallest to largest standard deviation in the simulation holding a particular parameter constant.