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Health and Aging in Low-Resource Contexts: Three Essays on Healthy Life Expectancy in the Developing World

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Abstract
The population of the world is getting older. In 2010, worldwide, there were about 524 million people over the age of 65; by 2050, over 1.5 billion people will be in this age group. This shift in population will not affect only developed countries, however—much of this increase in the elderly population will occur in low- and middle-income countries. As populations age, low-income countries will need to invest in health care for older adults and in disease prevention programs to prevent or delay the onset of non-communicable diseases (such as heart disease, stroke, and cancer). Past research on population-level health in the developing world has been widely hindered by a lack of high-quality longitudinal data. My dissertation uses recently-collected longitudinal data to gain insight into overall trends in health in low- and middle-income contexts. My first chapter uses a multi-state life table approach to investigate the overall level of health and functional ability (the ability to carry out tasks of daily life) among the rural population in Malawi. I find that this population experiences a substantial burden of disability in later life, and that these high levels of disability greatly limit work efforts among older individuals. In my second chapter, I conduct a cross-national comparison of health and disability-free life expectancy using data from recent longitudinal surveys in Costa Rica, Mexico, Puerto Rico, and the US. I find that current disability-free life expectancy at age 65 is comparable across these populations, though future trends are uncertain. My third chapter investigates how Malawi's 2008 rollout of Anti-Retroviral Therapy (ART) to rural clinics affected overall population health and mortality. I find that the introduction of ART led to substantial declines in mortality and an increase in adult life expectancy, and that population morbidity also decreased after the introduction of ART.

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HEALTH AND AGING IN LOW-RESOURCE CONTEXTS:

THREE ESSAYS ON HEALTHY LIFE EXPECTANCY IN THE DEVELOPING WORLD

Collin Frederick Payne

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HEALTH AND AGING IN LOW-RESOURCE CONTEXTS: THREE ESSAYS ON HEALTHY LIFE EXPECTANCY IN THE DEVELOPING WORLD

DEDICATION

To Rachel, for everything.

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Thanks to my committee, the support staff in the Graduate Group in Demography, my cohort-mates, my Philly family, and my parents, sister, and lovely wife for all their help through the writing process. This work was in large part made possible by much needed sustenance from Prima Pizza, Cosmi's, Nomad, The Good King, and Royal Tavern.

ABSTRACT

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The population of the world is getting older. In 2010, worldwide, there were about 524 million people over the age of 65; by 2050, over 1.5 billion people will be in this age group. This shift in population will not affect only developed countries, however—much of this increase in the elderly population will occur in low- and middle-income countries. As populations age, low-income countries will need to invest in health care for older adults and in disease prevention programs to prevent or delay the onset of non-communicable diseases (such as heart disease, stroke, and cancer). Past research on population-level health in the developing world has been widely hindered by a lack of high-quality longitudinal data. My dissertation uses recently-collected longitudinal data to gain insight into overall trends in health in low- and middle-income contexts. My first chapter uses a multi-state life table approach to investigate the overall level of health and functional ability (the ability to carry out tasks of daily life) among the rural population in Malawi. I find that this population experiences a substantial burden of disability in later life, and that these high levels of disability greatly limit work efforts among older individuals. In my second chapter, I conduct a cross-national comparison of health and disability-free life expectancy using data from recent longitudinal surveys in Costa Rica, Mexico, Puerto Rico, and the US. I find that current disability-free life expectancy at age 65 is comparable across these populations, though future trends are uncertain. My third chapter investigates how Malawi's 2008 rollout of Anti-Retroviral Therapy (ART) to rural clinics affected overall population health and mortality. I find that the introduction of ART led to substantial declines in mortality and an increase in adult life expectancy, and that population morbidity also decreased after the introduction of ART.

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Disability Transitions and Health Expectancies among Adults 45 Years and Older in Malawi: A Cohort Modeling Approach

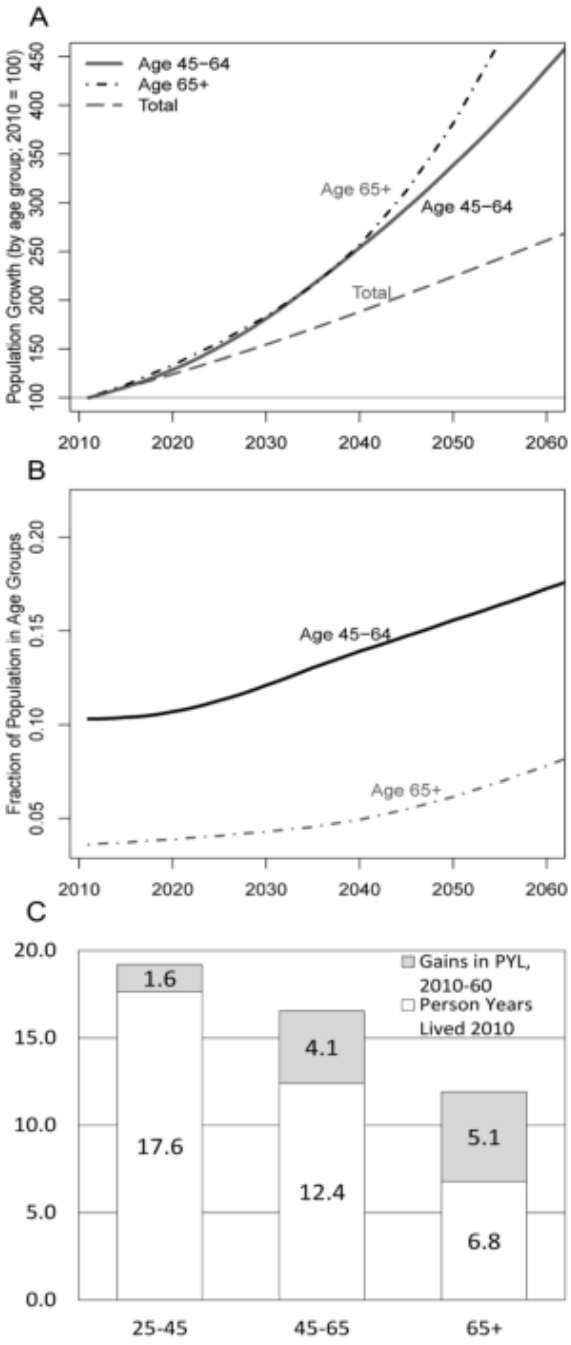
Collin F. Payne James Mkandawire Hans-Peter Kohler

1. INTRODUCTION

While rapid population growth continues to be a major social and policy issue in sub-Saharan Africa (SSA) (Cleland, Bernstein, Ezeh, Faundes, & Innis, 2006; H. Kohler, 2013), demographic and epidemiological trends of falling fertility and increasing life expectancy foreshadow the coming challenge of a growing elderly population in SSA. Due to high levels of morbidity, low levels of economic development, and widespread poverty, aging in SSA will likely be associated with a unique set of demographic and economic challenges (Heuveline, 2004; Zaba, Whiteside, & Boerma, 2004). The age group of ***mature adults*** (defined here as adults aged 45+) in this context deserves particular attention (Figure 1). The population of mature adults aged 45+ will grow more rapidly in the next decades than that of any younger 10-year age group in many SSA low income countries (LICs). By 2060, persons aged 45+ will be 25% of SSA's population (UN Population Division, 2010), up from 10% in 2010, and the 65+ population alone is expected to represent more than 5% of the SSA population after 2040 (Figure 1b). Over the next 50 years in SSA LICs such as Malawi, 80% of the additional persons-years lived among adults aged 25+ as a result of increasing life expectancies will occur among individuals aged 45+ (Figure 1c): 4.1 additional years, or 38% of the overall adult life expectancy gain, will occur among individuals aged 45–64, and 5.1 years, or 47% of the adult life expectancy gain, will occur among individuals aged 65+. HIV prevalence among mature adults is currently still relatively low (Freeman & Anglewicz, 2012), but is expected in increase as younger cohorts with higher prevalence age and benefit from higher life expectancy as a result of antiretroviral treatment (Hontelez et al., 2011).

Intertwined with this demographic transformation of SSA is the epidemiological transition, in which the primary causes of morbidity and mortality increasingly shift from communicable

Figure 1: Population growth by age group in SSA 2010–2060 (2010 = 100), share of total population by age groups, and person years lived by age group.



Panel (A) displays the projected population growth by age group in SSA, 2010-2060 (2010 = 100). Panel (B) displays the share of the total SSA population by age group. Panel (C) displays person-years lived by age group. Source: Authors' calculations based on UN population projections [5]

to non-communicable diseases. During 1990–2010, the disease burden attributable to childhood communicable diseases decreased in central, eastern, and western sub-Saharan Africa, both as a proportion of total disease burden and in their rank order, while risk factors for some non-communicable diseases and injury accounted for a larger disease burden in 2010 (Lim et al., 2012). SSA regions currently have among the globally highest levels of years-lived-with-disability (YLDs) for men and women after age 45 (Vos et al., 2012), with combined levels for SSA females 54% higher than Europe (16% for males) and 21% higher than Asia (16% for males). By 2030, chronic non-communicable diseases are estimated to cause 47% of deaths in Africa, compared with about 27% in 2008, while mortality from communicable diseases is predicted decline from 53% to 30% (WHO, 2005). Scholars and policy makers are only beginning to recognize the health and social policy challenges of this population aging in SSA LICs (Abegunde, Mathers, Adam, Ortegon, & Strong, 2007; Aboderin, 2010; Cohen & Menken, 2006; Dalal et al., 2011; Ebrahim, Pearce, Smeeth, & Casas, Jaffar, et al., 2013; Holmes et al., 2010; Hontelez et al., 2011; Institute of Medicine, 2011; Levitt, Steyn, Dave, & Bradshaw, 2011; Maher & Sekajugo, 2011; Mills, Rammohan, & Awofeso, 2011; Mills, Barnighausen, & Negin, 2012; Msyamboza et al., 2011; Negin, Mills, Barnighausen, & Lundgren, 2012; Scholten et al., 2011), particularly in contexts that have been substantially effected by the HIV/AIDS epidemic.

SSA LICs are characterized by high to very high rates of economic activity across all adult age groups (ILO, 2011). In Malawi, labor force participation is virtually universal even among for mature adults (98% for age 50–64, 90% for age 65+ based on the 2009 Malawi Welfare Monitoring Survey (WMS) (Malawi National Statistical Office, 2010). If low levels of disability among mature adults (age 45+) can be ensured, this population can contribute significantly to aggregate economic growth and individual/family well-being during the next decades. Contributions from mature adults are critical, as, in the in the absence of widespread institutionalized social security and health insurance programs, they can be providers of

intergenerational and intragenerational economic transfers which potentially ameliorate the consequences of the HIV epidemic and other social/economic crises for family members (I. V. Kohler, Kohler, Anglewicz, & Behrman, 2012; Lee & Mason, 2011; Merli & Palloni, 2006; Zagheni, 2011; Zimmer, 2009). Evidence suggests that chronic and disabling conditions among the mature adult population, resulting from the cumulative effects of poor nutrition and frequent exposure to infectious disease, lead to significant levels of functional limitations in day-to-day activities and a substantial gap between potential and actual economic productivity (Abegunde et al., 2007; FAO and BSF, 2008; Kandzandira, 2007; Msyamboza et al., 2011; Scholten et al., 2011).

Despite its importance for understanding the consequences of population aging and developing adequate policy responses, the evidence about the prevalence of disabilities, the level of functional limitations due to poor physical health, and pattern of health trajectories among older adults in SSA continues to be very limited. For example, while national health sector strategic plans in Malawi and other SSA countries highlight the need for policies to prevent disabilities and ensure access to curative and rehabilitative care among older individuals (Malawi Ministry of Health, 2005; Malawi Ministry of Health, 2011; African Union, 2007), there is a dearth of understanding among national and international decision-makers about the magnitude of the aging problem in SSA, the scope of old age-related health needs, and the trajectories of health and disability at mature and old ages (Aboderin, 2010; Ebrahim et al., 2013; Maharaj, 2013). Evidence from more developed contexts is generally not sufficient for understanding these emerging health issues and health-care-needs among the growing aging population in SSA as interactions among infectious/non-infectious diseases and/or exposure to malnutrition and poverty can result in distinct patterns of and risk factors for poor health and disabilities among mature adults (Ebrahim et al., 2013; I. V. Kohler, Soldo, Anglewicz, Chilima, & Kohler, forthcoming).

Our analyses seek to fill some of these gaps in existing knowledge by investigating how the

physical health of rural Malawians results in functional limitations, that is, by studying how physical health limits the day-to-day activities of individuals in domains relevant to this subsistence-agriculture context. We estimate age-patterns of functional limitations and the transitions over time between different disability states, and calculate health expectancies. To our knowledge, our estimates are the first micro-data-based health expectancies calculated in SSA. Together, these measures characterize processes of health, aging, and functional limitations and associated disabilities in a rapidly-growing but understudied portion of the SSA population, and can provide important insights into the potential gains in well-being and economic productivity arising from investments in the health of and health-care for mature and older adults in SSA.

2. METHODS

2.1. Context

Malawi is an opportune environment for studying epidemiologic and demographic transitions and their implications for the health and well-being of mature adults in SSA. It is one of the poorest countries in the world, ranked 153 of 169 in terms of the human development index (UNDP, 2010b), with about 15% of its population considered “ultra-poor”, i.e., with an estimated food consumption below the minimum level of dietary energy requirement (UNDP, 2010a). Life expectancy at birth is estimated to be 51 for men and 55 for women in 2010, and healthy life expectancy at birth is estimated at 44 years for males and 46 years for females (Salomon et al., 2012). While the Malawian per capita income is below the sub-Saharan average, Malawi is similar to other SSA countries and countries in the World Bank LIC group in terms of life expectancy, infant mortality, child malnutrition, access to clean water, literacy and educational enrollment (World Bank, 2011; WHO, 2010). In rural areas, where our study population is based, the majority of individuals engage in home production of crops, primarily maize, squash, tomatoes, potatoes, nuts, dark green leafy vegetables, and fruit, complemented by some market activities. While tuberculosis, malaria, and endemic

parasites (e.g., soil-transmitted helminths (STH) and schistosomia mansoni) have a relatively high prevalence (Chitsulo, Engels, Montresor, & Savioli, 2000; Guebbels & Bowie, 2006), chronic diseases such as hypertension and diabetes and disease risk factors such as tobacco use and alcohol consumption also effect a substantial proportion of mature and older adults in rural areas (Msyamboza et al., 2011). Moreover, while HIV/AIDS is widespread, the vast majority of the population—more than 85% of adults aged 15–49, and an even higher fraction among adults aged 50 and over—is HIV negative (DHS, 2011; Freeman & Anglewicz, 2012). Yet, HIV-negative individuals also confront a high disease-risk environment characterized by high levels of poverty, episodic malnutrition, poor sanitation, a high prevalence of infectious diseases and endemic parasites, and limited access to health care facilities. The cumulative load of these pressures may have substantial consequences for health, well-being and functional limitations that persist throughout the remaining life-course (Strauss & Thomas, 2007).

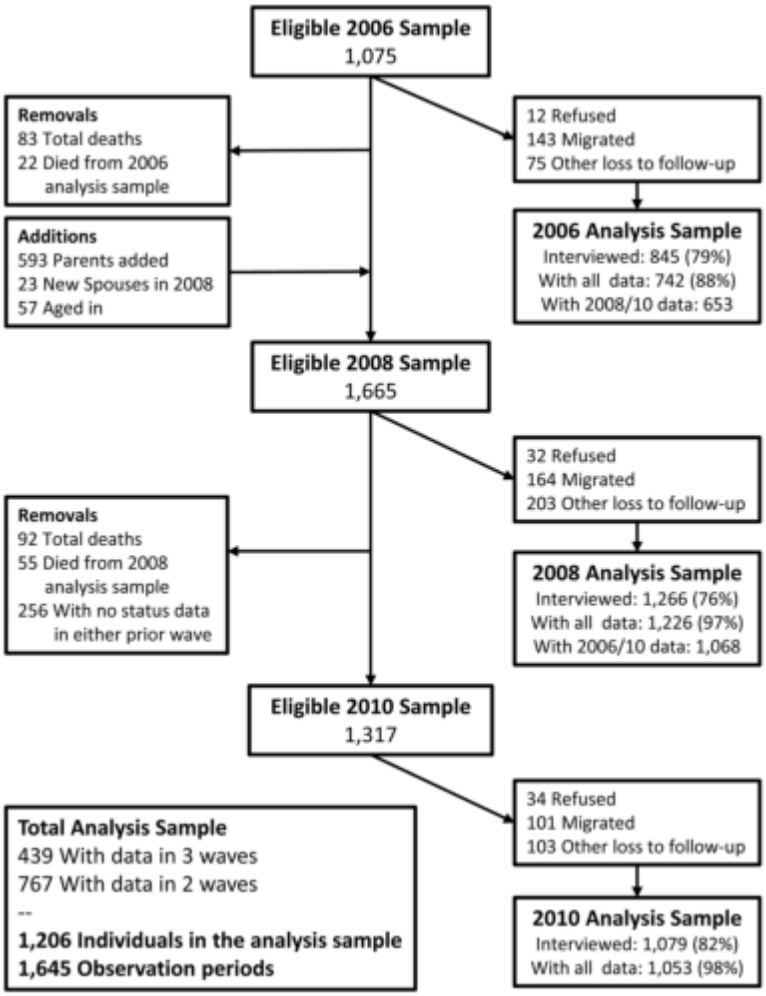
2.2. Data

The Malawi Longitudinal Survey of Families and Health (MLSFH) is a longitudinal study of the rural population in Malawi that monitors the social, economic and health conditions in one of the world's poorest nations. The study is based in three districts in rural Malawi: Rumphi in the North, Mchinji in the Center, and Balaka in the South (Figure S1). While these rural regions are similar in terms of their overall epidemiological, socioeconomic and subsistence-agriculture characterization (Guebbels & Bowie, 2006; Malawi NSO, 2002), the regions reflect some heterogeneity in terms of marriage patterns (Reniers, 2003), religious affiliations (Trinitapoli & Regnerus, 2006) [50], schooling (Grant, 2008), patrilineal vs. matrilineal inheritance and land-ownership (Kerr, 2005)[52], and HIV prevalence (DHS, 2011; Obare et al., 2009). MLSFH Respondents ($N_{2010} \approx 3,800$) are evenly split among the three study locations and clustered in 121 villages. MLSFH rounds were collected in 1998, 2001, 2004,

2006, 2008 and 2010. In 2008, the MLSFH added a sample of about 550 parents of original MLSFH respondents, substantially increasing the population of mature adults (aged 45+) in the study. The MLSFH sampling methods and related relevant data collection procedures are described in Text S1. Over 40% of the 2010 MLSFH study population is currently aged 45 years and older, and 12% is 65 years and older. The prevalence of HIV is estimated at 11% among 15–49 year-old individuals in Malawi (UNAIDS, 2010), and it has been shown to decline strongly with age at older ages (Freeman & Anglewicz, 2012). For example, HIV testing among mature adults (individuals aged 45+) in the 2008 MLSFH found an overall HIV prevalence of 3.3%. Most HIV+ mature adults were aged below age 55 (80.5%), and there were only two HIV-positive individuals over age 65 in the 2008 MLSFH. Though there may be important differences in disability trajectories among HIV+ and HIV– individuals, given the low HIV prevalence among mature adults our analysis do not differentiate by HIV status. This pooling of HIV+ and HIV– individuals in our study is substantively justified as the HIV prevalence among mature adult is low and HIV/AIDS is only one of the many diseases affecting the mature adult population in contexts such as Malawi (Aboderin, 2010; Lim et al., 2012; Maharaj, 2013; Vos et al., 2012).

