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SOUMAILA OUEDRAOGO

NIVEAUX ET TENDANCES DE LA MORTALITE DES PERSONNES AGEES EN AFRIQUE SUBSAHARIENNE

COMPARAISON DES SOURCES ET DES ESTIMATIONS

THESE PRESENTEE EN VUE DE L'OBTENTION DU GRADE DE DOCTEUR

DISCIPLINE : DEMOGRAPHIE

MEMBRES DU JURY

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Abstract

Since the 1950s, many indirect or semi-indirect methods have been developed either to adjust mortality estimates or to generate complete life tables in countries lacking high quality vital registration data. As a result, robust estimates of child and young adult mortality are now routinely produced from general population-based surveys in most sub-Saharan African countries. Yet, few efforts have been devoted to estimating mortality in adults aged 50 and above. With regard to the deficiencies that these data may have and the methodological issues in applying the adjustment methods required, this thesis seeks to answer the following questions. How to better estimate older adult mortality from imperfect data? Can consistent estimates be derived from indirect-based methods? If not, what could explain the possible differences across different sets of indirect estimates? Considering all the various sources, what are the most plausible levels of older adult mortality prevailing in sub-Saharan African countries? Are estimates from national source data consistent with those from local population in Health and Demographic Surveillance Systems? Do sub-Saharan African countries follow the same trends as developed countries in terms of the relationship between mortality in adults under 50 and mortality in adults over 50? Since the modal age of adult deaths is considered an additional and relevant indicator of longevity than life expectancy at birth, can this age be estimated to reflect a credible age distribution of deaths in such a context of imperfect data? If so, what are the features of the distribution of deaths in these populations? What are the levels and trends for females and males? Does the shifting mortality and compression hypothesis observed in developed countries hold in the sub-Saharan context?

In the first result-based chapter (chapter 2 in this document), I used recent household deaths reported in the last three censuses in Burkina Faso (1985, 1996, 2006) as a case study to evaluate various methods. After adjusting population and intercensal death counts for incompleteness using death distribution methods, I fitted Singular Value Decomposition (SVD) and Brass models, and specifically the Makeham model (MKH) for extrapolation to advanced ages where large age errors were suspected. I then compared the resulting estimates in terms of age patterns and risk of death between the ages of 50 and 80. I found large discrepancies between the various methods and models. Estimates from the SVD model were higher than those from both the adjusted data and the Brass model, which were consistent, but only before age 70. Extrapolation by the MKH model revealed obvious under-estimation in the adjusted data

beyond age 70, but of smaller magnitude than those suggested by the SVD model. When compared with the empirical data from high-quality civil registration systems compiled in the Human Mortality Database (HMD), only the estimates from the SVD and MKH models remained consistent beyond age 70. This work thus showed that the estimates of older adult mortality derived from indirect methods should be taken with extreme caution. It called for further refinements of the models to better reflect the observed mortality level at older ages. This analysis has been published in *Demographic Research.*

In the second result-based chapter (chapter 3), I extended this examination to multiple countries from sub-Saharan Africa by triangulating data from censuses, large-scale sample surveys and prospective data from local populations living in Health and Demographic Surveillance Systems (HDSS) dispersed throughout the African continent. Such prospective data, updated every 3, 6 or 12 months depending on the HDSS, are assumed to be of better quality than retrospective data from surveys and censuses. For census data, I use the death distribution methods to adjust mortality rates to account for under-coverage and for incompleteness of intercensal death reporting. It appears that the magnitude of these issues does not seem to reduce over time. Furthermore, additional systematic errors may result from age heaping and other undetected deficiencies. For surveys which may probably affected by the same kind of errors, I only adjusted the mortality rates to the mid-year of occurrence of reported deaths. These census/survey-based estimates were modelled using the indirect modelling approach of Sharrow and colleagues (2014) that allows accounting for excess mortality due to HIV in young adults. Overall, the African data, especially those from countries heavily affected by HIV, bear the mark of severe disruptions in age-specific mortality profiles. Regarding mortality levels, model-based approach which accounts for HIV prevalence while smoothing and adjusting the mortality rates appears to be the best compromise in both low and high HIV settings that is consistent with HDSS data and vital registration data from high-income countries such as those from HMD. However, it results in lower estimates of older adult mortality than expected for similar levels of younger adult mortality, when compared to the HMD empirical mortality data.

The last result-based chapter (chapter 4) attempts to analyze mortality and longevity in the region from the perspective of the modal age at death (M) in adults, by looking at the age-specific distribution of deaths. Although census and survey data are limited in highlighting annual trends because of their irregularity and the need for combining censuses together for the

analysis, the supplementation of the resulting estimates with those deduced from HDSS makes it possible to follow trends at least partly. The analyses show that the levels of M prevailing in most sub-Saharan Africa countries were reached by developed countries since the mid-1900s, and give a picture of the gap that separates sub-Saharan Africa from developed countries in terms of living conditions and health. Furthermore, the analysis of the distribution curves of deaths by age paves the way for new perspectives on the analysis of HIV mortality, which has strongly affected many countries in Eastern and Southern Africa. The effects have sometimes been so perverse that the bulge in deaths at young adult ages due to HIV has caused the disappearance of the normal bulge in deaths at older ages, resulting in a drastic drop in M. Therefore, M, whether it occurs late or exceptionally early, remains an indicator of longevity in the sense that it gives an indication of the most common length of life among adults. However, it cannot be considered an indicator of mortality at older ages, especially in certain sub-Saharan contexts, such as those where HIV has had devastating impact. Moreover, these analyses show that HIV does not only affect young adults. A growing number of people aged 50 and over are living with HIV. Although they tend to live normal lives under antiretroviral treatment, these AIDS survivors are entering ages where they have to cope with chronic and degenerative diseases. It is questionable whether they are entering these ages with the same physical health as seronegative adults over 50.

When used to estimate mortality in older adults and whether adjusted for incompleteness of death reporting as in censuses, data from general population-based surveys could still be marred by systematics errors, especially at older ages that generally affect downwardly the resulting mortality estimates. Hence, estimating mortality in older adults in sub-Saharan Africa require some part of modelling to correct for the downward bias. However, careful attention should be paid to the model-based estimates in their ability to credibly reflect the observed mortality level at older ages.

Keywords

Older adults, mortality, sub-Saharan Africa, estimates, levels, trends, modal age at death, census, survey, Health and demographic surveillance system, life tables, indirect methods, modelling

Chapter 1
Introduction générale[1]

Environ une décennie après l'adoption de la Déclaration d'Alma Ata en faveur des soins de santé primaires en 1978, de nombreux pays d'Afrique subsaharienne ont mis en place l'Initiative de Bamako en vue de réformer leurs systèmes de santé pour favoriser l'accès aux soins et réduire les inégalités de santé. D'abord centrés sur les enfants, les efforts vont s'étendre à la santé des mères à la faveur de la Conférence Internationale pour la Population et le Développement au Caire en 1994. Dès lors, la réduction de la mortalité infanto-juvénile et maternelle sera inscrite dans les priorités des politiques de santé et développement de nombre de pays de la région. Ces facteurs politiques combinés à divers progrès socioéconomiques et sanitaires ont permis une accélération de la réduction de la mortalité infanto-juvénile (Garenne et al., 2000; Garenne & Gakusi, 2006; Pison, 2010) et même maternelle (Zureick-Brown et al., 2013). En effet, même si les niveaux restent élevés, la mortalité des enfants, mesurée par le risque pour un nouveau-né de mourir avant d'avoir atteint son cinquième anniversaire ($_5q_0$), qui était estimée au début des années 1950 à 309‰ à l'échelle de l'Afrique subsaharienne (United Nations, 2019) atteignait 180‰ en 1990 et serait actuellement de 76‰, soit une réduction de 58% dans les 30 dernières années (UN IGME, 2020). Quant au rapport de mortalité maternelle, bien que difficile à estimer, il aurait diminué d'environ 44% sur la période 1990-2017, atteignant 542 décès pour 100 000 naissances vivantes en 2017 (WHO et al., 2015, 2019). Certes, ces progrès ont été ralentis par l'apparition et la montée fulgurante du VIH et d'autres crises économiques et sanitaires qui ont marqué la fin du 20e siècle, toute chose qui a induit une relative stagnation de la durée de vie moyenne à la naissance autour de 50 ans sur la décennie 1990-2000. Cependant, la poursuite des efforts ainsi que l'introduction et la vulgarisation des traitements antirétroviraux ont favorisé une reprise et permis d'enregistrer des gains d'espérance de vie à la naissance estimés à plus de dix ans (United Nations, 2019; Wang et al., 2016). Ces gains ont également touché les âges de la vie adulte, notamment celle de la vie reproductive du fait de la réduction de la mortalité maternelle (Canudas-Romo et al., 2014), et probablement aussi de la mortalité par VIH (Masquelier, Reniers, et al., 2014). Ces progrès s'accompagnent d'une modification du profil sanitaire des populations, désignée sous le nom de transition épidémiologique (Omran, 1971,

[1] As the dissertation is written in English, a French version of the introduction is required at the beginning. The English version follows after this one.

2005). D'un point de vue démographique, elle se traduit par un déplacement de la survenue des décès vers des âges de plus en plus avancés (Bongaarts, 2005; Bongaarts & Feeney, 2002, 2003). Ce processus affecte concomitamment la fonction des risques de décès, celle de survie et la densité de la fonction de distribution de décès dans la mesure où ces différentes fonctions sont liées. Il se manifeste progressivement par une rectangularisation de la fonction de survie (Martel & Bourbeau, 2003; Nagnur, 1986; Nusselder & Mackenbach, 1996; Paccaud et al., 1998; Wilmoth, 2007; Wilmoth & Horiuchi, 1999). Outre les maladies infectieuses encore persistantes à ce stade du processus, les personnes âgées doivent faire face au fardeau supplémentaire de multi-pathologies chroniques et dégénératives inhérent au vieillissement de la population (Fries, 1980, 2000), particulièrement précoce en Afrique subsaharienne (Agyei-Mensah & Aikins, 2010; Astagneau et al., 1992; Audain et al., 2017; Duthé & Pison, 2008; Masquelier, Waltisperger, et al., 2014; Murray & Lopez, 1997; Niamba et al., 2016; Prost, 2000; Salem & Jeannée, 1989; Soura et al., 2014; Varenne, 2007). Comme dans les pays développés ayant atteint des niveaux de mortalité faible (Kannisto, 2000; Thatcher et al., 2010), il devrait en résulter une compression des décès aux âges élevés, notamment dans le contexte subsaharien où les systèmes de santé sont sous équipés et peu adaptés aux besoins des plus âgés. Dès lors, l'étude de la mortalité des personnes âgées, jusque-là négligée dans les agendas politiques nationaux et internationaux, apparait comme une nécessité.

Si l'on considère comme âgé tout individu de 60 ans ou plus, le poids de la population des personnes âgées reste encore faible en Afrique subsaharienne. En 2019, cette population représentait seulement 4,7% de la population de la région selon les perspectives mondiales de population (United Nations, 2019). De plus, cette région est caractérisée par une transformation lente des structures par âge qui ne laisse pas transparaitre la croissance rapide de cette frange de la population (Masquelier & Kanté, 2017) dont les effectifs pourraient tripler dans les trente prochaines années (United Nations, 2019). En revanche, si l'on retient plutôt la limite de 50 ans comme recommandée par l'Organisation mondiale de la santé pour la définition des personnes âgées en Afrique subsaharienne (Ferreira & Kowal, 2006; Kowal et al., 2010; Kowal et al., 2000, 2001; Sagner et al., 2002), cette population est estimée à 9,9% en 2019 et pourrait passer à 14,8% à l'horizon 2050. La figure 1 ci-dessous reprend l'évolution passée et la projection future de la population des personnes âgées dans cette région du monde. Dans des pays comme le Ghana, le Rwanda, le Gabon ou l'Afrique du sud, elle pourrait passer respectivement de 11,9% à 18,9%, 10,7% à 19%, 11,2% à 20,2% et de 16,6% à 27,4% (United Nations, 2019). Ainsi, à

l'instar du rythme de croissance des 65 ans ou plus, celui des 60 ou plus et même des 50 ans ou plus excèdera en moyenne plus de 3% (Tabutin & Schoumaker, 2020). Le Nigeria, le pays le plus peuplé du continent, devra ainsi faire face aux besoins d'environ 52 millions de personnes de plus de 50 ans en 2050 dont pratiquement la moitié aura 60 ans ou plus. En outre, avec une baisse concomitante de la fécondité, le rapport de dépendance des plus vieux est amené à augmenter fortement dans une région où le système de protection sociale est déjà en souffrance (Bailey & Turner, 2002; Golaz, 2013).

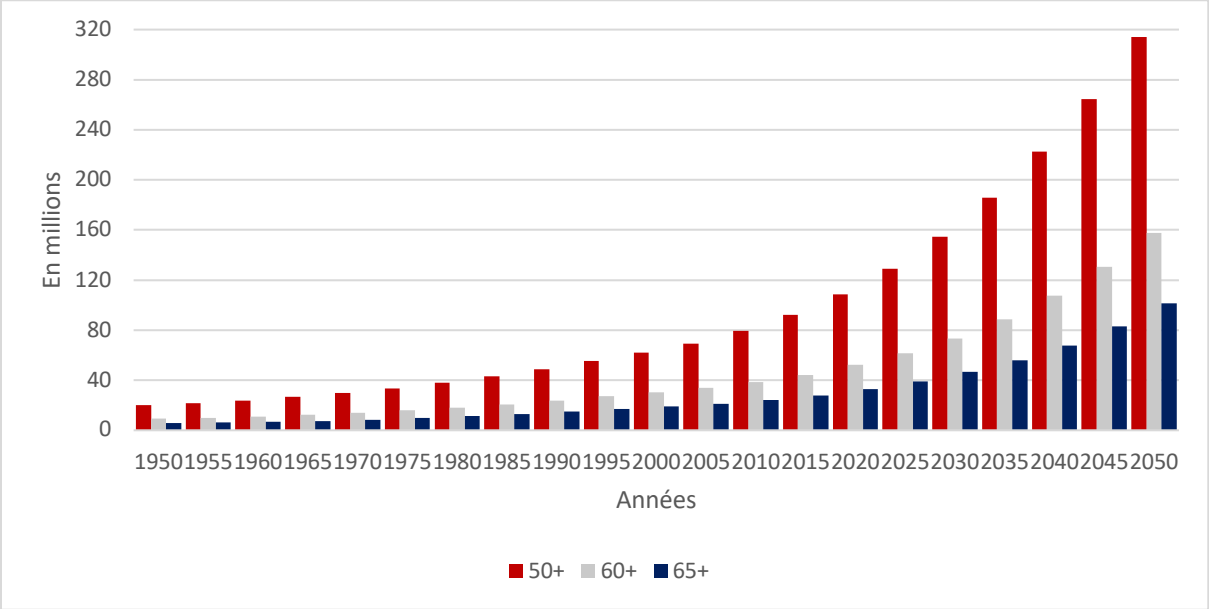

Figure 1 : Évolution de la population des personnes âgées, Nations Unies, Perspectives mondiales de population 2019, Données extraites via le site web interactif le 09/09/2021

Ainsi, le vieillissement de la population d'Afrique subsaharienne est entamé et nécessite une attention particulière. En effet, ces personnes âgées constituent un groupe spécifique avec des besoins particuliers (Ferreira & Kowal, 2006; Pillay & Maharaj, 2013). En particulier, elles vivent en général en milieu rural (Schoumaker, 2000) et recourent beaucoup à la médecine traditionnelle pour leurs problèmes de santé (Duthé et al., 2010; Massengo, 2002). Outre la pauvreté qui les affecte plus particulièrement, elles doivent également faire face à des difficultés d'accessibilité à des services de santé peu adaptés à leurs besoins (Antoine & Golaz, 2010). En plus du double fardeau des maladies infectieuses et des maladies non transmissibles, ce tableau épidémiologique est particulièrement complexe avec la dégradation précoce de leurs capacités fonctionnelles (Cambois et al., 2019). Dans le même temps, sur la période 2015-2019, 36% des

décès survenaient au-delà de 50 ans en Afrique subsaharienne et cette proportion devrait atteindre 62% sur la période 2050-2055 (United Nations, 2019). Qu'importe les réserves qu'on peut émettre à l'encontre de ces projections, elles ont le mérite d'interpeller sur le poids déjà important des décès au-delà de 50 et leur évolution spectaculaire probable. S'inscrivant dans la Déclaration politique et le plan d'action international de Madrid sur le vieillissement adoptés en 2002, le rapport mondial sur le vieillissement et la santé produit par l'Organisation Mondiale de la Santé mentionne au nombre des actions prioritaire à prendre, l'amélioration de la mesure, du suivi et des connaissances relatifs à la santé des personnes âgées (WHO, 2015). Cela passe nécessairement par la mise à disposition de statistiques fiables sur les différentes dimensions du vieillissement, y compris la mortalité. Faute cependant de sources de données appropriées, peu de travaux traitent de la question.

Les données de mortalité sont généralement issues de la statistique publique : les effectifs sont estimés à partir des dénombrements opérés et les décès proviennent idéalement des statistiques de l'état civil, notamment à travers un système complet d'enregistrement légal de toutes les naissances et de tous les décès. Ces statistiques sont essentielles pour la planification, le suivi et une évaluation rigoureuse de l'impact et des progrès des politiques et programmes de santé, ainsi que pour orienter la recherche en santé (Rao et al., 2004). La mise en place de systèmes d'enregistrement des décès demande beaucoup de ressources et peut prendre plus d'un siècle, comme cela a été le cas dans de nombreux pays. C'est probablement la raison pour laquelle des pays comme l'Inde et la Chine se sont concentrés sur des systèmes d'enregistrement des décès basés sur des échantillons qui permettent de fournir des statistiques de mortalité représentatives du niveau national en attendant le déploiement de systèmes complets (Rao et al., 2004). En Afrique subsaharienne, de nombreux pays ont mis en place des systèmes d'enregistrement des faits d'état civil, mais ils sont généralement incomplets, avec une couverture géographique très partielle et de faibles niveaux de complétude. La situation est meilleure pour l'enregistrement des naissances que pour celui des décès.

Selon la Commission Économique des Nations Unies pour l'Afrique, la couverture de l'enregistrement des naissances est passée de 40% à 57 % entre 2012 et 2015 dans la région, tandis que l'enregistrement des décès peine à décoller (UN ECA, 2017). En effet, les registres officiels de décès ne rendent compte que d'un décès sur trois et seuls quatre pays de la région

répondent aux normes internationales en termes de couverture de l'enregistrement des décès et de certification de la cause du décès (Sankoh et al., 2020). La figure 2, produite par la Division des Statistiques des Nations Unies, illustre bien cette situation et donne une idée de la couverture de l'enregistrement des actes d'état civil entre la région et d'autres parties du monde, et au sein même de la région. En raison de toutes ces déficiences, l'étude de la mortalité de manière générale s'appuie sur des sources de données moins conventionnelles, notamment les données d'enquêtes en population générale, en particulier les recensements, les enquêtes par sondage auprès des ménages et, de plus en plus, les systèmes de surveillance en population locale.

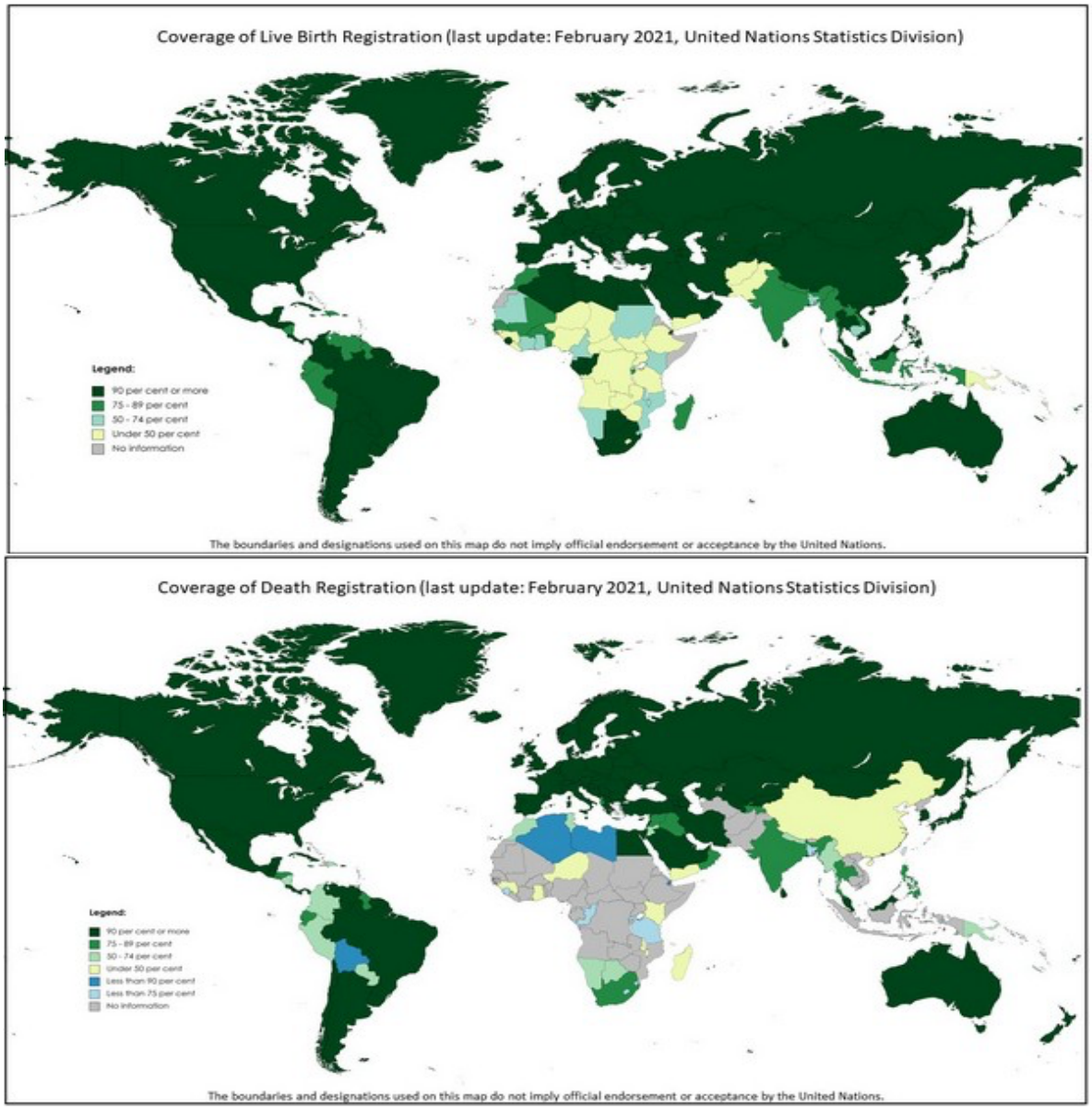

Figure 1 : Couverture de l'enregistrement des naissances et des décès en Afrique subsaharienne et dans le monde, Division des Statistiques des Nations Unies, 2021

Dans les recensements de population, les dénombrements se font au sein des ménages et une section « mortalité » y figure souvent, incluant des questions sur tous les décès survenus au sein de chaque ménage au cours des douze derniers mois précédant l'interview. Ces questions, adressées au répondant, généralement le chef de ménage, permettent de renseigner pour chaque décès, le sexe et l'âge au décès. De par son exhaustivité et sa couverture de tous les âges, c'est la principale source pour l'étude de la mortalité par âge des personnes âgées. Malheureusement, les déclarations d'âge des personnes âgées sont parfois de mauvaise qualité dans les recensements (Pison & Ohadike, 2006; Randall & Coast, 2016). Ces problèmes sont généralement plus prononcés pour les âges au décès (méconnaissance des âges, imprécisions sur les âges et dates de décès, omissions de décès, etc.) et posent d'importants défis pour l'analyse et l'estimation de la mortalité à ces âges.

Outre cette section, des questions sur la survie des parents ont été introduites dans certaines enquêtes. Tirant avantage de la relation démographique entre la proportion d'orphelins et les expériences de mortalité de leurs parents qui a été décrite initialement par Lotka (1939) et utilisée plus tard par Henry (1960) pour estimer la mortalité adulte, plusieurs travaux ont proposé de transformer les proportions de parents en vie issues des données de recensement en probabilité conditionnelle de survie (Blacker, 1977; Brass & Bamgboye, 1981; Brass & Hill, 1973; Chackiel & Orellana, 1985; Hill & Trussell, 1977; Preston & Chen, 1984, 1984; Timaeus, 1991, 1992; Timaeus & Nunn, 1997; Zlotnik & Hill, 1981). Connue sous l'appellation méthode des orphelins (orphanhood), cette approche s'appuie sur des modèles théoriques de fécondité et de mortalité qui ne sont pas nécessairement conformes au contexte subsaharien pour la conversion des proportions de parents en vie en probabilité de survie, en particulier du fait de la forte mortalité liée au sida. En outre, elle est beaucoup sensible aux biais d'adoption et de sélection (Hill & Trussell, 1977; Magadzire, 2010; Mukiza-Gapere, 1989), malheureusement fréquents dans le contexte subsaharien. Par ailleurs, elle permet de générer des indices de mortalité agrégés plutôt qu'une mortalité par âge et se prête plus à l'estimation de la mortalité depuis les jeunes âges adultes qu'à la mortalité au-delà de 50 ou 60 ans. Dans le même ordre d'idée, la méthode du veuvage (widowhood) basée sur la survie du premier conjoint d'adultes déjà mariés (Hill, 1977) ou la méthodes des frères et sœurs basée sur la proportion de frères et sœurs survivants ont été proposées (Hill & Trussell, 1977; Timaeus et al., 2001). De toutes

ces méthodes dites indirectes, la méthode des frères et sœurs parue la plus prometteuse et la plus populaire. Elle doit son succès en partie à sa prise en compte dans le vaste programme périodique de production de données d'enquêtes démographiques et de santé (EDS), notamment pour l'estimation de la mortalité maternelle (Graham et al., 1988, 1989). Ces enquêtes collectent des informations sur les âges à l'enquête ou les âges au décès et le timing du décès, autorisant un calcul « direct » de la mortalité, sans devoir approximer la durée d'exposition au risque de décès. Bien que les potentiels biais issus de telles données fassent débat (Hill, 2003; Masquelier, 2013; Obermeyer et al., 2010; Odimegwu et al., 2018), cette méthode reste largement vulgarisée pour la production de série d'estimations de la mortalité adulte, et continue de susciter de l'intérêt au sein de la communauté scientifique (Feehan & Borges, 2021). Malheureusement, en plus de générer des indices de mortalité agrégés ($_{35}q_{15}$, $_{45}q_{15}$), elle aboutit à des résultats peu plausibles au-delà de 60 ans en raison du fait qu'elle est adossée à des données d'enquêtes qui ne portent pas sur la population des personnes âgées, car les données sont collectées auprès de femmes âgées de 15 à 49 ans, qui fournissent des informations sur des frères et sœurs qui ont approximativement le même âge. En sus des problèmes évoqués, la méthode des frères et sœurs telle qu'appliqué dans les enquêtes auprès des ménages dénotent divers types d'erreurs, dont les erreurs d'âge particulièrement prononcées chez les plus âgés (Helleringer et al., 2014; Masquelier, 2014; Masquelier et al., 2020). Quelques enquêtes nationales de type EDS ont permis une mesure directe de la mortalité aux âges élevés, car elles ont introduit des questions supplémentaires sur les décès à tous les âges au cours des douze derniers mois, comme dans les recensements, mais les échantillons étaient tels que les décès enregistrés au-delà de 60 ans étaient peu nombreux (Bendavid et al., 2011). Cela a amené les auteurs à considérer les estimations obtenues sur cette base avec précaution, d'autant que les niveaux de mortalité étaient en dessous de ceux produits par la Division de Population des Nations Unies (UNPD) et l'Organisation Mondiale de la Santé (OMS).

Pour compléter les données de recensement et d'enquêtes, des systèmes de suivi démographique et de santé de populations locales (Health and Demographic Surveillance Systems - HDSS) ont été mis en place en Afrique subsaharienne. Il s'agit de sites délimités localement dans lesquels un recensement initial de la population est effectué en déterminant le plus finement possible les âges des individus recensés ; ce recensement est suivi de passages répétés lors desquels les évènements démographiques sont enregistrés (Pison, 2005). A chaque passage, les informations sur les entrées (immigrations et naissances) et les sorties

(émigrations et décès) sont recueillies, de même que divers indicateurs socio-économiques et de santé (unions, grossesses…). Par ailleurs, ces systèmes collectent des informations sur les circonstances des décès et produisent des données sur les causes de décès, par le biais de la méthode d'autopsie verbale. Certes, ce système n'est pas représentatif du niveau national et ne peut remplacer l'état civil. Toutefois, il permet de disposer de données de qualité non disponibles par ailleurs sur la mortalité puisque celles-ci sont moins affectées par les omissions de décès, les erreurs d'âge et de datation que les données rétrospectives. L'observation des tendances de la mortalité permet de comprendre les transformations épidémiologiques dans le temps et peut servir d'alternative à court et moyen terme pour alimenter la planification et le suivi des politiques de population et de santé au regard de la richesse des informations qu'il permet d'offrir (Ye et al., 2012). En outre, on peut en tirer des enseignements pour l'implémentation d'échantillon représentatif national pour l'enregistrement des faits d'état civil. À ce jour, on en dénombre plus d'une trentaine en Afrique subsaharienne dont une partie des données a été rendue publiquement accessible dans le cadre de la plateforme ishare[2] du réseau INDEPTH (Sankoh & Byass, 2012). Ainsi, une exploitation des données des HDSS et leur comparaison avec les données issues des recensements et enquêtes nationales offrent des perspectives intéressantes d'analyse de la mortalité des personnes âgées.

Les limitations des sources disponibles en Afrique subsaharienne conditionnent les méthodes à utiliser pour l'étude et l'analyse de la mortalité, et particulièrement pour les personnes âgées (Bendavid et al., 2011). Faute d'estimations directes fiables, les estimations de la mortalité des personnes âgées ont régulièrement été déduites de la survie en dessous de 60 ans à l'aide des table-types de mortalité (Coale et al., 1983; Coale & Demeny, 1966; Ledermann, 1969; United Nations, 1955, 1982a). A la faveur d'enquêtes spécifiques, la production d'indices de mortalité relatives aux enfants, voire même aux adultes a suscité le développement d'approches qui permettent d'estimer par interpolation une table complète de mortalité en utilisant comme standard un schéma empirique de mortalité qui présente un niveau de mortalité infanto-juvénile sensiblement proche à celui de la population d'étude (Ewbank et al., 1983). Par la suite, Brass introduira une approche plus formelle de modélisation relationnelle de ces tables de mortalité à un paramètre qui utilise les probabilités de survie depuis la naissance (Brass, 1971a; Brass et al., 1968) alors que les techniques indirectes d'estimation de la mortalité adulte permettaient

[2] https://www.indepth-ishare.org/index.php/catalog/central

souvent de générer des probabilités conditionnelles telles que ${}_{45}q_{15}$ ou ${}_{10}q_{25}$ dont l'utilisation auraient pu permettre d'améliorer les estimations. Ainsi, des modèles relationnels plus récents indexés à un large ensemble de tables empiriques de mortalité ont été développés pour générer des tables de mortalité complètes et lissées lorsque des informations sur la mortalité des enfants (${}_5q_0$) et celle des adultes (${}_{45}q_{15}$) étaient disponibles (Clark, 2019; Murray et al., 2003; Sharrow et al., 2014; Wilmoth et al., 2012). En permettant de reconstruire des tables de mortalité complètes à partir d'information limitées, ces modèles ont révolutionné la modélisation indirecte de la mortalité. Par exemple, l'introduction de la décomposition des valeurs singulières a permis de prendre en compte des paramètres supplémentaires comme la prévalence du VIH et même par extension la couverture en antirétroviraux pour mieux capter l'excès de mortalité dû au VIH, notamment aux jeunes âges adultes (Clark, 2015a; Sharrow et al., 2014). Il n'en demeure pas moins que ces modèles ne s'appuient que sur la mortalité avant 60 ans (${}_5q_0$, ${}_{45}q_{15}$) pour inférer le reste de la table de mortalité. Il est donc nécessaire de vérifier et de valider la plausibilité des estimations prédites pour les adultes plus âgés.

Les diverses sources de données disponibles et les méthodes d'estimation existantes constituent le socle de cette recherche doctorale dont l'objectif général est de mieux connaitre la mortalité des personnes âgées, ses tendances et sa structure en Afrique subsaharienne. En tenant compte du contexte subsaharien, avec notamment d'une part la recommandation de considérer 50 ans comme seuil pour les personnes âgées (Kowal & Dowd, 2001; Sagner et al., 2002), et d'autre part les difficultés d'estimation aux âges très avancés du fait des faibles effectifs et des erreurs d'âge particulièrement très prononcées, je limiterai dans la mesure du possible les estimations aux 50-79 ans. De manière spécifique, cette recherche vise à répondre aux questions suivantes :

☞ ***[Q1] Dans quelle mesure les données imparfaites se prêtent-t-elles à l'estimation de la mortalité des personnes âgées ? Bien que calibrées à partir de données non-africaines, les méthodes existantes permettent-elles de produire des estimations concordantes ? Sinon, qu'est ce qui pourrait expliquer les différences ? Quelle méthode serait préférable ?***

Ces questions reposent sur l'hypothèse selon laquelle, en dépit des biais de sélection probables et des problèmes liés à la qualité des données, les recensements, à travers des informations fournies sur les décès au cours des douze derniers mois, offrent des perspectives intéressantes

d'estimation de la mortalité des personnes âgées moyennant une part de modélisation. Par ailleurs, même si les différentes méthodes n'aboutissent pas à des estimations concordantes, comme c'est le cas avec les méthodes d'estimation indirecte de la mortalité chez les jeunes adultes (Odimegwu et al., 2018), le croisement de diverses sources permet de mettre en évidence la plausibilité des estimations de certaines méthodes par rapport à d'autres. Dans le chapitre 2 de cette thèse qui vise à répondre à ces questions, nous confrontons différentes méthodes d'estimation en les appliquant aux données des recensements de 1985, 1996 et 2006 du Burkina Faso.