Data for the current analyses come from MLSFH Waves collected in 2006, 2008, and 2010 that contain the longitudinal health data required for our analyses. Functional limitations and the resulting disability states of individuals are determined based on a set of questions on self-reported health and disabilities based on a locally-suitable version of the SF-12 health survey (Ware, Kosinksi, & Keller, 1996), a survey instrument for measuring self-reported health that has been validated in SSA and globally. Non-response primarily resulted from respondents moving to another area or being temporarily absent, fewer than 3% of respondents refused to be interviewed at each wave. Because of our focus on transitions in disability status among mature adults over time, our analysis sample is restricted to individuals who were at least 45 years old and who participated in at least two MLSFH

Figure 2: MLSFH Sample Flow 2006-2010.



rounds (or were interviewed once but died between MLSFH rounds). Figure 2 describes the detailed sample flow over the three MLSFH waves in our analysis, and Table S1 provides basic descriptive statistics for the study population used in our analyses. Mortality between waves was ascertained by the survey team when respondents could not be found for follow-up interviews during the MLSFH. Since exact dates of both deaths and transitions between ability statuses are not available, events are assumed to occur at the midpoint between survey waves. Individuals with missing information on demographic characteristics or self-reported limitation status were removed from the analysis sample. To our best knowledge,

the MLSFH is the only dataset from a SSA LIC context that provide longitudinal health data sufficient to allow for the analyses conducted in this paper. Comparison between the 2004 Malawi DHS and the 2004 MLSFH sample showed that the MLSFH was broadly representative of the overall rural population in Malawi (Anglewicz, Adams, Obare, Kohler, & Watkins, 2009), and was similar in many socioeconomic and health conditions to other LICs in SSA (World Bank, 2011). Comparisons of our 2010 MLSFH mature adult analysis sample characteristics to the age 45+ rural sample of the nationally-representative 2010–11 Third Malawi Integrated Household Survey (IHS3) (IHS, 2012) also show that basic demographic and socioeconomic characteristics between our MLSFH study population and the IHS3 are overall quite similar (Table S1). Individuals aged 65 and over in the MLSFH were somewhat more likely to have ever attended school that those in the IHS3, and differences arise in the distribution of religion, where Muslims are overrepresented in the MLSFH due to the fact that about 1/3rd of the MLSFH study population is from the primarily Muslim region of Balaka.

The focus of the analyses in this paper is on the lived experience with disability. We therefore investigate how physical health results in functional limitations, that is, how disabilities due to poor health result in limitations on day-to-day activities of individuals in domains that are essential in this subsistence-agriculture context. Individuals are categorized in three different levels of functional limitations (disability states) at each MLSFH wave based on two questions from the SF-12 module about specific limitations resulting from poor physical health (with response categories being “limited a lot”, “limited a little”, or “not limited”): the first question focuses on limitations in cooking and cleaning, walking to meetings in the village, or tending to cattle and livestock; the second question focuses on limitations in carrying heavy loads, working on the farm, pounding maize, or digging a pit latrine. While both groups of activities can be limited as a result of poor physical health, and the above measures are thus correlated (Spearman rank correlation = .56), the physical demands of these activities are not identical. The first set focuses on activities that require an

ability to sustain a moderate amount of physical effort for a longer period of time, while the second set of activities requires a larger ability to exert physical strength. We construct a three-level parameterization of functional limitations in daily living activities, which we also refer to as disability state: respondents who indicated that they had no limitations in either set of activities are classified as healthy, respondents who answered “somewhat limited” on either question are classified as moderately limited, and respondents who answered “limited a lot” on either question are classified as severely limited. In addition, 29 individuals who were assessed by interviewers as being too ill or weak to respond to the MLSFH questionnaire were coded as severely limited. As a robustness check, we test two alternate parameterizations of disability states in supporting information: (*a*) a simpler two-level measure of functional limitation (healthy vs limited) instead of the three-level characterization of disability described above, and (*b*) a disability measure based on extent to which pain causes functional limitations during daily work activities.

2.3. Analysis

A major advantage of the multi-state life table (MSLT) approach used in this paper is that it allows a translation from the health transition probabilities estimated from longitudinal data to several important life-course measures of health. Our estimation methods are based on an adapted version of the Stochastic Population Analysis for Complex Events (SPACE) program (Cai et al., 2010). Specifically, to calculate MSLT functions such as health expectancies (HE), we rely on microsimulation, a well-established tool in demographic research (Brown et al., 2012; Cai & Lubitz, 2007; Wachter, Knodel, & Vanlandingham, 2002; D. A. Wolf, 1986; D. A. Wolf, Laditka, & Laditka, 2002; Zagheni, 2011). Initially, we create synthetic cohorts of 100,000 45-, 55-, 65-, and 75-year-old individuals with the same initial gender and functional limitation distributions as our study population (Supplemental Material Table S4). We then “age” these individuals forward year-by-year using age-and gender-specific mortality rates and probabilities of transitioning in and out of disability that are estimated from the MLSFH.

This process is then repeated at each age until death. The process is essentially the microsimulation equivalent of projecting the initial synthetic cohort population **P**, disaggregated by age, sex and health status, using $\mathbf{P}_t = \mathbf{Q} \cdot \mathbf{P}_t$, where **Q** is a projection matrix **Q** containing all age-and gender-specific health transitions rates and mortality rates (Schoen, 1988). After this process has played out for all individuals, the resulting synthetic cohort is analyzed to estimate HEs and other life-course health indicators. Point estimates shown are from transition probabilities and HE's estimated from the full sample. In the microsimulation approach health expectancy estimates are not a deterministic function of the transition rates, and instead result from a complex interplay between disability status, gender, and age as individuals move year-by-year through the simulation. Thus, the confidence intervals from our transition rate calculations are not directly applicable to our health expectancy estimates. Confidence intervals (CIs) for HEs, which reflect both the uncertainty of the estimated parameters and the uncertainty from the microsimulation, were created by re-estimating the above analysis sequence (estimating state-dependent transition probabilities, and applying them to a representative 100,000 person cohort using microsimulation) using 499 bootstrap re-samples of the original dataset, and incorporating stratification by village to account for complex sample design (Rao & Wu, 1988). To obtain our final 95% CIs, we took the central 95% of the distribution of these bootstrapped parameters.

We estimate the conditional probabilities of experiencing a health transition between the four disability states (healthy, moderately limited, severely limited and deceased) as function of age and gender, using a logistic discrete-time hazard model of the form

$$Log\left(\frac{p_{ij}(age,t)}{p_{ii}(age,t)}\right) = \beta_{0ij} + \beta_{1ij} \times age_t + \beta_{2ij} \times age_t^2 + \beta_{3ij} \times male$$

where $p_{ij}(age, t)$ is the transition probability from current health state i (with i = healthy, moderately limited, severely limited, deceased) to health state j (with i = healthy, moderately limited, severely limited, deceased) over the interval from time $t - 1$ to t, β_{0ij} is the intercept, β_{1ij} and β_{2ij} are the coefficients for age and age squared, and β_{3ij} is the coefficient for male. Transition probability estimates were obtained using PROC SURVEYLOGISTIC in SAS v9.3, accounting for variation at region, village, and individual level.

Analyses of attrition dependent on observable characteristics found that attrition in the MLSFH was negatively related to increasing physical limitation and age. Because these variables (along with sex) are present in our analysis model, the analyses appropriately account for censoring and attrition conditional on these observable characteristics. Under the assumption of conditional ignorability, differential attrition related to these included characteristics does not distort our findings (Alderman, Behrman, Kohler, Maluccio, & Watkins, 2001). Multiple imputation of missing data by chained equations (Rubin, 1996; van Buuren, Boshuizen, & Knook, 1999) was conducted to evaluate that the analyses are robust with respect to alternative assumptions regarding missingness of the data, with results provided in supporting information.

3. RESULTS

3.1. Observed health and work effort

Table 1 reports summary statistics of the analysis sample and the distribution of self-reported disability status across the three MLSFH survey rounds during 2006–10. With the introduction of the parent sample in the 2008 MLSFH, the mean age increases by five years, and the sex composition shifts from being majority male to majority female. As the sample ages, incidence of functional status limitations rises—by Wave 6, the majority of respondents

had some limitations on their activities. For example, in 2010, close to one third of respondents aged 45–64 indicate that they are moderately limited, and 8.5% severely limited in their physical activities, with both physical limitations being substantially more common among individuals aged 65+ (Table 1). Although the measures of physical limitation are not directly comparable, this basic pattern of high levels of disability among mature adults that increase rapidly with age are also found in the IHS3 (Table S1). Using data on time use, analyses of the MLSFH indicate that functional limitations and disabilities are associated with substantially reduced work efforts. For example, the percentage of individuals working for income within the past week decreases steadily with increasing disability (Table 1): individuals 45–64 are over 12 percentage points less likely (26 vs. 39%) to have engaged in work for income in the past week if they are severely limited, and severely limited individuals 65 and over are over 17 percentage points (9 vs 26%) less likely to work for income. Individuals who report limitations on physical activity also report that their work efforts (both within and outside the household) have been substantially limited by pain, with around 50% of moderately and 60–80% of severely limited individuals stating that pain interfered quite a Table 1 reports summary statistics of the analysis sample and the distribution of self-reported disability status across the three MLSFH survey rounds during 2006–10. With the introduction of the parent sample in the 2008 MLSFH, the mean age increases by five years, and the sex composition shifts from being majority male to majority female. As the sample ages, incidence of functional status limitations rises—by Wave 6, the majority of respondents had some limitations on their activities. For example, in 2010, close to one third of respondents aged 45–64 indicate that they are moderately limited, and 8.5% severely limited in their physical activities, with both physical limitations being substantially more common among individuals aged 65+ (Table 1). Although the measures of physical limitation are not directly comparable, this basic pattern of high levels of disability among mature adults that increase rapidly with age are also found in the IHS3 (Table S1). Using data on time use,

Table 1: Self-reported disability, percentage working for income in the past two weeks, pain interfering with work, and subjective well-being for mature adults (aged 45+) in the MLSFH

	2006		2008		2010		% (2010) worked for income in past 2 weeks		% (2010) pain interfered with work in last 4 weeks		% (2010) somewhat/ very unsatisfied with life	
	N	%	N	%	N	%	N	%	N	%	N	%
45-64												
Status												
Active	427	72.4%	537	67.4%	428	56.8%	165	38.5%	64	14.9%	16	3.7%
Mod. Limited	132	22.4%	200	25.1%	239	31.7%	82	34.3%	120	50.2%	23	9.6%
Sev. Limited	31	5.3%	41	5.1%	64	8.5%	16	26.2%	40	65.6%	16	26.2%
Dead	–	--	19	2.4%	23	3.1%	–	–		–		–
Male	316	53.6%	362	45.4%	340	45.1%	–	–		–		–
65+												
Status												
Active	34	54.0%	120	41.0%	87	24.6%	23	26.4%	18	20.6%	5	5.7%
Mod. Limited	20	31.7%	108	36.9%	142	40.1%	34	23.9%	75	52.8%	14	9.9%
Sev. Limited	9	14.3%	62	21.2%	93	26.3%	8	9.0%	69	77.5%	26	29.2%
Dead	–	--	3	1.0%	32	9.0%	–	–		–		–
Male	43	68.3%	142	48.5%	170	48.0%	–	–		–		–
Average Age	54.2		59.0		61.0							

Notes: Disability classification is based on MLSFH questions (i) “Do you have any health problems that limit you in carrying out moderate activities?” and (ii) “Do you have any health problems that limit you in carrying out strenuous activities?”, with each question providing a list of moderately/strenuous activities and response categories being “not limited”, “limited a little” and “limited a lot”. Individuals who indicate that they had no limitations in either set of activities are classified as healthy, those who respond “somewhat limited” on either question are classified as moderately disabled, and individuals who respond “limited a lot” on either question are classified as severely disabled. Deceased refers to mortality between survey waves among respondents who were interviewed in the MLSFH 2006 and/or 2008. Pain interfering with work is based on the question “During the past 4 weeks, how much did pain interfere with your normal work (including both work outside the home and housework)?” Individuals responding “moderately”, “quite a bit”, or “extremely” are classified as being limited by pain. Individuals responding “somewhat unsatisfied” or “very unsatisfied” to the question “How satisfied are you with your life, all things considered?” are classified as having low life satisfaction. Three severely limited individuals aged 45-64 and 4 severely limited individuals aged 65+ have missing values on working for income, pain interfering with work, and life satisfaction, and were removed from the denominator for percentage calculations.

analyses of the MLSFH indicate that functional limitations and disabilities are associated with substantially reduced work efforts. For example, the percentage of individuals working for income within the past week decreases steadily with increasing disability (Table 1): individuals 45–64 are over 12 percentage points less likely (26 vs. 39%) to have engaged in work for income in the past week if they are severely limited, and severely limited individuals 65 and over are over 17 percentage points (9 vs 26%) less likely to work for income. Individuals who report limitations on physical activity also report that their work efforts (both within and outside the household) have been substantially limited by pain, with around 50% of moderately and 60–80% of severely limited individuals stating that pain interfered quite a bit or extremely with their normal work during the past 4 weeks (Table 1). These gradients in economic activity by disability status persist in regression analyses that control for age and gender, and additional regression analyses show that increasing disability is also associated with fewer hours of family farm work; for example, controlling for age and gender, severely limited individuals contribute an average of 5.32 fewer hours of agricultural labor to the household per week (Table S2). For a 55 year-old man, this represents nearly a halving of

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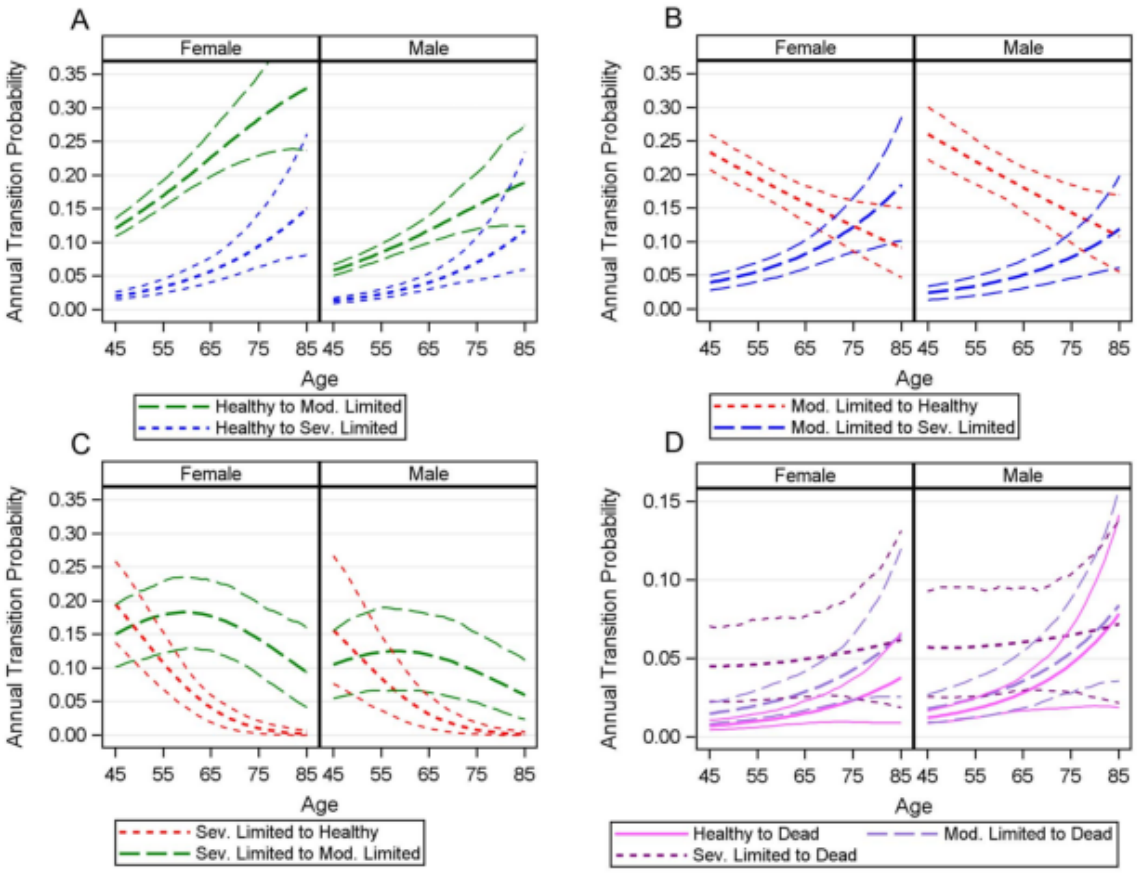
S2).

3.2. Health transition probabilities

Analysis of the 2006–2010 MLSFH reveals that individuals in this population experience a relatively large number of transitions between different disability states (healthy/moderately limited/severely limited) and death during the period of observation. Among respondents observed for all three MLSFH waves, 59% experience at least one and 22% experience two transitions between different disability states. Supplemental Material Table S3 shows the distribution of all transitions between disability states that are observed in our study population during 2006–2010. To gain insight into the dynamics of disability in this population, we model the underlying age-and gender-specific annual transition probabilities between states of physical limitation. Figure 3A illustrates the annual transition probabilities out of healthy status by sex, along with the 95% CIs (represented as the thin lines) based on 499 bootstrap resamples. At older ages, particularly above age 75, confidence intervals around our point estimates get quite large, primarily as a result of limited sample sizes at these advanced ages. As expected, transition probabilities towards increased physical disability rise sharply with age—a healthy man at age 45 has less than a .08 probability of being anything but healthy at age 46, but a healthy man at age 75 has only a .73 chance of remaining healthy at age 76. These figures are sharply higher for women, following a widely established pattern in contexts where disability and functional limitation transitions have been studied (Crimmins, Kim, & Sole-Auro, 2011; Oksuzyan et al., 2010). From healthy status, women are significantly more likely to enter into moderately limited status at all ages than are males, and are also significantly more likely to become severely disabled until about age 75.

The moderate limitation state is characterized by relatively high rates of entry and exit, though the probability of the direction of these transitions (upwards to severe limitation, downwards to healthy) changes substantially with age. Figure 3B describes the annual transition probabilities for a moderately limited individual at ages 45–85, along with the 95%

Figure 3: Estimated annual transition probabilities.



Panel (A) displays the annual probability of transitioning from healthy to moderately limited and severely limited. Panel (B) displays the annual probability of transitioning from moderately limited to healthy and severely limited. Panel (C) displays the annual probability of transitioning from severely limited to healthy and moderately limited. Panel (D) shows annual probability of mortality for healthy, moderately limited and severely limited individuals.

confidence interval around these estimated probabilities. At younger ages, individuals of both sexes are relatively likely to recover from stays in moderate limitation. The probabilities of recovery decline sharply with age, however—by about 70, women are more likely to become severely limited or die than to recover to healthy life (the corresponding age for males is about 78). Substantial sex differences in transition probabilities arise here as well—women are significantly more likely to become severely disabled and significantly less likely to remain healthy at almost all ages.

Transition probabilities from the severely limited status (Figure 3C) provide evidence that this is a fairly retentive state and that with increasing age, probabilities of exiting severe limitation by anything other than death decline sharply. As would be expected given the severity of the state, the probability of experiencing a full recovery from this state declines sharply over time—after age 49 for women (52 for men), recovering individuals are more likely to move to the moderately limited status than to fully healthy, and after age 64 for women (59 for men), individuals are more likely to die than to recover to healthy status. For both men and women, probability of full recovery to healthy life is almost zero after age 75. In the SSA LIC context studied here, functional limitations seem to have a quite strong impact on mortality (Figure 3D). At younger ages in particular, annual mortality rates from severe limitation are orders of magnitude higher than from healthy or moderately limited states—a 45 year old severely limited woman is about 6 times more likely to die than a healthy woman (5.3 times for men). Point estimates for transitions to mortality from healthy status are higher for men than women at all ages, though this difference is within the confidence interval. Overall, severe disability seems more predictive of death in men than in women, though given the small number of observed deaths the confidence intervals around these estimates are fairly large.

As a robustness check to verify that the estimated transition probabilities based on the MLSFH (Figure 3) reflect longer-term trends in health transitions in the population, we compare the age-specific proportions in each health status in both the MLSFH sample and

the synthetic cohorts created through microsimulation (Figure S2). We find that the simulated data, based on the predicted parameters estimated from the MLSFH sample, match quite closely with actual observed proportions sample population. With the exception of proportion healthy in older females, the proportions from the simulated data lie entirely within a 90% confidence interval around the MLSFH sample proportions (estimated through 999 bootstrap samples). The only substantial point of deviance comes in the proportion of healthy 75+ year-old women, where the microsimulation data predicts fewer healthy women than is observed in the data. However, the upturn in proportion healthy observed in the sample population is likely a result of the small sample of individuals in this age grouping, and we are confident that the parametrically-based microsimulation cohort more accurately represents the conditions in this rural population.

3.3. Health expectancies

Moving from the transition probabilities in Figure 3 to the corresponding *health expectancies* (HE) (Table 2 and Figures 4 and 5) allows us to understand how these age-and sex-specific annual probabilities of transition between disability states translate into years lived with functional limitation. As a validation test for our analyses, we compare our total life expectancy (LE) figures to 2009 WHO (WHO, 2011) and 2008 Malawi National Census life tables (NSO, 2012) (Figure S3). Our microsimulation-based MLSFH life expectancy estimates are in broad alignment with these other data sources, especially in light of the fact virtually all LE estimates at higher ages in SSA LIC contexts are subject to considerable uncertainty due to the lack of reliable vital registration data.

In addition to revealing remaining total life expectancy for mature adults, our microsimulation-based MSLT approach estimates the duration of life expected to be spent in healthy, moderately limited, and severely limited statuses. To our knowledge, information about HEs in different disability states was not available for Malawi or similar SSA LIC

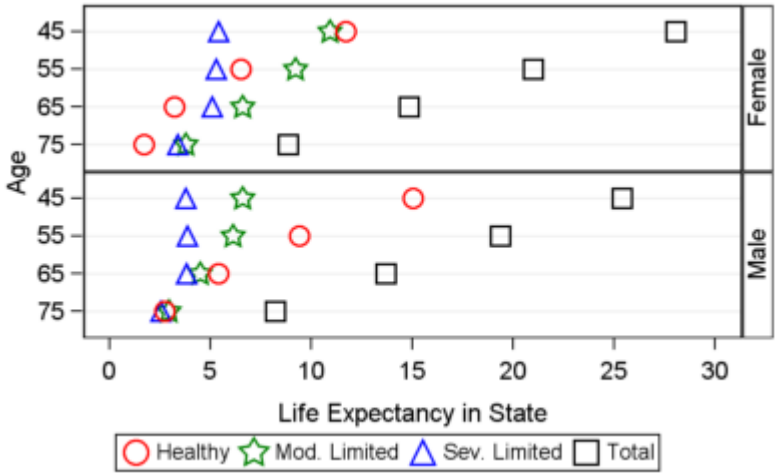
Table 2: Microsimulation-estimated average remaining life expectancy (LE) at ages 45–75, by sex

Age	45		55	
	Estimate	95% CI	Estimate	95% CI
Female				
Life Expectancy	28.04	(25.71 - 33.49)	20.97	(19.19 - 31.72)
Active	11.72	(10.43 - 13.77)	6.50	(5.44 - 9.50)
Mod. Limited	10.90	(9.44 - 13.39)	9.21	(8.04 - 14.48)
Sev. Limited	5.41	(4.31 - 7.06)	5.26	(4.23 - 7.79)
Male				
Life Expectancy	25.39	(23.31 - 28.83)	19.38	(17.51 - 25)
Active	15.06	(13.61 - 16.92)	9.41	(8.19 - 11.80)
Mod. Limited	6.57	(5.39 - 8.49)	6.11	(4.98 - 8.45)
Sev. Limited	3.76	(2.78 - 5.36)	3.86	(2.81 - 5.46)

Age	65		75	
	Estimate	95% CI	Estimate	95% CI
Female				
Life Expectancy	14.85	(13.46 - 21.61)	8.85	(8.20 - 15.14)
Active	3.21	(2.45 - 4.34)	1.69	(1.05 - 2.99)
Mod. Limited	6.58	(5.49 - 9.84)	3.78	(2.89 - 7.24)
Sev. Limited	5.06	(3.98 - 6.92)	3.38	(2.54 - 5.19)
Male				
Life Expectancy	13.70	(12.37 - 16.08)	8.23	(7.54 - 12.73)
Active	5.41	(4.42 - 6.72)	2.76	(1.96 - 4.10)
Mod. Limited	4.48	(3.60 - 6.19)	2.93	(2.27 - 5.37)
Sev. Limited	3.82	(2.76 - 5.40)	2.54	(1.83 - 3.72)

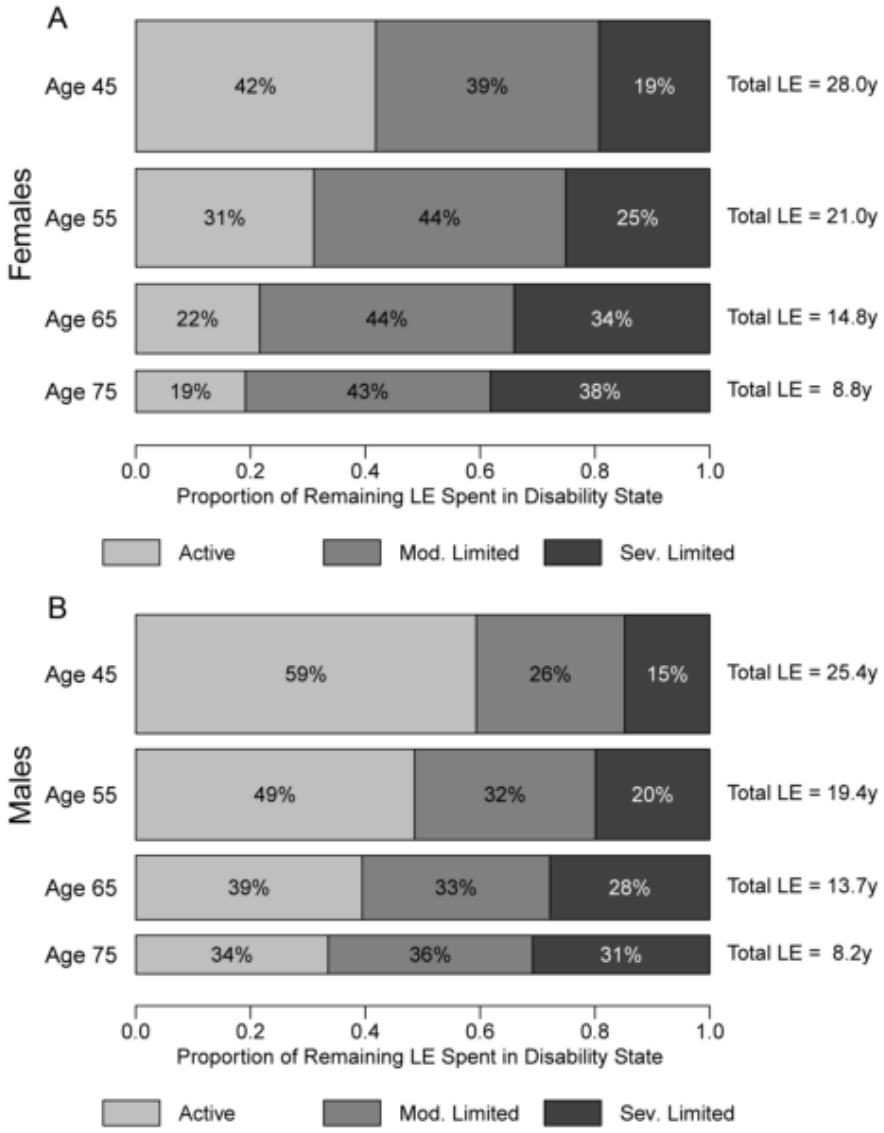
Notes: Estimates were obtained from synthetic cohorts of 100,000 45-, 55-, 65-, and 75-year olds created via microsimulation, based on observed transition rates from 2006–2010 MLSFH data.

Figure 4: Average number of years of active, moderately limited, severely limited, and total life expectancy



This figure shows a comparison between the number of years an average individual will spend in healthy, moderately limited, and severely limited life at age 45, 55, 65, and 75. Markers represent the overall distribution of life-years spent in each state, not the ordering of these life-years–individuals in our analysis can recover and relapse between disability states, so not all years of limitation are spent at the end of life.

Figure 5: Distribution of remaining life expectancy (LE) by disability state: healthy, moderately limited, severely limited.



This figure shows the proportion of remaining life an average individual will spend in healthy, moderately limited, and severely limited life at age 45, 55, 65, and 75, for females (Panel A) and males (Panel B). The height and area of each bar is proportional to the overall remaining life expectancy of the synthetic cohorts with initial ages of 45, 55, 65 and 75 years, and the differently shaded areas represent the distribution of the remaining life expectancy across the three disability states: healthy, moderately limited and severely limited. The bars do not necessarily reflect the ordering of these life-years by disability states as individuals in our analysis can recover and relapse between disability states, so not all years of limitation are spent at the end of life.

contexts prior to this study. Specifically, the estimated health expectancies in Table 2 and Figures 4 and 5 show that that mature adults in rural Malawi are expected to live a substantial number of their remaining life years—and thus a significant fraction of their remaining LE—subject to functional limitations and in a state of moderate or severe disability. For example, our analyses show that the average 45 year old woman is expected to live about 28 additional years, making her expected age at death almost 73 (the corresponding LE estimates for men are 25.4 and 70.4). However, a significant proportion of this remaining LE is subject to functional limitations. Our estimates suggest that, on average, a 45 year old woman will live almost 60% of her remaining life in some limited status, while an average male will be limited for about 40% of his remaining life. The high rates of transition between health states across the life-course mean that time spent in limited status does not occur solely at the end of life. Analysis of health expectancies in the simulated synthetic cohort of 45-year olds shows that, on average, a woman at age 45 will spend of 2.7 years in moderate limitation and 0.6 years in severe limitation before she reaches age 55 (these corresponding values for men are 1.6 and 0.4 years). Figure 4 emphasizes the age trends in years of life expectancy in healthy, moderately limited, and severely limited life. By 65, women expect to live only 3.21 of their remaining 14.85 years of life without functional limitation, and men expect to live only 5.4 remaining years without functional limitations. Figure 5 displays the proportions of remaining life expectancy spent in each disability state by age, showing a clear and progressive increase in the amount of remaining life spent moderately or severely limited. By 75, women are expected to live over 80% of their remaining life in some limited condition (this figure is 66% for men).

Calculating HEs from only the portion of the synthetic cohort starting in a given health state, as compared to the full empirical distribution of disability states observed at the various ages in the MLSFH (Table S1), has relatively small effects on the overall life expectancy and the fraction of the remaining life spent in the various disability states for cohorts starting at age

45 or age 55 (Figures S4, S5, and S6); at older starting ages, conditioning on an initial healthy state increases LE and reduces the proportion of the remaining life with disability. Conditioning on being initially moderately or severely limited, as is expected, reduces remaining LE and increases the fraction of remaining LE lived with disability.

To evaluate whether our results in Table 2 and Figures 4 and 5 are affected by attrition in the longitudinal MLSFH study, the above analyses were replicated using multiple imputation (MI) by chained equations (Rubin, 1996; van Buuren et al., 1999) to impute missing follow-up data for attritors (Table S5). The results using imputed values in Table S5 are in close agreement with the above results that were obtained without MI (Table 2 and Figures 4 and 5). The primary difference is that the MI models estimate a slightly shorter healthy life expectancy for males at age 45 and 55, and a slightly shorter total life expectancy for both sexes at age 45. None of these differences affects the substantive conclusions obtained from our analyses. Our conclusions are also robust with respect to using a 2-state rather than 3-state classification of functional limitations and disability, and our overall conclusions do not change using a classification of disability based on functional limitations resulting from pain during daily work activities (Tables S6 and S7).

4. DISCUSSION

Older individuals have received an inadequate attention in much of the current health-related research in low-income sub-Saharan contexts, despite the fact that poor health in this population is common, levels of disability are high, and economic productivity is often hindered due to persistent health-related functional limitations. While national health sector strategic plans in Malawi and other SSA countries have started to highlight the need for policies to prevent disabilities and ensure access to curative and rehabilitative care among older individuals, there is only a limited understanding of the trajectories of health and disability among mature and elderly adults in SSA, and of the health needs that will result from the oncoming growth of the mature adult and elderly population in many SSA contexts.

The required health-sector responses to population aging in SSA are thus inadequately informed by the existing literature, which has often focused on the health of younger individuals and/or health concerns resulting from infectious diseases, rather than chronic and/or non-communicable diseases and disabilities that affect older individuals.

The key contribution of this paper is its focus on the lived experience with disability among mature adults in rural Malawi, including both the levels of disability by age and the dynamics of disability transitions during the adult life course. Our analyses do not single out HIV/AIDS infected individuals. Rather, we treat this disease as one of many health concerns—chronic diseases, accidents, physiological aging, etc—that affect mature adults in SSA. Specifically, we investigate how overall physical health results in functional limitations, that is, how disabilities due to poor health result in limitations in day-to-day activities in domains that are essential for individuals in this subsistence-agriculture context. Individuals are categorized in three different disability states based on the functional limitations that they experience. Using a novel multi-state life table methodology, which has not been applied to this context before, this article provides insight into the processes of functional limitation in a rural SSA population by estimating the prevalence of functional limitations and the transition rates between different disability states. Our analyses find that levels of disability and functional limitations in this population are very high, and that rates of transition into disability statuses differ substantially across the life course. Rates of recovery from moderate and severe limitations decline very rapidly with age, and after age 65 a full recovery from severe functional limitations is very unlikely.

In addition to documenting the levels of disability and the transitions between disability states, our analyses estimate the expected years people in this rural population will live in healthy, moderately limited, and severely limited life. For example, women at age 45 are estimated to spend 58% of their remaining life with moderate or severe functional limitations, a fraction that rises to 78% at age 65; 45-year old men are expected to spend 40% of their

remaining live with moderate or severe functional limitations, rising to 60% at age 65. Since our measures of functional limitation are chosen to be appropriate for the physically demanding environment of a subsistence-agriculture lifestyle, making comparisons with estimated levels of disability in developed regions somewhat difficult. Even so, such comparisons may be useful if we conceptualize disability as the inability to fully physically function in one's environment. The proportions of remaining life spent with severe limitations at age 45 in Malawi are comparable to those of 80-year-olds in the U.S., and proportion of life with any limitations is far higher (Crimmins, Hayward, Hagedorn, Saito, & Brouard, 2009; Seeman, Merkin, Crimmins, & Karlamangla, 2010). Time spent in physical limitation is widely distributed across ages in our study population, with a substantial number of expected years of limitation occurring before age 55. Our results suggest that the high levels of moderate and severe physical disability among mature adults result from a rising relevance of chronic diseases combined with a life-long exposure to multiple infectious diseases, frequent poverty and widespread poor nutrition (Amuna & Zotor, 2008; Darnton-Hill, Nishida, & James, 2004; Schaible & Kaufmann, 2007).

The micro-data based analyses in this article represent a substantial methodological shift from previous measures of healthy life expectancy calculated for SSA, in particular the Global Burden of Disease (GBD) reports (Salomon et al., 2012). Though the GBD estimates of healthy life expectancy provide a useful metric for cross-national comparisons, the metric of healthy life expectancy at birth is not readily applicable to life-course experience of an adult. The methodology utilized in this study allows for deeper insight into processes of disability than provided by the GBD, more accurately characterizing the fluidity between health states over time and across the population. These results show that individuals in this society experience a lengthy struggle with disabling conditions in later life, with high probabilities of remitting and relapsing between states of limitation. This level of in-depth understanding of this population's burden of disease is only possible through analysis of

micro-data.

In evaluating the results from this MSLT estimation, which to our best knowledge has been applied in this paper for the first time for analyzing health transitions in SSA, several limitations need to be kept in mind. Individuals who experience a health transition between MLSFH waves are assumed to only experience a single transition during the 2-year period between surveys, which likely misses shorter-term transitions between health statuses. As the focus of this article is on functional limitations (which tend to be longer in duration) and not acute health conditions, we are reasonably confident that this assumption does not unduly bias our health expectancy estimates and their interpretation (Gill, Allore, Hardy, Holford, & Han, 2005; D. Wolf & Gill, 2009). The MLSFH does not provide data on the individual diseases or medical conditions which result in functional limitations, limiting our ability to identify specific causes of the high disability burden we observe. In common with other life-table based measures, health expectancies (HE) estimates assume stationary of transition rates over time—that is, they apply to the lived experience of a synthetic cohort where our estimated age-specific rates of transition remain constant for the foreseeable future, and thus will not exactly match the lived experience of any single cohort. Thus, our results do not take into account any shifts in disability prevalence that may have occurred during the 4-year study period. Our current analyses follow a first-order Markov chain, and are thus not state-duration-dependent—that is, transition probabilities are not adjusted by duration of stay in a given state. This assumption results from the left-censored nature of our data—though we can tell what functional status a person was in at entry into the dataset, we do not know their duration of stay in that state. Recent work on the Semi-Markov Process (SMP)-EM algorithm (Cai et al., 2008) rectifies some of the left-truncation biases introduced by state-duration-dependent modeling, but was deemed too computationally intensive and complex given the sample size available in the MLSFH.

Our findings suggest that the high burden of functional limitations and disabilities endured by

this rural mature adult population results in a substantial gap between potential and actual economic productivity. Functional limitations are associated with a lower likelihood of working for income and reduced work efforts in agriculture, key aspects of individuals' livelihoods in rural SSA LIC contexts. Given the lack of institutionalized social and economic support systems, Malawi and other SSA LICs can ill-afford this productivity gap resulting from functional limitations among mature adults at already "relatively young old ages". This significant role of mature adults was summarized at the inauguration of the Malawi Ministry of Persons with Disabilities and The Elderly with: "*[M]any older people are able to make significant contributions as income-earners, providers of care, sources of knowledge and experience, and guardians of traditions. Since the effects of the ageing process are certain to continue for many years to come, agriculture and rural development will be increasingly dependent on older persons. Therefore, policy makers must find better ways to ensure that older people are able to 'age successfully': have good health, be physically and mentally active, and remain actively involved in community life*" (FAO and BSF, 2008).

Our findings make an important contribution to the debate about policy responses and interventions targeting chronic disease and disability in low-income settings, particularly in SSA. We show that moderate and severe functional limitations—which have a substantial negative effect on individuals' economic activities— are a major challenge in a subsistence agriculture setting that is characteristic of many rural SSA LIC contexts. However, the older population has largely been left out of the recent large-scale health-focused interventions and policies implemented in SSA, particularly those focusing on Millennium Development Goals-related groups (Beard et al., 2012). Many policy-makers in SSA are hesitant to direct financial resources to the elderly population, and see investment in health resources for the aging population as "irrelevant to core national development interests" (Aboderin, 2010). Our analyses suggest that this sentiment is misguided–the high burden of disability among mature adults is associated with substantial loss of direct labor output, with potentially

important intergenerational consequences for children and younger adult family members. Mature adults suffering from functional limitations and related disabilities are likely to be a drain on the scarce time and material resources of families and they may make reduced net downward transfers towards children and younger adults (I. V. Kohler et al., 2012). Investments in improving the health of this growing population have the potential to significantly improve aggregate economic growth, and our analyses provide important empirical support to recent editorial and policy papers that have argued for a greater attention to mature and older adults within national health policies and international donor-funded health programs in SSA LICs (Aboderin, 2010; Institute of Medicine, 2011; Levitt et al., 2011; Maher & Sekajugo, 2011; Mills et al., 2012).