☞ ***[Q2] Quels sont les niveaux de mortalité des personnes âgées observables dans les pays d'Afrique subsaharienne pour les périodes pour lesquelles on dispose des données ? Les estimations issues des données de sources nationales concordent-t-elles avec celles issues du suivi démographique des populations au niveau local ? Les pays d'Afrique subsaharienne suivent-ils les mêmes tendances que les pays développés en termes de relation entre mortalité chez les adultes de moins de 50 ans et mortalité chez les adultes de 50 ans ou plus ?***

Ces questionnements sont le prolongement des questions abordés au chapitre 2. Ils sont abordés dans le chapitre 3 où nous étendons les analyses en incluant des données de recensements de plusieurs autres pays d'Afrique subsaharienne afin de couvrir la grande diversité des profils épidémiologiques des pays de la région. En plus de ces données, nous mobilisons également les données d'enquêtes nationales pour lesquels nous disposons des informations sur les décès au cours des douze derniers mois ainsi que les données des HDSS. Même si les niveaux estimés sont différents, les estimations issues des données de suivi de populations locales africaines devraient concorder avec les données de sources nationales des mêmes populations, notamment en termes de relation entre indices de mortalité à différents âges. Par ailleurs, l'Afrique subsaharienne suit probablement une trajectoire épidémiologique aux âges avancés qui s'écarte de celle observée par le passé dans les pays développés du fait des spécificités des tendances observées aux âges plus jeunes (Murray et al., 2000). Par exemple, elle a bénéficié des progrès de la médecine réalisés dans les pays à faible mortalité qui a favorisé une réduction plus rapide de la mortalité des enfants (Desgrées du Loû & Pison, 1995; Garenne & Gakusi, 2006; Pison, 2010). En outre, l'avènement de la pandémie du VIH y a

structurellement affecté la mortalité des jeunes adultes, du moins dans une partie de la région. De ce fait, la mortalité des enfants et celle des adultes n'ont pas forcément évolué en tandem comme par ailleurs (Masquelier, Reniers, et al., 2014).

☞ ***[Q3] Peut-on estimer les âges où se concentrent les décès des personnes âgées dans le contexte subsaharien dépourvu de statistiques nationales de manière à refléter une distribution plausible des décès dans les populations étudiées ? Si oui, quels sont les particularités des courbes de distribution des décès dans ces populations ? Quels sont les niveaux et tendances chez les femmes et les hommes âgés ? L'hypothèse de déplacement et de compression de la mortalité observée dans les pays développés s'observe-t-elle dans le contexte subsaharien ?***

L'espérance de vie étant une moyenne, elle est sensible aux fluctuations d'échantillonnage et aux valeurs extrêmes. À ce titre, nous pensons comme Goldfarb et Pardoux (2013) qu'il est intéressant d'étudier le mode comme indicateur supplémentaire à la moyenne pour apprécier différentes distributions. Dans le cas des décès, le mode de la distribution des décès adultes pourrait être un indicateur alternatif pertinent pour l'analyse de la longévité, comme il l'est pour les pays développés (Canudas-Romo, 2008; Horiuchi et al., 2013; Kannisto, 2001a; Thatcher et al., 2010). Cependant, cette distribution a été fortement perturbée durant la crise du VIH/sida avec un risque de décès à l'âge adulte qui s'est extrêmement élevé dans certains pays d'Afrique australe et orientale. En dehors des pays sévèrement affectés par le VIH qui pourraient avoir connu un recul de l'âge modal des décès adultes, la progression est probablement restée timide étant donné les évolutions aux autres âges et le peu d'attention donnée en termes de santé publique à cette catégorie d'âge. Ces derniers développements seront abordés dans le dernier chapitre de la thèse.

Chapter 2
General introduction

About a decade after the adoption of the Alma Ata Declaration on Primary Health Care in 1978, many countries in sub-Saharan Africa set up the Bamako Initiative with the objective of reforming their health systems so as to improve access to care and reduce health inequalities. Initially focused on children, efforts were extended to maternal health at the International Conference on Population and Development in Cairo in 1994. From then on, the reduction of child and maternal mortality will be a priority in the health and development agenda of many countries in the region. These political factors combined with various socio-economic and health advances have led to an acceleration in the reduction of child mortality (Garenne et al., 2000; Garenne & Gakusi, 2006; Pison, 2010), and even of maternal mortality (Zureick-Brown et al., 2013). Indeed, even if the levels remain high, child mortality, as measured by the risk of a newborn dying before reaching his or her fifth birthday ($_5q_0$), which was estimated in the early 1950s at 309‰ across sub-Saharan Africa (United Nations, 2019) reached 180‰ in 1990 and is currently estimated to be 76‰, i. e., a reduction of 58% in the past 30 years (UN IGME, 2020). As for maternal mortality ratio, although difficult to estimate, it has reportedly decreased by about 44% over the period 1990-2017, reaching 542 deaths per 100,000 live births in 2017 (WHO et al., 2015, 2019). Admittedly, this progress was slowed by the emergence and rapid rise of HIV and other economic and health crises at the end of the 20th century, all of which led to a relative stagnation of life expectancy at birth at around 50 years over the decade 1990-2000. However, sustained efforts and the introduction and roll-out of antiretroviral treatment have led to a recovery, with gains in life expectancy at birth estimated at more than ten years (United Nations, 2019; Wang et al., 2016). These gains have also affected adult life, including reproductive life due to reductions in maternal mortality (Canudas-Romo et al., 2014), and probably also in HIV mortality (Masquelier, Reniers, et al., 2014). These improvements are accompanied by a change in the health profile of populations, referred to as the epidemiological transition (Omran, 1971, 2005). From a demographic point of view, it results in a shift in the occurrence of deaths towards increasingly advanced ages (Bongaarts, 2005; Bongaarts & Feeney, 2002, 2003). This process concomitantly affects the risk of death function, the survival function and the density function of the distribution of death as these different functions are linked. It progressively leads to a rectangularization of the survival function (Martel & Bourbeau, 2003; Nagnur, 1986; Nusselder

& Mackenbach, 1996; Paccaud et al., 1998; Wilmoth, 2007; Wilmoth & Horiuchi, 1999). In addition to infectious diseases that are still persistent at this stage of the process, older people face the additional burden of chronic and degenerative multipathologies due to ageing (Fries, 1980, 2000), which starts early in sub-Saharan Africa (Agyei-Mensah & Aikins, 2010; Astagneau et al., 1992; Audain et al., 2017; Duthé & Pison, 2008; Masquelier, Waltisperger, et al., 2014; Murray & Lopez, 1997; Niamba et al., 2016; Prost, 2000; Salem & Jeannée, 1989; Soura et al., 2014; Varenne, 2007). As in developed countries which achieved low mortality levels (Kannisto, 2000; Thatcher et al., 2010), this should result in a compression of deaths at older ages, particularly in the sub-Saharan context where health systems are under-equipped and poorly adapted to the needs of the elderly. Therefore, the study of older adult mortality, hitherto neglected in national and international policy agendas, appears to be a necessity.

If one considers as older any individual aged 60 years or more, the share of older adults in the population in sub-Saharan Africa is still low. In 2019, this population represented only 4.7% of the region's population according to the World Population Prospects (United Nations, 2019). Moreover, this region is characterized by a slow transformation of age structures that does not make apparent the rapid growth of this segment of the population (Masquelier & Kanté, 2017), whose numbers could triple in the next thirty years (United Nations, 2019). On the other hand, if we take the age limit of 50 years as recommended by the World Health Organisation for the definition of older adults in sub-Saharan Africa (Ferreira & Kowal, 2006; Kowal et al., 2010; Kowal et al., 2000, 2001; Sagner et al., 2002), this population is estimated at 9.9% in 2019 and could rise to 14.8% by 2050. Figure 1 below shows the past evolution and future projection of older adult population in this region of the world. In countries such as Ghana, Rwanda, Gabon and South Africa, it could increase from 11.9% to 18.9%, 10.7% to 19%, 11.2% to 20.2% and 16.6% to 27.4% respectively (United Nations, 2019). Thus, as for the rate of increase for those aged 65 or more, the rate of increase for those aged 60 or more and even for those aged 50 or more will on average exceed 3% (Tabutin & Schoumaker, 2020). Nigeria, the most populous country on the continent, will thus have to cope with the needs of about 52 million people over the age of 50 in 2050, almost half of whom will be 60 or over. Moreover, with a concomitant decline in fertility, the old-age dependency ratio is set to rise sharply in a region where the social protection system is clearly weak (Bailey & Turner, 2002; Golaz, 2013).

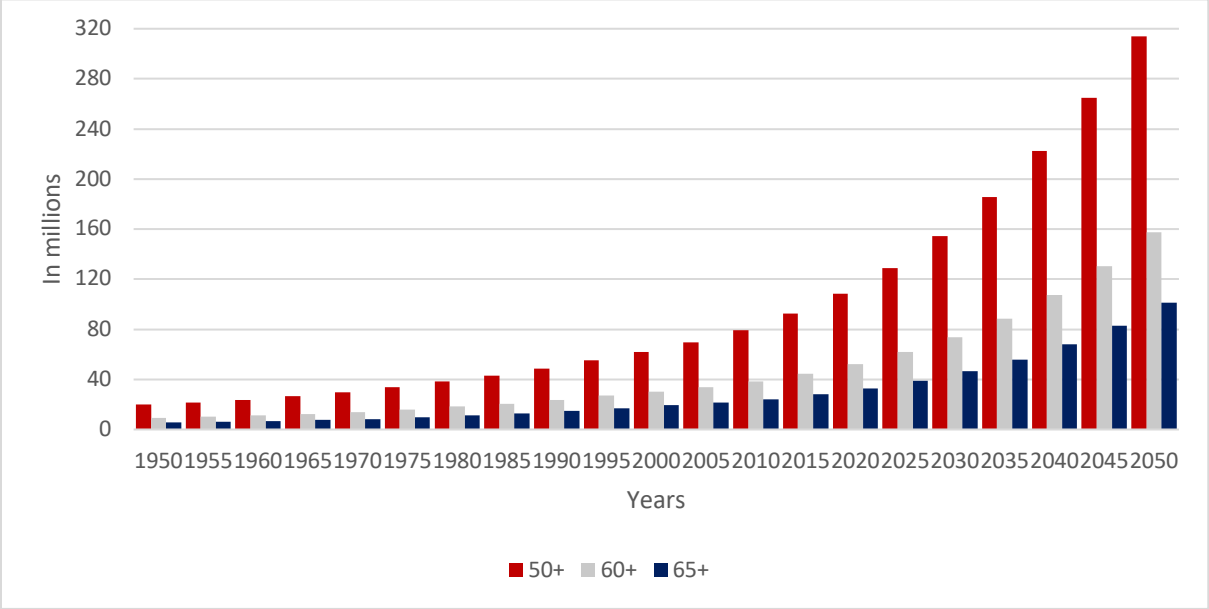

Figure 1: Changes in older adult population, United Nations, World Population Prospects 2019, Data retrieved via the interactive website on 09/09/2021

Thus, the ageing of the population in sub-Saharan Africa has begun and requires special attention. Indeed, these older people constitute a specific group with specific needs (Ferreira & Kowal, 2006; Pillay & Maharaj, 2013). In particular, they tend to live in rural areas (Schoumaker, 2000) and rely heavily on traditional medicine for their health problems (Duthé et al., 2010; Massengo, 2002). In addition to the poverty that affects them more particularly, they also face difficulties in accessing health services that are poorly adapted to their needs (Antoine & Golaz, 2010). In addition to the double burden of infectious diseases and non-communicable diseases, this epidemiological picture is particularly complex because of the early deterioration of their functional capacities (Cambois et al., 2019). At the same time, over the period 2015-2019, 36% of deaths occurred over the age of 50 in sub-Saharan Africa and this proportion is expected to reach 62% over the period 2050-2055 (United Nations, 2019). Whatever doubts one may have about these projections, they do have the merit of highlighting the already high proportion of deaths over 50 and their probable spectacular evolution. In line with the Madrid Political Declaration and International Plan of Action on Ageing adopted in 2002, the World Report on Ageing and Health produced by the World Health Organization mentions improving the measurement, monitoring and knowledge of the health of older adults as a priority action to be taken (WHO, 2015). This necessarily involves the production of reliable statistics on the various

dimensions of ageing, including mortality. However, due to the lack of appropriate data sources, there is little work on this issue.

Mortality data are usually derived from official statistics: headcounts are estimated from enumerations and deaths are ideally derived from vital statistics, including a comprehensive system of legal registration of all births and deaths. These statistics are essential for planning, monitoring and rigorous evaluation of the impact and progress of health policies and programmes, and for guiding health research (Rao et al., 2004). Establishing death registration systems is resource-intensive and can take more than a century, as has been the case in many countries. This is probably why countries such as India and China have focused on sample-based death registration systems that provide nationally representative mortality statistics while waiting for the deployment of comprehensive systems (Rao et al., 2004). In sub-Saharan Africa, many countries have established vital registration systems, but they are generally incomplete, with very partial geographical coverage and low levels of completeness. The situation is better for birth registration than for death registration. According to the United Nations Economic Commission for Africa, birth registration coverage increased from 40% to 57% between 2012 and 2015 in the region, while death registration is struggling to take off (UN ECA, 2017). Indeed, official death registers only report one in three deaths and only four countries in the region meet international standards in terms of death registration coverage and certification of cause of death (Sankoh et al., 2020). Figure 2, produced by the United Nations Statistics Division, illustrates this situation and gives an idea of the coverage of civil registration between the region and other parts of the world, and within the region itself. Because of all these limitations, the study of mortality in general relies on less conventional data sources, including general population survey data, particularly censuses, household sample surveys and, increasingly, local population surveillance systems.

In censuses, enumeration is done within households and a 'mortality' section is often included, with questions on all deaths that occurred in each household during the last twelve months prior to the interview. These questions are generally directed to the head of the household and provide information on the sex and age at death for each death. Because of its completeness and its extension to all ages, it is the main source for studying age-specific mortality in older adults. Unfortunately, age reporting for this segment of the population is sometimes of poor quality (Pison & Ohadike, 2006; Randall & Coast, 2016). These problems are generally more

pronounced for ages at death (unknown ages, inaccurate ages and dates of death, omissions of deaths, etc.) and raise important challenges for the analysis and estimation of mortality at these ages.

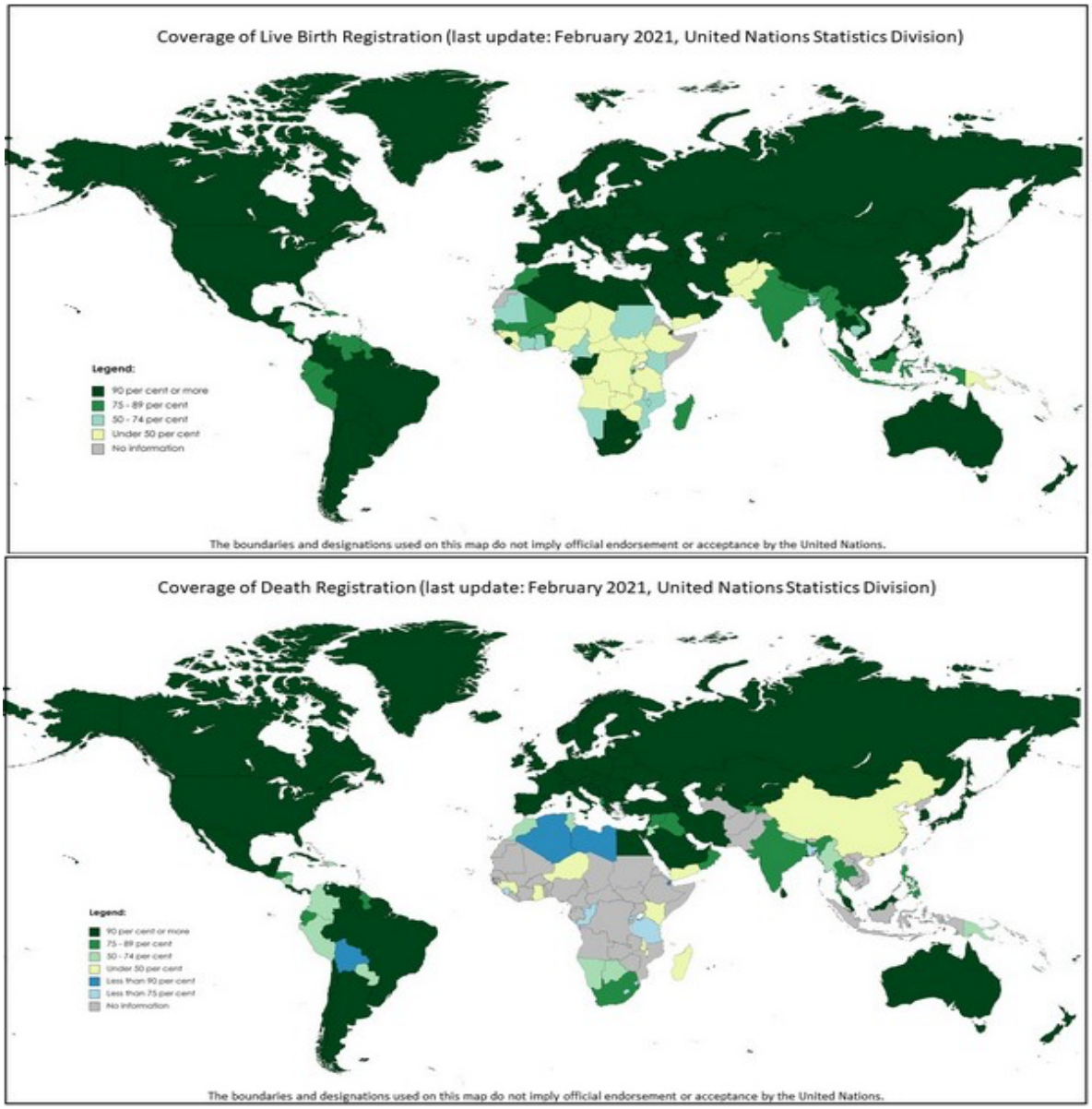

Figure 2 : Birth and Death Registration Coverage in Sub-Saharan Africa and the World, United Nations Statistics Division, 2021

In addition to this section, questions on parental survival have been introduced in some surveys. Taking advantage of the demographic relationship between the proportion of orphans and mortality experiences of their parents which was first described by Lotka (1939) and later used by Henry (1960) to estimate adult mortality, several studies have proposed to transform the proportions of surviving parents from census data into conditional probability of survival (Blacker, 1977; Brass & Bamgboye, 1981; Brass & Hill, 1973; Chackiel & Orellana, 1985; Hill & Trussell, 1977; Preston & Chen, 1984, 1984; Timaeus, 1991, 1992; Timaeus & Nunn, 1997; Zlotnik & Hill, 1981). Known as the orphanhood approach, it relies on theoretical models of fertility and mortality that are not necessarily consistent with the sub-Saharan context for converting the proportions of surviving parents into survival probabilities, particularly because of the high mortality associated with AIDS. In addition, it is highly sensitive to adoption and selection biases (Hill & Trussell, 1977; Magadzire, 2010; Mukiza-Gapere, 1989), which are unfortunately common in the sub-Saharan context. Furthermore, it allows producing aggregate mortality indices rather than age-specific mortality and is more suitable for estimating mortality from young adulthood onwards than for mortality beyond age 50 or 60. Similarly, the widowhood method based on the survival of the first spouse of already married adults (Hill, 1977) or the sibling method based on the proportion of surviving siblings have been proposed (Hill & Trussell, 1977; Timaeus et al., 2001). Of all these so-called indirect methods, the sibling method appeared to be the most promising and popular. It owes its success in part to its inclusion in the large-scale, periodic programme of data production for Demographic and Health Surveys (DHS), particularly for the estimation of maternal mortality (Graham et al., 1988, 1989). These surveys collect information on ages at survey or ages at death and the timing of death, allowing a "direct" calculation of mortality, without the need to approximate the duration of exposure to the risk of death. Although the potential biases in such data are debated (Hill, 2003; Masquelier, 2013; Obermeyer et al., 2010; Odimegwu et al., 2018), this method is still widely used for producing series of adult mortality estimates, and continues to raise attention in the scientific community (Feehan & Borges, 2021). Unfortunately, in addition to generating aggregate mortality indices ($_{35}q_{15}$, $_{45}q_{15}$), it leads to implausible results beyond the age of 60 because it is based on survey data that do not cover older people, as the data are collected from women aged 15-49, who provide information on siblings of approximately the same age. In addition to the problems mentioned, the sibling method as applied in household surveys shows various types of errors, including age errors that are particularly pronounced among the older ones (Helleringer et al.,

2014; Masquelier, 2014; Masquelier et al., 2020). A few national DHS-type surveys have provided a direct measure of mortality at older ages, as they have introduced additional questions on deaths at all ages in the last 12 months, as in censuses, but the samples were such that few deaths were recorded above age 60 (Bendavid et al., 2011). This led the authors to consider the estimates obtained on this basis with caution, especially as the resulting mortality levels were below those produced by the United Nations Population Division (UNPD) and the World Health Organization (WHO).

As a complement to census and survey data, Health and Demographic Surveillance Systems (HDSS) have been set up in sub-Saharan Africa. These are locally delimited sites in which an initial census of the population is carried out by determining the ages of the individuals counted as accurately as possible; this census is followed by repeated visits during which demographic events are recorded (Pison, 2005). At each visit, information on entries (immigrants and births) and exits (emigrations and deaths) is collected, as well as various socio-economic and health indicators (unions, pregnancies, etc.). In addition, these systems collect information on the circumstances of deaths and produce data on the causes of death, using the verbal autopsy method. Of course, this system is not representative of the national level and cannot replace civil registration. However, it does provide quality mortality data not otherwise available, as these are less affected by omissions of deaths, age and dating errors than retrospective data. Monitoring trends in mortality allows for an understanding of epidemiological transformations over time and can serve as an alternative short- and medium-term input to population and health policy planning and monitoring because of the wealth of information it provides (Ye et al., 2012). In addition, lessons can be learned from them for establishing a nationally representative sample for civil registration. To date, there are more than thirty such samples in sub-Saharan Africa, some of whose data have been made publicly available through the INDEPTH ishare[3] platform (Sankoh & Byass, 2012). Thus, the use of HDSS data and their comparison with data from censuses and national surveys offer interesting perspectives for analyzing older adult mortality.

The limitations of available sources in sub-Saharan Africa dictate the methods to be used for the study and analysis of mortality, particularly for the elderly (Bendavid et al., 2011). In the absence of reliable direct estimates, mortality estimates for older adults have regularly been

[3] https://www.indepth-ishare.org/index.php/catalog/central

inferred from survival below the age of 60 using standard life tables (Coale et al., 1983; Coale & Demeny, 1966; Ledermann, 1969; United Nations, 1955, 1982a). The production of mortality indices for children, and even for adults, has led to the development of approaches which make it possible to estimate complete life tables by interpolation, using as a standard an empirical mortality pattern which has a level of under-5 mortality close to that of the study population (Ewbank et al., 1983). Subsequently, Brass introduced a more formal approach to relational modelling of these one-parameter life tables using survival probabilities from birth (Brass, 1971a; Brass et al., 1968), whereas indirect techniques for estimating adult mortality often generated conditional probabilities such as ${}_{45}q_{15}$ or ${}_{10}q_{25}$, which could have been used to improve the estimates. Thus, more recent relational models indexed to a large set of empirical life tables have been developed to generate complete and smoothed life tables when both child (${}_5q_0$) and adult (${}_{45}q_{15}$) mortality information are available (Clark, 2019; Murray et al., 2003; Sharrow et al., 2014; Wilmoth et al., 2012). By allowing the reconstruction of complete life tables from limited information, these models have revolutionized indirect mortality modelling. For example, the introduction of singular value decomposition has made it possible to take into account additional parameters such as HIV prevalence and even, by extension, antiretroviral coverage to better capture excess mortality due to HIV, especially at young adulthood (Clark, 2015a; Sharrow et al., 2014). However, these models only rely on mortality before age 60 (${}_5q_0$, ${}_{45}q_{15}$) to infer the rest of the mortality table. It is therefore necessary to check and validate the plausibility of the predicted estimates for older adults.

The data sources available and the existing estimation methods form the basis of this doctoral research. Its general objective is to better understand the mortality of older adults, its trends and its structure in sub-Saharan Africa. Considering the sub-Saharan context, with, on the one hand, the recommendation to consider age 50 as the threshold for being an older adult (Kowal & Dowd, 2001; Sagner et al., 2002), and, on the other hand, the estimation issues at advanced ages due to the small size of the population and the pronounced age errors, I will limit the estimates to the 50-79 year olds as much as possible. Specifically, this research aims to answer the following questions:

How can we better estimate older adult mortality from limited data? Although most of the models described above are based on non-African mortality patterns, can consistent estimates be

derived from these methods? If not, what could explain the possible differences? Which method is preferable?

☞ ***[Q1] How can we better estimate older adult mortality from limited data? Although most of the models described above are based on non-African mortality patterns, can consistent estimates be derived from these methods? If not, what could explain the possible differences? Which method is preferable?***

These questions are based on the assumption that, despite probable selection biases and data quality issues, censuses, through information provided on deaths in the last 12 months, offer promising opportunities for estimating older adult mortality trough some modelling. Furthermore, even if the methods do not produce consistent estimates, as is the case with methods for indirectly estimating mortality among young adults (Odimegwu et al., 2018), cross-checking various sources can highlight the plausibility of the estimates of some methods compared to others. In Chapter 2 of this dissertation, which aims to answer these questions, we compare different estimation methods using data from the 1985, 1996 and 2006 censuses of Burkina Faso.

☞ ***[Q2] What are the mortality levels among older people in sub-Saharan African countries for the periods for which data are available? Are estimates from national data sources consistent with those from local population surveillance? Do sub-Saharan African countries follow the same trends as developed countries in terms of the relationship between mortality among adults under 50 and mortality among adults 50 years of age or older?***

These questions are an extension of those addressed in Chapter 2 and are addressed in Chapter 3, where we extend the analyses by including census data from several other sub-Saharan African countries in order to cover the wide diversity of epidemiological profiles of the countries in the region. In addition to these data, we also use national survey data for which we have information on deaths in the last 12 months and HDSS data. Even if the estimated levels are different, the estimates from local African population surveillance data should be consistent with data from national sources for the same populations, especially in terms of the relationship between mortality indices at different ages. Furthermore, sub-Saharan Africa is likely to follow an epidemiological trajectory at older ages that differs from that observed in the past in developed countries because of the specificities of the trends observed at younger ages (Murray et al., 2000). For example, it has benefited from medical advances in low-mortality countries

that have led to a more rapid reduction in child mortality (Desgrées du Loû & Pison, 1995; Garenne & Gakusi, 2006; Pison, 2010). In addition, the advent of the HIV pandemic has structurally affected young adult mortality, at least in some parts of the region. As a result, child and adult mortality have not necessarily evolved in tandem as elsewhere (Masquelier, Reniers, et al., 2014).

☞ ***[Q3] In the sub-Saharan context, where there are no national statistics, can the ages at which deaths of older adults are concentrated be estimated to reflect a plausible distribution of deaths in the populations studied? If so, what are the features of the distribution of deaths in these populations? What are the levels and trends for older females and males? Does the shifting mortality and compression hypothesis observed in developed countries hold in the sub-Saharan context?***

Since life expectancy is a mean value, it is sensitive to sampling fluctuations and extreme values. As such, we agree with Goldfarb and Pardoux (2013) that it is interesting to study the mode as an additional indicator to the mean to assess different distributions. In the case of deaths, the mode of the adult death distribution could be a relevant alternative indicator for the analysis of longevity, as it is for developed countries (Canudas-Romo, 2008; Horiuchi et al., 2013; Kannisto, 2001a; Thatcher et al., 2010). However, this distribution was severely disrupted during the HIV/AIDS crisis, with the risk of death in adulthood rising dramatically in some southern and eastern African countries. Apart from countries severely affected by HIV that may have experienced a decline in the adult modal age of death, the increase is likely to have been small given changes at other ages and the limited public health attention given to this age group. These latter developments will be discussed in the final chapter of the thesis.

Chapter 2

Estimation of older adult mortality from imperfect data: a comparative review of methods using Burkina Faso censuses[4]

1. Introduction

In countries that have a poor vital statistics system, mortality estimates are derived from general population-based surveys. These sources suffer from a variety of age errors that are reflected in the data in different ways, including age heaping and age misstatements (Pison and Ohadike 2006; Preston et al. 1999; United Nations 2018). In sub-Saharan Africa, the problem is more pronounced for older adults (Randall and Coast 2016). Most of this population is illiterate, without any birth certificates, and therefore unaware of their true age. For those who do have a birth certificate, they are backdated and very often have an imprecise reference to their year of birth and sometimes have no indication of the month and day of birth. These issues make it difficult to know or to accurately approximate their actual ages during surveys and censuses. This is even more difficult when it comes to estimating the age at death of deceased adults. In this context, how can we accurately estimate older adult mortality?

In a broad sense, adult mortality refers to the mortality of people aged 15 and over. To make a clear distinction with mortality at older ages, the concept of adult mortality is used restrictively in demographic analysis to denote the mortality of people between the ages of 15 to 50 and more generally up to 60 years old (Timaeus, Dorrington, and Hill 2013). Until now, life tables remain the best tool for analysing and describing mortality at any age, whether through a real or a synthetic cohort. But in contexts where the data is poor, constructing life tables should involve the use of indirect or semi-indirect methods such as death distribution methods to correct the data. Depending on how realistic the assumptions underlying these methods are, the reasonableness of the resulting mortality estimates could be compromised. Hence, attention should be paid to the assumptions underlying these methods, especially those that appear unrealistic.

Methods used to correct data

[4] Published in Demographic research: Volume 43 (2020), Article 38, Pages 1119-1154

In the past, efforts have been made to assess and correct for incompleteness of death and population counts from census data using death distribution methods (DDMs). One group of DDMs is based on the Growth Balance equation of a population (Brass 1975; Gray 1986; Hill 1987). The other method, known as the Cohort Extinct method, relies on the ratio between the number of people of a certain age and older that are alive in a population and the total number of deaths expected above that age in the future (Preston et al. 1980; Preston and Hill 1980). Both methods were first developed for census data from one point in time assuming the observed population is stable or almost stable. It was shown later that the assumption of stable population underlying both methods could be relaxed when two censuses are available (Bennett and Horiuchi 1981, 1984; Gray 1986; Hill 1987). Other variants of these methods have been developed, but they require reliable death registration records to perform consistency checks between enumerated population and recorded deaths at a certain advanced age (Andreev 2004; Machemedze and Dorrington 2011; Terblanche and Wilson 2015b, 2015a; Wilmoth et al. 2017). However, there is no such external accurate source of death registration records in many sub-Saharan African countries. Hence, the extended versions of the Growth Balance and the Cohort Extinct methods, termed respectively as the Generalized Growth Balance (GGB) and the Synthetic Extinct Generation (SEG) methods (Dorrington 2013), have become popular. They allow the assessment of the relative coverage of one census compared to the other in estimating the completeness of the intercensal deaths. As a result, these methods remain suitable and among the most widely used for countries lacking vital registration systems when the underlying assumptions are checked. A detailed description of these methods can be found in Tools for Demographic Estimation, an open resource[5] developed by the International Union for the Scientific Study of Population (IUSSP).

The price for relaxing the assumption of stable population when using the extended DDMs is to come up with a single point estimate from two censuses. Apart from this assumption, attention should be paid to three other assumptions that are less restrictive but may lead to incorrect estimates of death completeness (Adair and Lopez 2018; Dorrington 2013; Murray et al. 2010). The first is that the level of completeness is constant above a certain age limit and age is accurately reported for both population and deaths. Age heaping has been shown to have a negligible effect, unlike age misreporting, whose effects could disrupt this assumption and affect

[5] https://demographicestimation.iussp.org/

the reliability of the resulting estimates (Murray et al. 2010). However, these effects may be partly diminished by reducing the limits of the open age group of the age distribution until they correspond to the constancy condition required in the diagnostic plots when applying DDM methods. The second assumption is that the coverage of the two censuses considered when applying a method is assumed to be similar at all ages and invariable over time. The authors of the SEG method (Bennett and Horiuchi) suggested taking into account a possible differential coverage of the two censuses by correcting age-specific intercensal growth rates with a delta factor (δ) as the relative coverage of the first census compared to the second. Rather than estimating the δ factor and using it to correct intercensal growth rates as just explained, Hill and others (2004, 2009) preferred combining both methods by applying the GGB method first and then using the resulting adjusted population as input for the SEG method. The last problematic assumption underlying DDMs is that the population is closed to migration even though these methods are quite sensitive in contexts of high migration. They have therefore been improved to take this issue into account (Bhat 2002; Hill and Queiroz 2010). In the absence of reliable information about the type and age structure of recent population movements generally collected in censuses, Hill and others (2009) suggested that the minimum age for assessing the completeness of death reports be raised from 15 to 30 years or above, while Murray and colleagues (Murray et al. 2010) suggested using the GGB method for ages 40-70, the SEG method for ages 55-80, and the hybrid GGB-SEG method for ages 50-70. Following these precautionary measures does not eliminate all the errors in the data but may be helpful in improving any mortality measure based on them.

Indirect approaches for adjusting life tables

Various approaches have been developed to generate life tables from defective data. Rather than using raw data as is done in countries with a good vital statistics system, a first approach is to correct data to compute life tables directly without any further adjustment. For example, death distribution methods could be used for that purpose (Dorrington 2013; Hill and Choi 2004). There are also variable-r procedures that do not require adjustment for the completeness of intercensal deaths when constructing a slightly more accurate life table. Two variants of this procedure were used to estimate mortality in previous studies (Merli 1998; Preston et al. 1996). The procedure uses age-specific growth rates with either successive age distributions of censuses, or age distribution of intercensal deaths. When applying these methods to Vietnam,

the census-based method was more sensitive to differential census coverage and residual intercensal migration than the death-based method (Merli 1998). The death-based method is derived from the cohort extinct method developed by Paul Vincent (Vincent 1951).

To overcome the scarcity of reliable data sources for mortality estimation in most developing countries, the idea of empirical life tables was put forward in the 1950s (United Nations 1955). The objective was to take advantage of the experience of countries for which there was a better knowledge of mortality patterns to establish a repertoire of mortality patterns. For example, the level of child mortality observed in any population could be used to identify the overall age-specific mortality level that better describes it. This idea was later taken up and refined in various studies (Coale and Demeny 1966; Coale et al. 1983; Ledermann 1969; United Nations 1982). The most popular empirical model life tables remain those of Coale-Demeny (CD) and the United Nations (UN). The construction of the CD model life tables was largely based on European sources. Based on seemingly similar mortality patterns and the relationships between child and adult mortality, four regional families were constructed, each tabulated by sex into twenty-four levels of mortality with a minimum life expectancy at birth of 20 years for level 16. The UN model tables were assembled from data from a few developing countries, but the only African data included were from Tunisia. The UN tables have also been subdivided, but into five main families. These tables and the CD model life tables have been criticized for being based on limited empirical data, uniparametric and therefore inflexible, and, above all, for not reflecting the contemporary epidemiological experiences of many countries, particularly the HIV/AIDS crisis in some sub-Saharan countries (Murray et al. 2000).

Noting that the logits of two survivorship probabilities may be related linearly, in the 1970s, Brass introduced a new model for life tables that allows for correction of the survival function from deficient data. The model generates a complete survival function using a standard survival function (Brass 1971, 1975). Its approach makes it possible to avoid generating life tables directly from an empirical age pattern of mortality. One important issue with this method is finding the appropriate standard survival function. In addition, if accurate information on child mortality is available, it allows for better adjustment of the overall mortality level compared to

[6] The four families of patterns from the CD model life table are: North (mostly from Scandinavian countries), South (Mediterranean European countries), East (Eastern European countries), and the Western pattern, which is used as the residual pattern. The model has been updated and extended to close the tables beyond age 100.

the standard. The Coale-Demeny and United Nations model life tables are a good repository for choosing a standard. But as stated before, these empirical life tables are from developed countries and do not necessarily reflect the age pattern of mortality of developing countries, including those from sub-Saharan Africa. It was shown later that the assumption of linearity used in the Brass logit transformation is not satisfactory, and a modification of the model was introduced with correction factors based on the level of child and adult mortality, again with respect to a standard provided with the model (Murray et al. 2003). Considering adult mortality contributes to a better adjustment of the overall shape of mortality and the assumption of linearity. This paved the way for the use of two input parameters, namely the levels of child mortality and adult mortality between 15 and 50 or 60 years of age to generate complete life tables, including old-age mortality. Using 719 life tables from the Human Mortality Database7 (HMD), an indirect and flexible log-quadratic model (LQ) with two input parameters was developed to estimate complete life tables based on either child mortality only, or child and adult mortality. By relating in log-scale age-specific mortality rates to child mortality using a quadratic regression, the model coefficients were derived from the first term of a singular value decomposition of the matrix of the regression residuals (Wilmoth et al. 2012). The LQ model is expressed as follows:

$$\log(\mu_x) = a_x + b_x h + c_x h^2 + v_x k \qquad (1)$$

where a_x, b_x, c_x and v_x are constant age-specific coefficients related to age groups x denoted by {0, 1-4, 5-9, 10-14, …105-109, 110 +}, h is equal to $\log({}_5q_0)$ and k depicts the deviation of the observed age pattern of adult mortality (${}_{45}q_{15}$) from that of a standard. Wilmoth and colleagues argued that the model performs as well as the modified logit of Brass but is preferable because of its flexibility.

It was shown later that the singular value decomposition (SVD) technique, on which the LQ model is based, has many properties and is a powerful tool for summarizing, smoothing and

[7] "The Human Mortality Database (HMD) contains original calculations of death rates and life tables for human populations (for countries or areas), as well as the input data used to make these calculations. The input data consist of death counts from vital statistics, plus census counts, birth counts, and population estimates from various sources. […] The database is limited by design to populations where death registration and census data are virtually complete, since this type of information is required for the implementation of the standardized methodology used to reconstruct historical data series. As a result, the countries and areas included in the database are relatively wealthy and for the most part highly industrialized". See https://www.mortality.org.

modelling age-specific demographic quantities (Clark 2015). Recently, Clark (2019) used this approach to develop a general model indexed by child (5q0) and adult (45q15) mortality indices. In order to better capture as much variability as possible, the model was calibrated using 4610 complete life tables for each sex from historical periods that are contained in HMD.

Objective and research questions

In sub-Saharan Africa, where mortality beyond age 50 is less studied, the developments mentioned above open a new era to better estimate old-age mortality, at least until age 70, which is considered the threshold of premature deaths (Norheim et al. 2015). Even up to age 80 can be considered a starting cut-off age from which frailty and decline in functional abilities occur markedly (Kafkova 2016; Kannisto 1992; Thatcher et al. 1998; Wilmoth and Dennis 2007). One of the few papers trying to assess old-age mortality is one from Bendavid and colleagues (2011), which used household deaths during the last twelve months to directly derive estimates from eight country-specific household surveys. They themselves argued that the sample size (around 75 deaths on average beyond age 60) was very low to draw any valuable conclusions. Apart from this, other estimates available are those derived from international agencies' databases (WHO, UNPD, IHME) or national statistical offices based on census data. In addition, reliable estimates are available for sub-populations from Health and Demographic Surveillance Systems (HDSS). Notwithstanding age errors and risks of omission, the comparison of mortality estimates from deaths during the last twelve months preceding the censuses with those of the areas covered by three HDSS in Senegal has produced fairly consistent results, even between the ages of 60 and 80 (Masquelier et al. 2016). Unfortunately, mortality levels estimated from these data may not always reflect those at the national level since these data are not representative. In addition, individuals lost to follow-up, and even probable cases of age exaggerations could also distort observed mortality levels. Deaths within households during the year preceding a census appear to be the most suitable source for studying older adult mortality in the sub-Saharan context. They provide a higher number of deaths at older ages compared to surveys. Using such information from the last three censuses in Burkina Faso, our aim is to contribute to a better understanding and knowledge of older adult mortality in Burkina Faso. We seek to answer the following questions: How can we better estimate older adult mortality from limited data? Although most of the models described above are based on non-African mortality

patterns, can consistent estimates be derived from these methods? If not, what could explain the possible differences? Which method is preferable?

In the following sections, after a brief review of the data and their quality, we will present the analytical methods used to answer our research question. We will then present and discuss the results.

2. Data and methods

2.1. Data description

As one of the least developed countries of the world, Burkina Faso is a Western African country that lacks a reliable vital statistics system. In order to provide comprehensive information to policy makers, many surveys and censuses have been carried out, but censuses are the only sources that collect information on mortality for all ages. All the following analysis will be based on the enumerated population and the reported deaths from the 1985, 1996, and 2006 censuses provided by the National Institute of Statistics and Demography (INSD) of Burkina Faso. For the enumerated population, a random sample of 50% of the population was provided for each census. Compared to the 10% samples usually available on the IPUMS platform, this is an important sample size. Using the total sex-specific population sizes recorded in the census reports and the age distribution of the study sample, it was possible to draw the age distribution of the total population by year and sex. During these censuses, deaths that occurred within households during the last twelve months preceding each census were recorded by sex with the age at death. For the analyses, 100% of the data on the reported deaths were provided. At the end, we had the age distribution of the population as well as death counts tabulated between the ages of 0 to 98 years and over.

In the case of the census data from Burkina Faso, a general overview is shown in Table 1 below for both population and deaths. Unknown ages in resident populations never exceeded 0.5% in the three censuses. This is mostly due to some basic techniques given to interviewers to approximate the true ages of respondents. However, about 29% of ages at death were not reported in 1996, while this proportion remained low and almost constant in 1985 and 2006. At the same time, an exceptional rise in deaths is noticeable in 1996. No mention is made of the

reasons for this spike in deaths, but it may be due to a combination of the effects of the meningitis and measles epidemics with about 43,000 cases of meningitis and 32,400 cases of measles recorded in health facilities in 1996 (DGISS 2011; Nicolas 2012).

Table 1: The 1985, 1996, and 2006 censuses data, Burkina Faso

	Total size	Females (%)	Unknown ages (%)
Population			
1985	7,964,701	51.87	0.1
1996	10,312,613	51.80	0.4
2006	14,017,261	51.71	0.5
Deaths			
1985	75,634	47.00	2.8
1996	157,097	47.04	29.2
2006	116,201	45.41	3.3

Source: Author's calculations based on Burkina Faso censuses data provided by the INSD

These epidemics happened in conjunction with the adverse effects of structural adjustment plans for the state's disengagement from social sectors, including the health sector. In addition, the level of health service attendance gradually declined from 32% in 1986 to 18% in 1996 (INSD 2000). However, there was a relative stable sex-specific distribution with about 52% in favour of resident females and 45 to 47% for deceased females, regardless of census.

Additional problems were observed in the data when looking at age distribution through age pyramids plotted in Figure 1 below. These pyramids were built without the unknown ages. As expected for a developing country like Burkina Faso characterized by high fertility, the population-based pyramids of the three censuses are triangular in shape, i.e. with large bases that shrink gradually with age (INDEPTH 2003; Pison and Ohadike 2006). The population-based pyramids show age heaping at ages with terminal digits 0 and 5, with a stronger preference for 0. Another problem noticed is the under-enumeration of children under two years, especially those under one year regardless of gender. This phenomenon also affects 11-year-olds in all censuses, as well as individuals aged 24, 34, 44, 54 and 64, particularly in the 1985 census. In general, this highlights the problem of incompleteness of the census data. Regarding the distribution of deaths, there is a concentration of deaths in the early years of life. Except in 2006, these deaths are more concentrated at birth and then decrease gradually, regardless of gender.

The exception noted in 2006 could reflect an under-reporting of newborn deaths rather than a real decrease in infant mortality. Beyond 5 years, deaths are almost uniformly distributed, with slight increases or decreases in young adults until age 80, from which the proportions start declining. As for populations, a noticeable preference for terminal digit 0 and 5 also affects the reported ages at death. The phenomenon is perceptible beyond age 15, and sometimes extends to terminal digit 6, particularly in the elderly in 1996 and adults in 2006.

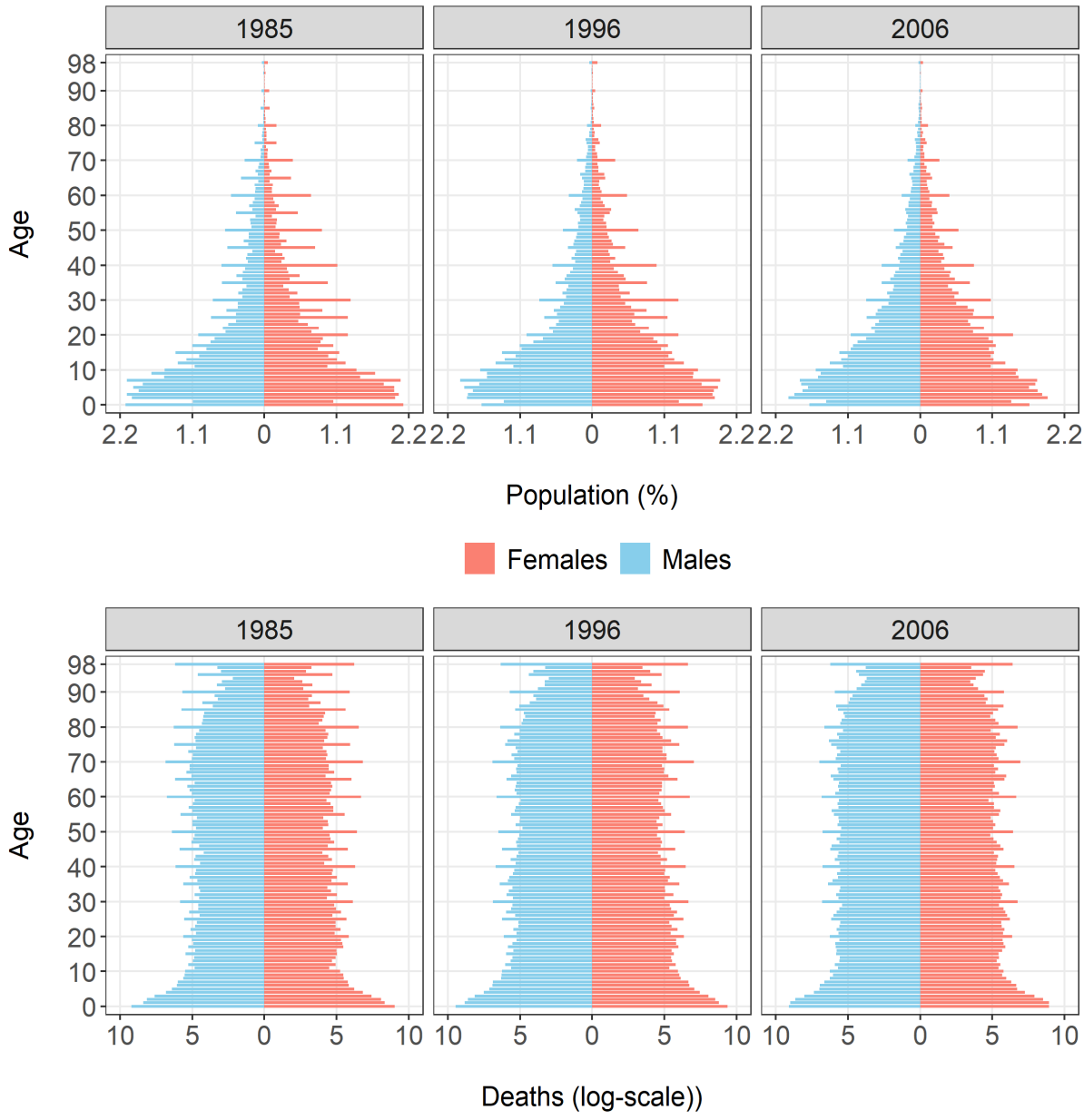

Figure 3 : Age distribution of population and deaths in 1985, 1996, and 2006, Burkina Faso

Source: Author's calculations from the census data provided by the INSD

2.2. Methods for correcting the data

Age heaping

The magnitude of age heaping in the data could be assessed using age ratios (AR). Before calculating AR, demographers used to aggregate the data in 5-year age groups. Rather than using classic 5-year age groups (15-19, 20-24, 25-29, ...) that are more sensitive to preference for terminal digits 0 and 5, Blacker, cited by Dorrington, suggested using non-classic age groups centred on ages subject to heaping (13-17, 18-22, 23-27, ..). This approach could be a simple solution to reduce the effect of age heaping on further estimations without distorting the data as much. It also makes it possible to redistribute unknown ages without being totally absorbed by the ages subject to heaping. Without any prior knowledge of the age distribution of unknown ages, we assume they have the same age structure as individuals of known ages. As a reminder, Hobbs (2004) suggested to calculate the AR for an age group i by using the formula below that gives sufficient weight to the central age group:

$$AR_i = \frac{3 \times N_i}{N_{i-1} + N_i + N_{i+1}} \quad (2)$$

When ARs in deaths are compared to those in populations, a value close or equal to 1 would mean that age heaping is of similar magnitude within the two age structures. In Figure 2 below, there is no clear picture whether age heaping is more pronounced in deaths than in populations, given the irregular fluctuations observed around 1. The only evidence is that age heaping is more pronounced in deaths at age groups that contain terminal digit 0, and inversely in populations at age groups containing terminal digit 5. On the other hand, the magnitude of the fluctuations increases with age, but it decreases with time. This shows that the older people got, the more they tended to round their ages, much more in the past than recently. Although there is no clear gender difference, the phenomenon seems slightly more marked in females in some places. In general, the observations made above apply to both classic and non-classic age groups. However, non-classic age groups result in less pronounced age heaping. It should be noted that the phenomenon tends to increase in deaths beyond age 70 and 68 respectively, in classic and non-classic age groups, regardless of gender and year. In 2006, with non-classic age groups for example, age heaping was more prominent in deaths starting from around the age of 70 (centre of the 68-72 age group), but with less fluctuations for males than for females.

Because of potential effects of such anomalies, attention should be paid to any resulting estimates.

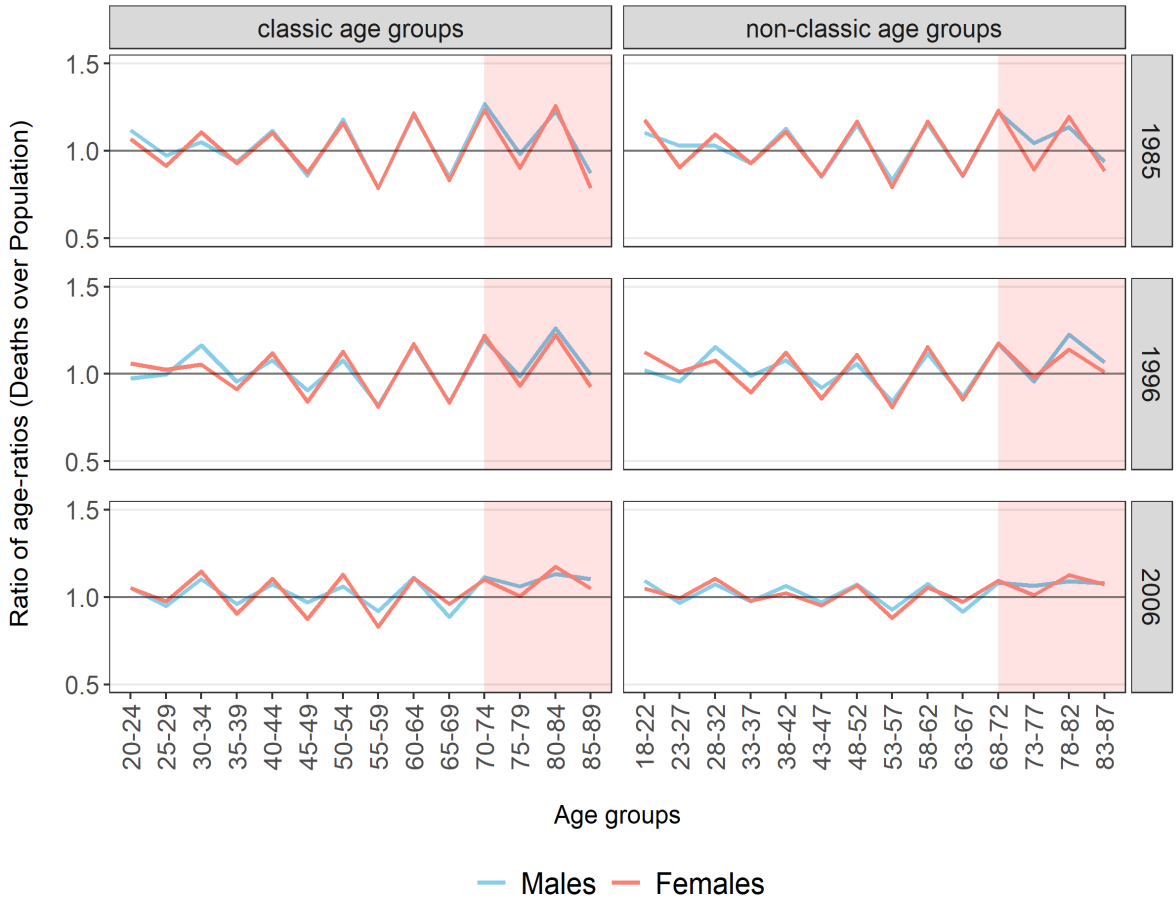

Figure 4: Comparison of age ratios in deaths and population in 1985, 1996, and 2006, Burkina Faso

Source: Author's calculations from the census data provided by the INSD

Systematic age misstatements

The tendency to round ages to terminal digits 0 and 5 and fluctuations that result from this could lead to systematic age misstatements. For example, if several 64-year-old individuals are reported to be 65, there would be a trough in the 64-year-olds and a peak in the 65-year-olds that could suggest under-enumeration in the former and over-enumeration in the latter. Such systematic age misstatements are generally corrected when using non-classical age groups centred on ages subject to heaping. However, not all the age misstatements are related to age

heaping. Some of them are due to omissions caused by disintegrated households. These cases occur most often with single households. But in the context of Burkina Faso, where the extended family is still widespread, the cases of disintegrated single households may be quite small. On the other hand, omissions due to unreported deaths could be more important. Other kinds of errors such as age exaggeration may also be important in such a context where being old confers a certain social status. For example, an individual aged 64, instead of rounding off his age to 65, could attribute to himself an age greater than 70, or be assigned an exaggerated age if he/she had died. These kinds of exaggerations in age declarations are difficult to detect and correct. As their amplitudes exceed 5 years, the 5-year age groupings cannot dilute them and reduce their potential effects. It is well known that age at death is more often exaggerated at older ages and leads usually to substantial downward bias in mortality rates (Booth and Gerland 2015; Murray et al. 2010; Palloni et al. 2016; Preston et al. 1999). Palloni and others (2016) used an age misstatement pattern from Costa Rica as a standard to correct their effects for mortality estimation in Latin America. Such a pattern does not exist in Burkina Faso, or even more broadly in West Africa, making it difficult to use this approach. An assessment and correction for data incompleteness could help to mitigate this problem to some extent.

Correction for census coverage and incompleteness of deaths

I used the hybrid death distribution method that combines the GGB and SEG methods. To choose the minimal age that allows controlling for migration effect, we explored information on international migration over the past twelve months collected in the Burkina Faso censuses. As a result, the use of out-migration data in countries that are not attractive such as Burkina Faso raises questions, especially when they aim to improve estimates. Analysis of the migration data from censuses in Burkina Faso (Table 2) shows that there are irregularities that affect their reliability. But it is known that data on international immigration are generally better captured than data on international emigration. These data often suffer from important omissions and misinformation about the final destination of migrants (Dabiré 2016).

Table 2: Net migration of recent international migrants (last 12 months), Burkina Faso, from the 1985, 1996, and 2006 censuses

Ages	1985		1996		2006	
	Females	Males	Females	Males	Females	Males
< 15	6,674	6,312	379	-493	7,626	7,162
15-19	-1,077	-7,992	-1,382	-16,690	379	-7,707
20-24	246	-12,971	-493	-24,060	1,472	-10,043
25-29	789	-8,085	17	-15,650	1,926	-5,573
30-34	443	-3,557	326	-8,928	1,228	-2,626
35-39	380	-1,733	230	-4,478	882	-1,330
40-44	330	-750	154	-2,584	517	-840
45-49	220	-238	119	-1,385	360	-423
50-54	175	-3	85	-790	204	-329
55 +	331	334	144	-551	368	19
Unreported ages	4,133	4,680	-659	-3,556	108	-67
Total	**12,644**	**-24,003**	**-1,080**	**-79,165**	**15,071**	**-21,758**

Source: INSD, extracted from the 1985, 1996, and 2006 census reports

The trend from these data is that Burkina Faso has remained a country of emigration. Regardless of the census, this emigration seems to affect males more and is concentrated in the 15-39 age group. Beyond this age, international migration appears to be of lesser magnitude to substantially affect population dynamics. On the other hand, extensive internal migration can be observed in countries such as Burkina Faso towards urban areas and economic poles. But these are not likely to affect mortality estimates at the national level.

Thereafter, I opted for using non-classical age group data with less pronounced age heaping. To avoid the effect of under-enumeration of children observed in population age pyramids that could not be addressed by any death distribution method, I truncated the data from age 13. An *R* package is now available to implement death distribution methods (Riffe et al. 2017). When the minimal age is specified, the algorithm behind the package can automatically pick up the age range that minimizes the mean squared errors for adjusting the completeness. In the absence of reliable information on the type and age structure of population movements, and based on the age pattern of net migration observed in the table above, I assessed the completeness starting from age 38 in the same vein as suggested by Hill et al. (2009) and Hill and Choi (2009). For each sex and period, the algorithm retained this age as the lower age limit and identified 77 as the upper age limit beyond which the fit would be worse and would have resulted in a greater mean squared error. Overall, this is concordant with the magnitude of age

heaping noticed previously in the 70s when comparing age-ratios in deaths and population. It is also possible that other kinds of errors such as age overstatements are present beyond these ages. Regarding the census differential coverage as shown in Figure 3 below, the second census was always over-enumerated compared to the first, except for males in 1996-2006. As for the completeness of intercensal deaths, it is about 71% and 73% for females respectively in 1985-1996 and 1996-2006, while for males it was 77% and 73% respectively.

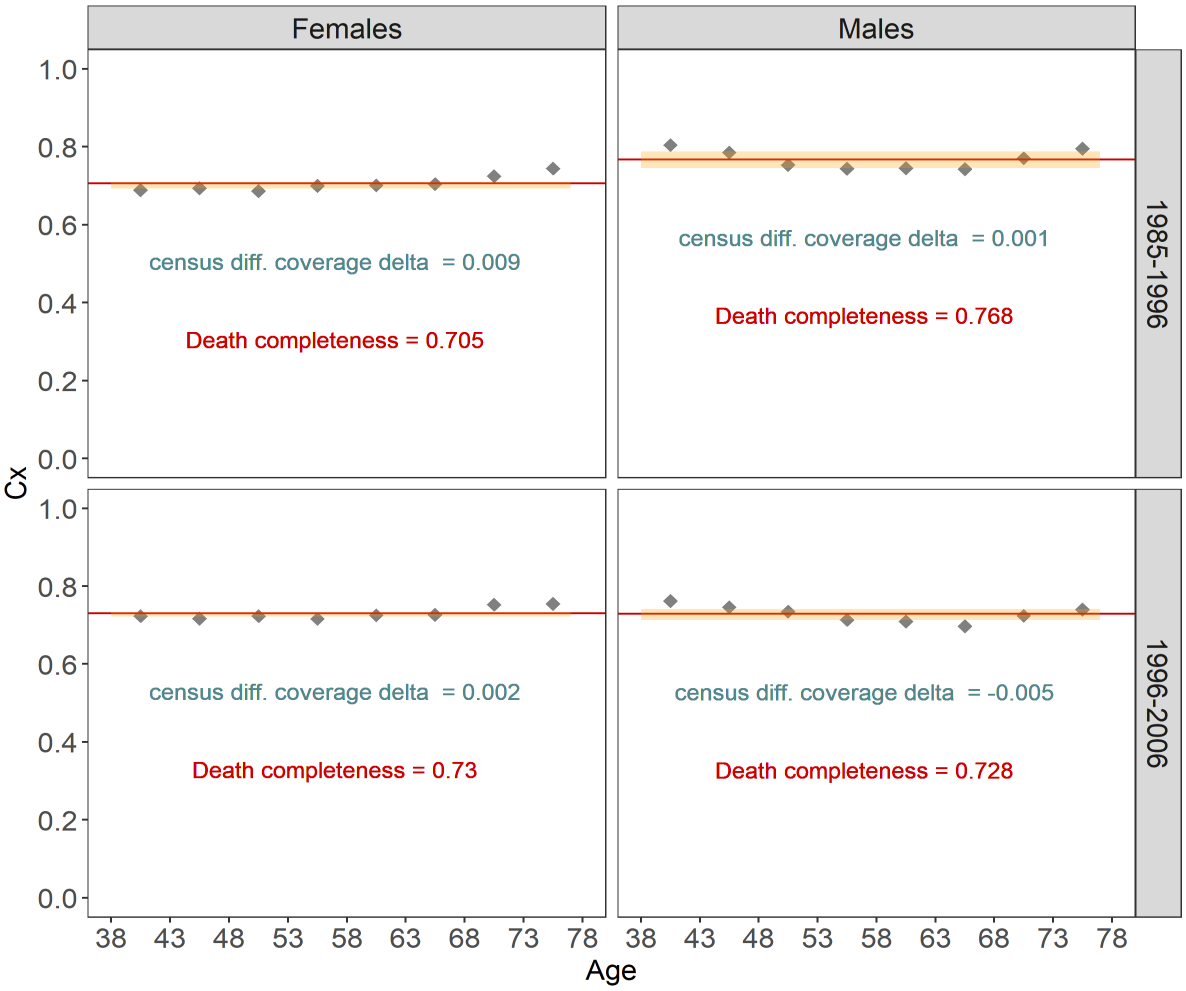

Figure 5 : Census differential coverages and incompleteness of intercensal deaths in the 1985, 1996, and 2006 censuses, Burkina Faso

Source: Author's estimations from the census data provided by the INSD

When looking at the diagnostic plot, the dots are well aligned for females and the orange band representing the interquartile range of completeness levels of death is quite narrow. From the

age group 68-72 onwards, the dots diverge slightly upwards from the band. This is also consistent with the age-ratio analysis above and may be due to an effect of age exaggeration. Males, on the other hand, the dots are less well aligned than for females. Overall, there is an acceptable alignment of points, at least until age 68.

2.3. Procedures for estimating older adult mortality

Our analyses are not interested in the oldest old people who are defined as people aged 80 or older in many studies. Instead, the indicator of interest is the probability of death between age 50 and 80 ($_{30}q_{50}$). I first computed a basic estimate directly from the adjusted intercensal person-years-lived and the adjusted intercensal deaths with the age range of 50 to 80 ($_{30}\hat{q}_{50}$), then by 10-year age intervals, mainly $_{10}\hat{q}_{50}$, $_{10}\hat{q}_{60}$, $_{10}\hat{q}_{70}$. Since important age heaping was noticed in deaths beyond age 70, I split $_{30}\hat{q}_{50}$ into $_{20}\hat{q}_{50}$ and $_{10}\hat{q}_{70}$.

In addition to life tables generated directly from the data adjusted for incompleteness of deaths, I use different model-based approaches. First, I used the Brass relational model with the regular standard age pattern from INDEPTH Network for sub-Saharan Africa. As this standard is constructed based on classical 5-year age groups, I proceeded by interpolation to determine the survivors at the boundaries of the classical age groups. Second, I used the SVD-based model from Clark (2019) which has the advantage of minimizing errors compared to the LQ model when estimating age-specific mortality rates. Since this model is indexed by $_5q_0$ and $_{45}q_{15}$, I used the interpolated number of survivors at age 15 (l_{15}) and age 60 (l_{60}) in order to estimate $_{45}q_{15}$ from the adjusted data tabulated using non-classical age groups. For the child mortality ($_5q_0$) input, I used country-specific estimations of child mortality for Burkina Faso from the United-Nations Inter-agency Group for Child Mortality Estimation (UN-IGME). These estimates are based on all national data sources available for all countries, and there is consensus on the Bias-reduction Bayesian B-spline model used to derive them (Alkema et al. 2014). However, the indices $_5q_0$ were estimated using the geometric mean of its yearly estimates over the two intercensal periods. These input parameters are summarized in Table 3 below.

Table 3: Estimated adult mortality and the corresponding levels of child mortality, Burkina Faso, from the 1985, 1996, and 2006 censuses

Basic estimates	Source	Females		Males	
		1985-1996	1996-2006	1985-1996	1996-2006
${}_{45}q_{15}$	Estimated	0.335	0.296	0.401	0.412
${}_{5}q_{0}$	UN-IGME*	0.191	0.165	0.205	0.177

Note: (*) The UN-IGME estimates are interpolated over each intercensal period by using a geometric mean.

In addition to the Brass model that is calibrated with the INDEPTH African data and the SVD model which is calibrated mostly with data from developed countries, including historical data, I fitted a parametric model to the data as a final approach. Unlike mortality beyond age 80, whose functional shape is still the subject of debate in aging societies, there seems to be a consensus on the Gompertzian nature of the age patterns of human mortality between the ages of 30-80 as reported in multiple studies (Horiuchi and Wilmoth 1998; Saikia and Borah 2014; Thatcher 1999; Thatcher et al. 1998; Vaupel 1997). For example, assuming human mortality to follow the Kannisto (Kannisto 1992) model as the simplest form of logistic model, mortality patterns before age 80 were used to fit and interpolate life tables to the oldest old ages in the Human Mortality Database (HMD) (Wilmoth et al. 2017). This approach is used to circumvent irregular fluctuations generally observable at the extreme ages of life due to either data quality, or heterogeneity and low population size (Gavrilov and Gavrilova 2011). Hence, taking advantage of the monotonic Gompertz increase of the force of mortality between ages 30-80, I used the Makeham model (Makeham 1860) as a Gompertz-based model that allows accounting for constant background mortality at younger adult ages, and thus removing some of the distortion of the basic Gompertz between age 30 and 40. The data adjusted for incompleteness of deaths are then fitted over the age range 38-42 to 68-72, which seems less impacted by age errors (as shown in the age-ratios plot and the diagnostic plot related to the death distribution method). Then, the model parameters are used to extrapolate a mortality pattern until age 80 and over. This approach leads to a smooth mortality curve and allows checking the consistency with the age pattern of the input data, mainly beyond age 70. Any clear deviation of the fitted age pattern from the one derived from the adjusted used as inputs could reflect an effect of age errors.