Aging in the Americas: Disability-Free Life Expectancy among Adults Age 65 and Older in the United States, Costa Rica, Mexico, and Puerto Rico.

Collin F. Payne

1. INTRODUCTION

Population aging in Latin America and the Caribbean (LAC) will not proceed along known paths already followed by more developed countries (Palloni, McEniry 2007). In particular, the pace by which the age composition of countries in LAC will shift is nearly unprecedented. Fertility rates have dropped to near or below replacement level in almost every country in Latin America, and life expectancy at age 60 has nearly doubled in most countries in LAC since 1950 (Palloni, Pinto-Aguirre & Pelaez 2002). A typical country in LAC will reach a population with 15% of individuals over the age of 60 in less than half the time that this shift took in the US (Palloni, Pinto-Aguirre & Pelaez 2002, Kinsella, Velkoff 2001). The care of this aging population is one of the largest challenges facing countries in LAC. However, rigorous research on how these additional years are spent is lacking. This population is growing faster and living longer than ever before, but what portion of this additional life is spent with disability? How do the country-wide levels of disability and rates of chronic non-communicable diseases (NCDs) compare across the region, and to more developed contexts such as the United States? The answers to these questions will impact social welfare and have substantial repercussions for national health systems, retirement and disability patterns, and the demand for long-term care for the aging in both institutional and family settings (Cotlear 2011).

The primary aim of this paper is to estimate and compare disability-free life expectancy (DFLE) between the US and countries in LAC, and to gain insight into current age patterns of disability onset and recovery from disability in these populations. I center on

understanding the lived experience with disability among the aging population as measured by the activities of daily living (ADL) scale. Specifically, I estimate the rates of transitions between life without disability, disabled life, and death in these populations, and use these parameters to estimate the DFLE of individuals in the Costa Rica, Mexico, Puerto Rico, and the United States. Together, these measures characterize processes of disability in the growing elderly population of LAC, and can provide important insights into how current disability conditions in these populations may impact future demands from health care systems, pension programs, and social services.

Background: The four contexts compared in this study (three countries—the United States, Costa Rica, and Mexico—and one territory, Puerto Rico) comprise a range of differing economic and demographic conditions, health care systems, and pension systems. Each of the four contexts studied here have similar life expectancy at age 60, though levels of GDP per capita, human development index, and health expenditure per capita vary dramatically (Table 1). *Mexico:* The population aged 65+ in Mexico is one of the most rapidly growing in the world. Though this population currently comprises 9.4% of the total population, it is projected to more than double in the next 25 years (US Census Bureau 2014). Life expectancy currently stands at 79 for females and 74 for males (Cotlear 2011). Mexico has closely followed the classical epidemiological transition (Omran 1977), with a marked decline in deaths from infectious disease since the 1980s and an increase in deaths from chronic and degenerative diseases—from 58% of deaths in 1990 to 75% of deaths in 2005 (Pan-American Health Organization 2007, Stevens et al. 2008). Mexico's total fertility rate is slightly above replacement level, but has dropped rapidly since the mid 1980's (The World Bank 2014). Although health

Table 1. Economic and Health Conditions

	Costa Rica	Mexico	Puerto Rico	US
GDP Per Capita 2011 (current US $)	9,386	9,749	27,678	51,749
Health Expenditure per capita, 2011 (current US $)	943	620	--	8,608
LE at birth, Males	77	74	74	76
LE at birth, Females	81	79	82	81
LE at age 60, Males	21	20	20	20
LE at age 60, Females	24	22	25	24
Total Fertility Rate 2011	1.8	2.2	1.7	1.9
Population, 2011	4,737,680	119,361,233	3,694,093	311,587,816
Human Development Index	62	61	52	3

Sources: World Bank World Development Indicators 2013, UN Population Division World Population Prospects

2006 and 2012, UN Development Programme 2013 Human Development Report

conditions have improved, availability of medical care lags behind many other upper-middle income countries. Mexico has some of the lowest rates of availability of health care resources in LAC, particularly in hospital beds and physicians per thousand people (The World Bank 2014). Many elderly individuals did not participate in the formal labor market in their early life, and only about half are covered by Mexican Institute for Social Security (Instituto Mexicano del Seguro Social or IMSS) health care services (Aguila et al. 2011). This population either forgoes health insurance or relies on public health programs such as Popular Health Insurance (Seguro Popular de Salud or SPS), where they may incur substantial out-of-pocket expenditures for health care (Aguila et al. 2011).

Costa Rica: Costa Rica, located on the Central American isthmus, is often cited as a model for other middle income countries. Though it differs little from most other countries in LAC in terms of GDP per capita, it has achieved a level of life expectancy, access to public health services and sanitation, environmental protection, and social security coverage among the highest in the Americas (Rosero-Bixby 2008). Costa Rica underwent a very rapid demographic transition—life expectancy rose from around the

mid 40's in the 1930's to around 70 by 1970, and infant mortality dropped continuously during these years before rapidly declining in the 1970s (Rosero-Bixby 1990). Life expectancy at birth and at age 60 are comparable or even higher than values for the US. The population is still rather young—about 7% of Costa Ricans currently over the age of 65, though this will rapidly grow to over 22% by 2040 (US Census Bureau 2014). Costa Rica has attained these impressive health and development metrics with a surprisingly low level of health expenditure per capita—only $943 per year in 2011, about 11% of the US' spending (The World Bank 2014). The Costa Rican Department of Social Insurance (Caja Costarricense de Seguro Social or CCSS) was established in 1941, and universalization of health care coverage in 1973 consolidated the control of medical facilities to the CCSS. The Costa Rican health system is characterized by a focus on primary care and preventive medicine, a decentralization of health services, and emphasis on training and capacity-building in rural clinics (Eriksson, Mohs & Eriksson 1990). The public health insurance system covers about 88% of the population (Saenz, Bermudez & Acosta 2010), and the government provides no-cost insurance for the destitute population (Rosero-Bixby 2004).

Puerto Rico: Puerto Rico is a commonwealth of the United States, located in the Caribbean. The population is already fairly old compared to other LAC contexts due to both demographic aging and high rates of out-migration to the US mainland among the younger population, but the older population is projected to continue growing in coming years. Over 16% of the population is currently over the age of 65, and by 2040 this population is estimated to be about 27.4% of the island's total population (US Census Bureau 2014). Rates of GDP per capita sit below the US but substantially above Costa Rica and Mexico. As US citizens, Puerto Ricans pay Medicare insurance and thus are covered by the Medicare insurance system after the age of 65. Though health insurance

coverage is high, preventative care is often poor—only 14% of the diabetic population has received a deep eye test, only 16% are monitored for nephropathy, and 82% have poor control of their blood sugar. Only around half of the female population at risk had received a mammography or PAPS test (Colón 2005).

United States: The United States is one of the highest income countries in the world, with a fully modern healthcare system and a completed epidemiological transition. About 14% of the population is currently age 65 and older, a figure which will rise to about 21% by 2040. GDP per capita and health expenditure per capita rank among the highest in the world and the US also ranks high on the number of hospital beds and doctors per 1000 individuals (The World Bank 2014). The US had essentially completed its epidemiological transition by the 1920's (Omran 1977), meaning that the vast majority of the current 65+ population was not exposed to high rates of communicable disease in early life. At 65, individuals are eligible for Medicare, a federal health insurance program for the elderly, and are also eligible for pension payments from Social Security. Even though access to care is high, the US still has persistently lower life expectancy outcomes than many other similarly wealthy nations (Ho, Preston 2010)

Literature Review: Differences in adult health across populations are driven primarily by two complex and interrelated sources of variation. The first of these are childhood or early-life sources, including fetal environment, childhood nutritional and epidemiological environment, and rates of infant and child mortality during early life. Cohorts reaching the ages 65+ in Latin America were exposed to a vastly different set of early-life conditions when compared to the 65+ population in the US—these cohorts experienced much higher rates of disease and episodic malnutrition both in utero and in early life, both of which are associated with increased risks of non-communicable disease, adult mortality, and late-life disability (Huang, Soldo & Elo 2011, McEniry 2013, Ben-Shlomo,

Kuh 2002). A number of LAC-focused studies (Palloni et al. 2006, Monteverde, Noronha & Palloni 2009) suggest that the higher disease burden and episodic malnutrition experienced by LAC's aging population during early life may contribute to successive cohorts at higher risk of disability and chronic disease. However, there is also the possibility that differential selection effects may lead to fairly healthy cohorts of 65+ individuals in LAC. The current cohorts of older adults in LAC may be a selective group—that is, they could represent only the "hardiest" survivors of cohorts exposed to high child and infant mortality (Gerst-Emerson et al. 2015), and may thus have a lower burden of disabling conditions.

The second set of factors driving cross-national differences in adult disability are adult or late-life sources such as exposure to advanced medical technology and care for non-communicable diseases, declining physical activity, and exposure to lifestyle behaviors like smoking and consumption of high-calorie convenience foods. As described above, the older population in most of LAC has spent substantially less time exposed to these factors than the older population in the US. How this exposure affects the health LACs elderly population is somewhat unclear—recent access to modern medical technology should result in improving health outcomes, but access to high-quality care is not as widespread in LAC as in the US. Economic development and urbanization may also lead to an increase in unhealthy behaviors such as a sedentary lifestyle and obesity in LAC, but older cohorts in these countries have had a substantially shorter exposure to these conditions than older cohorts in the US.

Although a great deal of study of disability-free life expectancy and the aging process has been conducted in the US and other developed contexts, research on aging and disabilities is lacking in lower and middle-income countries. This gap in the literature is due in part to the unavailability of high-quality data, and in particular longitudinal data, on

aging populations in much of the developing world (Ebrahim et al. 2013). Existing research into health expectancies in LAC has largely relied on cross sectional data or used the limited longitudinal follow-up data collected by some countries following the cross-sectional Study of Health, Well-Being, and Aging in Latin America and the Caribbean (SABE), where the long time periods between waves of data collection (5+ years) may result in substantially biased estimates when used to estimate current status data (Gill et al. 2005, Wolf, Gill 2009). Even with these data constraints, a small but growing body of literature is emerging on aging and disability in LAC. Research from Mexico shows that individuals with diabetes experience a much diminished life expectancy (10 years of reduced LE at age 50) and a high burden of self-care limitations (Andrade 2010). Recent work by has also found that Hispanic migrants in the US experience a protracted period of disability in older age, even as they expect to live more total years than White or non-Hispanic Black populations (Hayward et al. 2014). In contrast, a recent article by Gerst-Emerson et al (Gerst-Emerson et al. 2015) found that Mexican adults aged 50+ experienced fewer transitions into disability compared to non-Hispanic Whites in the US, and were more likely to recover from disability.

I focus on DFLE as an easily interpretable metric for comparing population-level disability in a cross-national context. DFLE distinguishes between years that are free of limitations on activities and years with activity limitations, and provides a more nuanced view of population-level disability than simple life expectancy. DFLE combines mortality and morbidity into a single measure, providing a convenient and easily interpretable metric for measuring population-level health (Minicuci et al. 2004).

While we can make informative comparisons of healthcare systems, economic development, and epidemiological histories across these four contexts at the macro level, little existing research has compared processes of disability in the aging population

between LAC and the US. This article compares the DFLE of the elderly population between the very different contexts of the US and the three Latin American countries under study—Mexico, Puerto Rico, and Costa Rica. The primary goal of this research is to understand the current outcomes of the complex interplay between early-life and late-life influences on health, and to gain insight into present and possible future trends in disability in these populations.

2. METHODS

Data: Data from my analysis come from four sources: The Costa Rican Longevity and Healthy Aging Study (CRELES), collected in 2005, 2007, and 2009 (Rosero-Bixby, Fernández & Dow 2013); the Mexican Health and Aging Survey (MHAS) collected in 2001 and 2003 (MHAS Mexican Health and Aging Study, 2001 & 2003); the Puerto Rican Elderly: Health Conditions (PREHCO) survey collected in 2002-2003 and 2006-2007 (Palloni, Davila & Sanchez-Ayendez 2013); and the United States' Health and Retirement Survey (HRS) from 2004, 2006, 2008, and 2010 (RAND Center for the Study of Aging 2014). Data instruments and collection procedures from CRELES and MHAS are largely based on HRS methodologies (McEniry, Moen & McDermott 2013), and PREHCO asks a large suite of highly comparable questions on ADL activities, demographics, chronic conditions, and interactions with the health care system. In each country, my sample consists of all available non-institutionalized primary respondents age 65 and older with data on ADL limitation.

I conceptualize disability within the framework of the disablement process (Verbrugge, Jette 1994, Kasper, Freedman 2014), wherein disability is defined as a gap between an individual's capacities (physical, sensory, or cognitive) and the demands of a given activity in that individual's particular environment. As such, disability is not a purely

health-based measure, but is influenced by environment and accommodation. I investigate patterns of self-reported disability by using the ADL scale to create two distinct states of physical health: **active** individuals with no reported limitations on ADL activities, and **ADL disabled** individuals with one or more limitations on ADL activities. I parameterize ADL disability as difficulty on any of the following five activities: bathing, eating, getting in/out of bed, toileting, and walking across a room. Where necessary, proxy responses on ADL limitation are used for data from HRS, CRELES, and MHAS. Direct questions on ADLs were not asked of proxy respondents in PREHCO—proxy respondents were asked if the target respondent was capable of staying home alone without problems, a very similar measure of ability to self-care. Individuals judged by the proxy respondent as not capable of staying home alone without problems are counted as ADL disabled.

Methods: Initially, I compare rates of disability, chronic conditions, and sociodemographic variables across these four contexts to gain a baseline understanding of health conditions. I then use a multi-state life table (MSLT) to translate the longitudinal data from each country into estimates of DFLE and life expectancy with ADL limitations. This estimation method is based on an adapted version of the Stochastic Population Analysis for Complex Events program (Cai et al. 2010, Payne, Mkandawire & Kohler 2013). This method relies on weighted data from nationally-representative sample surveys to estimate MSLT functions such as total life expectancy, DFLE, and disabled life expectancy at the population level. Specifically, to calculate MSLT functions such as healthy and ADL limited health expectancies (HEs), I use microsimulation to create synthetic cohorts of 100,000 65-, 75-, and 85-year-old individuals with the same initial gender and ADL limitation distributions as the study populations. I then ‘‘age’’ these individuals forward year by year using age- and gender-specific mortality rates and

probabilities of transitioning in and out of disability estimated from the data. This process is then repeated at each age until death. The resulting synthetic cohort is analyzed to estimate DFLE and other life-course health indicators. The process is essentially the microsimulation equivalent of projecting the initial synthetic cohort population **P**, disaggregated by age, sex, and disability status, using $\mathbf{P_t = Q \cdot P_i}$, where **Q** is a projection matrix **Q** containing all age- and gender-specific disability transition rates and mortality rates (Schoen 1988).

Sample attrition varied somewhat between the four data sources. For the eligible sample of respondents, attrition was 13.3% between the two waves of PREHCO, 4.3% between the two waves of MHAS, about 8% between each wave of CRELES, and about 4% between each wave of HRS. Prior to the microsimulation described above, I conducted multiple imputation of missing data by chained equations (van Buuren, Boshuizen & Knook 1999). The multiple imputation models included the full set of ADL questions, age, and all demographic and health information from Table 2. For each sample, 10 datasets with imputed ADL disability and mortality outcomes for attrittors were generated. In the microsimulation approach, DFLE estimates are not a deterministic function of the transition probabilities, and instead result from the interplay between disability status, gender, and age as individuals move year by year through the simulation. Thus, confidence intervals (CIs) from the transition calculations are not directly applicable to the DFLE estimates. CIs for DFLE, which reflect both the uncertainty of the estimated parameters and the uncertainty from the microsimulation, were created by re-estimating the above analysis sequence (estimating state-dependent transition probabilities from each multiply-imputed data set and applying them to a representative 100,000-person cohort using microsimulation) using 200 bootstrap resamples. The results from these resamples are then aggregated across the 10 multiply

imputed datasets, resulting in 2000 parameter estimates. The final point estimates presented are the median of the distribution of these 2000 bootstrapped parameters, with CIs defined as the central 95% of the resulting distribution. All analyses are completed using sample weights normed to the respective national population.

To estimate the conditional probabilities of experiencing a transition between the three modeled states (active, ADL disabled, and deceased), I generate datasets in person-year format, assuming that transitions between disability states occur midway between observations. I then model the annual transition probabilities as a function of age and gender, using a multinomial logistic discrete-time hazard model of the form

$$Log\left(\frac{p_{ij}(age,t)}{p_{ii}(age,t)}\right) = \beta_{0ij} + \beta_{1ij} \times age_t + \beta_{2ij} \times age^2 + \beta_{3ij} \times female$$

(1)

where p_{ij}(age, t) is the transition probability from current state i (with i = active or ADL disabled) to state j (with j = active, ADL disabled, or deceased) over the interval from time t − 1 to t, β_{0ij} is the intercept, β_{1ij} is the coefficient for age, β_{2ij} is the coefficient for age^2, and β_{3ij} is the coefficient for female. An analysis model including an age*female interaction was also tested, but the coefficients were not significant at α=.05 and the DFLE and transition probability results were minimally changed; it was thus removed in favor of the simpler model. Transition probability estimates were obtained using PROC SURVEYLOGISTIC in SAS v9.4, accounting for survey weights and sample design.

3. RESULTS

Sample Characteristics: Table 2 presents the baseline sociodemographic and health characteristics of the four samples. All presented results use national-level sample weights to represent the aging population of the countries under study. We see that the

basic sample demographics are somewhat different between the four samples—the US over 65 population skews older than in Mexico, Puerto Rico, or Costa Rica. Individuals in the US, Puerto Rico, and Costa Rica were substantially more likely to have visited a doctor in the past year (or, in the US case, two years) than individuals in Mexico at baseline. Almost 60% of the US sample reported having smoked over the course of their lifetime, compared with 45% of Mexican elderly, 42% of Costa Rican elderly, and 34% of Puerto Rican elderly. Rates of doctor-diagnosed NCDs vary somewhat between countries. Hypertension is common across the four samples, though somewhat higher in the US and Puerto Rico. Diagnosis of cancer, stroke, and arthritis are also more common in the US, though this could be due to variation in medical practices or frequency of doctor's visits (particularly in the case of Mexico). Almost 30% of the Puerto Rican elderly population has been diagnosed with diabetes, compared with about 20% for the other countries. In the case of heart attack, the US sample categorized multiple heart conditions together, which likely leads to the substantially higher reported rate.