Table 4: Summary of the methods used and the main advantages and disadvantages

Methods	Principles	Advantages	Disadvantages
Adjusted data	Hybrid death distribution method combining GGB + SEG	Allows to correct the data for incompleteness and census differential coverage with the possibility to reduce the effects of migration and age exaggerations at older ages	Assumption of constant completeness of death
BRASS model	Relational model indexed on a standard age pattern of mortality	Allows deriving an entire life table from fragmentary or imperfect mortality data	Depend on whether the age pattern of mortality used as standard to fit the model reflect the demographic and epidemiological experience of the population under study
SVD model	empirical model indexed by ${}_5q_0$ and ${}_{45}q_{15}$	Indexing any available pair of parameters of ${}_5q_0$ and ${}_{45}q_{15}$ with empirical age patterns of mortality from HMD to generate full life tables	Depend on whether the age patterns of empirical life tables used to calibrate the model reflect the demographic and epidemiological experience of the population under study. Poor prediction of age specific mortality schedules could lead to erroneous mortality levels.
MKH model	Gompertz-based parametric model able to draw background mortality at younger ages with the monotonic linear increase of the force of mortality until at least age 80	Possibility to fit the model to an age range (65 or 70 for example), and then extrapolate to age 80	Depends on the data quality over the age range used to fit the model parameters before extrapolation, and the upper limit of this age range should not fall within the age ranges suspected of obvious and pronounced age errors

Source: Author's summary

To achieve that, we used the expression of the Makeham (MKH) model provided by Horiuchi et al (2013) as follows:

$$\mu_x = \beta e^{\beta(x-M)} + \gamma \qquad (3)$$

where β, M and γ are the parameters of the model. Each of the methods described above has advantages and disadvantages, and the main ones are summarized in Table 4 above.

3. Results and Discussion

3.1. Age pattern of older adult mortality

After adjusting the data for incompleteness, the resulting mortality curve shows some slight fluctuations, probably due to the remaining effects of age heaping, with peaks in age groups centred on ages ending in 0 and troughs for those centred on ages ending in 5 (see Figure 4 below).

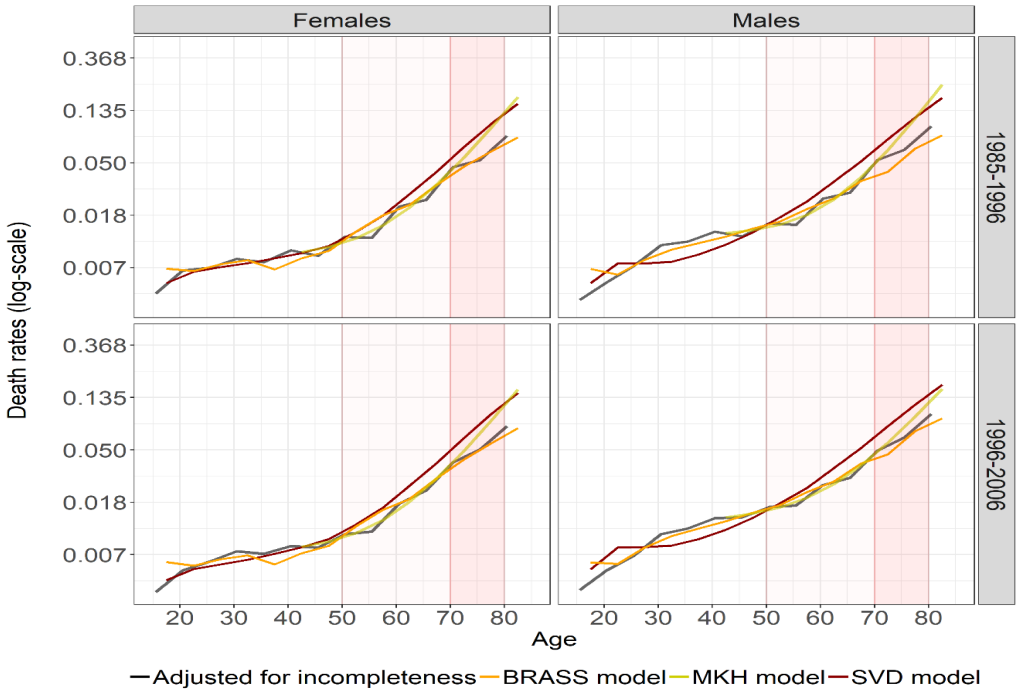

Figure 6 : Age patterns of older adult mortality from different methods, Burkina Faso using the 1985, 1996, and 2006 censuses

Source: Author's estimations from the census data provided by the INSD

Before age 50, there is a mortality hump between age 20 and 35 that is somewhat flattened in females while it is more apparent in males and extends to age 40. This mortality hump can be explained by several factors, including multiple risky behaviours in young adults in addition to maternal mortality, the importance of which is well known in females of reproductive age (Anderson and Ray 2018; Melaku et al. 2014; Rao et al. 2006; Streatfield et al. 2014).

Beyond age 50, the pace of the curve seems to define a linear trend that is not very disturbed by fluctuations. When applied to the data adjusted for incompleteness of death, the BRASS, the MKH and SVD models result in age patterns of mortality that differ in some respects. Regarding these age patterns, the BRASS model fits well the data adjusted for incompleteness of death up to age 70 but deviates slightly from it downwards beyond that age. When the data adjusted for incompleteness of deaths are used to fit the MKH model over the age groups from 38-42 to 68-72 and then extrapolate beyond this, a clear upward deviation is evident beyond age 70. The SVD model, on the other hand, does not adequately capture the mortality hump at younger ages. Between 50 and 80 years, the age pattern described by the model remains well above that described by the data adjusted for incompleteness of death, with a gap that gradually widens beyond age 70. Although the former uses the same level of adult mortality ($_{45}q_{15}$) as the latter as an input.

3.2. Age and sex-specific differences between mortality indices

Following the analysis of the age schedule of mortality, Figure 5 below summarises the mortality levels derived from each method for $_{10}q_{50}$, $_{10}q_{60}$ and $_{10}q_{70}$, and then for the aggregated indices $_{20}q_{50}$ and $_{30}q_{50}$. Regardless of the method and whatever the mortality indice considered, the risk of death is higher among older males than among older females. In addition, female mortality seems to have decreased slightly between the two intercensal periods, while male mortality does not seem to have improved. In the 50-80 age range, the risk of death increases with age and reaches its highest levels between the ages of 70 and 80. This configuration is observed regardless of the method, sex, and intercensal period considered. This is illustrated by the steeper slopes of the curves displayed on the left side of each graph in Figure 5, showing the change from $_{10}q_{60}$ to $_{10}q_{70}$.

The aggregated indice ${}_{30}q_{50}$ estimated from the data adjusted for incompleteness of deaths are 0.628 and 0.591 for females, compared with 0.692 and 0.691 for males over the intercensal periods 1985-1996 and 1996-2006, respectively.

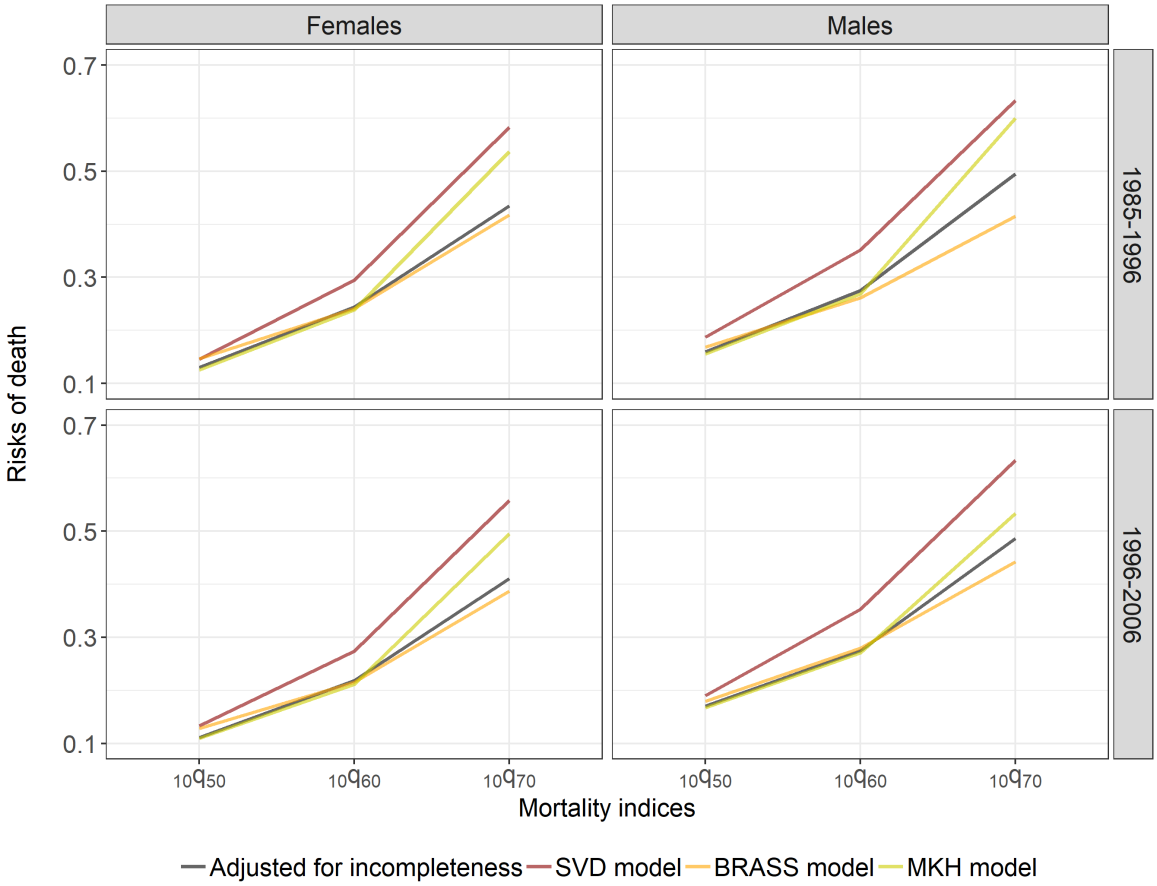

Figure 7 : Risks of death at older ages, by sex and period, Burkina Faso

Source: Author's estimations from the census data provided by the INSD

The Brass model results in levels of ${}_{20}q_{50}$ that are consistent with the estimates from the adjusted data. However, there is a lower mortality between age 70 and 80 that is more noticeable in males over the two intercensal periods. Regarding the MKH model, the risks of death are, not surprisingly, identical to those derived from the adjusted data from age 50 to 70. However, the mortality predicted by extrapolation from age 70 onwards results in levels of ${}_{10}q_{70}$ that are higher than that those estimated from the adjusted data, regardless of sex and period. In terms of aggregated indice ${}_{30}q_{50}$, the risks of death are 0.692 and 0.645 for females over the periods 1985-1996 and 1996-2006, respectively. For males, these risks are estimated at 0.753 and 0.717 respectively over the two intercensal periods. In accordance with Figure 4 on mortality curves,

the highest mortality levels are observed with the SVD model over the entire 50-80 age interval. Among females, there risks of death are estimated at 0.749 and 0.722 compared to risks of death of 0.807 and 0.808 for males over the periods 1985-1996 and 1996-2006 respectively.

The inconsistencies between the different methods in terms of differing age patterns and levels of mortality raise questions. The good fit of the Brass model to the adjusted data up to the age of 70 could mean that the age patterns of mortality before this age were not strongly affected by age errors. It also highlights the capacity of the African age-specific standard proposed by the INDEPTH network to describe age-specific mortality in countries with poor vital statistics. However, the deviation of the resulting age pattern beyond age 70 assumes either that mortality is overestimated in the data adjusted for incompleteness of death or that the INDEPTH African age-specific standard underestimates mortality beyond age 70. The first assumption is less plausible insofar as in African contexts such as Burkina Faso, the data, even when adjusted for incompleteness of death remain marred by important age exaggerations, mainly at advanced ages which should lead to an underestimation of mortality, and not the opposite. The second assumption is more tenable, mainly because of the scarcity of deaths in the data from observatories on which the INDEPTH standard is based. Indeed, these data are generally made up of small numbers at advanced ages.

It may be that the various corrections made to the data (use of non-classic age groups, adjustment of completeness of death and census coverage) were effective enough to make them close to reality, at least until around 70 years ago. In this case, the age pattern described by these data described beyond age 70 is obviously underestimated, irrespective of period and sex, if one considers the upward deviation observed with the extrapolation from the MKH model. However, this underestimation seems to be less pronounced in males over the period 1996-2006. It is possible that age heaping, which was clearly more prominent in male deaths than in male populations in 2006, may have contributed to lessen the effect of this underestimation. Such an underestimation could be explained by omissions and age exaggerations at older ages as well, the effects of which have been discussed in many previous studies (Dechter and Preston 1991; Elo and Preston 1994; Hill et al. 2000; Preston et al. 1996, 1999). Thus, to consider the estimates from the MKH model as plausible is to assume that it is from the age of 70 onwards that age errors have a downward effect on mortality estimates. This is corroborated by the work of Bendavid and colleagues (2011). Comparing age-specific probabilities of death derived from

Demographic and Health Surveys (DHS) with those estimated by World Health Organization (WHO) and United Nations Population Division (UNPD), they found noticeable underestimations of mortality starting beyond age 65-70 for DHS estimates.

If it is assumed that the SVD model predicts an age pattern of mortality that reflects the observed pattern of mortality, this would lead to the assumption that mortality adjusted for incompleteness deaths is still underestimated even before age 70. Yet the diagnostic plots of the data correction (Figure 3), although not perfect, have produced relatively well-aligned dots that would give confidence in the plausibility of the resulting estimates at least up to age 70. Even so, any underestimation is not expected to have a major effect before this age. It is probably this plausibility of the estimates derived from these data that allowed for an adequate fit up to age 70 with the Brass model using a standard age pattern derived from African data. Rather than admitting a general underestimation at older ages, one might also think that the predicted age pattern of mortality from the SVD model is not suitable to describe the age pattern of the observed mortality in Burkina Faso. One possible explanation of this discrepancy could be that this and other models that have been calibrated with empirical mortality data mainly from developed countries do not necessarily reflect the demographic and epidemiological experiences of African countries, including Burkina Faso. Indeed, like other African countries, Burkina Faso has benefited from the medical advances of developed countries with the adoption of expanded programmes of immunization and control of childhood diseases. These advances have contributed to an accelerated drop in child mortality from 0.327 to 0.135 from 1960 to 2010, i.e. a drop of about 60% in half a century (United Nations 2019). Unfortunately, child and adult mortality do not necessarily evolve in tandem as has been the case in developed countries (Masquelier, Reniers and Pison 2014). Adult mortality has remained high in many African countries and very little progress has been made in improving longevity among the oldest. Such epidemiological pathways may have created discrepancies with those observed in developed countries that are likely to affect models for predicting age-specific patterns of mortality from those countries. Moreover, predictions made with models such as the SVD model rely on mean-age patterns from the combination of empirical life tables used, which may deviate from the detailed age-specific mortality schedule it seeks to predict, or may predict mortality at some ages better than others. In addition, for example, the fact that these models use as input an aggregated adult mortality indice that ranges from age 15 to 60 may not capture detailed mortality between these two ages with good accuracy and may confound predictions beyond

age 60. All these reasons can be sources of disturbance and affect the quality of the predictions. This is perhaps why in the literature, reservations have been expressed about the indirect estimation of age-specific mortality schedules from the traditional model tables (Hu and Yu 2014; Murray et al. 2000).

Since there are no sampling errors, the differences observed with the SVD model seem too large to be overlooked. Before attempting to analyse these differences in depth, one could think that the redistribution of 29% of deaths with unknown ages may have led to this poor adjustment with the SVD model. As shown in Table 5 below, when comparing the levels of adult mortality ($_{45}q_{15}$) obtained after redistribution and correction of the observed data with the United Nations (UN) estimates, they remain very close even with a 2-year lag, resulting thus in levels of $_{30}q_{50}$ that are quite similar. If the redistribution of unknown ages had resulted in inconsistent levels of $_{45}q_{15}$ compared to those of the United Nations, one would have thought that the observed differences in old age could have resulted from this redistribution. It is therefore unlikely that the differences observed with the SVD model that use $_{45}q_{15}$ as an input parameter are related to the redistribution of unknown ages.

Table 5: Estimated adult probabilities of death compared with the United Nations World Population Prospects (UN WPP) estimates for Burkina Faso

periods	Period length	Sources	$_{45}q_{15}$		$_{30}q_{50}$	
			Females	Males	Females	Males
1985 - 1989	5	UN WPP	0.288	0.345	0.726	0.784
1985 - 1996	11	Estimated	0.335	0.401	0.749	0.807
1990 - 1994	5	UN WPP	0.301	0.361	0.731	0.790
1995 - 1999	5	UN WPP	0.302	0.374	0.730	0.795
1996 - 2006	10	Estimated	0.296	0.412	0.722	0.808
2000 - 2004	5	UN WPP	0.297	0.349	0.722	0.781

Source: Author's calculations, United Nations World Population Prospects 2019

3.3. Consistency checks with empirical mortality data

A good understanding of the differences in mortality levels resulting from all the methods used requires a comparison of the estimates for Burkina Faso with the mortality experiences of developed countries based on HMD data as shown in Figure 6 below. Since the effects of age errors appeared to be pronounced only beyond age 70, our mortality indice $_{30}q_{50}$ was split

between ${}_{20}q_{50}$ and ${}_{10}q_{70}$. First, by relating ${}_{20}q_{50}$ to adult mortality (${}_{45}q_{15}$), the estimates for Burkina Faso coincide with those of most HMD countries, regardless of the method used. On the other hand, by relating ${}_{10}q_{70}$ to ${}_{45}q_{15}$, the consistency appears less obvious between the estimates for Burkina Faso and those of HMD countries, in particular the estimates derived from data adjusted for incompleteness of deaths and those derived from the Brass model despite the use of the INDEPTH African standard. This tends to corroborate the suspicions of underestimation of mortality beyond age 70 mentioned above.

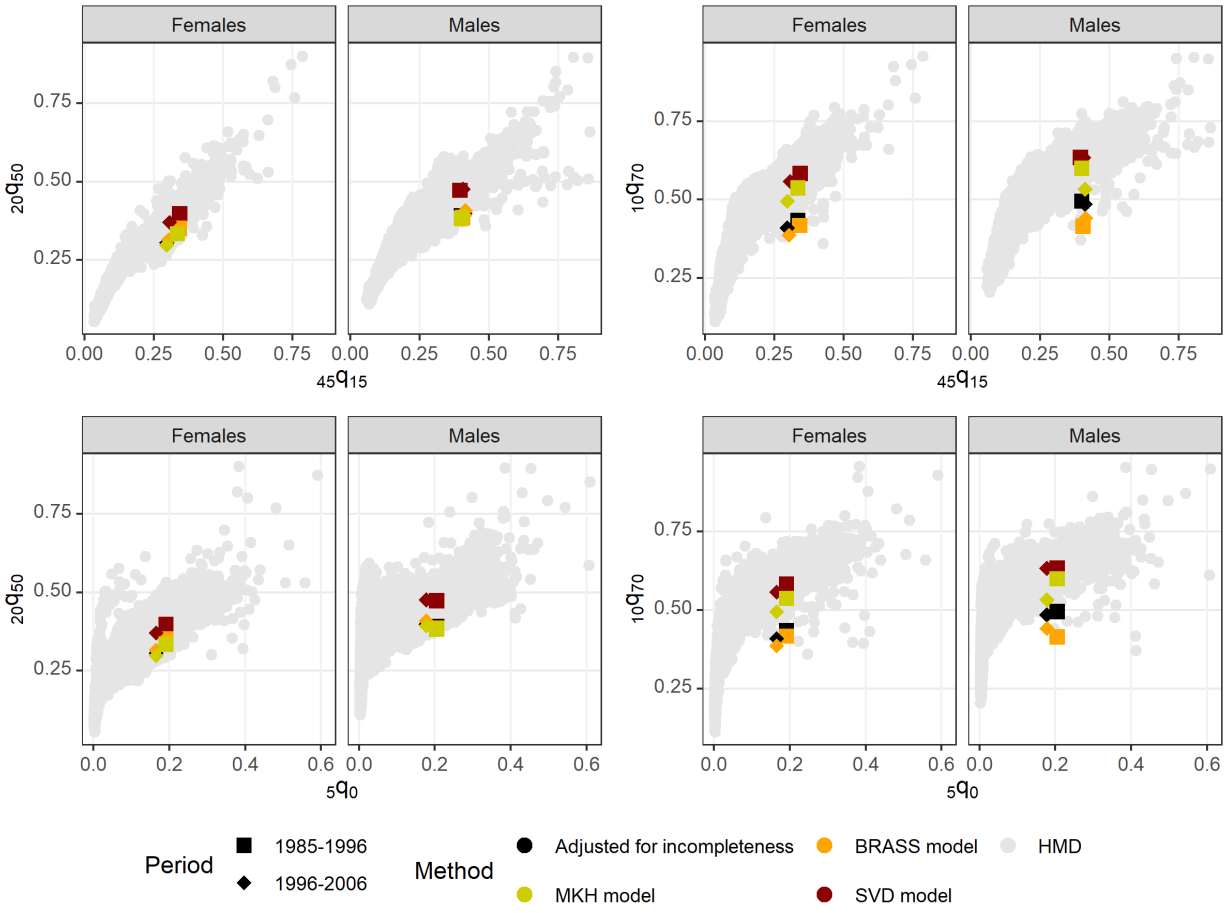

Figure 8: Consistency between mortality levels observed in Burkina Faso and in empirical data from HMD

Source: Author's calculations, Human Mortality Database (www.mortality.org)

Furthermore, it underlines the inadequacy of the African INDEPTH African standard for adjusting mortality at older ages, particularly in males where underestimation seems more noticeable. In their paper on the log-quadratic model for indirect mortality estimation, Wilmoth and colleagues

(2012) also noted that the INDEPTH data were consistent with historical data, but only at younger ages. At older ages, they pointed out the potential downward bias that could result from misreporting of age in these data. In addition, the problem of the small size of the INDEPTH data at older ages could contribute to amplify this effect.

When data are extrapolated beyond 70 years using the MKH model, the resulting estimates of mortality between 70 and 80 years appear more plausible in terms of agreement with the scatterplot of historical HMD mortality experiences. However, these estimates indicate lower mortality than predicted by the SVD model, which also results in a level of mortality that is consistent with historical mortality experiences. In addition to adult mortality, the relationship of both ${}_{20}q_{50}$ and ${}_{10}q_{70}$ to child mortality (${}_{5}q_{0}$) shows a similar pattern to that described above when compared to historical data.

Overall, only the estimates from the SVD model and those extrapolated from the MKH model remain well consistent with historical data beyond age 70, but the estimates from the SVD model are always higher. This raises the question of whether the estimates extrapolated from the MKH model are optimistic, or whether it is rather the SVD model that is pessimistic in overestimating mortality at older ages. With a view to removing such ambiguity, future research on SVD-type models should consider adult mortality up to at least age 70. Thus, rather than considering adult mortality between the ages of 15 and 60, the 15 to 50 age range should be favoured. This age range encompasses the period of reproductive life for females, but also corresponds exactly to the period of youth in general and, by ricochet, to the period of risk behaviours. Such a range would better account for the mortality hump in young adults and would reduce the likelihood of death shifts from the under-50 to the over-50 age group when modelling. Incorporating an additional input that covers the 50-70 age group (or older if information is available) would allow better prediction of observed mortality while avoiding the very late age groups where age errors are large.

4. Conclusion

Estimating mortality beyond age 50 in sub-Saharan Africa remains a complex task. Data are generally affected by various age errors that need to be well understood before deriving any estimates. In the case of Burkina Faso, data from the 1985, 1996, and 2006 censuses revealed

age heaping problems, possible systematic age exaggerations and deficiency in their completeness. This last problem was solved using the GGB-SEG hybrid death distribution method to correct census coverage and the incompleteness of intercensal deaths. Other checks identified ages at which age errors appeared to be evident. Comparing age ratios in deaths and population showed that age heaping was more pronounced in deaths than in populations beyond age 70. For age exaggerations, there are some that are complex to detect, but those that are systematic have been mitigated by using non-classic age groups. Controlling for potential effects of migration allows deriving estimates of older adult mortality from the adjusted data over the intercensal periods, which appeared to be quite good, at least up to age 70.

When compared with estimates from data adjusted for incompleteness of deaths, estimates from the Brass model were consistent up to age 70, giving credibility to these data up to that age. However, the downward deviation observed beyond this age with this method calls into question the relevance of using the INDEPTH African standard age pattern to estimate mortality beyond age 70, at least for Burkina Faso. Moreover, fitting the MKH model to the adjusted data and its extrapolation beyond age 70 confirmed the suspicion of important age errors beyond 70 years, and their effects in terms of underestimation of mortality in the corrected data. On the other hand, the fit of the SVD model to the adjusted data resulted in higher levels of mortality before and after age 70. However, it remains unclear whether the upward deviation observed with the SVD model is due to an underestimation of mortality in the adjusted data, especially before age 70. This is particularly so since the relationships between the estimates within the age range 50-70 from the adjusted data and both adult and child mortality are consistent with empirical data. Inconsistencies with empirical data are only apparent beyond age 70, but these are removed when considering extrapolations from the MKH model. This raises the question of whether the SVD model overestimates mortality at older ages and calls for further refinement of the model to remove any ambiguity.

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6. Appendix

Table 6: Age-specific mortality risks of death at older ages, by sex period and method, Burkina Faso

Indices	Methods	Females		Males	
		1985-1996	1996-2006	1985-1996	1996-2006
${}_{10}q_{50}$	Adjusted for incompleteness	0.130	0.111	0.160	0.171
	BRASS	0.146	0.128	0.168	0.180
	SVD	0.145	0.133	0.187	0.190
	MKH	0.125	0.109	0.155	0.167
${}_{10}q_{60}$	Adjusted	0.244	0.219	0.275	0.275
	BRASS	0.241	0.215	0.261	0.278
	SVD	0.295	0.274	0.351	0.353
	MKH	0.238	0.212	0.269	0.271
${}_{10}q_{70}$	Adjusted	0.434	0.410	0.495	0.486
	BRASS	0.418	0.387	0.415	0.442
	SVD	0.583	0.558	0.634	0.633
	MKH	0.537	0.495	0.600	0.534
${}_{20}q_{50}$	Adjusted	0.342	0.306	0.391	0.398
	BRASS	0.352	0.315	0.385	0.409
	SVD	0.397	0.370	0.473	0.476
	MKH	0.334	0.298	0.382	0.393
${}_{30}q_{50}$	Adjusted	0.628	0.591	0.692	0.691
	BRASS	0.622	0.580	0.641	0.670
	SVD	0.749	0.722	0.807	0.808
	MKH	0.692	0.645	0.753	0.717

Source: Author's calculations from the census data provided by the INSD

Table 7 : Population and deaths within households during the last twelve months prior to the 1985, 1996 and 2006 censuses by classic age groups, Burkina Faso

Age groups	Males			Females		
	1985	1996	2006	1985	1996	2006
Population						
<1	168,190	173,307	235,076	168,445	172,953	232,149
1-4	566,312	716,178	996,347	562,667	706,055	974,301
5-9	731,758	913,212	1,174,911	717,386	884,926	1,139,127
10-14	484,377	707,108	899,683	452,184	669,879	845,895
15-19	390,663	534,289	709,625	377,990	549,372	764,424
20-24	255,789	339,975	531,077	318,359	427,317	654,690
25-29	210,488	285,811	448,437	299,959	381,723	561,713
30-34	169,554	248,868	363,941	226,993	322,473	431,371
35-39	161,718	205,573	298,537	206,619	261,594	358,954
40-44	130,246	173,594	250,617	169,326	217,336	299,555
45-49	127,461	144,962	194,046	145,198	165,000	232,537
50-54	107,337	127,985	167,010	122,686	152,338	192,433
55-59	93,622	102,643	132,041	95,229	105,827	141,234
60-64	81,160	93,390	111,167	91,599	102,291	127,889
65-69	60,816	66,374	80,986	58,490	65,814	82,824
70-74	39,784	54,438	64,263	47,839	60,956	72,688
75-79	21,847	31,412	36,942	24,464	30,998	39,986
80-84	11,873	15,297	21,899	19,110	20,589	28,574
85-89	6,583	6,199	9,550	8,629	7,947	12,068
90+	8,963	9,520	9,162	13,219	15,842	15,483
unknown	4,696	20,745	33,416	5,077	20,498	40,621
Deaths						
<1	9,973	12,968	8,785	8,365	11,640	7,474
1-4	10,856	17,627	18,480	10,065	16,300	16,608
5-9	1,961	4,313	3,817	1,654	3,679	2,851
10-14	841	1,739	1,715	667	1,408	1,254
15-19	842	1,411	1,639	963	1,593	1,536
20-24	787	1,221	1,652	952	1,631	1,808
25-29	730	1,645	1,703	878	1,661	1,850
30-34	746	2,180	2,023	880	1,513	1,900
35-39	792	1,748	1,882	809	1,128	1,439
40-44	876	1,659	2,094	852	1,148	1,484
45-49	860	1,235	1,808	716	763	1,067
50-54	1,131	1,301	1,985	897	1,030	1,256
55-59	939	1,003	1,724	672	741	945
60-64	1,525	1,557	2,121	1,211	1,339	1,515
65-69	1,216	1,210	1,722	785	976	1,305
70-74	1,532	1,879	2,305	1,202	1,753	1,827
75-79	969	1,299	1,833	675	989	1,339
80-84	820	1,067	1,621	917	1,111	1,547
85-89	481	555	1,018	399	526	834
90+	992	1,167	1,285	1,087	1,529	1,315
unknown	1,223	24,419	2,225	907	21,437	1,608

Table 8 : Population and deaths within households during the last twelve months prior to the 1985, 1996 and 2006 censuses by non-classic age groups, Burkina Faso

Age groups	Males			Females		
	1985	1996	2006	1985	1996	2006
Population						
<1	168,190	173,307	235,076	168,445	172,953	232,149
1-4	566,312	716,178	996,347	562,667	706,055	974,301
5-7	473,297	583,786	747,247	467,391	568,278	726,036
8-12	569,263	779,800	1,005,673	536,981	738,471	952,309
13-17	438,533	622,138	784,547	404,369	599,634	770,734
18-22	303,504	399,929	594,813	363,195	495,775	745,843
23-27	223,684	299,676	481,883	308,899	398,258	593,280
28-32	185,889	265,929	399,952	259,925	351,335	482,284
33-37	160,472	218,561	313,563	202,193	271,358	369,009
38-42	144,523	186,083	269,933	190,743	238,862	328,310
43-47	125,055	148,376	209,486	143,859	167,391	247,805
48-52	117,351	139,053	177,069	134,493	166,309	212,377
53-57	95,236	108,005	138,810	96,760	112,521	149,101
58-62	88,187	99,850	125,070	98,236	111,051	143,446
63-67	66,495	72,386	88,957	63,841	69,300	89,362
68-72	45,982	61,602	72,712	53,116	68,585	82,136
73-77	24,691	36,976	42,837	25,928	34,305	43,003
78-82	14,610	20,165	27,896	21,797	24,466	34,389
83-87	7,606	7,581	12,482	9,634	8,915	14,060
88+	9,661	10,754	10,964	13,919	17,408	17,961
unknown	4,696	20,745	33,416	5,077	20,498	40,621
Deaths						
<1	9,973	12,968	8,785	8,365	11,640	7,474
1-4	10,856	17,627	18,480	10,065	16,300	16,608
5-7	1,434	3,226	2,881	1,174	2,809	2,170
8-12	1,094	2,296	2,119	899	1,788	1,493
13-17	827	1,500	1,543	783	1,418	1,344
18-22	846	1,325	1,759	1,102	1,837	1,884
23-27	766	1,457	1,727	887	1,669	1,848
28-32	761	2,130	1,997	968	1,654	1,977
33-37	737	1,855	1,836	767	1,134	1,525
38-42	926	1,770	2,075	935	1,243	1,487
43-47	783	1,259	1,823	667	767	1,169
48-52	1,136	1,334	1,996	945	1,045	1,257
53-57	927	996	1,701	641	714	953
58-62	1,458	1,474	2,130	1,171	1,302	1,452
63-67	1,199	1,230	1,751	825	956	1,258
68-72	1,577	1,867	2,277	1,243	1,766	1,857
73-77	1,071	1,310	1,883	651	1,049	1,315
78-82	892	1,220	1,761	942	1,155	1,647
83-87	558	664	1,166	481	596	929
88+	1,048	1,276	1,522	1,135	1,616	1,507
unknown	1,223	24,419	2,225	907	21,437	1,608

Chapter 3

Mortality among older adults aged 50+ in sub-Saharan Africa: Triangulating census, survey and prospective mortality data

1. Background

The considerable decline in child mortality in recent decades in Sub-Saharan Africa has led to substantial gains in life expectancy in this region, from 49 years in 1990 to 61 years in 2019 (United Nations, 2019). However, child survival has not evolved in tandem with adult survival, and there has been only modest progress in reducing mortality in adults aged 15-59 (Masquelier, Reniers, et al., 2014). This is in part due to various health crises that affected the region during the 1990s and 2000s, most notably the HIV/AIDS epidemic that has led to surges in risks of dying in early adulthood. In recent years, adult mortality has declined again, thanks largely to the scale-up of antiretroviral therapy in adults aged 15-49, who are most affected by HIV/AIDS. In contrast, according to the United Nations, mortality in adults aged 50 or older has declined regularly since 1990, with life expectancy at age 50 increasing from 21.5 years in 1990-1995 to 23.4 in 2015-2020 (United Nations, 2019). Driven by population ageing and improvements in survival before age 50, an increasing share of deaths occurs in older adults in the region. Already more than a third of all deaths in Sub-Saharan Africa occur above age 50 (36% in 2015-2020), and this percentage could rise to 60% by 2050 (United Nations, 2019). However, mortality estimates in this age group are informed by very sparse data, due to the incompleteness of civil registration and vital statistics systems (CRVS) in sub-Saharan Africa. Mortality rates below age 5 can be accurately measured from birth histories collected among females of reproductive age in surveys and censuses, or indirectly inferred from proportions of surviving children, while mortality in adults aged 15-49 can be derived from sibling survival histories. Unfortunately, there is no equivalent data source for adults above age 50 or 60. Sibling survival histories yield few reports of deaths above age 50, as these are collected among respondents aged 15-49 who report on their siblings who are approximately of the same age. Reports on parental survival can be used to estimate mortality up until age 75, but from age 25 onwards, with no possibility to restrict the analysis to old-age mortality (Timaeus, 1992). The only nationally-representative data sources available on mortality beyond age 50 are the data on recent household deaths tabulated by age, as collected in censuses and large-scale sample surveys. But such data are known to be prone to various inaccuracies such as systematic

misstatement and underreporting of deaths, to the point that often need heavy adjustment (Timæus, 1991). Two avenues have therefore been used for estimating old-age mortality in Sub-Saharan Africa. First, Bendavid and colleagues (2011) produced mortality levels beyond age 60 directly from reported household deaths in 10 countries, almost without adjustment, except for heaping on certain round ages. They found that the resulting mortality was much lower than that from the World Health Organization (WHO) or the United Nations Population Division (UNPD). Second, empirical estimates on old-age mortality have been discarded entirely, and mortality rates have been inferred from survival below age 60 using model life tables (Coale et al., 1983; Coale & Demeny, 1966; Ledermann, 1969; United Nations, 1982a). When information is available on either the level of child mortality or another index (such as adult mortality), these standard patterns of mortality schedules make it possible to produce a complete life table by interpolation (Ewbank et al., 1983). In addition to these one-parameter life tables, Brass introduced his relational approach (Brass et al., 1968; Brass, 1971c). When the survival function of a target population has deficiencies, for example due to recall errors, but a reliable survival function of a population is available, then this function can be used as a standard to smooth to adjust the mortality curve of the target population. The Brass approach is, however, limited in that it uses survivorship probabilities from birth, while indirect techniques of adult mortality estimation often generate conditional probabilities such as ${}_{45}q_{15}$ or ${}_{10}q_{25}$. Hence, when information on child (${}_{5}q_{0}$) and adult mortality (${}_{45}q_{15}$) are available from empirical measurements, more recent relational models make it possible to generate entire and smoothed life tables by indexing these indices to a large set of life tables (Clark, 2019; Murray et al., 2003a; Sharrow et al., 2014; Wilmoth et al., 2012). This idea was first introduced by Murray and colleagues (2003) and refined by Wilmoth and colleagues (2012) who exploited singular value decomposition (SVD) but could not consider more than two mortality indicators as inputs, namely life expectancy at birth (e_0), child mortality (${}_{5}q_{0}$), or both child and adult mortality (${}_{45}q_{15}$). This latter model was calibrated using 719 life tables of high-income countries from the Human Mortality Database (HMD). A key limitation, however, is that these earlier model life tables were not calibrated with data from countries/periods of high HIV prevalence so that, instead of fitting the HIV-related mortality hump well, they tend to produce a high and flat mortality pattern that is not reflecting actual age-specific rates. Subsequently, Sharrow and colleagues (2014) exploited more properties of SVD, allowing for additional inputs such as HIV prevalence, and where appropriate, antiretroviral therapy (ART) coverage in children and adults. Their model was

intended as an urgent response to the lack of model life tables suitable for estimating mortality patterns for high-prevalence countries by fitting the unique age-specific pattern of HIV-related deaths. It was calibrated using 320 sex-specific life tables from the 2010 revision of World Population Prospects covering five-year period from 1970 to 2010 (United Nations, 2011). These life tables are not truly empirical in the same way as those used in HMD. Rather, they are modelled from the best available estimates, albeit limited, derived from surveys and censuses. Prior to 2010, access to ART remained limited in sub-Saharan Africa and its impact on mortality was still modest. There were still few consolidated statistical sources to measure for the effect of treatment at a national scale. However, the forthcoming scale-up of ART coverage was anticipated in the model parameterisation. The model proposed by Sharrow and colleagues (2014) is probably the most elaborated model to reconstruct complete life tables from limited data, but it completely discards mortality beyond age 60 and relies only on mortality before age 60 ($_5q_0$, $_{45}q_{15}$ and young adult HIV prevalence). There is therefore a need to ascertain and validate the plausibility of estimates predicted for older adults.

This study aims to estimate mortality levels among the population aged 50 and over in 18 countries in sub-Saharan Africa, using available censuses and national surveys for which information on annual deaths by sex and age within households are available. I confront estimates obtained with different approaches as well as various data sources. In addition, I resort to data from Health and Demographic Surveillance Systems (HDSS) monitoring local populations and providing high-quality mortality data (INDEPTH Network, 2002; Sankoh & Byass, 2012). The longitudinal nature of HDSS data gives them greater precision in terms of dating events and annual number of deaths, which minimises recall errors and their effects on the estimates. They allow assessing the extent to which the relationship between mortality indices at different ages is consistent with those observed in censuses and national surveys. A comparison of all these estimates with other empirical sources referring to countries with high-quality civil registration will ascertain whether sub-Saharan African countries have an epidemiological trajectory similar to that observed in the past in high-income countries in terms of levels of older adult mortality.

2. Data and Methods

2.1. Data sources

I use data referring to population counts and deaths tabulated by sex and age occurring in households (over the 12 months prior to the data collection), as collected in large-scale sample surveys and censuses in Sub-Saharan Africa. Most tabulations come from the *Demodata* database of the United Nations Population Division. The series have been supplemented by other data obtained directly from the national statistics institute (Burkina Faso 1996, 2006) or from census reports available online (Eswatini 2017, Guinea 2014, Lesotho 2016, Malawi 2018, Mozambique 2017, Senegal 2013, Sierra Leone 2015). The series covers 45 censuses (18 countries), 8 DHS (7 countries), 2 DHS-type surveys (2 countries) and 6 other household-based surveys (6 countries). Overall, our dataset covers 18 countries, located mostly in Eastern, Southern and Western Africa (Table 1).

Table 9 : Available censuses and surveys with data on recent household deaths

Regions/Countries	Censuses	DHS	Other DHS-type	Other surveys
Eastern and Southern Africa				
Botswana	1981, 1991, 2001, 2011			1998 ***, 2006 ***
Eswatini	1997, 2007	2006		
Lesotho	1986, 1996, 2006, 2016			2001***
Malawi	1987, 1998, 2008, 2018	2010		
Mozambique	1997, 2007, 2017			
Namibia	2001, 2011	2007		
South Africa	1996, 2001, 2011			
Tanzania (United Republic)	1988, 2002		2007*	
Uganda	2002, 2014	2006	2011*	
Zambia		2007		2008**
Zimbabwe	1992, 2002, 2012	2006		1997
Middle and Western Africa				
Burkina Faso	1985, 1996, 2006			2008**
Central African Republic	1988, 2003			
Guinea	1983, 1996, 2014			
Mali	1987, 1998, 2009			
Nigeria		2008, 2013		
Senegal	2002, 2013			
Sierra Leone	2004, 2015			

Source: United Nations Population Division (UNPD), the DemoData database
Notes: (*) Annual Household Survey (AHHS); (**) Global Fund Facility Survey (GFFS); (***) Other surveys

Table 10 : Number of deaths in adults aged 15 and over and corresponding person-years from population follow-up in 26 sub-Saharan African HDSS

Region/HDSS	Countries	Reporting period	Duration of period	Observed deaths	Observed person-years
Eastern Africa					
Dabat*	Ethiopia	2009-2015	7	1,559	314,843
Harar*	Ethiopia	2012-2016	5	786	174,085
Kersa	Ethiopia	2008-2016	9	5,492	626,393
Kilite Awlaelo	Ethiopia	2010-2014	5	1,467	325,669
Kombewa	Kenya	2011-2015	5	5,178	634,661
Nairobi*	Kenya	2003-2015	13	5,676	771,459
Karonga	Malawi	2003-2017	15	3,791	516,423
Chokwe	Mozambique	2010-2016	7	5,312	547,031
Ifakara	Tanzania (United Republic)	1997-2014	18	13,886	1,497,840
Magu	Tanzania (United Republic)	1994-2012	19	4,667	471,143
Rufiji	Tanzania (United Republic)	1999-2014	16	13,441	1,226,718
Iganga/Mayuge	Uganda	2005-2016	12	5,783	717,351
Southern Africa					
Africa Centre	South Africa	2000-2017	18	14,554	1,224,420
Agincourt	South Africa	1993-2017	25	16,989	2,073,285
Dikgale	South Africa	1996-2016	21	2,955	362,339
Western Africa					
Nanoro	Burkina Faso	2009-2015	7	2,852	379,544
Nouna	Burkina Faso	1998-2015	18	12,286	1,230,983
Ouagadougou*	Burkina Faso	2009-2015	7	2,464	556,439
Taabo	Cote d'Ivoire	2009-2016	8	2,793	316,090
Farafenni**	Gambia	1994-2015	22	7,497	772,469
Dodowa	Ghana	2006-2011	6	4,691	637,777
Kintampo	Ghana	2006-2014	9	8,078	1,143,723
Navrongo	Ghana	1993-2014	22	21,348	1,582,459
Bandafassi	Senegal	1985-2016	32	4,955	338,694
Mlomp	Senegal	1985-2016	32	2,251	243,672
Niakhar**	Senegal	1994-2016	23	12,674	996,324
Total				**183,425**	**19,681,834**
Adults aged 15 +				***120,115***	***11,507,581***
Adults aged 50+				***71,967***	***2,356,625***

Source: Indepth network (http://www.indepth-ishare.org/index.php/catalog/central), downloaded on 14 June 2020. [HDSS with stars (*) are urban sites. Those with (**) are sites for which important irregular fluctuations have been observed and which have been discarded for lack of explanation, notably from 1990 to 1993 for Farafenni and from 1985 to 1993 for Niakhar].

To compile a database of high-quality mortality rates, data from HDSS have been obtained through the INDEPTH network's ishare platform. These are data collected on small-scale geographical areas where the enumerated populations are monitored through annual or more

regular household visits. Such repeated data collection makes it possible to capture any most entries in the areas under surveillance by birth or immigration as well as most exits by emigration or death. HDSS have been extensively used to study cause-specific mortality (Streatfield, Alam, et al., 2014; Streatfield, Khan, Bhuiya, Alam, et al., 2014; Streatfield, Khan, Bhuiya, Hanifi, Alam, Bagagnan, et al., 2014; Streatfield, Khan, Bhuiya, Hanifi, Alam, Ouattara, et al., 2014), but less frequently exploited for the evaluation of age patterns of mortality in general, apart from initiatives aimed at deriving model life tables for sub-Saharan Africa (INDEPTH Network, 2004) or validation studies of retrospective surveys (Helleringer et al., 2014, 2014; Masquelier et al., 2021). Admittedly, these data are not representative of the national level, and the small population size in some sites and more specifically at advanced ages means that there is a lot of stochastic variation around mortality rates. However, there are ways to reduce these fluctuations and extract the true underlying age pattern of mortality prevailing in these sites, for example through statistical modelling or by pooling data from several years or ages. In this study, I use data from 26 HDSSs, most of which are located on rural areas (22). They are scattered across 12 countries in sub-Saharan Africa and cover Eastern (12), Southern (3) and Western (11) Africa (Table 2).

2.2. Estimation methods and adjustments

To each data source, I applied corrections to provide the best possible estimate of deaths and person-years needed to estimate age-specific mortality rates.

Census/survey-based estimates

When analyzing censuses, I used death distribution methods to estimate the completeness of death reporting (Hill, You, & Choi, 2009). I used the "hybrid method" which applies to two consecutive censuses. It consists in applying the *Generalized Growth Balance* (GGB) method (Hill, 1987) to correct the relative coverage of the first census compared to the second, and then applying the *Synthetic Extinct Generation* (SEG) method (Bennett & Horiuchi, 1981, 1984) to assess and correct for the incompleteness of intercensal deaths. By allowing the coverage of the first census to be adjusted relative to the second, the method relaxes the unrealistic assumption of similar census coverage underlying the original SEG method. The method is also applicable to non-stable populations such as those in countries in the sub-Saharan region that

have experienced significant demographic changes in recent decades. Nonetheless, two important assumptions still underpin the hybrid approach: the completeness of deaths in adults is assumed to be invariant above a certain age limit and net migration is assumed to be negligible. The selection of age interval for assessing completeness is based on graphical visualization to choose the highest age limit that produces relatively constant levels of completeness. The methods have also been extended to account for migration, but in the absence of reliable data on net migration in the region, I do not account for this. However, I assess the completeness of deaths from a minimum age of 35 as recommended by Hill and colleagues (2009) to circumvent the disruptive effects of migration on data referring to young adults.

Regarding large-scale sample surveys, I do not resort to death distribution methods. There is no proven method, nor an accurate gold standard of age distribution of deaths to assess the completeness of deaths in such surveys as is censuses. There are fewer surveys that collected data on recent deaths making it difficult to apply death distribution methods which require two successive sets of surveys conducted in a relatively short period of time. In addition, while being nationally representative, such surveys have relatively small sample sizes to estimate mortality and sampling variation make the estimates of completeness highly uncertain. However, there is no evidence that survey data are of poorer quality than census data. It is possible that they are of better quality thanks to longer training, more elaborated questionnaires, and longer time devoted to the interviews. To estimate age-specific mortality rates from surveys, I simply calculated the population that would have been enumerated in the middle of the reference period by backward projection using the growth rates from the World Population Prospects (2019). Growth rates r_x by age and sex were obtained as:

$$r_x = \frac{log(P_{t_1}) - log(P_{t_0})}{t_1 - t_0}$$

The first set of estimates are derived directly from these two sources above: census data adjusted for incompleteness of deaths and survey data adjusted for the mid-period of death occurrence when computing the corresponding person-years. Hence the term “census/survey-based” to describe them afterwards.

Model-based estimates

The second set of estimates stems from the HIV model of Sharrow and colleagues (2014) which generates full age-specific mortality rates, including at older ages, using information on mortality before age 60, notably child mortality ($_5q_0$) together with adult mortality ($_{45}q_{15}$). The indicator for adult mortality is taken from census/survey-based estimates. Under-five mortality for the corresponding period is obtained from the United Nations Interagency Group for Child Mortality Estimation[8]. The only empirical measures on mortality beyond age 50 that the model uses are referring to the age group 50-59 as this is contributing to $_{45}q_{15}$. Beyond the age of 60, the "model-based estimates" completely disregard deaths reported within households and are inferred from life tables that were used to calibrate the model. In addition, the model incorporates HIV prevalence to capture the excess mortality that may arise from it, an excess mortality that is generally sharp in young adults and whose effect may be modulated depending on ART coverage. Although the model conceptually allows for the inclusion of ART coverage in children and adults, this information is not available in such detail. Indeed, information available from UNAIDS on ART coverage among children refers to under-15s and not under-5s in reference to the under-5 mortality used as input in the model. Similarly, existing information on ART coverage in adults refers to adults aged 15 and over, not adults under 50, in reference to the 15-49 prevalence used in the model, nor to the age group 15-59 related to the adult mortality index used in the model. Moreover, free ART policy only started to be rolled out in most African countries in the period 2005-2010 before spreading. Even currently, ART coverage has increased significantly, but is still not universal in many countries. It is therefore unlikely that before 2010, accounting for ART coverage will significantly impact the predictions of the model, as most of the periods covered by the data in this study are before or only slightly beyond that year. Therefore, only HIV prevalence in adults under 50 is considered for the implementation of the model.

HDSS-based estimates

Estimating age-specific mortality rates from HDSS data requires special processing to reduce the stochastic variations associated with small sample sizes. The true underlying age patterns of mortality are not immediately apparent because at certain ages there are no deaths at all, although it is highly unlikely that the risk of dying is zero at those ages (Bijak & Bryant, 2016).

[8] This information can be found at: https://childmortality.org/

Options for addressing this problem could include using smoothing methods that allow capturing the general age schedule underlying the data by interpolating missing points (Camarda, 2008; De Beer, 2012; Hastie & Tibshirani, 1990), or aggregating data over several years or geographic sites, or treating each site separately and imposing a parametric function to derive estimates in a Bayesian modelling framework (Alexander et al., 2017). Another option that avoids any modelling while preserving the yearly series that makes the richness of these data would be to simply aggregate the data by five-year age groups. I have opted for the latter option which substantially reduces the fluctuations due to 0 deaths and allows producing abridged life tables as with censuses/surveys.

In summary, I compare the methods by benchmarking the census/survey-based and the model-based estimates against the universe of HDSS estimates, in terms of both consistency and plausibility of mortality age patterns and levels, while focusing on the age window 50-79 years. I also compare our estimates with those from HMD in terms of the relationship between the risk of dying between ${}_{35}q_{15}$ on the one hand and ${}_{10}q_{50}$, ${}_{10}q_{60}$, ${}_{10}q_{70}$ and ${}_{30}q_{50}$ on the other. Before doing so, I assess age reporting from the data sources and the completeness of death reporting in censuses.

3. Results

3.1. Assessment of age reporting

Systematic errors due to age misreporting may be assessed by comparing age ratios in deaths and in the population, with a focus on adults aged 50 upwards. The closer the points for deaths (or for population) are to 1, the more reliable are the recorded ages at death (or in population). On the other hand, when the points are far below 1, this suggests a high likelihood of under-reporting, just as points far above 1 would suggest a high likelihood of over-reporting. If points are not centred on 1, but rather roughly aligned along the diagonal, it simply means that the age ratios at death and in population differ only little. In this case, the age errors would be of similar magnitudes in both deaths and population, and they are expected to simply cancel each other out.

As shown in Figure 1 below, there are no obvious differences in age errors between census and survey data or between females and males in each geographical area. Instead, the picture is clearly different between the two geographical areas, particularly between adults under 50 and those aged 50 and over. In the Eastern and Southern zone, with some exceptions in deaths, I also notice no obvious differences between age ratios for age groups with ages ending in -0 and those containing ages ending in -5. However, the age ratios in population appear tighter around 1 compared to the age ratios in deaths, both in adult females and males under 50 and in those aged 50-69. This first picture suggests that errors reported ages at death are not of the same magnitude as errors in reported ages in population for adults aged 50-69. Although to a lesser extent, I notice that from age 70 onwards, age errors in population tend to vary in the same direction as in deaths in a way that moves towards the diagonal. As a result, age errors will neutralise to some extent above age 70 than they would before that age. Hence, an upward adjustment of mortality data could lead to an overestimation of mortality in ages 50-69 where age errors in deaths are more pronounced. Therefore, careful attention should be paid to estimates for this age segment as opposed to the 70+ age group where the estimates are likely to be more plausible if adequately corrected.

In Middle and Western Africa, age ratios for adults under 50 are concentrated around 1 for both females and males, and both in deaths and in population, although the dispersion is relatively larger in deaths. However, for adults aged 50 or over, the configuration is quite different. A clear dichotomy exists between age groups with ages ending in -0, which are distinguished by age ratios above 1, and age groups with ages ending in -5, characterised by age ratios below 1. Furthermore, I note that the points are so aligned as to draw a slope that almost merges with the diagonal, even beyond age 70. Yet, it can be seen that the slope towards the diagonal appears closer for females. This suggests that in this area, age errors from age 50 onwards are almost of the same magnitude in deaths and in population, especially for females. Knowing this should help in better analyzing the mortality levels inferred from these data.

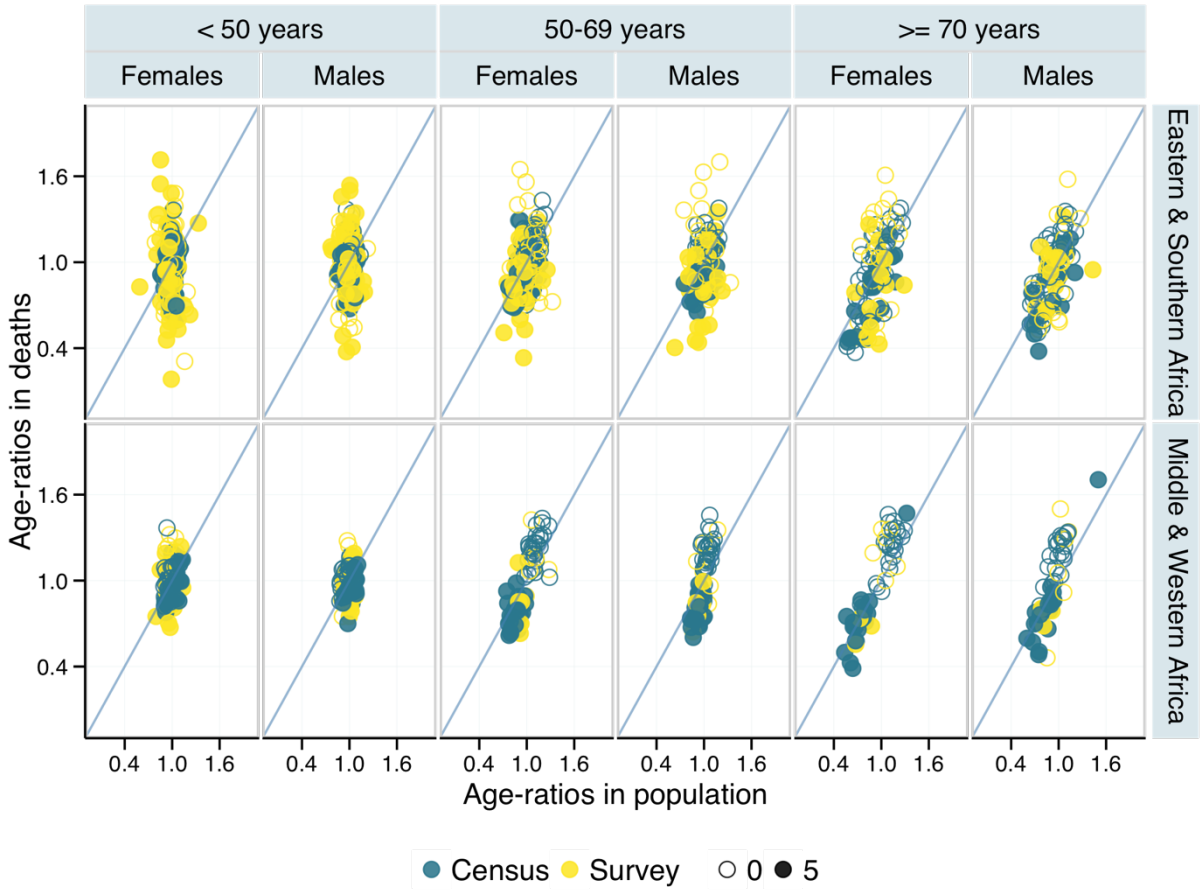

Figure 9 : Age-ratios in deaths compared to age-ratios in population by sub-region, data source, sex and age given its terminal digit

3.2. Completeness of death reporting

Using the R package DDM (Riffe et al., 2017), I applied death distribution methods to account for incompleteness of death reporting and census under-coverage, thus improving the initial estimates by adjusting them upwards by a constant term. Table 3 below summarizes the levels of completeness of death reporting, the relative coverage of one census to another, and the age intervals for assessing these estimates. Considering a minimum age of 35 years, the latter intervals are not necessarily the same by sex, period and country. The lengths of these age intervals are determined by a function of the package that allows, on the basis of the open-ended age group, to determine the optimized age range that minimises the mean square errors of the regression line for adjusting the completeness.

Except for Mozambican males and females (1997-2007), Mozambican females (2007-2017) and Senegalese males for whom the minimum age group was advanced to the 40-44 age group, the minimum age group of 35-39 years allowed for sufficiently aligned levels of age completeness in most cases. Regarding the maximum age to be used for completeness adjustment, excluding the open-ended age group, the 70-74 age group allowed for satisfactory alignment in most cases. However, this age was advanced to 75-79 in a few cases. Coverage levels vary from one census to the next. The largest gap in coverage is observed among males in Central African Republic between the 1988 and 2003 censuses. Males were over-enumerated in 1988 compared to 2003 (1.5). Also, females in Sierra Leone were under-enumerated in 2015 compared to 2004 (0.73).

Following Table 3, Figure 2 below displays the sex ratio in census relative coverage. The discrepancies observed in Sierra Leone and the Central African Republic appear implausible as the enumeration has affected both sexes. In the case of Sierra Leone, for example, the under-enumeration of females was about 27% in the 2015 census compared to the 2004 census, while the enumeration of males was practically similar between the two censuses. In the Central African Republic, on the other hand, males enumerated in 2003 appeared to be about 50% more numerous than those enumerated in 1988. In other words, almost half of the Central African males would not have been enumerated in 1988. Yet there is no such discrepancy among women. A likely reason for such under-enumeration would be a significant emigration of the male population before 1988, followed by a massive return during the intercensal period 1988-2003. One could also think that the method of estimating coverage does not work well in the case of the Central African Republic, perhaps because the intercensal period is quite long (15 years). Table 3 above indicates that deaths are under-reported in most cases. The lowest levels of completeness are recorded among both males and females in Malawi (1987-1998), Mali (1987-1998, 1998-2009) and among females in Lesotho (1986-1996) with values below 50%. However, significant over-reporting of deaths was observed among females in Sierra Leone in 2004-2015 (2.85) as well as among males (1.40), among females in Senegal in 2002-2013 (2.17) and among both males and females in Namibia in 2001-2011 (1.40), but these high estimates are questionable.

Table 11 : Completeness of death reporting, relative coverage between censuses and the fitted age intervals used for its assessment

Regions/countries	Intercensal periods	Open-ended age	Fitted age intervals		Census relative coverage[1]		Completeness of deaths	
			Females	Males	Females	Males	Females	Males
Eastern & Southern Africa								
Botswana	1981-1991	75+	35-74	35-74	1.076	1.196	1.131	1.182
Botswana	1991-2001	75+	35-74	35-74	1.097	1.209	0.920	0.901
Botswana	2001-2011	75+	35-74	35-74	1.028	1.062	0.726	0.761
Eswatini	1997-2007	75+	35-74	35-74	0.902	0.971	0.811	0.823
Lesotho	1986-1996	85+	35-74	35-74	0.975	0.976	0.487	0.623
Lesotho	1996-2006	85+	35-74	35-79	0.980	0.890	0.982	1.303
Lesotho	2006-2016	85+	35-74	35-79	1.115	1.102	0.744	0.923
Malawi	1987-1998	85+	35-74	35-74	1.023	1.035	0.309	0.453
Malawi	1998-2008	85+	35-74	35-74	0.997	0.972	0.511	0.589
Malawi	2008-2018	85+	35-74	35-74	1.038	1.045	0.604	0.719
Mozambique	1997-2007	80+	40-79	40-79	0.947	1.026	0.716	0.780
Mozambique	2007-2017	80+	40-79	35-74	0.914	0.976	0.793	0.855
Namibia	2001-2011	90+	35-74	35-74	0.919	0.930	1.406	1.402
South Africa	1996-2001	85+	35-74	35-74	1.064	1.043	0.770	0.828
South Africa	2001-2011	85+	35-74	35-74	1.027	1.046	0.581	0.697
Uganda	2002-2014	80+	35-79	35-79	0.951	0.974	0.852	0.850
Tanzania (United Republic)	1988-2002	80+	35-74	35-74	1.003	1.103	0.793	0.725
Zimbabwe	1992-2002	75+	35-74	35-74	0.929	0.903	0.812	1.005
Zimbabwe	2002-2012	75+	35-74	35-74	1.022	1.012	0.852	0.957
Middle & Western Africa								
Burkina Faso	1985-1996	90+	35-74	35-79	0.881	0.835	0.803	1.088
Burkina Faso	1996-2006	90+	35-74	35-74	0.964	1.057	0.754	0.729
Central African Republic	1988-2003	75+	35-74	35-74	0.982	1.504	0.522	0.679
Guinea	1983-1996	90+	35-74	35-74	1.000	1.039	0.683	0.660
Guinea	1996-2014	85+	35-79	35-79	0.806	0.937	0.997	1.007
Mali	1987-1998	80+	35-74	35-74	0.944	0.991	0.399	0.476
Mali	1998-2009	80+	35-74	35-74	0.980	1.036	0.364	0.404
Senegal	2002-2013	90+	35-74	40-79	0.972	1.041	2.173	1.035
Sierra Leone	2004-2015	80+	35-74	35-79	0.738	1.020	2.849	1.395

Source: Calculations from Authors, using the R package DDM

[1] A relative coverage of one census to another greater than 1 means that the delta factor is negative and implies the adjustment from the first census to the second, and vice versa.

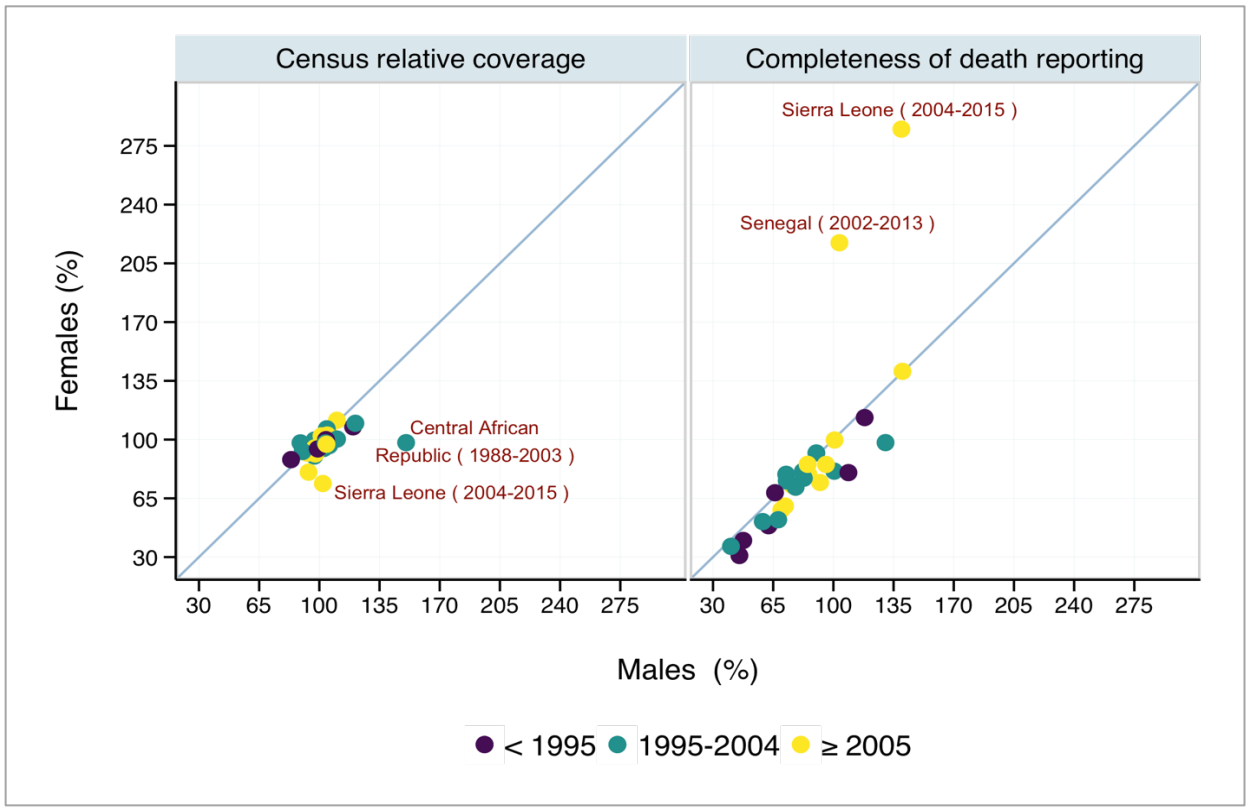

Figure 10 : Sex ratios in census relative coverage and completeness of death reporting

When looking at the sex ratio in terms of the estimated completeness of reported deaths over the intercensal periods (shown in Figure 2), males and females differ little from each other, except particularly among Senegalese and Sierra Leonean women, where the estimates are well above expectations. Since the estimate of intercensal deaths depends on deaths reported during the censuses concerned, this implies that there was over-reporting of deaths in one of the two censuses. Of course, this may be the result of poor data collection management. However, it can also happen that there are more deaths than expected in the case of violence, devastating epidemics, or more likely, because of errors about the reference period and inclusion of some past deaths in the census reports. Even so, it is unlikely that these will exceed the expected number of deaths by more than two to three times, as is the case in these two countries. Moreover, such a situation should affect both sexes equally. A diagnostic plot is drawn up in the appendix for each country, intercensal period and sex to have an overall view of the alignment of the points to validate the hypothesis of the relative invariance of completeness by age from a certain age.

Overall, neither the relative coverage of censuses nor the completeness of death reporting seems to indicate a clear improvement over time. Hereafter, we will not analyse the estimates for these specific outliers, except for Senegal where we are able to compare the estimates with other sources such as the HDSS. Notwithstanding the adjustments implied by these findings, the estimates could still be biased for age groups where systematic errors exist or where age errors in both deaths and population are not of similar magnitude to offset each other as is the case mainly in adults aged 50-69 in most Eastern and Southern African countries. In the other cases of older adults (see Figure 1) where the points are only roughly but not perfectly aligned along the diagonal, residual errors should remain also as these would not completely cancel out after adjusting the data.

3.3. Overview of age profiles of African adult mortality

In reviewing the age profiles of mortality, countries from Middle and Western Africa show unsurprisingly distinct patterns in adults under 50 compared to those from Eastern and Southern Africa, as shown in Figure 3 below. In the former, there is a barely perceptible relative hump in mortality in both census and model-based estimates. In addition, model-based estimates agree very well with census-based estimates at these ages. For adults aged 50 upwards, age profiles of mortality in Middle and Western African countries such as Burkina Faso, Guinea or Mali, where HIV is less prevalent, follow a regular pattern in continuation of the pattern observed at younger ages. Again, there is good agreement between estimates inferred from the model and those based on censuses, although a very modest upward deviation emerges between age 70 and 80, which is likely to worsen and become more apparent at very advanced ages.