Table 2. Baseline Sample Characteristics

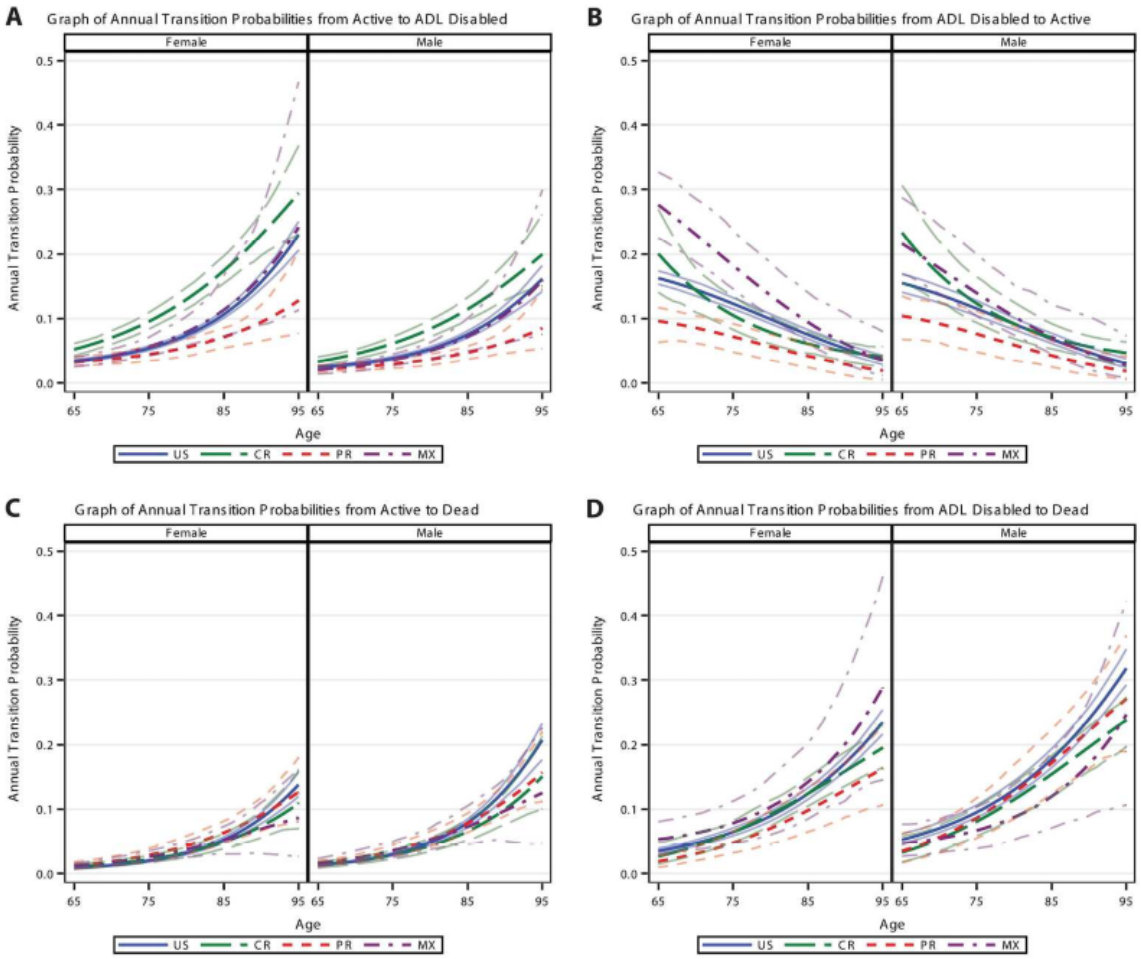
	Costa Rica - CRELES Wave 1 (2005)		Mexico - MHAS Wave 1 (2001)		Puerto Rico - PREHCO Wave 1 (2002)		USA - HRS Wave 7 (2004)	
	Prop.	95% CI	Prop.	95% CI	Prop.	95% CI	Prop.	95% CI
Age								
65-74	0.60	(0.58 - 0.62)	0.59	(0.56 - 0.62)	0.60	(0.58 - 0.63)	0.52	(0.51 - 0.54)
75-84	0.31	(0.29 - 0.33)	0.29	(0.27 - 0.32)	0.31	(0.28 - 0.33)	0.37	(0.36 - 0.38)
85+	0.09	(0.09 - 0.1)	0.12	(0.09 - 0.15)	0.09	(0.08 - 0.1)	0.11	(0.1 - 0.11)
Sex								
Female	0.53	(0.51 - 0.56)	0.54	(0.51 - 0.57)	0.57	(0.54 - 0.59)	0.57	(0.56 - 0.58)
Marital Status								
Married/Cohabiting	0.55	(0.53 - 0.57)	0.39	(0.36 - 0.42)	0.47	(0.44 - 0.49)	0.57	(0.56 - 0.58)
Visited Doctor in Past 12 Months	0.91	(0.89 - 0.92)	0.64	(0.61 - 0.67)	0.88	(0.87 - 0.9)		--
Visited Doctor in Past 24 Months		--		--	--	--	0.95	(0.95 - 0.96)
Ever a Smoker[a]	0.42	(0.4 - 0.44)	0.45	(0.42 - 0.48)	0.34	(0.31 - 0.36)	0.57	(0.56 - 0.58)
Disability								
Difficulty on 1+ ADLs	0.16	(0.14 - 0.17)	0.16	(0.13 - 0.18)	0.14	(0.12 - 0.16)	0.17	(0.16 - 0.18)
NCD's								
Hypertension	0.50	(0.48 - 0.52)	0.42	(0.39 - 0.45)	0.59	(0.57 - 0.62)	0.59	(0.58 - 0.6)
Stroke	0.05	(0.04 - 0.06)	0.04	(0.03 - 0.05)	0.06	(0.04 - 0.07)	0.10	(0.1 - 0.11)
Cancer	0.07	(0.05 - 0.08)	0.02	(0.01 - 0.02)	0.07	(0.05 - 0.08)	0.18	(0.17 - 0.19)
Heart Attack/MI[b]	0.05	(0.04 - 0.06)	0.04	(0.03 - 0.05)	0.11	(0.1 - 0.13)	0.30	(0.3 - 0.31)
Diabetes	0.21	(0.19 - 0.22)	0.17	(0.14 - 0.19)	0.28	(0.25 - 0.3)	0.19	(0.18 - 0.19)
Arthritis	0.16	(0.14 - 0.18)	0.26	(0.24 - 0.29)	0.50	(0.47 - 0.52)	0.65	(0.64 - 0.66)
BMI								
<20	0.07	(0.05 - 0.08)	0.08	(0.06 - 0.1)	0.07	(0.06 - 0.08)	0.07	(0.07 - 0.08)
20-30	0.69	(0.67 - 0.72)	0.76	(0.73 - 0.79)	0.68	(0.65 - 0.7)	0.71	(0.7 - 0.72)
30+	0.24	(0.22 - 0.26)	0.15	(0.13 - 0.18)	0.25	(0.23 - 0.28)	0.21	(0.2 - 0.22)
Education								
0-6	0.82	(0.8 - 0.84)	0.89	(0.86 - 0.91)	0.47	(0.44 - 0.5)	0.05	(0.05 - 0.06)
7-11	0.08	(0.07 - 0.09)	0.08	(0.06 - 0.1)	0.21	(0.19 - 0.23)	0.22	(0.21 - 0.23)
12+	0.10	(0.08 - 0.11)	0.04	(0.03 - 0.05)	0.32	(0.3 - 0.34)	0.73	(0.72 - 0.73)
Income								
Public Pension[c]	0.63	(0.61 - 0.65)	0.14	(0.12 - 0.17)	0.98	(0.98 - 0.99)	0.99	(0.99 - 0.99)
Health Insurance								
Public	0.96	(0.95 - 0.97)	0.50	(0.47 - 0.53)	0.84	(0.82 - 0.86)	0.98	(0.97 - 0.98)
Private	0.02	(0.01 - 0.03)	0.03	(0.02 - 0.04)	0.14	(0.12 - 0.16)	0.01	(0.01 - 0.02)
None	0.02	(0.02 - 0.03)	0.47	(0.44 - 0.5)	0.02	(0.01 - 0.02)	0.01	(0.01 - 0.01)
Total Sample Size	2,480		3,530		2,880		10,492	
Proportion Proxy Respondents	0.16		0.12		0.09		0.08	

Notes:
All presented results use national-level sample weights.
a) Includes all individuals who report having smoked over 100 cigarettes in their lifetime
b) US sample (HRS) also includes wider range of heart conditions; this figure is not directly comparable across samples

Elderly individuals in Mexico and Costa Rica, and to a lesser extent Puerto Rico, had substantially fewer years of formal education than individuals in the US. Older adults in the US and Puerto Rico almost universally receive Social Security, while only 63% of Costa Ricans and 14% of Mexicans received a pension from the government at the first wave of data collection. Likewise, most individuals in the US and Puerto Rico are eligible for health insurance through Medicare, and almost all older individuals in Costa Rica receive health care from the CCSS. In Mexico, a much smaller proportion of individuals receive publically provided health insurance, and over 47% of individuals over 65 in the 2001 MHAS sample reported having no insurance. The proportion of individuals requiring the assistance of a proxy varied somewhat across the four samples, from a high of 16% in CRELES to a low of 8% in HRS.

Multi-State Transition Probabilities: To gain insight into the dynamics of old-age disability in these four populations, I model the underlying age-and gender-specific annual transition probabilities between disability states. Figure 1 illustrates the annual transition probabilities between active life, ADL disabled life, and death by sex, along with the 95% CIs (represented as the thin lines) based on bootstrap resampling. At older ages, particularly above age 85, confidence intervals around the point estimates grow quite large for Mexico, Puerto Rico, and Costa Rica, primarily as a result of limited sample sizes at these advanced ages. Transition probabilities from active life to ADL disability (Panel A) rise sharply with age, though there are substantial differences in the patterns across populations. Annual probability of disability onset doubles from age 65 to age 85 among both males and females in the US, Costa Rica, and Mexico, but increases only by 1.5 times in Puerto Rican females and males. This decreased rate may result from differences between data sources—the gap between waves of data

Figure 1: Annual transition probabilities between disability states in CRELES (CR), MHAS (MX), PREHCO (PR), and HRS (US) data.



Panel A displays the annual transition probabilities from active life to ADL disability, Panel B displays transition probabilities from ADL disability to active life, Panel C displays transition probabilities from active life to death, and Panel D displays transition probabilities from ADL disability to death.

collection in PREHCO was 3-4 years rather than 2 years (as in HRS, CRELES, and MHAS), which likely results in fewer observed transitions. This may result in somewhat downwardly biased estimates of DFLE from the PREHCO data compared to the other populations. In addition, Table S1 displays the regression coefficients estimated from Equation 1 for each country and transition. As would be expected given the variation observed in Figure 1, there is some significant variation in coefficients across countries, though directions of the coefficients for most transitions are similar across countries.

Annual probabilities of becoming ADL disabled are higher for women, following a widely established pattern in contexts where disability transitions have been studied (Crimmins, Kim & Sole-Auro 2011, Oksuzyan et al. 2010). Rates of recovery from ADL disability (Panel B) drop substantially with increasing age. By about 85, disabled individuals are more likely to die within the next year than to recover to disability-free life. Some variation between countries exists in these transition rates—probabilities of recovery are high in Mexico and low in Puerto Rico, but with increasing age these cross-national differences diminish.

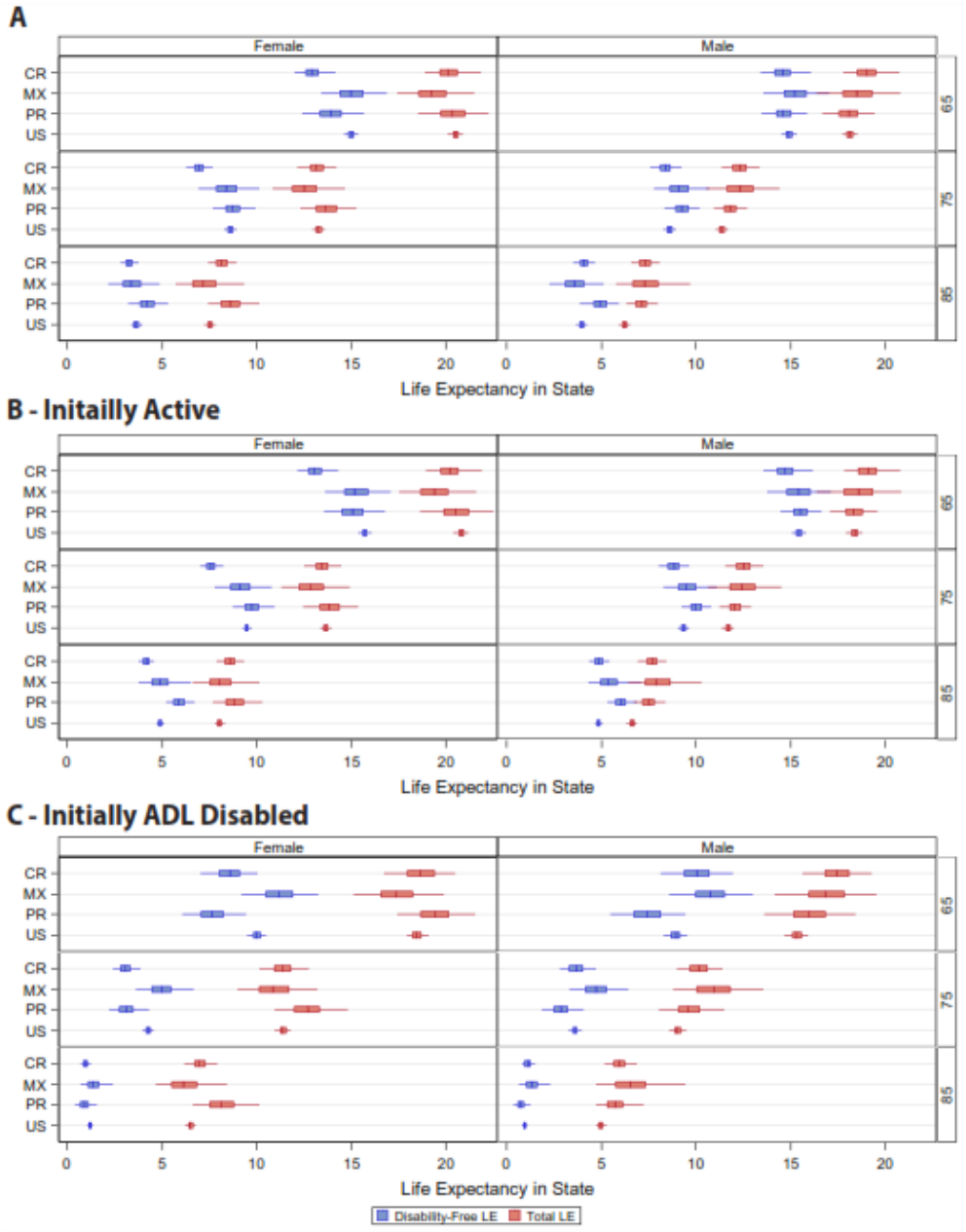
Mortality rates from active life (Panel C) and ADL disabled life (Panel D) provide evidence that disability has a strong association with mortality. Throughout later life, individuals with ADL disability have a higher mortality rate, and mortality rate estimates from disabled life are largely quite similar across countries. Point estimates for mortality from active status are higher for men than women at almost ages, though this difference is often within the confidence interval.

Life and Disability-Free Life Expectancies: Moving from the transition probabilities in Figure 1 to the corresponding life and disability-free life expectancies, Figure 2 translates the age-and sex-specific annual probabilities of transition between disability states into

years lived with ADL limitation. In Figure 2, lines represent the central 95% of the distribution of bootstrapped outcomes, and the boxes span the first to third quartile of the outcome distribution with a vertical line at the median. In addition to revealing remaining total life expectancy for the aging population, the microsimulation-based MSLT approach estimates the duration of remaining life expected to be spent disability-free with confidence intervals determined through bootstrap replication. Supplemental Table S2 provides the estimated life and health expectancies across these four populations, and supplemental Table S3 provides estimated life and disability-free life expectancies using listwise deletion rather than multiple imputation to account for missing data. Supplemental Table S4 tests an alternative parameterization of disability using difficulty on 2+ ADLs as a threshold; cross-national differences at ages 65 and 75 are again minimal in this parameterization, though due to small sample sizes DFLE for those aged 85 could not be estimated in all countries.

Figure 2A displays the total and disability-free life expectancy estimates for the full sample, regardless of initial disability status. Remaining total life expectancy at age 65 is about 20 years for females in each of the four countries, making the total life expectancy about 85 (these figures are about 18.5 and 83.5 for males). However, there is some country-to-country variation in expected longevity. Mexican females' life expectancy lags behind the US by about one year at age 65. Males have overall similar life expectancies across populations, with a few minor variations. A comparison of life expectancies from multiple life tables (Supplemental Figure S1) shows that the MSLT-based LE estimates from microdata may contain some upward bias in life expectancy compared to estimates from national vital statistics, though these differences are generally not substantial and within the 95% CI.

Figure 2: Estimated total and disability-free life expectancy.



This figure shows a comparison between the years an average individual will spend in remaining disability-free and total life at ages 65, 75, and 85 by country. Lines represent the central 95% of the distribution of bootstrapped outcomes, and boxes span the first to third quartile of the outcome distribution with a vertical line at the median. Panel A presents the DFLE and life expectancies of all individuals at ages 65, 75, and 85. Panels B and C presents the DFLE and life expectancies of individuals who were initially active (B) and ADL disabled (C) at ages 65, 75, and 85.

Moving to disability-free life expectancies, females aged 65 and 75 in Costa Rica expect to live about 1.5 fewer disability-free years compared than their counterparts in the US. A 65-year old female in Puerto Rico expects to live about one fewer year with ADL disability compared with her counterpart in the US, though these differences subside at later ages. For males, there are no substantial differences in DFLE across the four populations, though Costa Rican males expect to live about one year longer than US males at age 65. Proportion of remaining life spent free of ADL limitations is fairly stable across the four populations, a surprising finding given the variation in income, health infrastructure and expenditure, and health indicators between these four contexts. Females in Costa Rica expect to live slightly less of their remaining life disability-free at ages 65, 75, and 85 when compared to the US, but few other differences approach significance. Overall, males expect to spend about 10% more of their remaining life free of ADL disability at all ages when compared to females.

Though the unconditional life and disability-free life expectancies in Figure 2A provide an informative overview of the later-life disability conditions in each population, delving deeper into the life expectancies conditional on entry state (that is, conditional on being healthy or ADL limited at age 65, 75, or 85) provides a more detailed picture of late life disability patterns. Conditional DFLE estimates for those initially healthy (Figure 2B) and initially ADL limited (Figure 2C) provide strong evidence that initial disability status is strongly related to total LE and DFLE in later life. A healthy female at ages 65, 75, and 85 will expect to live, on average, about two additional years compared to 65-, 75-, and 85-year-old females with ADL limitations, and will spend a substantially smaller proportion of her remaining life with no ADL limitations. The gap between initially healthy and initially limited individuals is largest in Puerto Rico and Costa Rica, resulting from the low transition rates from ADL limitation to healthy life (observed in Figure 1). These

findings are of similar magnitude for males—males with no ADL limitations at ages 65, 75, and 85 live substantially longer lives than males with ADL limitations at these ages. Individuals with ADL limitations at age 85 expect to live almost their entire remaining life with ADL limitations.

Figure S2 provides the smoothed age-specific proportions in ADL-limited life in each population, as well as the proportions from the microsimulation-generated synthetic cohorts based on each population. The proportion disabled at each age in each sample (solid lines) are quite similar across countries, though the proportion disabled appears somewhat lower at older ages in Puerto Rico. The simulated data matches closely with observed proportions in each sample, suggesting that the proportion disabled by age in these populations has been fairly stable by cohort and period in recent decades.

4. DISCUSSION

The purpose of this article is to estimate and compare current levels of DFLE between the US and countries in LAC, and to gain insight into future disability trends in these populations. I use a microsimulation-based multi-state life table to analyze both the levels of disability by age and the dynamics of disability in later life. This investigation provides a wealth of information about the life course experience with disability in these aging populations, utilizing high-quality longitudinal data to observe and model patterns of transitions between disability-free and ADL disabled life. I compare the processes of functional limitation in three LAC populations with the US, estimating the prevalence of functional limitations and the transition rates between different disability states. Rates of transition into disability statuses differ substantially across the life course—rates of recovery from ADL disability decline very rapidly with age, and across populations individuals 85 and older are more likely to die within the next year than to recover to

disability-free life. Females in Costa Rica, Puerto Rico, Mexico, and the US expect to live about 20 additional years at age 65, and males expect to live about 18 additional years. Though total life expectancy for 65-year-old males and females in Costa Rica, Puerto Rico, and the US is similar, women in Costa Rica expect to spend slightly more of their remaining life with ADL disability. Across the four populations, women, on average, will live a higher proportion of their remaining live subject to disability compared to men.

The 65+ populations in Costa Rica, Mexico, and Puerto Rico were exposed to a vastly different set of epidemiological, nutritional, economic, and public health conditions than the 65+ population in the US, but these four populations are at near-parity in terms of DFLE. This is a surprising finding, and one that is not easy to interpret. Late-life health results from a complex interplay between early- and late-life sources, and there are likely counterbalancing effects occurring in these populations that lead to these overall similarities. In Costa Rica, Mexico, and Puerto Rico, high early-life mortality selection of weaker individuals has likely lead to smaller, but healthier, cohorts of older individuals. In the US, the proportion of individuals surviving to older ages is likely much higher, but these individuals have experienced higher rates of smoking and other poor health behaviors.

Though at present these forces are leading to similar levels of DFLE across these populations, the future trends of disability in LAC are still very much in question. Successive generations entering into later life have spent less and less time subject to poor epidemiological conditions in childhood and young adulthood, suggesting that disability conditions among LAC's elderly population may indeed improve in coming decades. However, in the thinking of (Palloni, Souza 2013), the rapid technological shifts in healthcare and public health programs in LAC in the 1930's-1950's led to reduced mortality selection and higher survival rates of individuals who were exposed to a heavy

burden of disease and nutritional deficits in early life. In this study, the youngest individuals from MHAS were born in 1936, in CRELES this figure is 1940, and in PREHCO this figure is 1937. Thus, only the very youngest individuals in my analyses were exposed to these technological advances in early life. Data from continuing rounds of MHAS and CRELES will be key to measuring and understanding whether a stagnation or reversal in LE and DFLE is happening in LAC.

Though the similarities in overall DFLE are remarkable, patterns of transitions between disability states vary fairly substantially across countries. These differences suggest that there may be fundamental differences in the underlying mechanisms driving the disability burden in each country. Future research is needed to disentangle how cross-national differences in early-life and late-life exposures may lead to these differential patterns of transition in and out of disability.

In evaluating the results from this MSLT estimation, several limitations need to be considered. Individuals who experience a health transition between waves of data collection in the four surveys used are assumed to experience only a single transition during the period between surveys, which likely misses shorter-term transitions between health statuses. The MSLT modeling approach is limited in incorporating time varying covariates, thus my analyses could not simultaneously model ADL disability and the underlying health conditions which may have resulted in these limitations. In common with other life-table based measures, health expectancy estimates assume stationary transition rates over time, and thus will not match the lived experience of any single cohort. My current analyses follow a first-order Markov chain, and are thus not state-duration-dependent—that is, transition probabilities are not adjusted by duration of stay in a given state. The HRS-style ADL questions utilized in this study do result in some ambiguity about whether the instrument is measuring underlying or residual disability

(Freedman 2000). Even though the questions asked were exactly the same across the four studied populations (aside from questionnaire translation), respondent interpretation may have varied across setting. Further research is needed to determine how strongly results from Mexico, Costa Rica, and Puerto Rico generalize to other similar contexts in Latin America.

The DFLE estimates presented here are based directly on individual-level reporting of ADL disability from nationally-representative panel surveys. This approach to calculating population-level health represents an approach that is substantially different than most other metrics of population health, such as those of the Global Burden of Disease (GBD) reports (Salomon et al. 2012, Vos et al. 2012). The DFLE results in this paper are a direct metric of the burden of disability experienced by individuals in these populations. This direct measurement of later-life health conditions contrasts with GBD's sequela-based estimates, where national-level burdens of individual diseases are summed up to estimate the total disability burden of a population.

Combined, these results suggest that at present, the growing elderly populations in Costa Rica, Puerto Rico, and Mexico are not experiencing a substantially higher burden of disability than the US. This parity in levels of disability is particularly important given that the elderly populations of Costa Rica, Mexico, and Puerto Rico lived many years exposed to poor childhood conditions and a very different epidemiological context than prevails in these countries today. Though these four populations are reaching similar levels of overall DFLE, they may be taking very different paths to this outcome. These analyses present a first step towards understanding how early-life and late-life conditions have affected current patterns of disability and DFLE in LAC, and how these countries compare to more developed contexts.

The Population-Level Impact of ART Rollout on Adult Health and Mortality in Rural Malawi

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INTRODUCTION

The reversal of the drastically increased adult mortality caused by the HIV pandemic in sub-Saharan Africa (SSA) through a large-scale roll-out of antiretroviral treatment (ART) is arguable one of the greatest global health successes in recent decades (Joint United Nations Programme on HIV/AIDS 2013). While life expectancy in the rest of the world continued to increase from the late 1980s through the 2000s, much of SSA saw reductions in life expectancy, with a particularly large rise in mortality among young and middle-aged adults (World Health Organization, 2014). Beyond the simple loss of life, these declines in life expectancy and massive burden of disease have had negative impacts on child survival, household income, availability of skilled labor, and work efforts (Barnett & Whiteside, 2006). The large-scale roll-out of ART in SSA has reversed these trends. ART works by interrupting the replication of the HIV virus, enabling an individual's immune system to recover to a functional state and, when utilized as prescribed, can improve survival to levels almost on par with the non-HIV infected (Mills et al., 2011). Starting in the early 2000s, access to ART through public-sector programs was greatly improved in SSA, often with support from international donors. Recent studies have started to document the success of these programs in terms of population-level declines in mortality (both HIV-related and all-cause) in South Africa (Bor, Herbst, Newell, & Bärnighausen, 2013; Larson et al., 2014), Malawi (Jahn et al., 2008), (S. Floyd et al.), and other countries in SSA (S. Floyd et al., 2012; Stoneburner et al., 2014).

An important limitation of this recent evidence about post-ART mortality change is that it is based exclusively on data obtained from populations enrolled in health and demographic surveillance sites (HDSS), with the notable exception of a small group of

studies based on aggregate-level data (Larson et al., 2014; Mwagomba et al., 2010; Stoneburner et al., 2014). Compared to the respective national population, HDSS populations are geographically concentrated, less socioeconomically and ethically heterogeneous, and often better-served by the health infrastructure (including but not restricted to ART services). Outside of existing geographically-specific HDSS sites, few individual-level estimates of ART's effect on all-cause mortality exist in SSA.

This paper uses a new and alternative approach, estimating the effect of ART availability in public clinics on population-level mortality and morbidity based on a geographically-dispersed sample in rural Malawi with substantial heterogeneity on ethnicity, religion, language, educational attainment, population density, and HIV prevalence. Specifically, we estimate age-specific mortality and morbidity among respondents and household/family members of respondents of the Malawi Longitudinal Study of Families and Health (MLSFH;(Kohler et al., 2014)). The MLSFH is a population-based sample, and the study population is not enrolled in a HDSS and has had only limited HIV testing and linkage-to-care.

As part of the MLSFH questionnaire, survey respondents reported on a detailed set of questions on the health and mortality of their resident and non-resident household/family members (see Supplemental Text 1). The MLSFH offered HIV voluntary testing and counseling services to primary respondents and their spouses in the 2004, 2006, and 2008 rounds of data collection, with referral to confirmatory testing at a local clinic for those with positive HIV results (Kohler et al., 2014), (Bignami-Van Assche et al., 2004). The MLSFH survey team did not interact directly with other members of the household roster, who comprise about 70% of the individuals in this study, with the exception of a small number of other household/family members who are also MLSFH respondents. This minimal health-related interaction with the sample population represents a

substantial difference from many HDSS sites, where interaction with the survey team is much more regular and population-wide exposure to HIV testing (and linkage to ART) is much higher (Asiki et al., 2013; Kasamba, Baisley, Mayanja, Maher, & Grosskurth, 2012; Mwita et al., 2007; Odhiambo et al., 2012; Tanser et al., 2008). In contrast, the MLSFH interviews respondents only once every two years, and only primary respondents and their spouses (representing only about 30% of observations in this study) are included in regular HIV testing. The MLSFH also had no part in the training, support, or management of ART provision, making the study population independent from the ART program that is being evaluated in terms of its effect on population-level mortality. This is in contrast to HDSS sites, where additional funds and training for ART provision above and beyond public financing are sometimes provided (Bor et al., 2013).

The advantage of our approach is that our estimates are obtained from a much more geographically-dispersed and socioeconomically more heterogeneous population than is the case in most HDSS-based studies that focus on study populations residing within specific areas with often above-average access to HIV testing and care. This increases our ability to generalize findings to the wider population in rural Malawi and other similar regions in South-Eastern Africa.

Our analyses focus on the health and mortality of individuals aged 15+, i.e., the adult ages most affected by HIV and the availability of ART, and compare all-cause morbidity and mortality between the period directly before ART became widely available (the period 2006-2008 in the MLSFH study areas) with all-cause morbidity and mortality after ART became available (the period 2008-2012 in our study areas). In addition to documenting the effect of ART-availability on age-specific mortality, we use adult life expectancy (LE) as a summary measure of the adult and old-age mortality conditions in this population. This measure summarizes age patterns of mortality across all adult and

old ages, and is the leading metric for comparing mortality conditions across populations.

Though multiple studies have investigated the success of introduction of ART services in reducing all-cause mortality (see above), relatively little is known about how ART introduction affects health and morbidity in SSA at a population level. To fill this gap, we utilize respondent-provided information about the health of all household members (see Supplemental Materials) to investigate how population morbidity changed after the widespread availability of ART in rural Malawi. The existing clinical research on physical health and self-care of individuals in ART regimens suggest that individuals on treatment undergo a strong recovery of physical health (Booysen, Van Rensburg, Bachmann, Louwagie, & Fairall, 2007; Fox et al., 2010; Stangl, Wamai, Mermin, Awor, & Bunnell, 2007). However, clinically-based results are not likely to represent the full range of treatment outcomes in the general population, and the limited follow-up of these studies (generally under 1 year) may lead to an overestimate of both the positive health effects of treatment and long-term treatment adherence (Beard, Feeley, & Rosen, 2009). There may also be spill-over effects, as ART reduces care-taking obligations and economic constraints on households, both of which may have positive effects on population health even for HIV-negative individuals. Population health may also be affected because ART is known to increase work efforts and economic outputs (Thirumurthy, Galarraga, Larson, & Rosen, 2012). These effects of the expansion of ART on population health have not previously been carefully documented in SSA.

A limitation of our data source is that we do not have information on HIV status for the individuals under study—HIV biomarkers were collected in 2006 and 2008, but only for the main respondents of the MLSFH. However, by using all-cause morbidity and mortality as our outcomes, we effectively capture both changes due directly to increased

access of HIV+ individuals to ART, as well as all possible spill-over effects of ART availability on the HIV-negative population due to reduced care-taking responsibilities and changes in health-behaviors as a result of reductions in mortality risk perceptions (Baranov, Bennett, & Kohler, 2012).

METHODS

STUDY DESIGN AND PARTICIPANTS

Our analyses are based on the Malawi Longitudinal Survey of Families and Health (MLSFH), a longitudinal study of the rural population in Malawi monitoring social, economic, and health conditions in one of the world's poorest nations. The study is based in three districts in rural Malawi: Rumphi in the north, Mchinji in the center, and Balaka in the south (Figure S1). While these rural regions are similar in terms of their overall epidemiological and subsistence-agriculture characterization (Guebbels & Bowie, 2006; NSO, 2002), these regions reflect the heterogeneity of rural Malawi. For example: Rumphi district is primarily Protestant, the Tumbuka ethnic group and language are dominant (Kohler et al., 2014; Trinitapoli & Regnerus, 2006), and knowledge of Chewa (Malawi's national language) is much lower than in other regions. Rumphi has the lowest population density of the three districts at about 35 people per square kilometer (NSO, 2012), the lowest prevalence of HIV(DHS, 2011; Obare et al., 2009), and the highest rates of educational attainment (Grant, 2008) . Mchinji district is almost equally divided between Catholics and Protestants (Kohler et al., 2014), and Chewa is the dominant ethnic group and language (Trinitapoli & Regnerus, 2006). Mchinji's rates of educational attainment and HIV prevalence place it between Rumphi and Balaka (DHS, 2011; Grant, 2008), while its population density is comparable to Balaka at around 140 persons per square kilometer (NSO, 2012). The sample in Balaka is comprised mostly of the Yao and Lomwe ethnic groups (Kohler et al., 2014). Both Yao and Chewa are spoken

commonly, and the population is primarily Muslim (Trinitapoli & Regnerus, 2006). Educational attainment is the lowest of the three studied regions, HIV prevalence is the highest (DHS, 2011; Obare et al., 2009), and the residents tend to be poorer than in Rumphi and Mchinji (Grant, 2008). Maize is the primary crop grown in all three regions, though tobacco is commonly grown as a cash crop in Rumphi (and, to a lesser extent, Mchinji), and cotton is grown as a cash crop in Balaka.

MLSFH respondents (N≈3,800) are evenly split among the three study locations and clustered in 121 villages. MLSFH rounds covering the complete study population were collected in 1998, 2001, 2004, 2006, 2008, and 2010. In 2012, the MLSFH focused on respondents age 45 and older. The MLSFH sampling methods and related relevant data collection procedures are described in detail in a cohort profile (Kohler et al., 2014). Comparisons of the MLSFH to the nationally-representative Malawi Demographic and Health Surveys (MDHS) and the Malawi Third Integrated Household Survey (IHS3) show that basic demographic characteristics closely match the rural population of Malawi (Kohler et al., 2014).

Using funds from the Global Fund to Fight AIDS, Tuberculosis, and Malaria, the Ministry of Health in Malawi began rolling out free ART to eligible individuals in 2004. The first state of this rollout was based out of hospitals and clinics in primarily higher-population-density areas. Round 2 of the ART rollout started in 2006, expanding the availability of ART to already-extant smaller clinics and health facilities throughout the country. In the distinctly rural sample included in the MLSFH, median distance of respondents to the nearest ART clinic was 27 kilometers up until mid-2007, which made access to ART difficult given the limited means of transportation of most MLSFH respondents (essentially most would have to travel by foot or bike) (Baranov & Kohler, 2014). ART clinics opened between August of 2007 and March of 2008, shortly before data

collection for the 2008 round of the MLSFH. By the time of the 2008 MLSFH, median distance to the nearest ART clinic for MLSFH respondents had dropped to 8.9 kilometers (Baranov & Kohler, 2014).

The prevalence of HIV is estimated at 11% among 15- to 49-y-old individuals in Malawi (8.9% for rural and 17.4% for urban areas) (DHS, 2011, UNAIDS, 2010). Analysis of HIV biomarkers collected as part of the MLSFH between 2004 and 2008 show that infection is widely distributed across adult ages. HIV prevalence among primary MLSFH respondents in 2010 is higher among men age 50-65 (8.9%) than men ages 15-49 (4.1%), and prevalence is 8.3% among women ages 15-49 and 5.4% among women aged 50-65, with steep declines after age 65 (Freeman & Anglewicz, 2012).

The study population for this study consisted of (a) MLSFH respondents and (b) individuals who were reported on the MLSFH household/family rosters by respondents in 2004, 2006, 2008, 2010, and 2012. However, the 2004 questionnaire used a somewhat different household roster questionnaire, so our primary results will focus on the 2006-2012 rounds of survey collection. In each wave, primary respondents completed a family and household roster module that asked respondents to list the following members of their family/household independent of place of residence and whether they are alive or have deceased: spouses, parents and parents-in-law, children, and other persons who slept in the household the previous night or who usually sleep in the household. For each listed person, the MLSFH respondents provided information on the name, age, sex, relationship to primary respondent, whether the individual was alive and, if not, how recently they had died, educational attainment, marital status, and several questions on the individual's health. More detail on the household roster module is included as Supplemental Text 1.

Individuals reported on the MLSFH family/household roster were not previously linked across survey rounds to allow longitudinal analyses—both the order of individuals on the roster, and possibly the spelling of names by interviewers, could differ across waves. To overcome this limitation, we developed an iterative probabilistic matching algorithm to match individuals across multiple waves of MLSFH data collection using information on name, age, sex, and relationship to respondent. The matching process is described in greater detail in the Supplemental Text 2. Match rates between successive waves were 76-82% in 2006-2010, and 92% in 2012, with rates for close family members (parents, children, spouses) substantially higher. The higher match rate in 2012 resulted from the fact that household rosters were pre-populated with information from the 2010 survey. Failure to link is unlikely to introduce biases in our analyses (see Supplemental Text 2 and Tables S1 and S2).

To account for the complex migration patterns observed in Malawi, our analysis population included all resident and non-resident family/household members aged 15 and older (including the respondent themselves) who were linked across at least two survey waves. To avoid duplicate records that result from both husband and wife reporting on the same family/household members, we limited our analysis sample to individuals listed by female primary respondents and male respondents without a co-resident spouse in the MLSFH sample. With these restrictions, our analyses sample consists of 9,586 individuals listed by 1,869 primary MLSFH respondents, contributing 33,103 person years of observation during the period 2006-12. Table S2 presents selected characteristics of the analysis sample. A total of 735 deaths were observed between the 2006 and 2012 in our study population.

STATISTICAL ANALYSIS

Trends in adult life expectancy in the pre –ART (2006-2008) and post-ART (2008-2010, 2010-2012) period in the MLSFH study areas were analyzed using the Kaplan-Meier estimator (Allison, 2010, Kalbfleisch & Prentice, 2011), with 95% confidence intervals calculated using the Greenwood pointwise confidence interval (Hall & Wellner, 1980). Life expectancies were calculated separately for the periods 2006-2008, 2008-2010, and 2010-2012 as the area under the survival curve at ages 15+. Adult life expectancy measures the *additional* years a 15-year old would expect to live if subjected to the prevailing pattern of age-specific mortality rates in the population. As such, it does not apply to the mortality conditions of an actual cohort of individuals in the population, but is a synthetic cohort measure that serves as a summary indicator of population mortality during a given period. We also report the median length of life conditional on survival to age 15 as the age at which the survival curve for each period reached .5.

To investigate possible drivers of life expectancy gains, we compared the change in age-specific mortality rates between the pre-ART and post-ART periods by several potential explanatory variables. To increase sample sizes and reduce variance, we compare data from 2006-2008 (the “pre-ART” period) to combined 2008-2010 and 2010-2012 data (the “post-ART” period. We estimated a model by 15-year age groups for the full sample, as well as separate models by age groups 15-44y, 45-59y, and 60+y stratified by region, sex, and years of education. We estimated rate ratios using Poisson regression, with log-exposure time as the offset.