In contrast, in Eastern and Southern African countries such as Botswana, Eswatini, Lesotho, Mozambique, South Africa, Uganda or Zimbabwe where HIV is more prevalent, mortality curves below age 50 are characterised by an impressive hump after age 20, peaking around ages 30-34 for females and 35-39 for men, and then falling back before recovering a regular pattern after age 50. It is even more pronounced for model-based estimates. This may be because the model was estimated by considering only the prevalence of HIV in young adults without controlling for ART coverage. Following the hump at young adult ages, mortality curves should logically follow a phase of stagnation or a slight dip around age 45-49 before resuming a steady

linear upward trend on a log scale in line with the well-known pace of exponential increase in the force of mortality at these ages. When the hump in young adulthood is more peaked as is the case with model-based estimates, the stagnation or dip that follows is also more pronounced before resuming an increase beyond age 50. This may explain the discrepancies between the curves from model-based and census-based estimates, such as those observed in Botswana, Eswatini, Lesotho or South Africa, etc., particularly between age 50 and 65.

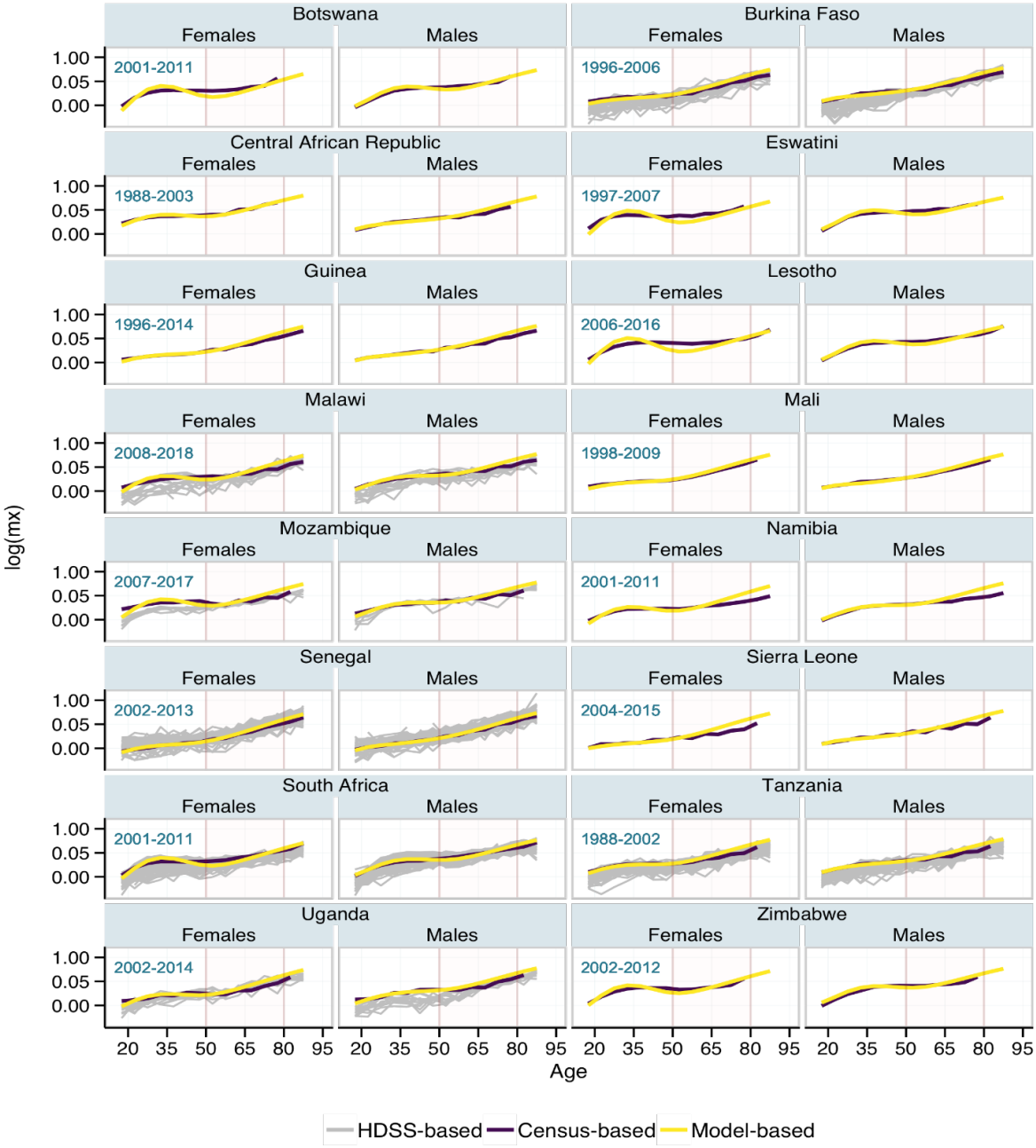

Figure 11 : Age profiles of adult mortality from the most recent census data with selected HDSS data in sub-Saharan Africa

For countries with HDSS sites, the census-based and model-based estimates are consistent with the universe of HDSS-based age-specific mortality patterns. Even for a country like Senegal, despite a level of completeness of death reporting that seemed implausible for females as compared to men, the correction of deaths leads to a good consistency between the census estimates and the HDSS estimates.

Moreover, it can be said that, despite using only fragmentary inputs to predict full life tables, i.e. child and adult mortality indices, as well as HIV prevalence in adults, model-based estimates succeed to a large extent in fitting age-specific mortality schedules as described by census-based estimates adjusted for incompleteness of deaths. A more complete picture requires an analysis of the resulting mortality levels.

3.4. Analysis of mortality levels in older adults

Figure 4 below summarises in box plots solely the levels of older adult mortality derived from each estimation method including those from HDSS data. As noted earlier, our analysis will focus on individuals aged 50-79 to avoid large errors that are common at very old ages. Hence, given the wide fluctuations that may occur in HDSS data at older ages, it appears reasonable to consider only the points contained within a 90% interval around the median so as to clear the resulting estimates from extreme values while preserving the wide variability among African local populations. This means treating the lowest 5% and the highest 5% as outliers.

Overall, as expected, males have a higher risk of death than their female counterparts, regardless of the age group and geographical zone considered, and whatever the estimation method used. In HDSS-based estimates, ${}_{30}q_{50}$ varies from 0.37 to 0.78 in females and from 0.52 to 0.86 in males in Middle and Western Africa. In Eastern and Southern Africa, it ranges from 0.37 to 0.73 in females and from 0.43 to 0.85 in males. If restricted to the interquartile range, which is tighter around the 50% median values of ${}_{30}q_{50}$, the maximum risk of death from HDSS is 0.68 and 0.78 in Middle and Western Africa compared to 0.60 and 0.73 in Eastern and Southern Africa for females and males respectively. In any case, the median estimate is 0.57 and 0.70 in Middle and Western Africa compared to 0.52 and 0.62 in Eastern and Southern Africa for females and males respectively. If one considers estimates from HDSS as a standard

and the range of mortality levels derived from them as the universe of possible values, then census, and survey and model-based estimates are all plausible.

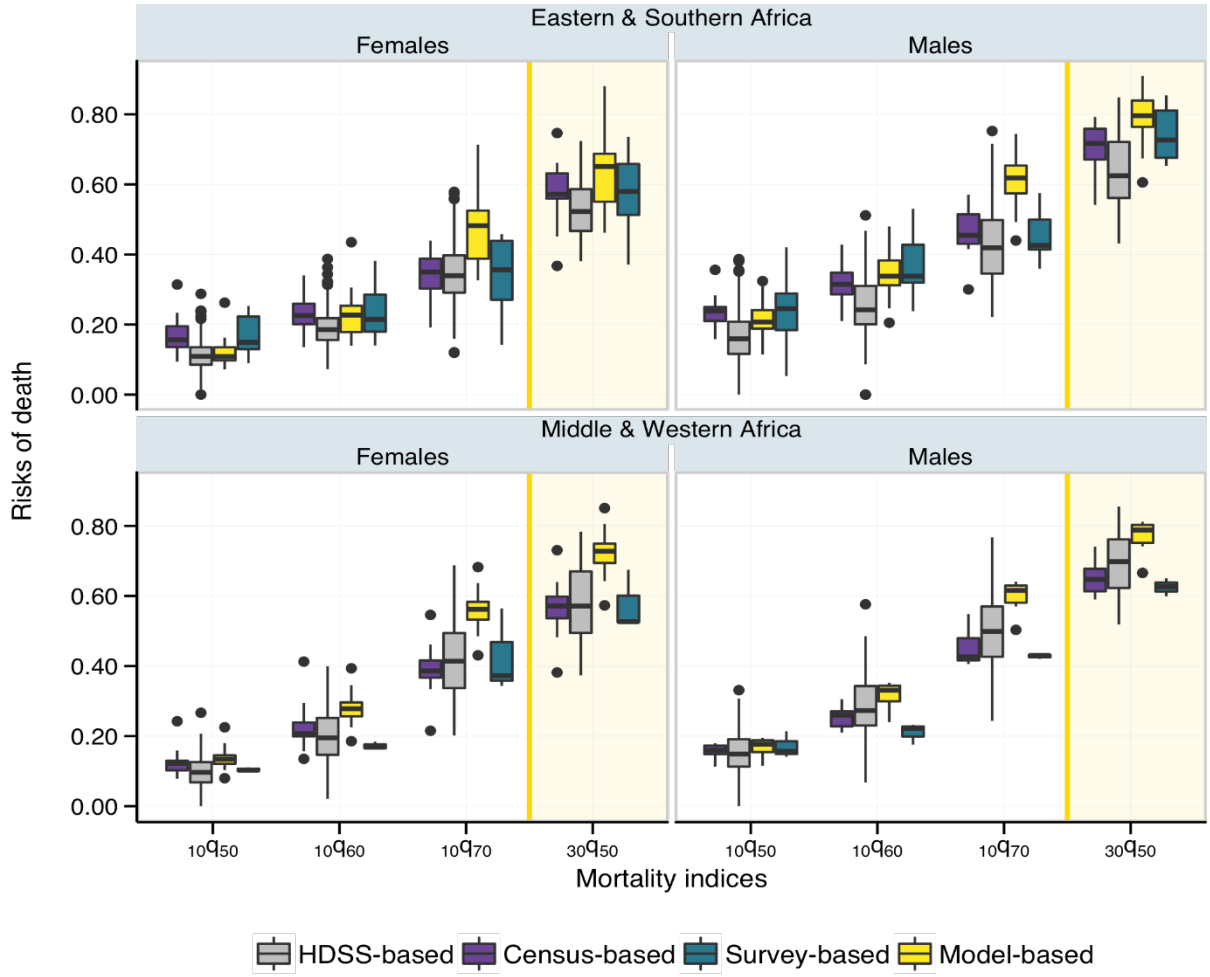

Figure 12 : Probabilities of death from age 50 to 79 estimated from census, survey and HDSS data in sub-Saharan African countries

More specifically, in Middle and Western Africa, the interquartile ranges of the probabilities of death in adults aged 50-79 that are derived from censuses and surveys coincide with those from HDSS data for both females and males. However, the medians of these estimates remain below those from HDSS data, particularly for survey-based estimates with a slightly larger gap for males. Given that deaths were under-reported in most censuses, the consistency of census estimates with HDSS estimates means that the corrections made to these data have greatly improved the estimates. Survey data were few but its estimates appear also consistent with

those from HDSS. Moreover, model-based estimates differ little from census and survey estimates between ages 50-59. They deviate slightly upwards between ages 60-69 and more widely over age 70, indicating either an underestimation of mortality notwithstanding the corrections made to census data, or an overestimation of mortality inferred from the model. Indeed, model-based estimates also yield mortality levels above those obtained from HDSS data, with medians that coincide more with the lower part of the top quartile. This tends to corroborate the hypothesis of an overestimation of the model-based estimates. Indeed, in a previous study, suspicions of overestimation of mortality in older adults were raised against the predictions of the SVD model (Ouedraogo, 2020) which seems equivalent to the Sharrow-HIV model in low-HIV contexts such as Middle and Western Africa. Yet, it does not invalidate the plausibility of the resulting estimates.

In the Eastern and Southern Africa, boxplots from census and survey-based estimates in ages 50-79 overlap with those from HDSS across the interquartile ranges, but with medians above those from HDSS for both females and males and particularly in ages 50-69. This picture suggests either an underestimation of mortality from HDSS between ages 50-69 or an overestimation of mortality from census and survey data in that age group. There are few elements to support the first hypothesis given that above the age of 70, mortality from HDSS become consistent with that from census and survey data. If one had observed that the HDSS estimates were consistent with those of censuses and surveys before age 70, but deviated downwards beyond age 70, one could have thought of a size effect that gives the illusion of low mortality at more advanced ages in HDSS. Conversely, the hypothesis of an overestimation of mortality from censuses and surveys seems more tenable. Indeed, the analysis of age ratios in Eastern and Southern areas (shown in Figure 2) had revealed that between ages 50-69, age errors were clearly more pronounced in deaths than in population. These errors are therefore replicated in the adjusted mortality rates since the correction factor for incompleteness of deaths is a constant that is independent of age. Moreover, if there is another possible reason why mortality inferred at the national level from censuses and surveys is higher than that from HDSS between the ages of 50-69, it could be HIV itself. It is known HIV mortality is increasingly affecting individuals aged 50 and over (Hontelez et al., 2011; Luther & Wilkin, 2007; Negin & Cumming, 2010; Simone & Appelbaum, 2008; Wallrauch et al., 2010). This is mainly due to access to antiretroviral therapy, which has improved the survival of young adults and shifted

deaths to older ages, mainly the 50s (Hontelez et al., 2012; Trickey et al., 2017), and especially for early HIV cases having access to these treatments. Knowing that HIV is more urban than rural in most cases (Cane et al., 2021; Dyson, 2003; Sing & Patra, 2015), and that treatment is more accessible in urban than in rural areas, and also that most HDSS are rural, it is not surprising to have a slightly lower mortality in HDSS data than in census and survey data which include urban settings.

3.5. Age patterns of mortality in African data compared to HMD

Regarding the relationship between mortality in young adults and mortality in older adults in high-HIV contexts such as Eastern and Southern Africa (see Figure 5 below), HDSS data conform better to those from HMD patterns. For similarly high levels of ${}_{35}q_{15}$, the corresponding estimates of ${}_{30}q_{50}$ are higher in HMD than in HDSS. Indeed, mortality of adults under 50 has reached levels rarely or never reached by HMD countries so that for certain levels of ${}_{35}q_{15}$, the corresponding estimates of ${}_{30}q_{50}$ in HMD exceed 0.9 and are tending towards 1. Furthermore, while the nature of the relationship between ${}_{35}q_{15}$ and ${}_{30}q_{50}$ in HMD is clearly curvilinear, that of HDSS is less so, particularly for females who are the most affected by HIV. As a result, when using, for example, a log-quadratic approach with the HMD data to predict ${}_{30}q_{50}$ from ${}_{35}q_{15}$, I obtain an adjusted R-squared of 0.83 for females and 0.72 for males. However, when applied to African data (estimates from censuses and surveys), the predictions exceed 1 in many cases and the prediction intervals appear implausible. Unfortunately, the shape of the relationship is less clear with HDSS data to drive such a model. Overall, census/survey-based estimates agree relatively well before age 60 with both HDSS and HMD data. However, they tend to depart downwardly from the two sources, causing many of the estimates to disagree with them, especially with HMD data, and particularly so for females. Model-based estimates are more consistent with estimates from HDSS and HMD, although these also show dispersions among females as with the census/survey-based estimates.

In Middle and Western Africa, where HIV prevalence is lower, the relationship between younger and older adult mortality derived from census/survey-based estimates is in good agreement with both HDSS and HMD estimates. Yet, based on the visual goodness of fit of each estimation method, model-based estimates are more consistent with both the African local populations (HDSS) and HMD data. Also, ${}_{30}q_{50}$ inferred from the model indicates a lower-than-average older

adult mortality observed elsewhere in empirical mortality data such as HMD for similar levels of younger adult mortality.

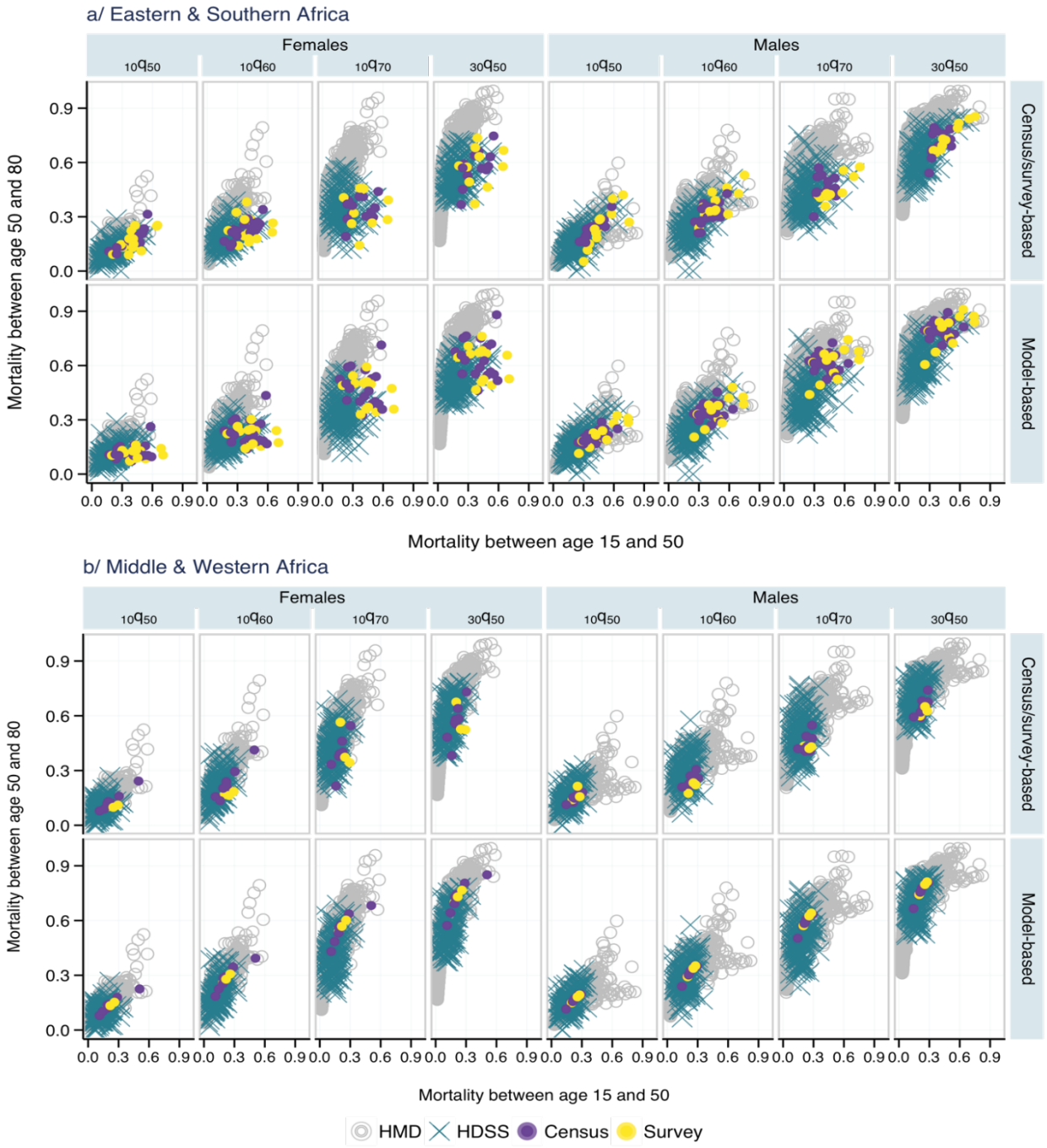

Figure 13: Observed mortality from censuses, surveys and HDSS in sub-Saharan Africa compared to empirical mortality from HMD in terms of relationships between the probabilities of death in older ($_{30}q_{50}$) versus younger ($_{35}q_{15}$) adults.

In order to further refine it to better address mortality at older ages in the particular context of sub-Saharan Africa, it would be needed to address the authors' own suggestions for improvement, such as accounting for ART coverage (Sharrow et al., 2014), exploiting more judiciously the properties of the Singular Value Decomposition (SVD) as suggested by Clark (2015), but also exploring more carefully the possibilities of extending the life tables used to calibrate it with HDSS data.

4. Conclusion

This paper is a first attempt to unpack the problem of estimating mortality in older adults in a context where the data to do so are rare and deficient. The subject is complex and in the absence of reliable data, we will keep relying on models. Comparing and contrasting them can provide valuable insights.

From the above analyses, it appears that the adjusted estimates derived from census data are tainted by systematic errors related to the coverage and completeness of death reporting. These errors do not seem to reduce over time and they require adjustments. Furthermore, the African data, especially those from countries heavily affected by HIV, confirm that age-specific mortality profiles have been significantly disrupted. Regarding mortality levels, model-based approach which accounts for HIV prevalence while smoothing and adjusting the mortality rates appears to be an answer to this problem in both high and low HIV settings. It results in relatively lower mortality at older ages than would have been estimates derived from model calibrated with empirical data such as those from HMD. However, the new configuration of HIV, notably its transposition to older adults due to the greater access of infected people to antiretroviral therapy, calls for a rethinking of these models to reflect mortality in general and more specifically that of older adults. A comprehensive exploration of HDSS data could help in this regard. Such data are useful for evaluating mortality data from general population surveys. In addition, they could be used to expand the universe of possible empirical mortality patterns and be helpful in modelling mortality, particularly in sub-Saharan Africa as suggested previously by other authors. In any case, older adult mortality in sub-Saharan Africa generally appears to be somewhat lower than would be expected if was to follow the same patterns seen in HMD countries with comparable levels of mortality in young adults. This demographic picture, together with the

declining fertility and the rapid decline in child mortality calls for a particular attention to ageing and its implications in terms of public policies. Having to face socio-economic burden and the natural burden of chronic and degenerative diseases, older adults in the region also have to cope with traditional infectious diseases such as malaria and HIV for those infected who survive to older ages due to antiretroviral treatment. The emerging infectious diseases such as Ebola, which affects all ages, and Covid-19, which is particularly lethal in older people, could further impact on the longevity of older adults and undermine health systems that are already weak.

5. Appendix

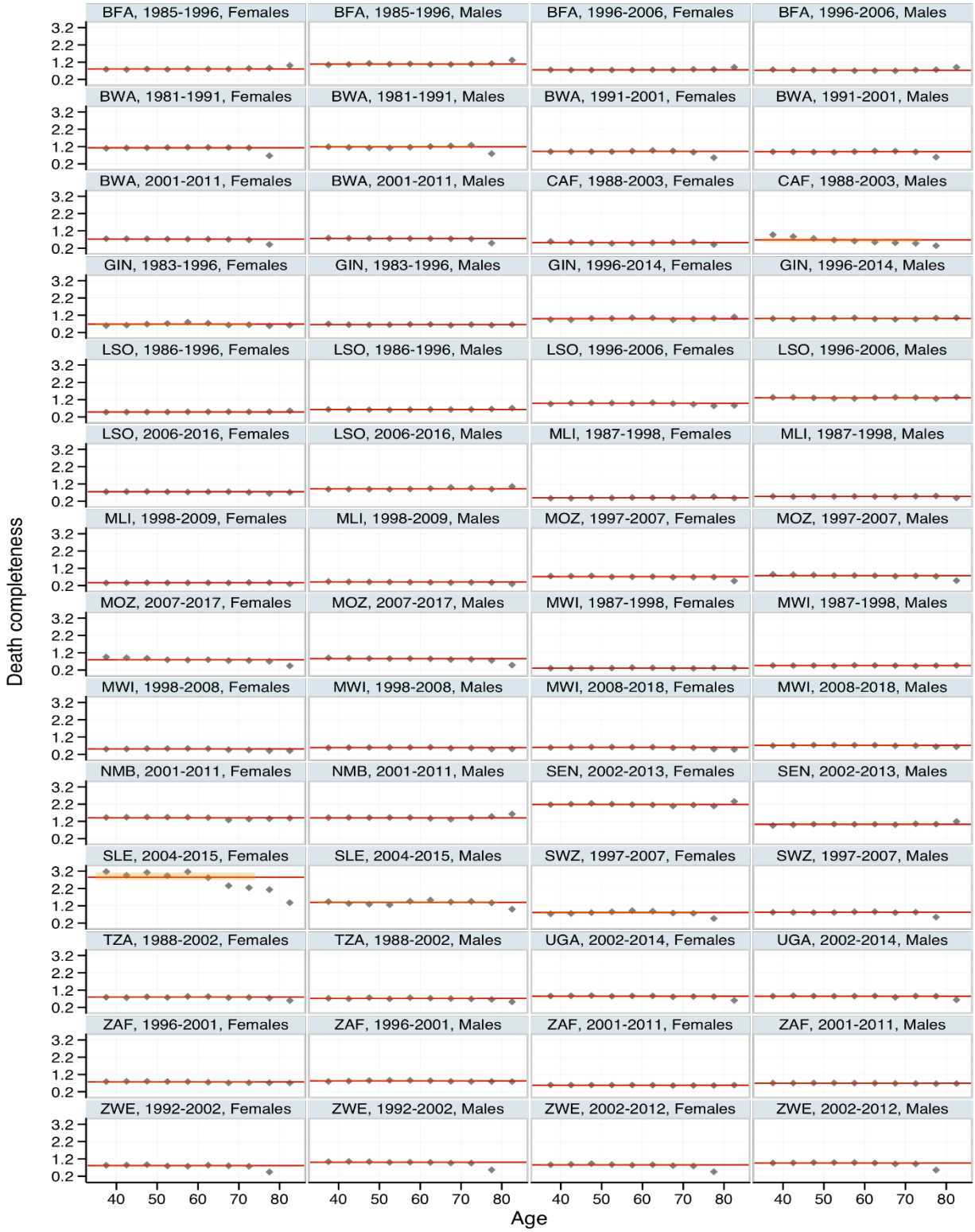

Figure 14 : Diagnostic plot of death completeness from the hybrid death distribution (GGBSEG) by sex and intercensal period

Figure 15: Levels and trends of probabilities of death in ages 50-79 from HDSS, and model-based from surveys and censuses

Chapter 4

Adult modal age at death in contexts lacking good vital registration systems: insights from sub-Saharan African data[10]

1. Introduction

In mortality studies, the adult modal age at death (M) appears to be a relevant indicator for studying longevity. Defined as the age at which the maximum number of adult deaths occurs in a synthetic cohort of individuals experiencing similar mortality conditions, this indicator is less sensitive to improvements in mortality conditions in children and young adults compared to life expectancy at birth, which is highly sensitive to premature mortality (Canudas-Romo, 2008, 2010; Horiuchi et al., 2013; Ouellette et al., 2012). In low-mortality countries characterized by aging populations, many studies have been devoted to the analysis of this indicator and the dynamic of its evolution over time and space (Canudas-Romo, 2008, 2010; Cheung et al., 2005; Kannisto, 2000, 2001b, 2007; Missov et al., 2015; Ouellette, 2011; Ouellette et al., 2013; Ouellette & Bourbeau, 2011; Thatcher et al., 2010). This research has paved additional avenues for analyzing older adult mortality, which is still poorly studied in high-mortality countries.

Originally, the Mode is one of the central tendency parameters used to describe a statistical distribution. The idea of using it to describe natural life span was first initiated by Lexis (1878) who considered it as the threshold age of normal death in adults that is less influenced by extreme values. His works raised debates at that time in the scientific community (Véron & Rohrbasser, 2003). Indeed, thanks to the demographic transition where most developed countries have moved from a high mortality regime to a low mortality regime in children and young adults over the last century, there has been an increasing extension of the average life span, characterised by a rectangularization of survival curves (Wilmoth & Horiuchi, 1999). These demographic changes were accompanied by changes in health profiles and led to a multimorbidity (Fries, 1980, 2000), and a postponement of deaths to older ages (Kannisto et al., 1994; Kannisto, 2000, 2001b; Meslé & Vallin, 2002; Robine, 2001; Thatcher et al., 2010). As the age at which these deaths are maximum, M is now widely adopted as an indicator of interest in studying longevity and mortality, particularly through its location, the scale of deaths at M and the variability of deaths around or above M (Canudas-Romo, 2010; Horiuchi et al., 2013; Ouellette & Bourbeau, 2011). The location of M is defined as the level of normal or natural life

[10] Intended for publication

span as understood by Lexis. Thus, any improvement (or deterioration) in the survival of older adults would result in a shift of M to higher (or lower) ages. Variability is used to capture the extent of the concentration of deaths around or above M for the purposes of comparison, either with another population at the same period, or for the same population over time. One of the simple measures used for that purpose is SD(M+) as suggested by (Kannisto, 2000) in reference to the standard deviation above M or simply the standard deviation around M denoted by SD(M) as used by (Canudas-Romo, 2008). Other dispersion measures such as the interquartile range or deciles are also used in the literature to assess the variability. Theoretically, therefore, since the risk of death increases with age, as M increases, deaths will narrow around M, leading to a decrease in SD(M+). This process of narrowing of the average gap between the ages at death above M and M is known as the compression of mortality (Canudas-Romo, 2008; Kannisto, 2000). Regarding the scale of deaths at M, it refers to the modal value at M and is a complement to the other two by providing the extent of the concentration of adult deaths through its proportion at M. It also allows two similar modes with different proportions of deaths to be assessed differently. Currently, empirical mortality data for countries with good vital statistics from the Human Mortality Database (HMD) indicate that M exceeded 88 years for males in 2018 in few countries. For females, in the same year, a few more countries had M exceeding 90 years.

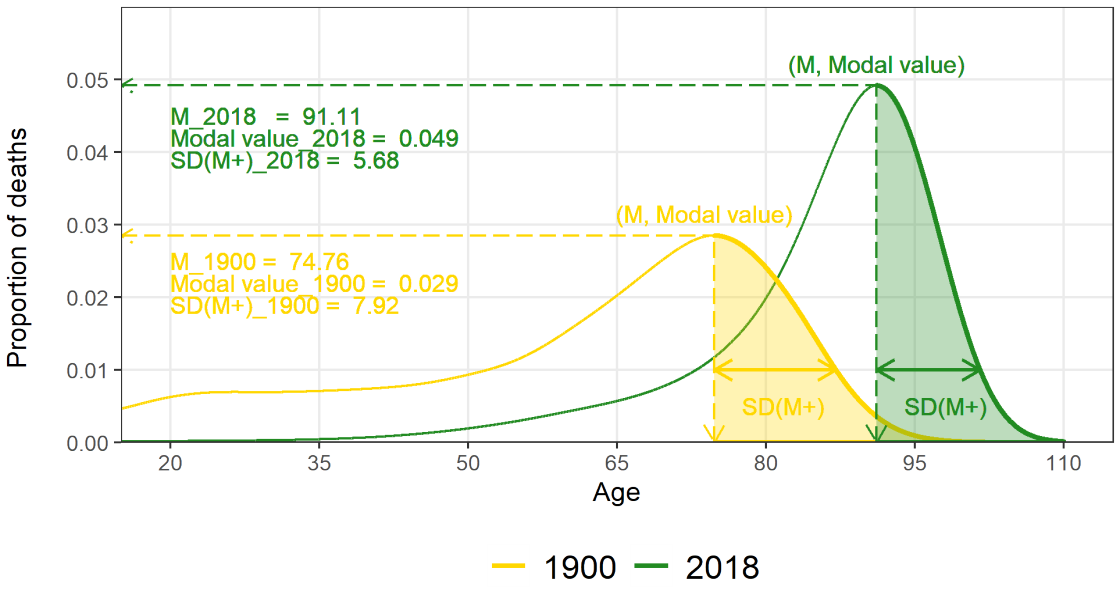

Figure 1 : Adult modal age at death in France in 1900 and 2018

For example, as shown in Figure 1 above, French females have gone from a value of M greater than 74 years in 1900 to 91 years in 2018, with an increase in the proportion of deaths at M from 3% to around 5% and a decrease in the average dispersion above M from 7.9 to 5.7. At the same time, the average age at death of adults aged 15 or over rose from 62 to 85.

In sub-Saharan Africa, knowledge about older adult mortality in general is very limited (Ouedraogo, 2020), and we know even less about longevity. Many infectious diseases are still pervasive and affect all segments of the population, including the elderly (Hontelez et al., 2011; Negin & Cumming, 2010; Wallrauch et al., 2010). In combination with age-related alterations and the high risks of developing chronic diseases, these older people face a double burden of diseases that could impact their longevity. However, poor vital statistics registration and poor data quality, particularly at older ages, make it difficult to estimate mortality and related indicators. A first attempt in analyzing the mode of age at death distribution was made on African data from three population surveillance sites in rural Senegal (Duthé et al., 2018). Estimates from this study ranged from 75 to 83 years for females and 72 to 77 years for males. The authors noted a weak trend characterized by a deterioration in health in the early 2000s. Moreover, they pointed out that the levels observed had been reached by low-mortality countries in the 1950s and even earlier. Another such study was conducted using data from one of the best death registration systems maintained by the Municipal Hygiene Office in Antananarivo, the capital of Madagascar (Quinquis, 2019). This study showed estimates of the most common age at death (M) ranging from 75-79 years for females and 65-77 years for males over the period 1986-2015. Over the same period, the dispersion of deaths beyond M decreased from 9 to 8 for females and from about 14 to 9 for males.

Since the 1950s, the emergence of indirect systems for generating life tables[11] have been developed to compensate for the lack of vital registration data (Hu & Yu, 2014). However, these approaches have many limitations, including the non-representativeness of the sample of life tables used to build them and their inability to account for the effect of devastating epidemics such as HIV on the age structure of the mortality to be fitted. Furthermore, most of them were based on a single parameter and were lacking in flexibility (Murray et al., 2000). Subsequently, the increasing use of questions on females 's birth history or on the survival of parents or

[11] These methods have been described in the previous chapter

siblings has favoured the estimation of aggregate mortality indices such as the probability of death for both children under 5 and adults up to age 60. Considering the combination of these two pieces of information as parsimonious enough to fully describe the age schedule of mortality in a given population, indirect systems for modeling life tables have been developed (Clark, 2019; Murray et al., 2003a; Sharrow et al., 2014; Wilmoth et al., 2012). These models offer ways to improve the quality of the estimated life tables and an opportunity to assess the modal age at death in sub-Saharan African countries. Using such approach to look at the adult modal age at death was attempted previously using secondary data from ${}_5q_0$ and ${}_{45}q_{15}$ available for many sub-Saharan African countries (Ouedraogo, 2019; Ouedraogo et al., 2019). The present paper is a continuation of these previous attempts through a triangulation of various African data sources, namely censuses, sample surveys and local population surveillance data. The purpose of this study is to improve the state of knowledge about mortality of the elderly in this region of the world. The objective of this work is to evaluate the relevance of M for the analysis of older adult mortality in the sub-Saharan context, which features a complex epidemiological picture. More specifically, the first main question underlying this paper is whether it is possible to estimate M in the sub-Saharan context lacking good vital statistics in a way that plausibly reflects the distribution and concentration of deaths in the populations under study. If so, the second question is to highlight any features in the curves of death distribution, especially the impact of HIV in some specific contexts, and derive M in females and males for each country-period. Ultimately, our task will consist in checking whether the hypothesis of shifting and compression of mortality observed empirically in developed countries is also perceptible in the sub-Saharan context.

2. Material and methods

2.1. Overview of the data[12]

This study relies on the three data sources used in the previous chapter, including censuses, nationally representative household sample surveys, and prospective data from health and demographic surveillance systems (HDSS). Since the analyses in this chapter will draw from

[12] For more details on these data, as well as census and survey data, please see the description in the data section of the previous chapter

age distribution of deaths, I selected censuses and surveys in which information on adult deaths that occurred in the last 12 months preceding the interview was collected by age and sex. The list of censuses/surveys that I use is shown in Table 1 below. Regarding the HDSS data, their longitudinal nature allows them to supplement the shortcomings of census and survey data by offering perspectives on time trends. In addition, since these data also come from African populations, they can be used to some extent to check the consistency and plausibility of estimates from census and survey data. A summary of these data is provided in Table 2 below.

Table 1 : Available censuses and surveys with data on recent deaths recorded within households by sex and age

Regions/Countries	Censuses	DHS	Other DHS-type	Other surveys
Eastern and Southern Africa				
Botswana	1981, 1991, 2001, 2011			1998[(c)], 2006[(c)]
Eswatini	1997, 2007	2006		
Lesotho	1986, 1996, 2006, 2016			2001[(c)]
Malawi	1987, 1998, 2008, 2018	2010		
Mozambique	1997, 2007, 2017			
Namibia	2001, 2011	2007		
South Africa	1996, 2001, 2011			
Tanzania (United Republic)	1988, 2002, 2012		2007[(a)]	
Uganda	2002, 2014	2006	2011[(a)]	
Zambia		2007		2008[(b)]
Zimbabwe	1992, 2002, 2012	2006		1997[(c)]
Middle and Western Africa				
Burkina Faso	1985, 1996, 2006			2008[(b)]
Central African Republic	1988, 2003			
Guinea	1983, 1996, 2014			
Mali	1987, 1998, 2009			
Nigeria		2008, 2013		
Senegal	2002, 2013			
Sierra Leone	2004, 2015			

Source: United Nations Population Division (UNPD), the DemoData database

Notes: [(a)] Annual Household Survey (AHHS); [(b)] Global Fund Facility Survey (GFFS); [(c)] Other surveys

Table 2: List of 26 HDSS in Sub–Saharan Africa by period covered and length of the follow–up

Regions	Countries	HDSS	Periods covered	Period length
Eastern Africa	Ethiopia	Dabat*	2009–2015	7
		Kersa	2008–2016	9
		Kilite Awlaelo	2010–2014	5
		Harar*	2012–2016	5
	Kenya	Kombewa	2011–2015	5
		Nairobi*	2003–2015	13
	Malawi	Karonga	2003–2017	15
	Mozambique	Chokwe	2010–2016	7
	Tanzania	Ifakara	1997–2014	18
		Magu	1994–2012	19
		Rufiji	1999–2014	16
	Uganda	Iganga/Mayuge	2005–2016	12
Southern Africa	South Africa	Africa Centre	2000–2017	18
		Agincourt	1993–2017	25
		Dikgale	1996–2016	21
Western Africa	Burkina Faso	Nanoro	2009–2015	7
		Ouagadougou*	2009–2015	7
		Nouna	1998–2015	18
	Côte d'Ivoire	Taabo	2009–2016	8
	Gambia	Farafenni	1993–2015	23
	Ghana	Dodowa	2006–2011	6
		Kintampo	2006–2014	9
		Navrongo	1993–2014	22
	Senegal	Bandafassi	1985–2016	32
		Mlomp	1985–2016	32
		Niakhar	1985–2016	32

Source: Indepth network (http://www.indepth–ishare.org/index.php/catalog/central), accessed 16 July 2018

Note: (*) these sites are located in urban areas

I supplemented these African data with mortality data from the Human Mortality Database from which I extracted the available set of period life tables, mainly from high-income countries. These latter are used to check the health trajectory of African populations against empirical mortality experiences from elsewhere.

2.2. Methodological aspects

Computation of life tables[13]

For the census data, I used the hybrid death distribution method, which requires two censuses to correct the data (Hill et al., 2005, 2009). This correction was performed by adjusting the relative coverage of one census to the other, and then correcting for incompleteness of deaths estimated over the intercensal period. As a result, two censuses yielded a single point estimate with reference to the intercensal period. I do not mention the limitations of such an approach, which have been discussed in the previous chapters. It allows for an upward correction of mortality estimates that are generally underestimated when based on unadjusted rates because of various errors, but does not eliminate all of them. As for survey data, no particular adjustments were made. I simply considered the deaths as they were reported. However, the population numbers were re-estimated to match the mid-year of occurrence of the reported deaths in order to estimate the person-years. These census/survey-based data are our first sources of estimates from which I was able to directly compute life tables by period.

The second source of estimates is model-based from census/survey data. For this purpose, I use an indirect mortality modeling approach that uses two indices of mortality before age 60 as inputs to infer mortality at all ages, including mortality beyond age 60 (Sharrow et al., 2014). These are adult mortality ($_{45}q_{15}$) estimated from census-adjusted data and survey data. It is supplemented by the under-five mortality rate ($_5q_0$). However, since the latter is highly uncertain when directly computed from censuses, it is borrowed from the annual series produced by the United Nations Inter-agency Group for Mortality Estimation (UN-IGME[14]). Such an estimate of $_5q_0$ is not free of errors, but appears to be one of the best available. Compared to other such models (Clark, 2019; Murray et al., 2003a; Wilmoth et al., 2012), the model developed by Sharrow and colleagues (2014), was preferred for its ability to account for excess mortality at young adult ages due to HIV by considering HIV prevalence among 15-49 year-olds as a third input, which is taken from the joint United Nations programme on HIV/AIDS (UNAIDS[15]). This

[13] The procedure for computing life tables from census and survey data is summarized here but has already been well described in Chapter 3

[14] https://childmortality.org/

[15] https://aidsinfo.unaids.org/

model, its strengths and weaknesses, and how I used it to estimate life tables have already been discussed in Chapter 3.

The final source of estimates used is HDSS data. These data have been processed to produce the distribution of deaths and person-years by year of age, sex and calendar year for each HDSS. Yet, due to small population sizes, large variations are introduced in the underlying age patterns of mortality. Some ages don't have any reported death while it is unlikely that the risks of dying are zero at these ages. As a sensible and well-suited way of estimation in small populations, Bayesian methods could also be used as a data-driven approach that does not over-smooth the data to eliminate real fluctuations in the data, thereby preserving its originality (Bryant & Zhang, 2019). As suggested by these authors, one can assume that deaths y_{xst} at age x, for sex s and at time t within a HDSS follow a Poisson distribution such that:

$$y_{xst} \sim Poisson(m_{xst}.\mathcal{E}_{xst}) \tag{1.1}$$

$$\log(m_{xst}) \sim Normal\left(\beta_0 + \beta_a^{age} + \beta_s^{sex} + \beta_t^{time} + \beta_{as}^{age*sex}, \sigma^2\right) \tag{1.2}$$

where (1.1) is the likelihood and (1.2) provide the prior for the underlying mortality rates m_{xst} associated to the population at risk of dying $\mathcal{E}_{xst}$. Then, the log-rates are expected to follow normal distributions with means varying by age, sex, time. The vector β that contains the main effects and interactions associated to these covariates have in turn priors that could be expressed as follows for age and sex:

$$\beta_x^{age} \sim N\left(0, \sigma_{age}^2\right) \tag{1.3}$$

$$\beta_s^{sex} \sim N(0,1) \tag{1.4}$$

$$\beta_{xs}^{age*sex} \sim N\left(0, \sigma_{age*sex}^2\right) \tag{1.5}$$

And as follow for time:

$$\beta_t^{time} = \theta_t + \nu_t \tag{1.6}$$

$$\theta_t = \theta_{t-1} + \omega_t \tag{1.6.1}$$

$$\nu_t \sim N(0, \sigma_\nu^2) \quad (1.6.2)$$

$$\omega_t \sim N(0, \sigma_\omega^2) \quad (1.6.3)$$

where β_t^{time} is assumed to follow a random walk with noise that allows distinguishing short-term unusual movement (ν_t) from permanent changes in the level of the distribution (ω_t). Additional specifications related to the covariates are necessary, but more detailed explanations of these and the general principles of the model can be found in *Bayesian demographic estimation and forecasting* (pp 69-92). The final estimate for each m_{xst} is a compromise between the predicted value from equation (1.2) and the direct estimate from y_{xst} and $\mathcal{E}_{xst}$ derived from equation (1.1). The model performs as a kind of local smoothing that maintains authentic and durable features while striping away transient features and random variability so that the true underlying age-specific mortality pattern becomes apparent. The modelled estimates stay more or less unchanged compared to the empirical data in cells where there are more data and they are pulled towards the predicted values from equation (1.2) where data are scarce (Zhang & Bryant, 2020). Markov Chain Monte Carlo (MCMC) simulation algorithm are used to generate a large sample of posterior distribution from which the forecasted median value of mortality rate at each age, sex and single year of time is considered as the most credible estimate (Bryant & Zhang, 2016). This approach appears preferable to keep the data disaggregated by single year of age for further analyses and estimations of the adult modal age at death.

Estimation of the Adult modal age at death (M)

Considering that deaths d_x observed at any age x follow a Poisson distribution with a mean equal to $\mathcal{E}_x * \mu_x$, where μ_x represents the force of mortality at age or within age group x et $\mathcal{E}_x$ the corresponding person-years, one can therefore estimate μ_x using a Poisson regression through a linear predictor $ln(\mathbb{E}[d])$ as follow:

$$ln(\mathbb{E}[d]) = ln(\mathcal{E} * \mu) = \ln(\mathcal{E}) + \ln(\mu) = \ln(\mathcal{E}) + \mathcal{B}\alpha \quad (2.1)$$

where $\mathcal{B}$ is the B-splines basis matrix and α is the vector of the respective coefficients of the regression to be estimated through a flexible non-parametric approach based on P-splines, which in turn allow penalizing the said coefficients (Horiuchi et al., 2013; Ouellette, 2011). In

this equation, the logarithm of person-years, $\ln(\mathcal{E})$, is denoted as the offset in Poisson regression models. It subsequently produces smoothed death counts, from which smoothed forces of mortality can be derived as follows:

$$\hat{\mu}(x) = exp\,(\mathcal{B}(\mathrm{x})\hat{\alpha}) \tag{2.2}$$

On the basis of the relationships between mortality force, survival and density functions, the smoothed probability density function to describe the age-at-death distribution can be derived as follows:

$$\hat{d}(x) = \hat{\mu}(x) * \hat{S}(x) \tag{2.3}$$

where $\hat{S}(x) = exp\left(-\int_0^x \hat{\mu}(t)\,d(t)\right)$ is the resulting smoothed survival function that can be calculated using standard numerical integration techniques. Furthermore, following the definition of M yields:

$$\widehat{M} = \max_x \hat{d}(x) \tag{2.4}$$

The functions "Mort1Dsmooth" and "Mort2Dsmooth" of the package *MortalitySmooth* (Camarda, 2012) are used for all the computations. In cases where observed deaths counts were not available (as is the case with the model-based estimates using ${}_5q_0$ and ${}_{45}q_{15}$), I used the functions ${}_nd_x$ and ${}_nL_x$ of the estimated life tables as proxy respectively of observed death counts and person-years lived to smooth forces of mortality and estimate M. Indeed, the ratio of these two functions allows the direct calculation of age-specific mortality rates and the approximation of the resulting force of mortality. Moreover, life tables used for the estimation of M are truncated from age 15 onwards.

3. Results

3.1. Method-based comparison of age patterns of mortality in HDSS

Figure 1 below shows an illustration of observed age-specific mortality data (in red) from few selected HDSS, handled using a Bayesian approach for estimation in small populations to screen out the noise in the data (in turquoise), and smoothed by P-splines (in yellow). The use of the Bayesian method to deal with the noise in the HDSS data produces less erratic curves than would have been the case with the source data. This makes sense as the objective of this

method is not to smooth but rather to tease out the noise in the data to extract the true age pattern. For example, in the case of Mlomp, where the population under surveillance is relatively small, if the mortality curve were to be determined solely by the ages at which deaths were recorded, it would have been higher and resulted in high mortality. The points at which deaths were recorded are thus counterbalanced by the points at which no deaths were recorded so as to produce a more realistic mortality curve. This is also seen at the very old ages in Nairobi, Nouna and Africa Centre HDSS where no deaths are recorded to counterbalance the cases of "0" deaths, resulting in a downward dip in the mortality curve.

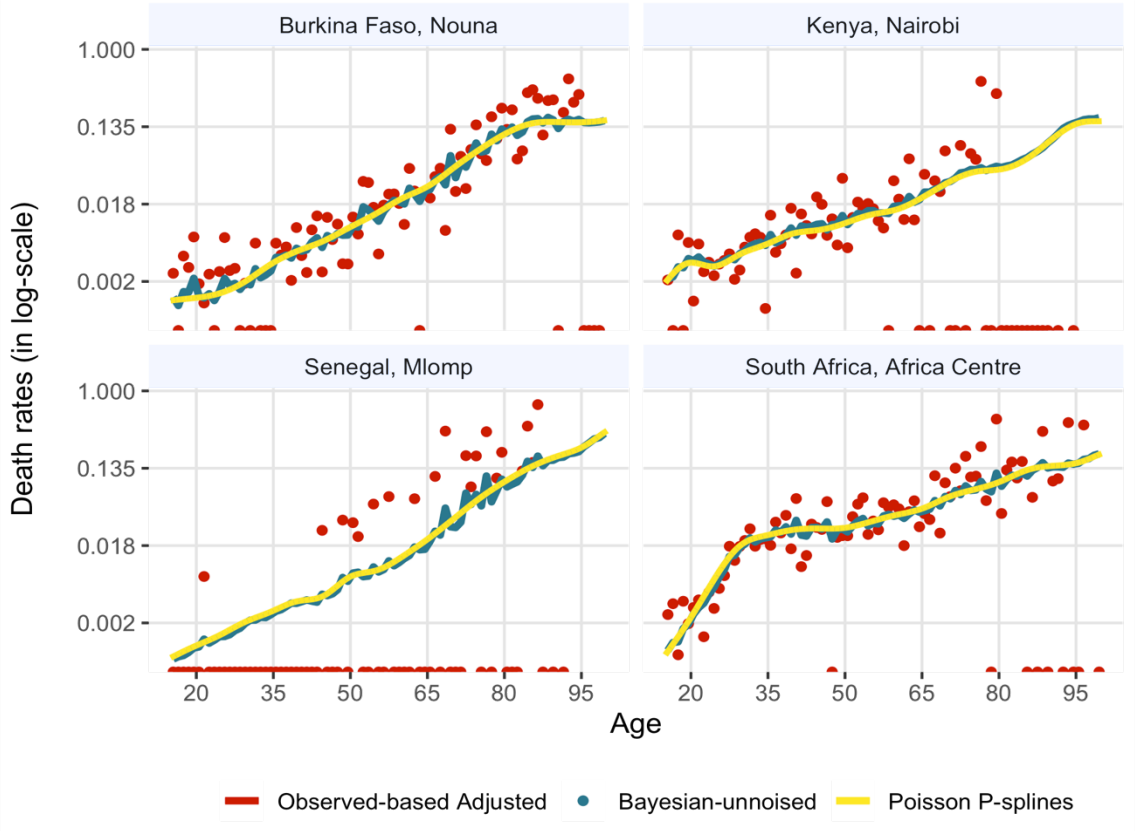

Figure 2 : Observed age-specific mortality patterns in 2010 within 4 selected HDSS, with both readjusted estimates based on a poisson model calibrated to a Bayesian approach suited for small population estimates to clean up noise in the data and smoothed estimates by P-spline through fine numerical integration for accurate location of M

Numerical integration of the unnoised mortality curves to the hundredths through P-spline smoothing along the age and time dimensions produces perfectly matched curves. The resulting curves of instantaneous mortality rates lend easily to the determination of M with a two decimal

precision. For census and survey data that were less erratic, Numerical integration by P-splines were applied directly to the data.

3.2. Age at death distribution in different sub-Saharan contexts

Figure 2 below illustrates different shapes of age at death distribution in sub-Saharan Africa based on data from 4 HDSS. In the case of Burkina Faso and Senegal, age at death distribution in adults are normally distributed in a bell shape with a distinctive peak that easily lends itself to the location of M.

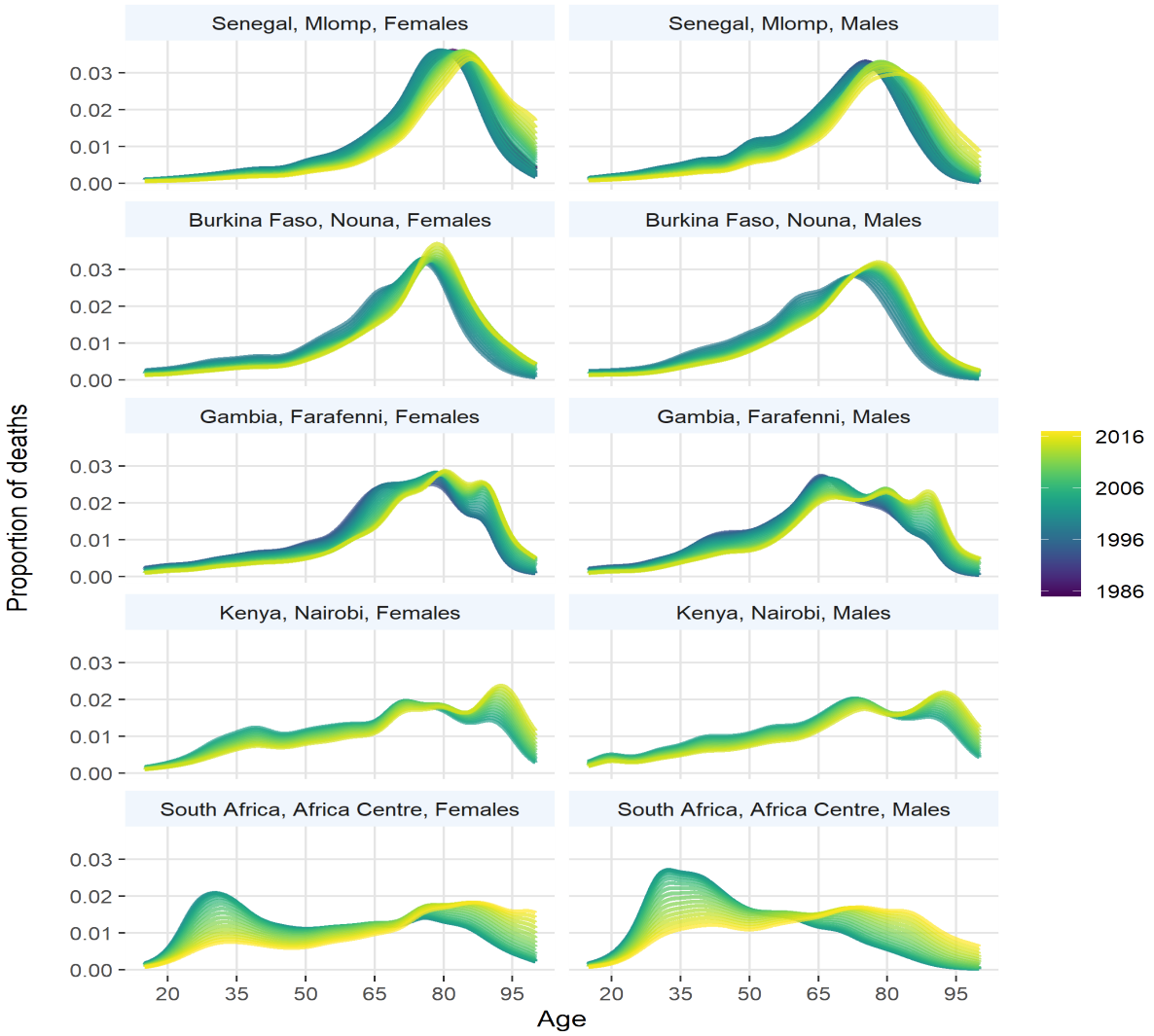

Figure 3 : Annual series of age at death distributions smoothed from year of age data in few selected HDSS arising from African data

This kind of shape is commonly observed in age at death distributions from empirical life tables in high-income countries. The case of the Farafenni HDSS in Gambia should also be similar, although there are several mortality bulges at older ages. Nevertheless, fatal epidemics such as HIV, which have strongly affected the age structure of mortality in many African countries, have certainly distorted the resulting age at death distribution. This can be seen in the Figure with the HDSS of Kenya (Nairobi) and South Africa (Africa Centre). For example, there is an earlier peak in deaths before age 50 among females in the Nairobi HDSS, probably due to HIV. This peak tends to disappear over time, certainly with the introduction of anti-retroviral therapy (ART) and a decline in the incidence of the disease due to increased awareness and protection methods. For males, such a peak is less apparent in young adults, probably because females were more affected by the disease in this HDSS. After age 50, two peaks in deaths appear, albeit on a different scale. This can be described as a bimodal distribution. However, if I follow the definition of M as the age at which the proportion of deaths is maximum, it is the last mortality hump that would be appropriate for determining M in this case. Yet the age corresponding to this last hump is so high (about 90) that it would be implausible. The pattern observed in Africa Centre HDSS is also eloquent. For both females and males, there is an impressive excess of deaths before age 50, although more pronounced for males.

At the beginning of the 2000s, when the epidemic was at its peak, death curves for young adult males were so high that they absorbed the natural hump usually arising at older ages and declined monotonically thereafter. In such extreme cases, one would consider the only mode at young adult ages (less than 35 years here) as our M. M is therefore not always related to older adults and its fall to young adulthood strongly reflects the shortening of longevity in such a context. Furthermore, as the mortality hump observed before age 50 decreases, there is a gradual shaping of the natural mortality hump in older adults until the decrease of the curve becomes non-monotonic and a hump indicating a maximum appears. This was the case from 2007 to 2008 for males in the Africa Centre HDSS when a maximum appeared in a second bulge of deaths that was gradually shaping in older adults, moving M from less than 33 to 67 years. Such a jump teaches us that in some contexts, M can fall drastically at young ages and can suddenly move back to older ages. Certainly, an improvement in survival at young adulthood will have contributed to this return, but it cannot explain an annual gap of 34 years which seems

rather inherent to the nature itself of the distribution of deaths by age. It seems to be a kind of equilibrium between deaths at young ages and deaths at old ages, so that if deaths are massively concentrated at young ages, very few people survive at older ages and the natural hump of deaths at these ages falls away, and vice versa. Such cases are typical of sub-Saharan Africa and reflect the dramatic impact of HIV at a certain period.

In any case, the multitude of death humps found in many HDSS at older ages does not make it easy to locate M. I assume that this is because the analyses in HDSS are done on small populations which could be affected by many fluctuations. The use of Bayesian modelling as a data-driven approach has unfortunately not been able to curb the impact of such fluctuations. These were certainly exacerbated by the fact that the data are compiled by year of age and by annual series, the aim being to have the finest possible detail. Usually, such data are aggregated both by five-year age groups and over several years (3, 5, 10, etc.). As the issue is mainly about fluctuations by age, I opted to aggregate the raw data by age and preserve the yearly series for easier trend analysis. Thus, I recalculated the HDSS life tables on this basis as in census and survey data. Graduation of the data by numerical integration using P-splines allowed us to reconstruct the age distribution of deaths to the nearest hundredth. The results are presented in Figure 4 below for the same HDSS presented in Figure 3. I note that graduation of the data by numerical integration from aggregated data in 5-year age groups made it possible to fix the issue of multiple death bulges at older ages while keeping the general shape of the death distribution curves. Nevertheless, it adjusts some of the fluctuations that were previously observed at certain ages. Moreover, whether using aggregated age data or single age data, an important lesson emerges from the annual series of age at death distributions from HDSS data. Namely, that as the magnitude of the death hump at young adult ages increases, certainly with the worsening of the HIV pandemic, that of the death hump at older ages decreases, and even that the hump itself disappears in extreme cases. However, there is a gradual return to normality in almost all high HIV settings, including extreme situations where the natural mortality hump at older ages had disappeared. This return to normality is accompanied by a reduction in the magnitude of the hump at young adulthood. This is due to efforts to control the pandemic, including reducing new infections and the spread and reducing barriers to accessing anti-retroviral drugs in many countries after 2010. This has resulted in an increase in prevalence due to improved survival of those infected, but with a decline in HIV-related deaths (Kharsany & Karim, 2016; Trickey et al., 2017).

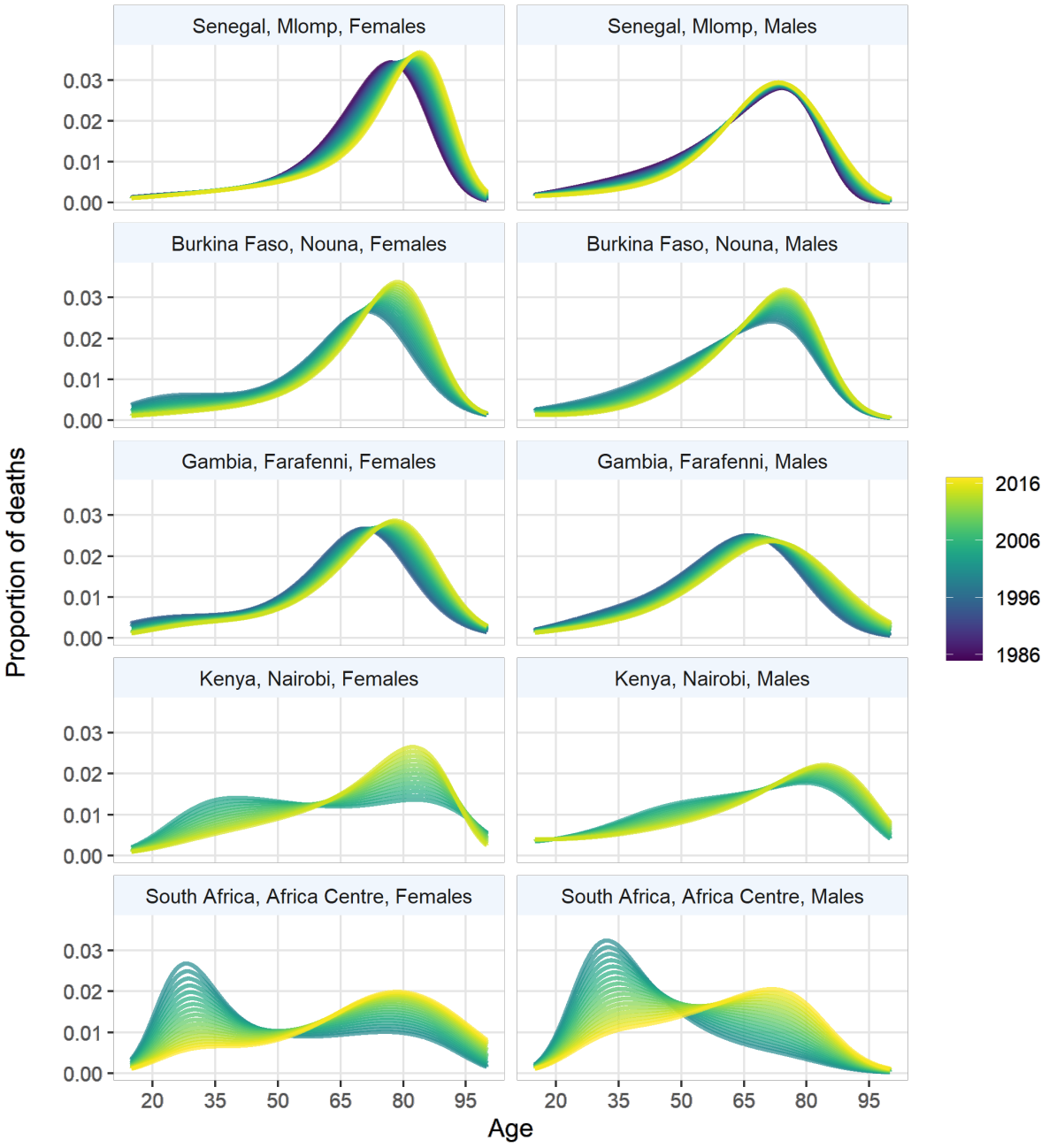

Figure 4 : Annual series of age at death distributions smoothed from 5-year age group data in few selected HDSS arising from African data

National population-based data from censuses and surveys data are less subject to the kinds of fluctuations noted above in HDSS data. However, the distortions caused in the age distribution of deaths in some countries highly affected by HIV deserve to be discussed. As in the HDSS, there are sometimes bimodal distributions with a death hump at young adult ages and another hump at older adults. Sometimes the hump at older ages disappears completely. In Figure 5

below, I present the age-specific distributions of deaths from the life tables by estimation method in the country-periods where questionable M levels have been found. This is the case for example in Eswatini (men 1997-2007), Lesotho (men 2006-2016), Malawi (1987-1998, males 1998-2008), Mozambique (men 1997-2007).

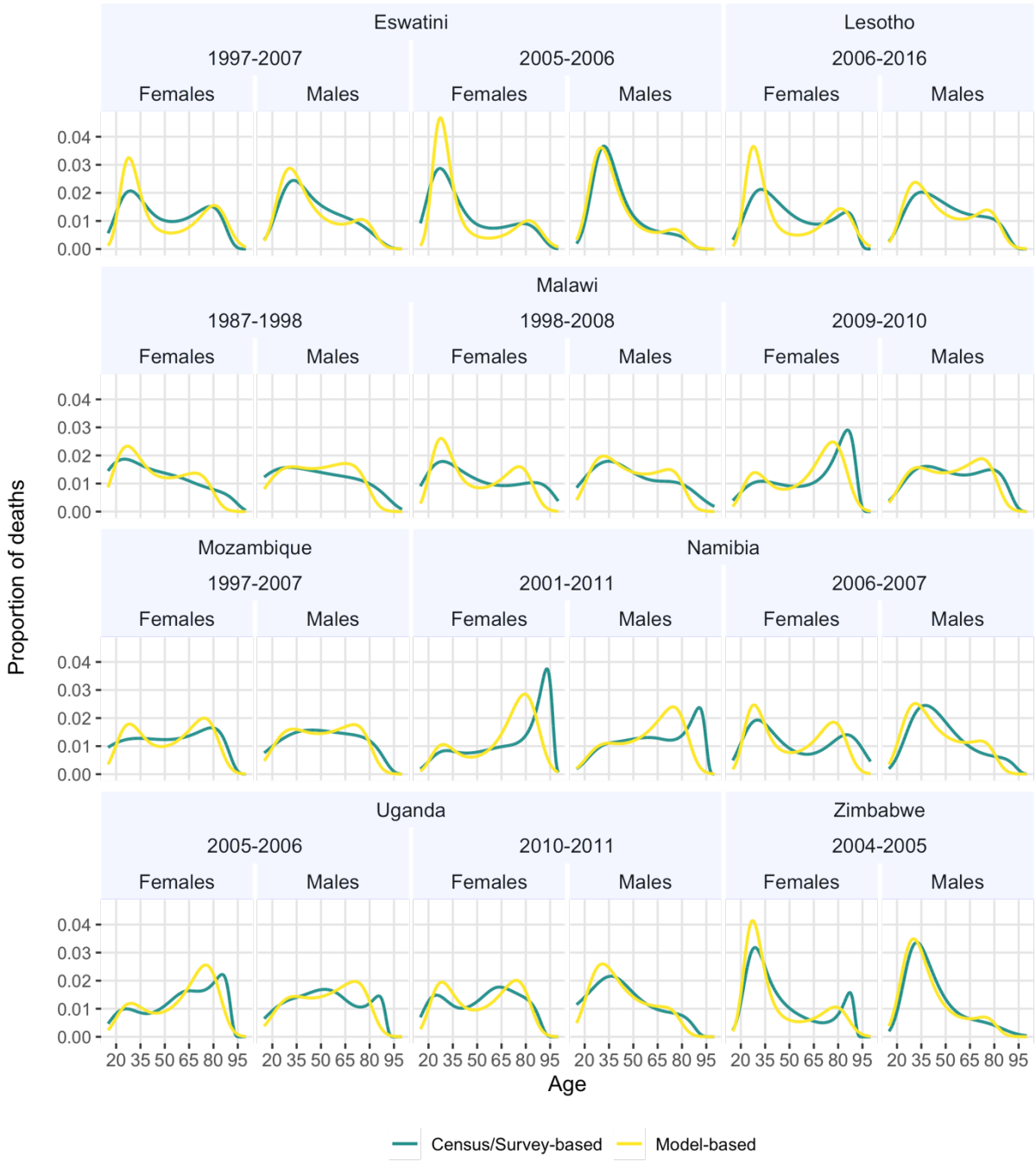

Figure 5 : Age at death distributions from census and survey data in few selected countries where M with remarkable distortions

Similar cases are also noted in some surveys, including among males in Zimbabwe (2004-2005), Eswatini (2005-2006), Malawi (1987-1998, 1998-2008), Namibia (2006-2007) and Uganda (2010-2011). In some other cases, such as among females in Namibia (2001-2011), Malawi (1998-2008, 2009-2010), Uganda (2005-2006) or Zimbabwe (2004-2005), very late onset of death is recorded, sometimes exceeding 90 years of age, and therefore appearing implausible as a location for M.