We also investigated trends in reported health for individuals in our sample. In the 2006, 2008, 2010, and 2012 questionnaires, primary respondents were asked to rate the general health of each member of the household roster, with responses of “excellent”, “good”, “fair”, “poor”, and “very poor”. We dichotomized these responses into two categories: individuals reported as having “poor” or “very poor” health are classified as

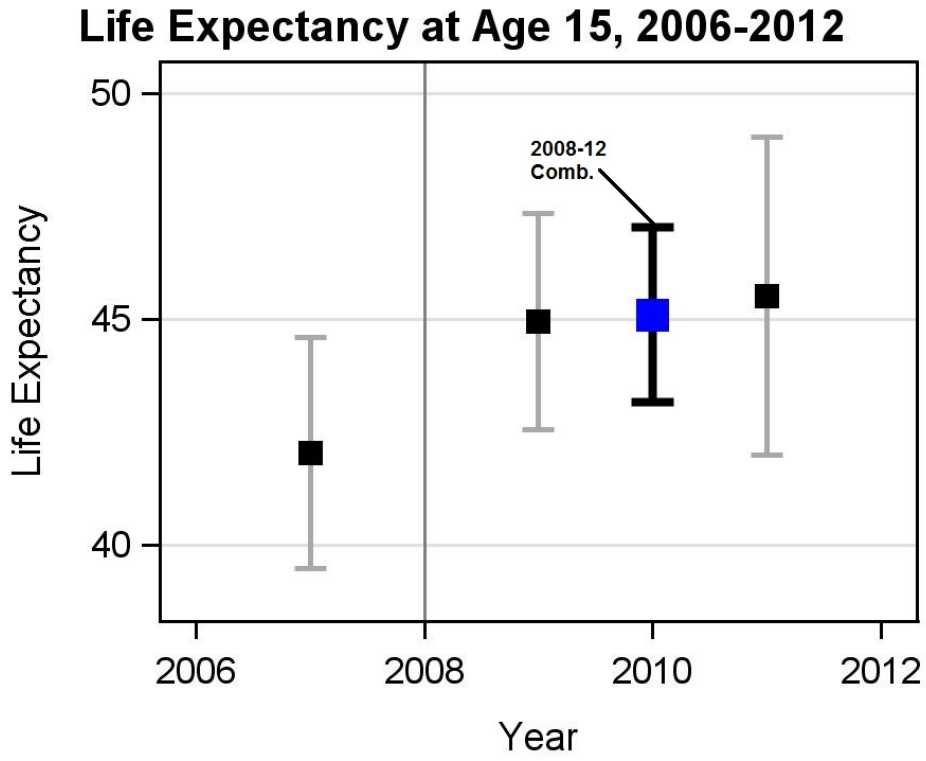
having *poor general health*. We use this measure to test whether population-level health improved after the 2008 rollout of ART to these regions. For the analysis of health, we restricted our sample to individuals living in the same traditional authority (a small geographic sub-region comprised of several closely interconnected villages ruled by a chief; there are 367 TAs in Malawi) as the primary respondent to increase the likelihood that primary respondents have current knowledge of the individual's health. We estimate the number of person-years lived with ill health by generating datasets in person-year format for each analysis period, assuming that individuals who moved between health statuses transitioned midway between survey periods. We divide the number of person-years lived with poor general health by the total number of person years lived for each period (2006-2008, 2008-2010, 2010-2012) and test for time trends using prevalence rate ratios.

RESULTS

a. Pre-Post ART Differences in Overall LE

Adult life expectancy (= LE at age 15) (Fig 1) before the introduction of ART (the period 2006-2008) was approximately 42 years in our study population (95% CI 39.4, 44.6), slightly below the 2010 GBD estimates for adult life expectancy in Malawi of 43.2y (Salomon et al., 2012). Adult life expectancy increased to approximately 45y (95% CI 42.5, 47.4) in the period directly after the introduction of ART (2008-2010), and was slightly higher in the following period (2010-2012) at 45.5y (95% CI 41.9, 49.1). The difference in life expectancy between the pre-ART period and the post-ART period (2008-2012 combined, LE 45.1y, 95% CI 43.1, 47.1) is highly statistically significant ($p<.01$). Life expectancies and 95% CIs for men and women separately are provided in Table S3. Sensitivity analyses using alternative definitions of the study population led to similar results (see Table S4).

Figure 1: Life Expectancy at Age 15, 2006-2012

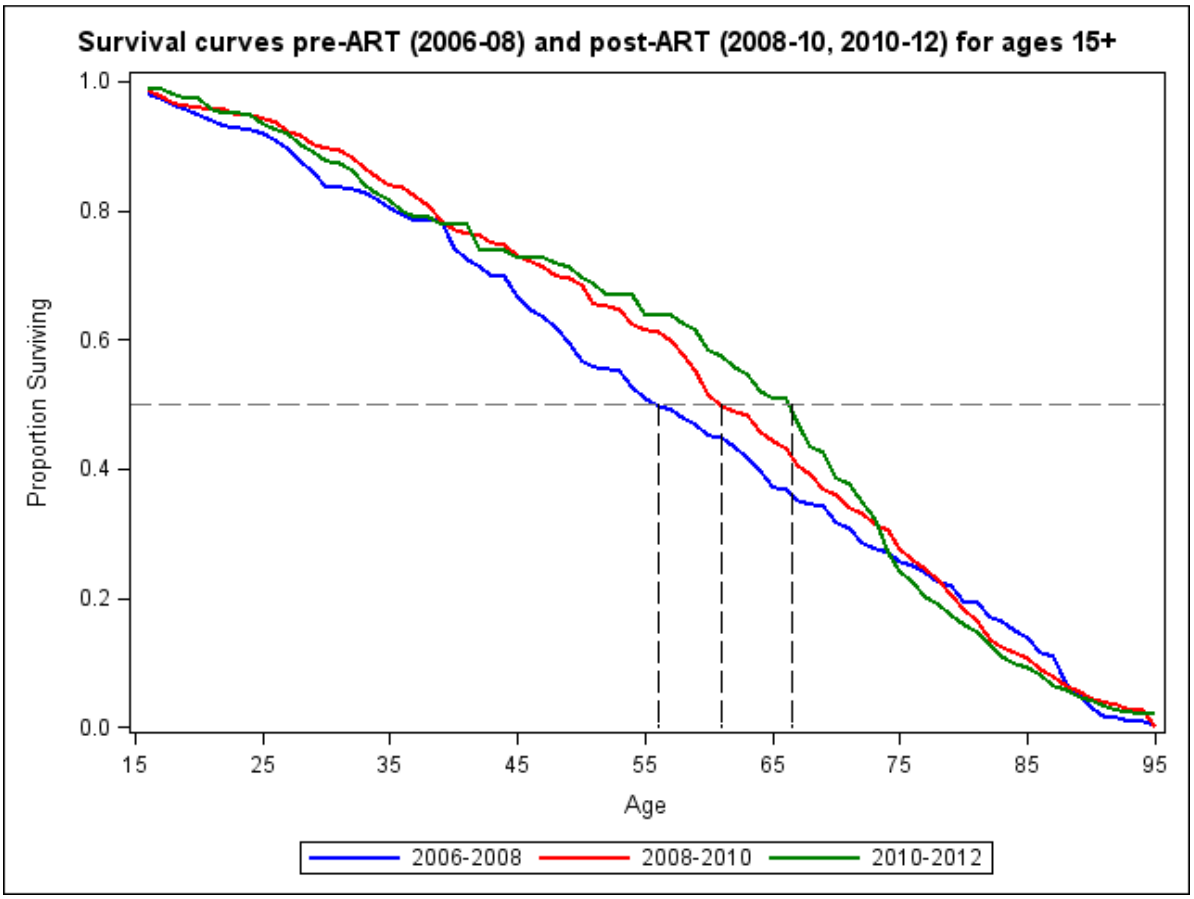


Notes: Life Expectancy at age 15 is the mean length of remaining life for a 15-year if subjected to the prevailing pattern of age-specific mortality rates observed during a given period of time. Estimates of life expectancy for the periods 2006-08, 2008-10, 2010-12, and 2008-12 combined are displayed as the squares, with 95% CIs. The timing of public-sector introduction of ART is shown using the grey vertical line.

Figure S2 (Supplemental Materials) replicates our analyses in Figure 1, but includes the 2004 MLSFH data and uses a restricted sample of individuals in the 2006-2012 surveys to correspond more closely to the household listing instructions of the 2004 MLSFH. Results suggest that LE declined from 2004 to 2008, consistent with the rise in mortality at the height of the HIV epidemic, and then began to increase after the introduction of ART to the study areas in 2008. This reversal of a declining LE trend after the introduction of ART is consistent with other studies of the population level effects of ART (Bor et al., 2013), but the limited size of this restricted sample leads to fairly wide 95% confidence intervals around our estimates.

Comparing the survival curves of the pre-ART and post-ART periods (Fig 2), the median length of life conditional on survival to age 15 rose by 11 years between 2006 and 2012, from 56 years (95% CI 51, 62) before the introduction of ART, to 61 years (95% CI 59, 65) in the period directly after the introduction of ART (2008-2010), to 67 years (95% CI 60, 70) in the period 2010-2012. For the post-ART period combined (2008-2012), median length of life conditional on survival to age 15 was 64 years (95% CI 60, 67). The survival curve moves outwards after the introduction of ART, though the divergence in the slope of the curves begins only around age 35 and continues until about age 55. After age 55, the survival curves run near-parallel, and they again converge in later life. Figure S3 displays the distribution of deaths at each age, using a life-table approach to account for possible differences in the age-distribution of the study population between waves. Reductions in deaths post-ART are evident in late middle age, from approximately ages 40-55y, and the distribution becomes substantially more right skewed after the introduction of ART in 2008.

Figure 2: Survival curves pre-ART (2006-08) and post-ART (2008-10, 2010-12) for ages 15+



Notes: Survival curves for pre-ART (2006-2008, blue line) and post-ART (2008-2010, red line, and 2010-2012, green line) periods. Conditional on survival to age 15, median age at death was 56y before the introduction of ART, rising after the introduction of ART to 61y in 2008-2010 and 67 in 2010-2012.

b. Pre-Post ART Differences in Mortality Rates

The all-cause mortality rate among those aged 15-59y declined by almost 30% between the pre-ART and post-ART periods (from 15.6 to 11.4 deaths per thousand, RR .73, 95% CI .59, .91), with the strongest declines in the 45-59y age group (Panel A of Table 1). At advanced ages (60+) these reductions subside. These changes in age-specific mortality rates share some similarities with previous studies of changes in mortality after the introduction of ART (Floyd et al., 2012; Floyd et al. 2010), though the effects of ART in this population are stronger in the middle and late middle age groups where HIV prevalence is highest (Freeman & Anglewicz, 2012).

Panel B in Table 1 shows that, among MLSFH study regions, mortality rates were highest in Balaka (where HIV+ prevalence is highest (DHS, 2011, Obare et al., 2009)) and lowest in Rumphi (where HIV+ prevalence lowest (Obare et al., 2009)), with Mchinji being in the middle. Despite these level differences, mortality rates declined in all three MLSFH regions (Panel B), albeit statistical significance of the decline is only obtained in one of the three sites (Mchinji) due to the reduction in sample size in these regional analyses.

Male mortality rates were substantially higher than female mortality rates in most age groups, and particularly over age 45 (Panel C). Declines in mortality are evident for both males and females (Panel C), with the strongest effects in the 45-59y age group for females and the 15-44y age group for males. However, similar to our regional analyses above, the decline in mortality is only statistically significant in the pooled male-female analyses (Panel A).

Reductions in all-cause mortality after the introduction of ART in the MLSFH study regions were strongest among more educated individuals (Panel D). Individuals aged

Table 1: Trends in mortality before and after introduction of ART to rural Malawi

	Pre ART (2006-2008)		Post ART (2008-2012)		Rate Ratio: Post/Pre		
Age	PY	Rate	PY	Rate	RR	95% CI	
A. Full Sample							
15-29	4362	10.1	7288	7.7	0.76	0.51	1.13
30-44	2902	13.1	4614	12.1	0.93	0.61	1.40
45-59	2697	27.1	4011	17.2	0.64	0.46	0.88
60-74	1941	35.5	2978	41.6	1.17	0.87	1.57
75+	807	78.1	1503	95.1	1.22	0.91	1.64
B. By Region[1]							
Mchinji							
15-44	2138	8.4	3093	9.4	1.11	0.60	2.13
45-59	785	29.3	1021	14.7	0.50	0.24	1.00
60+	633	45.8	1004	45.8	1.00	0.62	1.65
Balaka							
15-44	1955	18.9	2956	15.6	0.82	0.52	1.30
45-59	792	32.8	1221	23.8	0.72	0.41	1.28
60+	628	54.1	1139	69.4	1.28	0.85	1.98
Rumphi							
15-44	2045	8.3	3327	5.1	0.61	0.29	1.28
45-59	823	15.8	1412	8.5	0.54	0.22	1.28
60+	981	43.8	1540	57.1	1.30	0.90	1.92
C. By Sex							
Females							
15-44	3962	9.1	6356	10.4	1.14	0.75	1.77
45-59	1502	21.3	2374	11.8	0.55	0.32	0.95
60+	1368	32.2	2272	47.5	1.48	1.03	2.15
Males							
15-44	3302	13.9	5546	8.3	0.60	0.39	0.92
45-59	1195	34.3	1637	25.0	0.73	0.46	1.15
60+	1380	63.8	2209	72.0	1.13	0.86	1.48
D. By Level of Education							
Less than 5y of Education							
15-44	2495	17.2	4118	12.6	0.73	0.48	1.12
45-59	1370	23.4	1953	20.0	0.85	0.52	1.41
60+	1798	41.2	2977	56.8	1.38	1.04	1.84
5y or more of Education							
15-44	4769	8.2	7782	7.7	0.94	0.62	1.45
45-59	1310	27.5	2052	12.7	0.46	0.27	0.79
60+	888	42.8	1471	52.3	1.22	0.82	1.85

[1] Analyses by region use only individuals reported as primarily residing within that region

45-59 who completed 5 or more years of formal education experienced a strong and significant decline in mortality, while individuals with 4 or fewer years of completed education benefitted only from relatively small and statistically non-significant reductions in mortality rates. Pre-post differences were not significant for the 15-44y age groups for both the more and less educated.

c. Pre-Post ART Differences in Health

To understand how the introduction of ART may have affected population health, we compared the proportion of person-years spent with poor health in the pre-ART and post-ART periods. The percent of person-years lived in poor health declined substantially from the pre-ART period to the post-ART periods (Table 2, Panel A). Prevalence rate ratios comparing the 2008-10 and 2010-12 periods to the pre-ART period (2006-08) show that prevalence of poor health dropped by over 30% in ages 15-59 (from 60.3 to 40.2 person-years per thousand, RR .67, 95% CI .59, .75) (Panel B). Prevalence of poor health also declined in the age group 60-74, though there were no differences in the 75+ population.

As an extension of our analysis of mortality and health trends, we estimated the added years of life and healthy life associated with the introduction of ART to the study population. We compared observed changes in adult health and survival after the introduction of ART with a counterfactual scenario assuming that the population had been continuously exposed to the mortality rates and prevalence rates of poor health observed in 2006-2008. These rates provide a conservative counterfactual, as life expectancy would likely have continued to decline in the absence of ART (Fig. S2). In the study population, we observed 62 fewer deaths among those aged 15-59 in 2008-2012 than would be expected in the absence of ART, representing a decline of

Table 2: Person-years in poor health and prevalence rate ratios, pre- and post-ART

A) Percent of person-years lived with poor health, 2006-08 to 2010-12

	Pre-ART (2006-2008)		Post-ART (2008-2010)		Post-ART (2010-2012)	
Age	PY	% of PY in poor health	PY	% of PY in poor health	PY	% of PY in poor health
15-29	3822	3.4	3902	2.5	2024	1.9
30-44	2397	5.8	2466	4.1	809	4.7
45-59	2167	11.0	2187	7.4	1174	5.9
60-74	1300	26.4	1450	20.3	639	16.9
75-89	454	42.3	530	37.9	324	47.8

B) Prevalence rate ratios

	2008-10/2006-08			2010-12/2006-08			Post-ART/Pre-ART		
Age	Rate Ratio	95% CI		Rate Ratio	95% CI		Rate Ratio	95% CI	
15-29	0.72	0.55	0.95	0.57	0.39	0.82	0.67	0.52	0.86
30-44	0.71	0.54	0.93	0.82	0.55	1.18	0.74	0.58	0.94
45-59	0.67	0.55	0.83	0.54	0.40	0.70	0.63	0.52	0.75
60-74	0.77	0.66	0.90	0.64	0.51	0.80	0.73	0.63	0.85
75-89	0.90	0.73	1.10	1.13	0.91	1.41	0.99	0.82	1.18

approximately 25%. We also observed 254 additional years of healthy life among those aged 15-59 over what would be expected if the pre-ART prevalence of poor health continued unchanged, also representing a decline of about 25%.

DISCUSSION

Our analyses investigate the changes in life expectancy and health expectancies in Malawi during 2006—12 when ART was rolled out to rural parts of the country. These analyses, based on a representative sample of three heterogeneous rural regions in Malawi, capture the full population-level impact of the introduction of public-sector ART on adult life expectancy. Our estimates capture the direct effects of ART scale-up on the health and survival of HIV patients receiving ART, as well as spill-over effects on the health and mortality of people who are not on ART.

Using longitudinally-linked household roster information from a geographically dispersed, heterogeneous population with limited HIV testing and linkage-to-care, we document gains of 3.1 years of in adult life expectancy and 8 years of median length of life in the four years following the introduction of public-sector ART in rural Malawi. Though modest in comparison to the life expectancy gains in higher HIV settings (Bor et al., 2013), these increases are substantial for a population with an estimated 11% HIV+ prevalence rate. Moreover, these findings pertain to a geographically, demographically, and culturally more heterogeneous population than most HDSS populations on which prior estimates of the mortality change in response to ART were based.

We find evidence that mortality declined after the rollout of ART in all three regions covered by our data, despite differing HIV prevalence. Mortality declined among males and females, and more strongly among those with more formal education. Mortality declines were strongest in late mid-adult ages (45-59y), where a substantial fraction of the population is HIV+ (Freeman & Anglewicz, 2012), though reductions were evident for younger ages as well. The distribution of deaths (Fig. S3) suggests that there may be excess mortality among younger adults, and that additional gains in life expectancy are possible in this population.

We find that individuals in our sample experienced fewer years of poor health after the introduction of public-sector ART, and that these effects strengthened over time. To our knowledge, no other study has directly measured the impact of ART introduction on population-level health. The prevalence of ill health declined in all age groups 15-74 after the introduction of ART, and individuals aged 15-59 in this population spent over 25% fewer life-years with poor health in the four years after ART was introduced.

Although the reversal of the decline in life expectancy coincided with the scale-up of ART (Figs 1 & S2), our estimates may also capture health and mortality trends not linked to the scale-up of ART. As there is no counterfactual group in our analyses, we cannot directly identify the causal mechanism behind the observed mortality and morbidity declines. However, the coincidence of life expectancy increasing directly after the introduction of ART strongly suggests that the increased availability of ART was the primary driver of mortality decline. To our knowledge, no other major health interventions occurred during this time period. It is worth noting that these reductions in mortality occurred during a period of dramatic rises in food and oil prices, currency devaluation, political unrest, and reduced international aid in Malawi(Ellis & Manda, 2012; Wroe, 2012),

Combined, these results provide further support that the increased availability of ART in SSA is resulting in a substantial and sustained reversal of mortality trends, and leading to increases in both life expectancy and reductions in time spent in poor health. Our findings strengthen the body of evidence on the impact of ART, and helps assuage concerns that these reversals may not be occurring at the same magnitude outside of specific HDSS sites.