Thus, whether census data are adjusted simply for incompleteness of deaths or survey data are used directly to estimate life tables and derive M, the estimates are sometimes implausible, especially in older adults and more particularly in contexts of high HIV prevalence, where HIV-related disturbances are added to deficiencies in the data. When using model-based estimates derived from the same data using ${}_5q_0$, ${}_{45}q_{15}$ and the level of HIV prevalence, the shortcomings noted above appear less problematic. Indeed, in most cases where there are no death humps at older ages, the model adjusts the distribution of deaths and allows them to show through, even if they are sometimes of small magnitude, as for example among males in Eswatini (1997-2007, 2005-2006), Malawi (1987-1998, 1998-2008), Namibia (2006-2007) or Zimbabwe (2004-2005). This is also the case in Uganda (2010-2011), but the death hump shaping around age 70 is not high enough to depict a maximum so as to be considered as the mode for older adults. In this case, the unique mode will be the one observed at young adult ages. Furthermore, the modes observed prior to modelling at very old ages in Malawi (1998-2008, 2009-2010), Namibia (2001-2011) or Uganda (2005-2006) have been adjusted downwards.

It can also be noted that the model-based approach does not only adjust the distribution of deaths at older ages. At younger ages, the model induces a bulge of deaths at least similar to those depicted in the initial data, otherwise it leads to a much higher proportion of deaths. This can also be seen in Figure 5, especially for females. It is particularly pronounced in Eswatini, Lesotho and Malawi. This may be because the model is designed to include HIV prevalence among young adults aged 15-49 since they are the most at-risk segment of the population. Considering therefore the proportion of adults aged 15-49 infected in modelling mortality could induce a concentration of adult deaths aged 15-60 in the under 50s and a lower mortality between 50-60s so that the general level of 45q15 used as input in the model is preserved. This is certainly what emerges in the estimation of the distribution of deaths derived from the model, since in many countries the prevalence is higher among females than among males. This is

especially true in cases where HIV is very high. Consequently, it cannot be ruled out that the low proportion of deaths that may result from this modelling between 50 and 60 years of age will have a spillover effect beyond 60 years, at least to some extent, although the impact remains to be assessed.

Depending on whether one was detected early or late in the infection, whether one is on ART or not, survival can extend over many years (Ang et al., 2021; Brinkhof et al., 2009; Trickey et al., 2017). There is evidence that people living with HIV on ARVs are living longer and there are a growing number of people over 50 living with HIV as a result of the widespread availability and free access to ART since the late 2000s in many countries. It is not strongly established that these people recover the average lifespan of their uninfected peers. However, one can logically assume that this will lead to a shift of early deaths prevented in young adults to older adults. Those who designed the model anticipated these shortcomings by proposing to add as additional inputs the prevalence of children infected and on ART as well as the prevalence of adults on treatment (Sharrow et al., 2014). However, such information was not readily available at the time of this analysis. Rather than the proportion of under-fives on ART to remain in line with the child mortality index considered in the modelling ($_5q_0$), UNAIDS provides only the proportion of children under 15 years old. Similarly, among adults, the information available on ART coverage concerns more broadly the 15-and-over age group and not the 15–60-year-olds in reference to the adult mortality index used in the model ($_{45}q_{15}$). Furthermore, in the present analyses, there is little data on the post-2010 period when access to ARTs has increased significantly. Despite this, these perspectives are undoubtedly an important complement that could help to better adjust the distribution of deaths for new data on HIV that may become available.

3.3. Cross-validation through the shifting mortality and the compression hypothesis

In Figure 6 below, I relate the levels and standard deviations of M derived from census/survey and HDSS data to those from the Human Mortality Database (HMD). The empirical data from HMD broadly show a decrease in dispersion above M (SD(M+)) as M increases. Although from shorter annual series than HMD, data from local population monitoring are consistent with the latter and describe a similar decrease in both Middle and Western Africa and Eastern and Southern Africa sites. However, there are two exceptions, namely the Chokwe HDSS in

Mozambique (2010-2013) and the Africa Centre HDSS in South Africa (2000-2011), where extremely high standard deviations not seen elsewhere are observed. When comparing census/survey-based estimates to HMD estimates in terms of the relationship between M and SD(M+), a number of discrepancies emerge. First, there are clear deviations from the trajectory described by the empirical estimates from HMD.

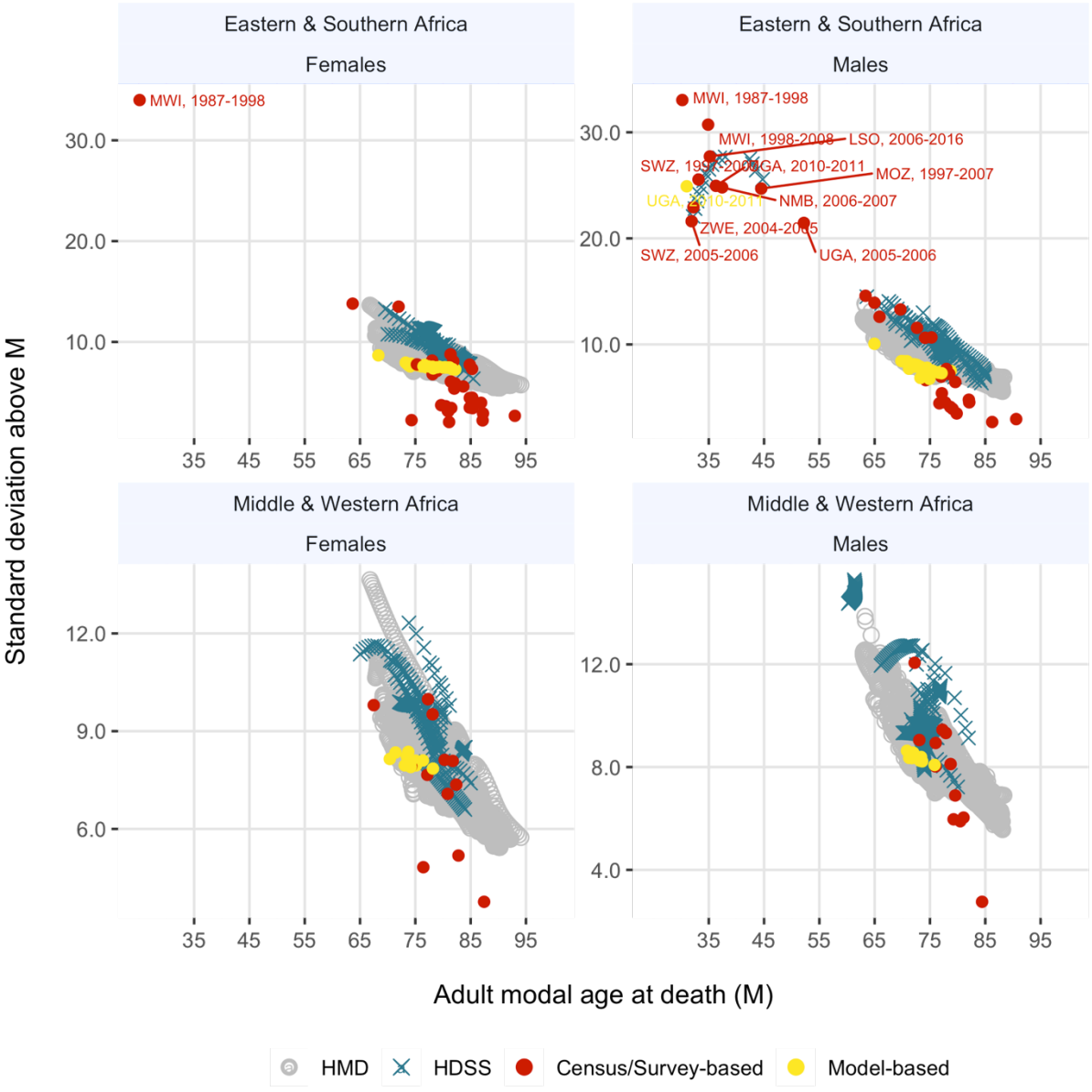

Figure 6 : Relationship between Adult modal age at death (M) and Standard deviation above SD(M+) from African data and Human Mortality Database (HMD)

Note : LSO=Lesotho, MWI=Malawi, NMB=Namibia, MOZ=Mozambique, SWZ=Eswatini, UGA=Uganda, ZWE=Zimbabwe

Such discrepancies are perhaps understandable for some countries with open-ended age intervals limited to age 75 so that any death hump that should occur beyond this age does not appear and only the death hump at young adult ages remains apparent. It can also be understood if one assumes that mortality experiences in many African countries are different from those in low-mortality countries. The former has benefited from the medical advances of the latter, all of which may have contributed to changes in the mortality profile and a modification of the hierarchy of causes of death that the advent of HIV has helped to accentuate. This complex epidemiological picture may have led to a different pattern than that followed by developed countries, most of which have achieved low mortality levels. If one can consider this hypothesis as acceptable, it is difficult to believe the M-levels estimated under it in some cases, weakening the census/survey approach, at least at older ages. As an illustration, census/survey-based estimates indicate levels of M that are sometimes higher than the maximum level of M achieved in low-mortality countries found in HMD. For societies that are just starting to age, it seems rather implausible that they can rival nations that are already in advanced stages of aging and have invested in a better health and social security systems. Therefore, this calls into question the reliability of estimates based directly on census/survey data. When the same census/survey data are modeled, the weaknesses outlined above are also overcome. The model-based estimates of M are lower and look plausible. In terms of M levels, model-based estimates from census/survey data are in good agreement with HDSS estimates. Likewise, they are also consistent with the empirical data from HMD. Furthermore, there is good agreement between model-based estimates and both HMD and HDSS data in terms of the relationship between M and SD(M+). However, the dispersion of deaths beyond M appears to be greater with the latter. This could be explained by the fact that in small populations such as those in HDSS, there is more variability in the ages at death among the oldest. Thus, the model-based approach appears the most promising indirect mortality modelling approach to date in its ability to incorporate the rather unique epidemiological experiences of HIV in many African countries. This does not preclude making some observations to further improve the performance of the model. Although the goodness of fit of the model can be improved by accounting for ART coverage in children and adults as proposed by the authors, additional improvements can be made. Rather than being calibrated with life tables that are themselves model-based, which the authors note as a shortcoming, one could expand the universe of empirical data for the model calibration, or even

calibrate the model exclusively with African data through judicious use of HDSS data. Such a perspective would be consistent with Clark's (2019) idea of the need to diversify the universe of empirical life tables used to calibrate such models. Furthermore, the production of age-specific statistics on HIV deaths should be integrated into UNAIDS efforts in view of the progressive increase in the population of 50+ year-olds living with HIV. Such an approach would help to better capture the overall impact of HIV on the age structure of mortality, including among older people. Addressing these suggestions and making fuller use of the singular value decomposition (SVD) properties (Clark, 2015a) used to design the model could help to further refine the model and produce a better representation of the reality we are trying to capture.

3.4. Levels and trends in M in sub-Saharan Africa

In light of the poor performance of the census/survey-based approach, the analysis of trends in M has been done using model-based estimates and those derived from HDSS data (see Figure 7 below). In general, it can be seen that progress in M over recent decades has remained modest, or even slowed down, or that M has even deteriorated in some contexts. Unlike HDSS and survey data, census estimates are represented by the median year of the corresponding intercensal periods. As such, they do not allow the annual evolution of M to be highlighted in detail. Thus, any deterioration, whether sudden or gradual, followed by an improvement in the health of older adults may not be explicitly highlighted in the trend analysis. Supplementing the analyses with HDSS estimates addresses this under the assumption that any change in older adult mortality affects the entire population, and by extension local populations from HDSS. Or rather that changes in HDSS are a reflection of trends at the national level. In general, there is good agreement between estimates based on censuses and surveys. In cases where HDSS-based estimates are also available, there is also good agreement, at least for sites that have been monitored over a long period (at least 10 years).

Indeed, for sites with relatively short follow-up periods, the conformity of M with the estimates from the censuses/surveys remains variable. Conversely, the longer the period, the more it provides a stable overall mean distribution from which the two-dimensional P-Splines smoothing method derives the annual series of distributions. This could explain the good agreement of the trend in M observed over 18 years in the Nouna HDSS in Burkina Faso with the levels of M observed in the 1985-1996 and 1996-2006 intercensal periods and in the 2006-2008 survey. The same applies to the good consistency between the intercensal estimate of M (2002-2013)

and the annual trends in M deduced from the HDSS of Bandafassi, Mlomp and Niakhar over 32 years in Senegal. It could also be due to higher quality of mortality data at advanced ages as the elderly were not born during the follow-up so their ages had to be reported in the first enumeration when the HDSS started.

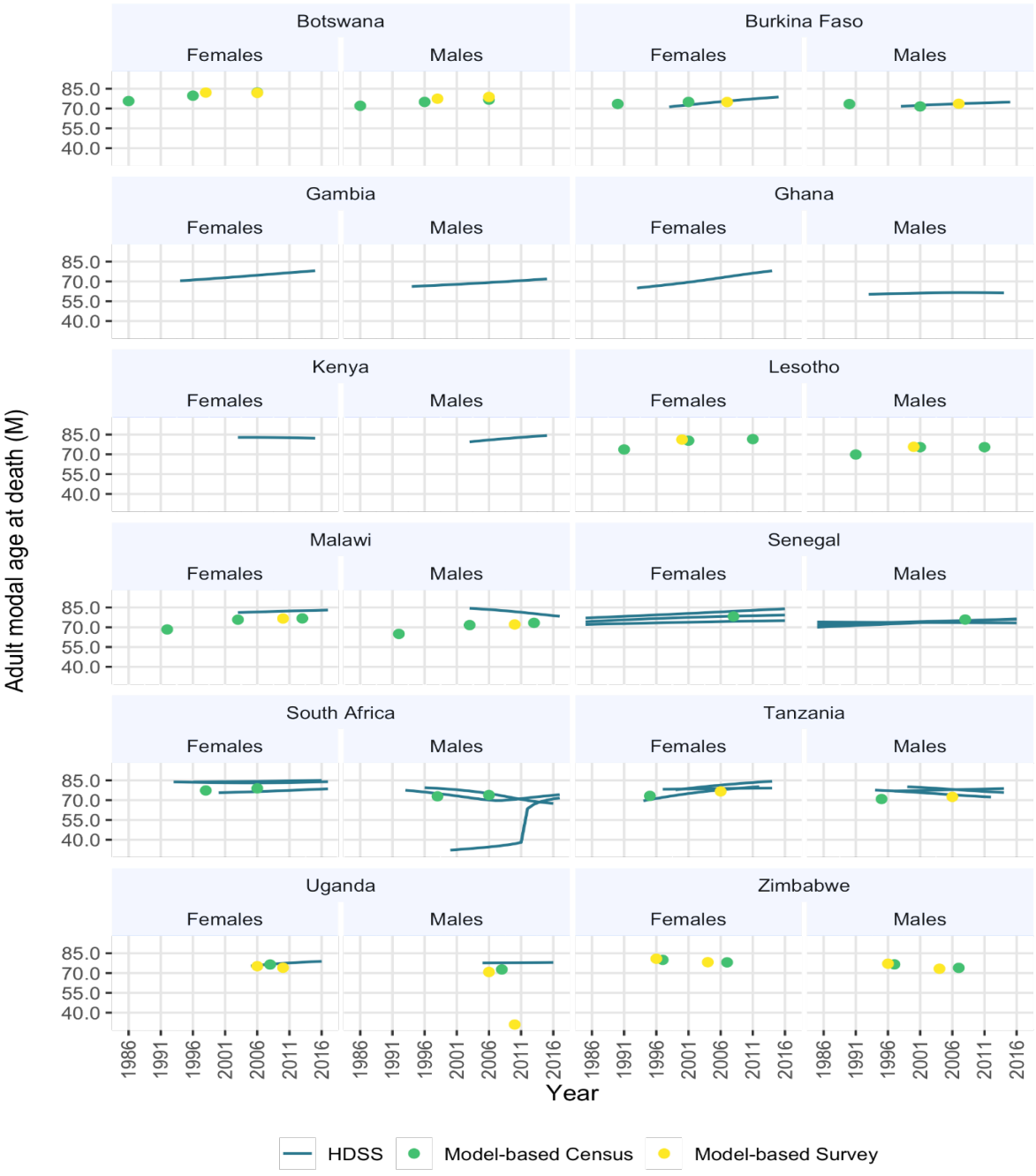

Figure 7 : Levels and trends of M in selected countries derived from census, survey and HDSS data

More generally, progress in M in these low HIV-affected countries has been quite timid, even stagnant among males. Such stagnation is also observed in Ghana with the Navrongo HDSS over a 22-year follow-up period, although with greater progress among females, which unfortunately cannot be confirmed with national estimates from censuses/surveys. In Gambia, similar progress was noted in the Farafenni HDSS but cannot be extrapolated to the national level.

Regarding countries heavily affected by HIV, there is a slowdown in progress and even sharp declines in M that can be seen in the annual changes from HDSS data. Botswana, for example, recorded progress in M from the 1980s to the mid-1990s, followed by a slowdown until the mid-2000s, which could be explained by the worsening of the HIV pandemic in the country. The same is true for Lesotho. In Zimbabwe, there was even a decline of M over almost the entire decade of the 2000s. In the case of South Africa, the deterioration in older adult survival is diluted in the multiyear estimates for the 1996-2001 and 2001-2011 intercensal periods, but is highlighted by HDSS data, especially among males. In an HDSS such as Africa Centre (see Figure 4 above), monitoring began in the early 2000s at a time when HIV had profoundly distorted the age distribution of deaths and favored the disappearance of the hump of deaths at older ages in favor of a single hump of deaths at young adulthood. This natural hump at older ages, which had disappeared, began to gradually reshape as the distribution of deaths was progressively normalizing until 2011, when it reached a maximum, prompting an upturn in M at older ages. About the drop in M at age 31 observed among Ugandan males in the 2010-2011 survey, this was illustrated by the death distribution curves seen earlier in Figure 5.

Overall, the analysis of M trends indicates modest progress in life extension for older adults. This is not surprising for countries which in majority have health systems that focus almost exclusively on reducing child and maternal mortality. Few efforts are made for the health of older adults despite their high vulnerability and the multi-morbidity they may suffer (Fries, 1980, 2000). In addition, the absence of a real social security system to cover their needs and care forces them to fall back on family solidarity systems (Golaz, 2013; Golaz et al., 2017). These also may have eroded over time, especially in contexts of severe HIV where young adults, who could have been helpful in caring for these older people, have been cut down in numbers by the disease. As a result, the roles were sometimes reversed in that it was the older adults who had

to take care of their older infected children (Chepngeno-Langat & Evandrou, 2013; Lee et al., 2021; Small et al., 2019; Tanyi et al., 2018).

4. **Conclusion**

Sub-Saharan Africa has certainly achieved a remarkable decline in child mortality. Among young adults, progress has been more mixed and, in some places, slowed by the onset of HIV, whose impact may have extended to older adults. This manuscript attempts to analyze mortality and longevity of the latter in this region of the world from the perspective of adult modal age at death (M), by looking at the age-specific distribution of deaths. Although census and survey data are limited in highlighting annual trends because of their irregularity and the need for multi-censal combinations (for censuses), the supplementation of the resulting estimates with those deduced from local populations in HDSS makes it possible.

In general, the levels of M that prevail in sub-Saharan Africa were reached by developed countries since the mid-1900s, and give a picture of the gap that separates the countries of this region from developed countries in terms of living conditions and health. Furthermore, the analysis of the distribution curves of deaths by age highlights the extent to which HIV has impacted on them, and distorts the study of the adult modal age of death in many countries in Eastern and Southern Africa. The effects have sometimes been so perverse that the bulge in deaths at young adult ages due to HIV has caused the disappearance of the normal bulge in deaths at older ages, resulting in a drastic drop in M. In such a case, the term adult modal age of death devoted to M is perfectly appropriate. However, there are cases where the death hump at older ages coexists with a more important death hump at younger ages. In this case, conforming to the definition of the mode would lead to choosing the mode at young adult ages even though it would not be relative to older ages. Conversely, choosing the mode relative to older ages while the highest modal value is observed in young adults would not be consistent with the mode definition. Only a definition of the mode as the age of the last hump would bring these two definitions together. And even then, if the single death hump occurs at young adult ages, again, M would not be related to older ages. From the above, M, whether it occurs late or exceptionally early, remains an indicator of longevity in the sense that it gives an indication of the most common length of life among adults. However, it is not always an indicator of mortality

at older ages, especially in cases of high-HIV exposure, as has been the case in many sub-Saharan African countries. It could also be the case in the event of a disease or other mortality crisis with a similar impact. In addition, many AIDS survivors are increasingly turning 50 and older, where they have to face an additional disease burden specific to older ages (Fries, 1980, 2000). With the emergence of new infectious diseases such as Covid-19, to which older adults are particularly vulnerable, attention should be paid to their frailty as consequence of cumulative decline in many physiological systems during a lifetime (Clegg et al., 2013; Fulop et al., 2010). Hence, these findings serve as a reminder of the need for more protective systems for an already fragile population.

General conclusion

Findings

Estimating mortality beyond age 50 in sub-Saharan Africa remains a very complex task. Through this doctoral research, I explored diverse estimation approaches by triangulating on the one hand African retrospective data from census and large-scale surveys in which information on deaths by age and sex was collected with, on the other hand, prospective data from HDSS. African retrospective data are generally affected by various age errors that need to be well understood before deriving any estimates. These include omissions of deaths (e.g. due to poor recall, deliberate attempts by interviewers to shorten interviews…), age heaping (i.e. an excess number of deaths at ages ending in -0 or -5), age exaggeration, and sample selection bias due to dissolution of households after a death.

Regarding my first set of research questions, one can say that estimating mortality in older adults in this region still requires extensive modelling. In census data for example, correcting for the relative coverage of one census to the other and adjusting for the expected incompleteness of intercensal deaths are not enough to clean the data from systematic errors that generally lead to an underestimation of mortality, particularly at very advanced ages. This was illustrated when using the parametric Makeham model to extrapolate mortality beyond age 70 in the case study of Burkina Faso. The Brass relational modelling also seems to be very dependent on the standard age pattern of mortality it uses. Only SVD-based models (Clark 2019) yield credible results at older ages. By providing prior information that credibly reflects observed mortality levels for children and young adults, such models make it possible to predict *a posteriori* mortality in the 50-79 age range that adjusts generally for the downward bias. Although consistent with the empirical data from low-mortality countries gathered in the Human Mortality Database (HMD), estimates predicted from the SVD model are suspected to overestimate mortality in older adults in low-HIV contexts.

My second set of research questions was related to the levels of older adult mortality that are prevailing in sub-Saharan African countries and whether estimates from national retrospective data are consistent with prospective data from HDSS. By extending the analyses to multiple countries, including high-HIV countries, and adding prospective data from HDSS, model-based estimates that account for the excess deaths resulting from HIV prevalence results in relatively

lower mortality in ages 50-79 than would have been expected from empirical data such as those from HMD, especially for countries heavily affected by HIV. In addition, the relationship between young adult mortality and older adult mortality is not curvilinear in high-HIV countries as was in HMD countries. But overall, our model-based estimates are more consistent with HDSS estimates. This suggests that African countries, mainly those severely disrupted by HIV do not follow the same pattern as most developed countries. Thereafter, despite their apparent reliability compared to other estimates, model-based estimates should be taken with caution. The new configuration of HIV, notably its transposition to older adults due to the greater access of infected people to antiretroviral therapy, calls for a rethinking of these models to account for recent trends so as to realistically reflect mortality in general and more specifically that of older adults.

The third set of research questions calls to explore the age distribution of adult deaths and to estimate the adult modal age at death (M) in African data. For these analyses, errors in data and the fact that some of them are limited to age 75 did not allow for a proper estimation of M. In contrast, it appears possible to estimate M from life tables predicted from model-based estimates. Such estimates of M are consistent across different data sources in terms of both levels and trends, with sex differences in favour of females as expected. The effects have sometimes been so perverse that the bulge in deaths at young adult ages due to HIV has caused the disappearance of the normal bulge in deaths at older ages, resulting in a drastic drop in M. Moreover, the levels of M that prevail in sub-Saharan Africa were reached by most developed countries since the mid-1900s, and give a picture of the gap that separates the countries of this region from developed countries in terms of living conditions and health. Notwithstanding this, the shifting mortality and compression hypothesis observed in developed countries hold in the sub-Saharan context with the negative relation between the level of M and its above standard deviation SD(M+). Moreover, the resurgence of mortality due to HIV over the 1990s to mid-2000s has also affected older adults, in addition to young adults. However, it cannot be considered an indicator of mortality at older ages, especially in certain sub-Saharan contexts, such as those where HIV has had devastating impact.

Contributions

This dissertation highlighted some issues when using recent household deaths from periodic population surveys and censuses to estimate older adult mortality in sub-Saharan Africa. In addition, it shed light on method-related issues when relying on models indexed by child and adult mortality to infer mortality at older ages from imperfect data. Such models, even if they produce estimates that appear the most plausible, still lack confidence intervals. This thesis also suggests that older adult mortality is not as high as would have been expected from mortality patterns from developed countries. Furthermore, it confirms that African countries, mainly those heavily affected by HIV follow a different mortality pattern compared to developed countries, hence calling for -1) a more careful and comprehensive use of HDSS data to increase the diversity of available empirical life tables and the need to -2) account for African mortality experience in building model life tables. In addition, this manuscript is the first attempt in analyzing the adult modal age at death in several African countries.

Limitations and perspectives

Limitations include data and methodological shortcomings. In censuses, the only modules that can be used to estimate older adult mortality are those referring to deaths in the last twelve months, but these are marred by various types of errors that need to be addressed. As for surveys, notably the Demographic and Health Surveys (DHS), whose multiplicity and regularity make them a primary source of mortality estimates, they remain rather limited to children and young adults. Only a few of them have begun to collect information on age-specific deaths in households. Regarding the potential of parental survival information collected in some of these sources, they are also subject to many biases (such as the orphanhood effect), are related to the estimation of past mortality (when estimated indirectly). Unless additional information is collected in the future to better refine these data, they can only produce aggregate estimates of mortality between ages 25-74, without being able to extract only mortality beyond the age of 50.

As for the methods, they depend heavily on the type of data available and the assumptions underlying them can sometimes be unrealistic. The better the quality of the data, the more the estimation methods are free of strong assumptions, and the less suspect the estimates are. Even if effective policies to expand vital registration systems were implemented, they will help to control errors, including those that appear to be systematic, in new generations. Among

adults, and especially older ones, the impact will be less and will only increase over time unless ways are found to improve age reporting. Models will therefore still be needed for estimating mortality in older adults. Therefore, efforts should be made to stimulate methodological innovations for improving data quality in the available data sources. Furthermore, very few data are available for estimating cause-specific mortality in sub-Saharan Africa, including especially in older adults. The only available information comes from local population surveillance system sites (HDSS) and a large share of deaths of the elderly remains of ill-defined causes (Duthé et al. 2010). Pending also the establishment of death certification systems, future research should consider the use of verbal autopsy methods, already widely used in HDSS, on national samples of recent annual deaths to generate reliable cause-of-death statistics and help better formulate health policies.

From the above, over the coming years, researcher could expand their research on older age mortality in three directions. The first will be to verify the ages of older adults in sub-Saharan Africa using multiple methods. Indeed, in high-income countries, where centenarians are increasingly recorded, techniques for verifying the ages of older adults rely on record linkages with historical birth registration records, including parish registers, or early census data (Bruzzone et al., 2010; Jeune & Skytthe, 2001; Poulain et al., 1999). In sub-Saharan African countries, such reference data sources exist in a few areas where the colonisers primarily settled (Siiskonen et al., 2005), and missions were established. However, these records barely survived the end of the colonial era. Only a few parish registers still exist at local levels in Ghana, Namibia, Uganda or Malawi. Other methods of age verification include 1) comparing the age reported by the individual, to an alternative measure of age approximated based on a life history calendar (e.g., including his/her marriage, first child, migration), or 2) obtaining an independent measure of age for older adults using computer vision algorithms as was done for women of childbearing age (i.e., extracting age-related images from photographs of the face, then estimating age using machine learning) (Helleringer et al., 2019). The resulting outcomes could then be used to improve demographic data collection in LMICs, and/or to adjust or correct age-dependent estimates from population surveys and censuses.

The second direction could consist in developing a new life table system for modelling mortality experiences in sub-Saharan Africa. For instance, none of the existing model life tables are tailored to the social and epidemiological conditions that recently prevail in LMICs (Clark, 2019;

Murray et al., 2000). For example, none of them include data from countries with high HIV prevalence (Sharrow et al., 2014). Moreover, the spread of antiretroviral treatment is extending the lives of persons infected with HIV, thereby shifting the increased risk of death from young adulthood to older ages. It leads to an increasing proportion of HIV+ in adults aged 50 or older (Hontelez et al., 2011; Luther & Wilkin, 2007; Negin et al., 2012; Negin & Cumming, 2010; Simone & Appelbaum, 2008; Wallrauch et al., 2010). These limitations related to existing model life tables call for urgently enlarging the diversity of data sources for model life tables, and in particular for compiling much better mortality data for Africa and other LMICs. Previous attempts to do so were based on only seventeen HDSS sites in Africa and were restricted to the five-year period 1995-1999 (INDEPTH Network, 2004). Since then, however, many more HDSS have been initiated in the region and the duration of population monitoring has been greatly extended, thus allowing for longer data series. Taking advantage of recent methodological developments, notably the use of singular value decomposition and the potential of Bayesian estimation methods (van Raalte, 2021), it would be possible to develop a new system of model life tables better suited to reflect the age profiles of mortality in sub-Saharan African countries. This new tool could serve as a reference for evaluating, correcting, and smoothing mortality data from general population surveys based on plausible hypotheses close to the reality of the context. Furthermore, a series of plausible age-specific mortality profiles over time should provide information on possible major epidemiological transformations underway in the population, just as it allows the impact of targeted interventions to be assessed.

As a third direction, one could seek exploring cause-specific mortality in sub-Saharan Africa with a particular focus on older adults. Sub-Saharan Africa has experienced a substantial decline in child mortality since the 1950s, and subsequently among young adults. As a result, the health profile of the population is changing and deaths are shifting to older ages, in accordance with the epidemiological transition theory (Omran, 1971, 2005). Age-related physiological alterations increase the frequency of degenerative diseases and favour the occurrence of non-communicable diseases (Fries, 1980, 2000). Old ages are associated with specific conditions that are more complex to treat, especially multimorbidity, highly prevalent in the global South (Banerjee et al., 2020).

One additional direction of research could be to explore mortality inequalities through indicators of lifespan disparity. Various recent works address this issue, but mainly in low-mortality

countries (Aburto & van Raalte, 2018; Bohk-Ewald et al., 2017; Kibele, 2012; van Raalte, 2011; van Raalte et al., 2012; Vaupel et al., 2011). It is entirely possible to extend these studies to high-mortality settings such as those in sub-Saharan Africa. The COVID-19 pandemic, whose case fatality rate sharply increases with age, also threatens to cause important excess mortality among older adults (Helleringer & Queiroz, 2021). In the absence of reliable statistics on causes of death, health policies and epidemiological interventions are drawn up without a clear view of the hierarchy of causes of death across the life course. The only existing statistics are those published by the World Health Organisation (WHO) and the Institute for Health Metrics and Evaluation (IHME). They are based on complex statistical models and extrapolations, rather than empirical data. Apart from these statistics, few sources produce such data. For some specific areas, mostly cities, CRVS provide series of deaths by cause, as in Antananarivo, the capital city of Madagascar (Masquelier, Waltisperger, et al., 2014). In HDSS, verbal autopsies are used to compensate for the lack of a medical certification system of causes of death. The verbal autopsy method produces cause-of-death statistics based on information related to the history of the disease, the symptoms occurred before death and collected from caregivers and relatives of the deceased (Chandramohan et al., 1994; Murray et al., 2014; Soleman et al., 2006). For future research, one can explore the possibility of nesting verbal autopsies within upcoming national surveys such as the DHS or MICS, or even large-scale sample of recent deaths reported in censuses (de Savigny et al., 2017; Hazard et al., 2020; Liu et al., 2016). This would allow obtaining representative estimates of the distribution of causes of deaths at the national and sub-national levels. In the context of the Covid-19 pandemic, one can estimate the direct and indirect effects of the COVID-19 pandemic on the health of older adults. In addition, a verbal autopsy study could also be accompanied by serology tests conducted with household survivors to help discern the causal effects of the pandemic on population health. Moreover, one can use HDSS data series to explore how the COVID-19 pandemic has affected the distribution of causes of death in local populations. Indeed, the Sustainable Development Goals (SDGs) include the reduction of premature mortality, i.e. deaths under the age of 70. Yet, for the sub-Saharan region, it is difficult to accurately describe mortality in young adulthood, even less so after age 50 and much less so after age 60. There is a total lag with studies conducted in northern countries on longevity, the limits of human lifespan and centenarians. This is probably due to the lack of progress in improving basic vital statistics, which has remained on the fringes of the priorities. Meanwhile, the covid-19 crisis has served as a reminder that this is a permanent and

crucial need, an imperative public health tool for obtaining data on the entire population at all ages, including data on deaths while accounting for certain socio-demographic characteristics. If the situation remains unchanged, the much hoped-for data revolution may remain a mere slogan in many countries of the region.

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