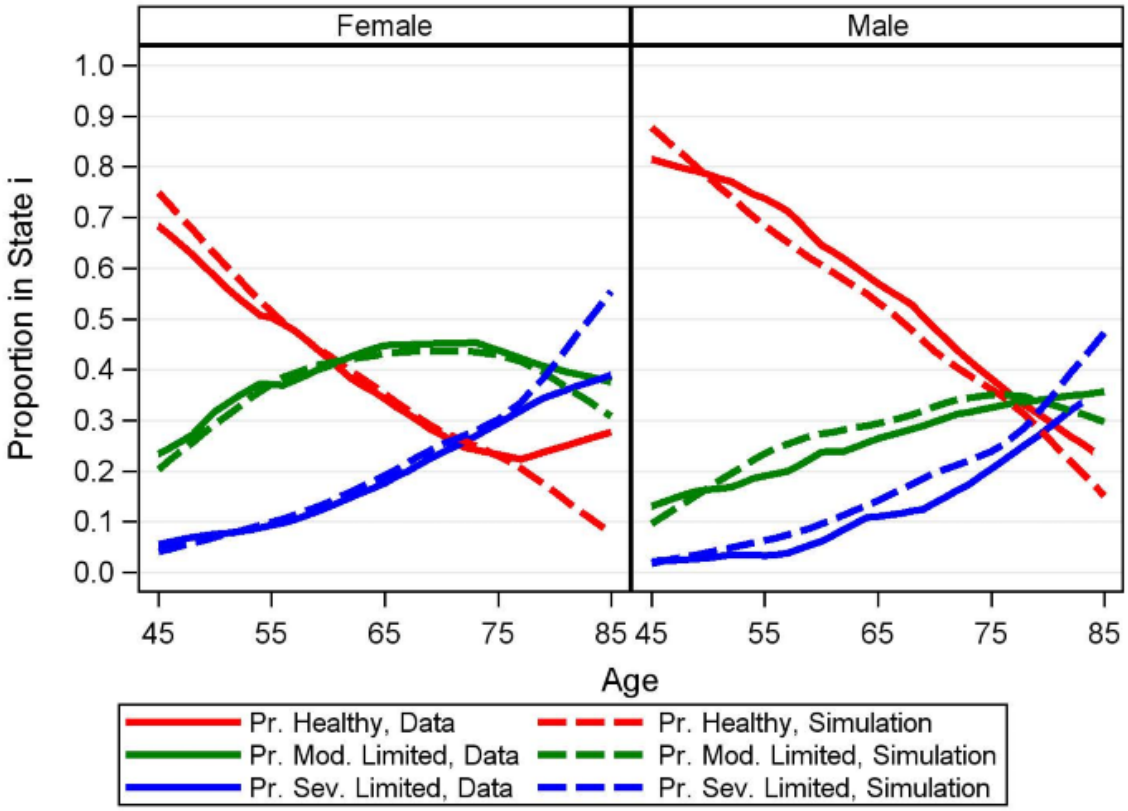
APPENDIX

Disability Transitions and Health Expectancies among Adults 45 Years and Older in Malawi: A Cohort Modeling Approach

Appendix Materials:

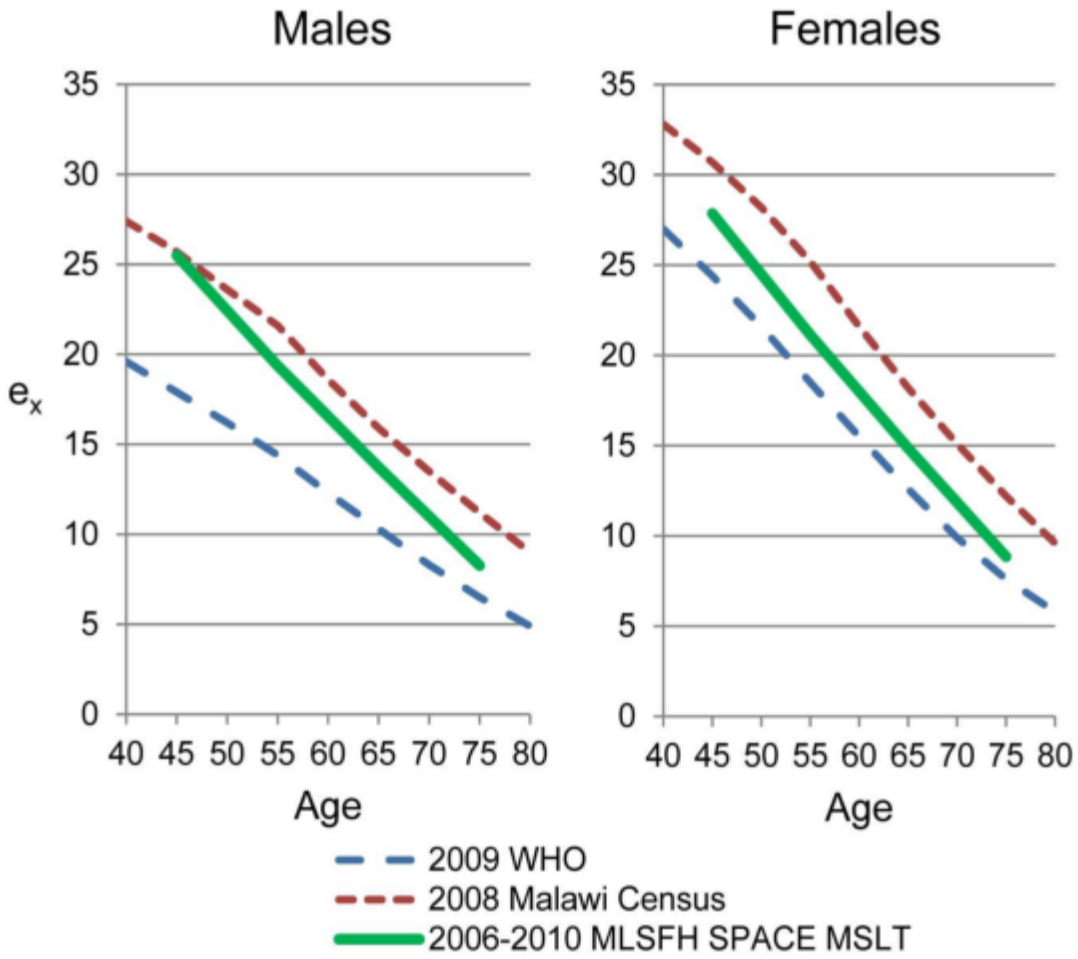
Figure S1: MLSFH study locations in Malawi.

Figure S2: Proportions in healthy, moderately limited, and severely limited status in MLSFH data and microsimulation cohort, by sex.



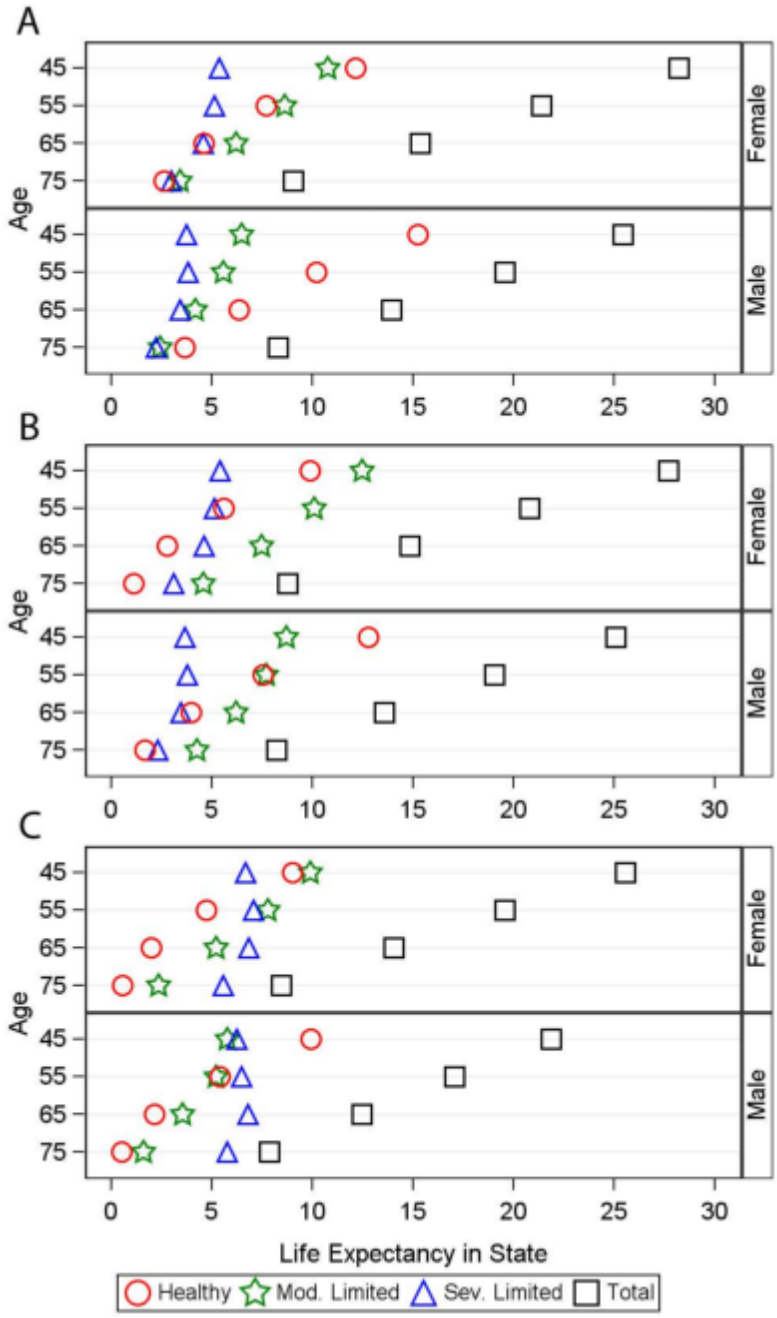
The figure shows a comparison between the age-specific proportions in each health status in both the MLSFH sample and the synthetic cohorts created through microsimulation. To smooth these data and gain an insight into the overall patterns of disability, we used a local non-parametric linear regression procedure (PROC LOESS) in SAS v9.3. Solid lines in this figure represent the proportions from the MLSFH data, and the dashed lines correspond to proportions from the microsimulation cohort.

Figure S3: Remaining life expectancy in various life tables, Malawi (males and females).



MLSFH life expectancies are estimated based on the 2006–10 MLSFH mature adult population using the microsimulation-based SPACE MSLT approach described in the main text. WHO life expectancy estimates for Malawi are estimated using model life tables that are calibrated using infant/child mortality levels [71]. 2008 Malawi Census life expectancy estimates are obtained from a life table combining estimates of infant and child mortality with age-specific mortality rates derived from household death data, adjusted for under-reporting of deaths [72].

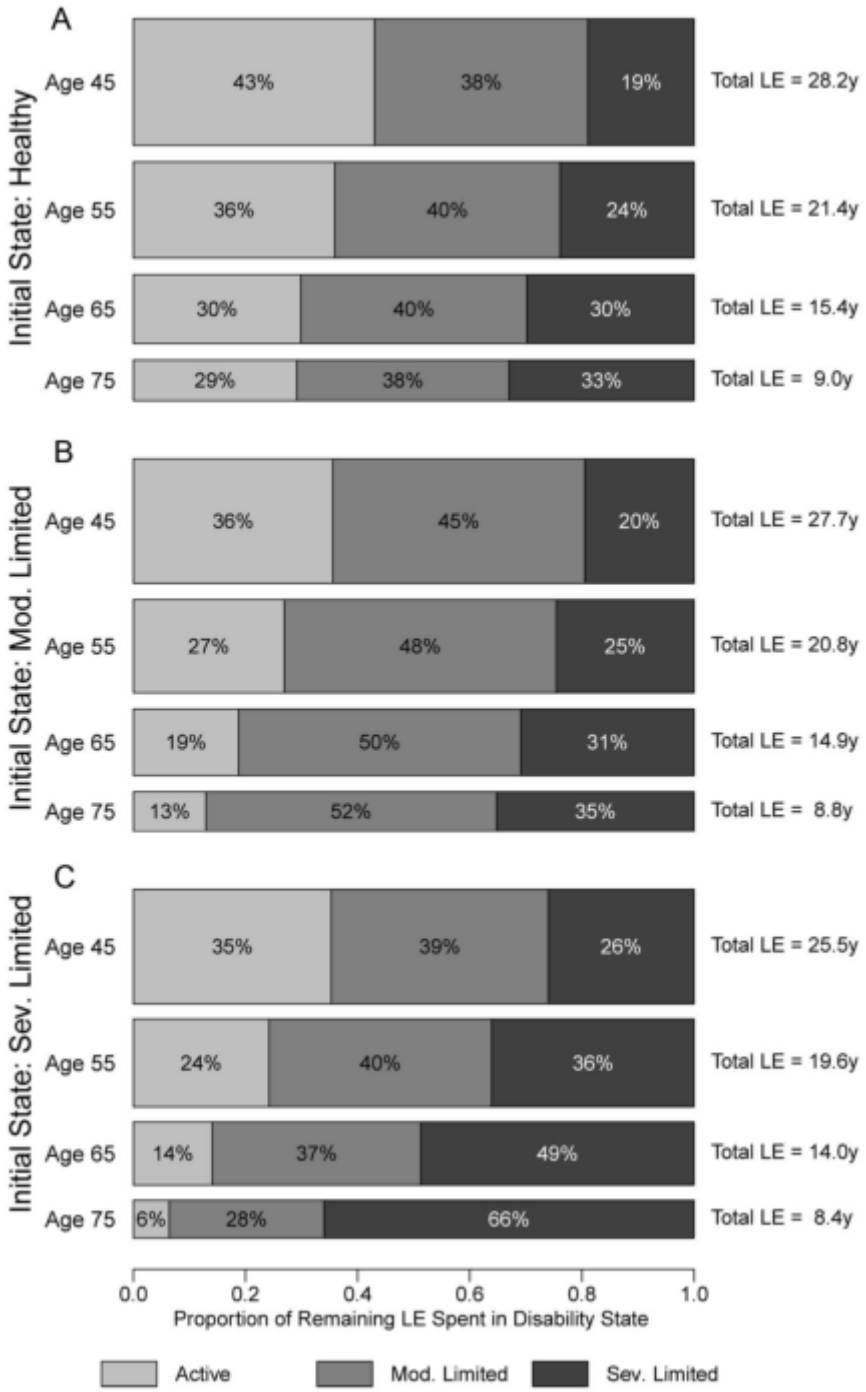
Figure S4: Average number of years of active, moderately limited, severely limited, and total life expectancy, conditional on initial disability status.



The graphs in this figure show a comparison between the number of years an average individual will spend in healthy, moderately limited, and severely limited life at age 45, 55, 65, and 75, **conditional** on initial disability status (that is, disability status at age 45, 55, 65, or 75 for the portion of the simulated synthetic cohort is either healthy (Panel A), moderately limited (Panel B) or severely limited (Panel C)). As in Figure 4, the markers represent the overall distribution of remaining life-years spent in each state, not the ordering of these life-years; individuals in our analysis can recover and relapse between disability states, so not all years of limitation are spent at the end of life. Differences in overall life expectancy between Panel (A), which conditions on all

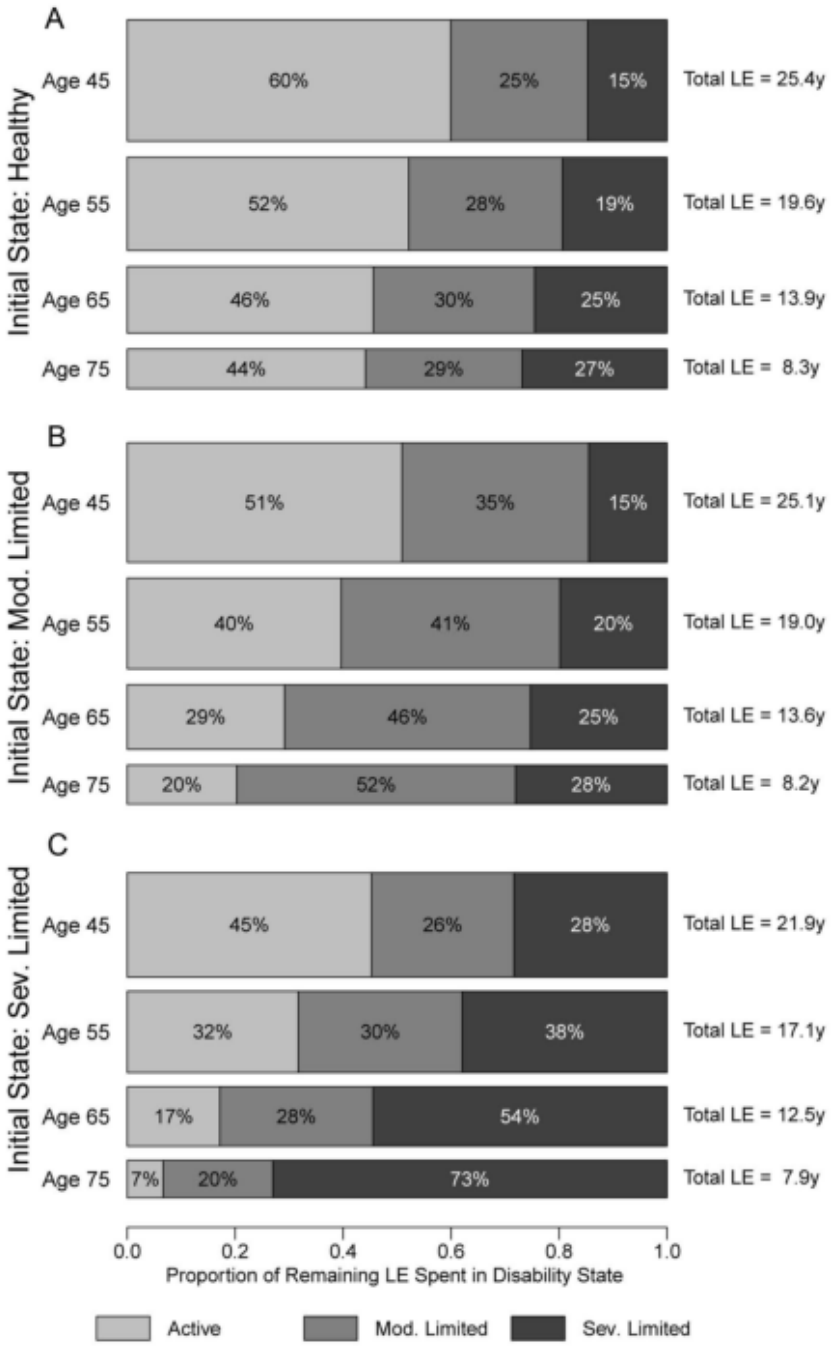
individuals being healthy at age 45, and Figure 4, in which members of the synthetic cohort have the full empirically observed distribution of disability states as shown in Table S4, are relatively small for cohorts beginning at age 45 or 55. This is due to two facts: first, at these ages a large fraction of the MLSFH population, and thus the initial health states of the simulated cohorts in Figure 4, are in the healthy state (see Table S4); and second, at these relatively young ages, the probability of recovering from a moderately limited or severely limited state are relatively high (Figure 3). Therefore, an initial moderately—and with lower probability, also a severely—limited state is likely to be transient. At older ages (i.e., a starting age of 65 and 75 years for the synthetic cohort), the differences between Figure 4 and Panel (A) increase as more individuals in Figure 4 enter the synthetic cohort with moderate or severe limitations, and these disabilities become increasingly persistent at older ages (Table S4 and Figure 3). Hence, conditioning on a healthy initial state in the synthetic cohorts (Panel A) implies that individuals live longer and live a larger fraction of their remaining life in the healthy or moderately limited state. Independent of the initial age (45, 55, 65 or 75) of the synthetic cohort, conditioning on an initial moderate or severe limitation (Panel B and C) implies that overall life expectancy of individuals in the synthetic cohort declines, and that individuals spend a larger fraction of their remaining lives (see Figures S5 and S6) in with moderately or severe functional limitations as compared to the synthetic cohort with the full observed distribution of disability states (as in Figure 4) or with only individuals initially in the health state (as in Panel A). This reduction in life expectancy, and the shift towards spending a larger fraction of the remaining life with disability as compared to Panel (A) and Figure 4, is most pronounced in Panel (C) where all members begin in a severely limited state.

Figure S5: Females: Distribution of remaining life expectancy (LE) by disability state (healthy, moderately limited, severely limited), conditional on the initial disability status for individuals in the synthetic cohort being either healthy (Panel A), moderately limited (Panel B) or severely limited (Panel C).



This figure shows the proportion of remaining life an average individual will spend in healthy, moderately limited, and severely limited life at age 45, 55, 65, and 75, conditional on the initial disability status for individuals in the synthetic cohort being either healthy (Panel A), moderately limited (Panel B) or severely limited (Panel C). The height and area of each bar is proportional to the overall remaining life expectancy of the synthetic cohorts with initial ages of 45, 55, 65 and 75 years, and the differently shaded areas represent the distribution of the remaining life expectancy across the three disability states: healthy, moderately limited and severely limited. The bars do not necessarily reflect the ordering of these life-years by disability states as individuals in our analysis can recover and relapse between disability states, so not all years of limitation are spent at the end of life.

Figure S6: Males: Distribution of remaining life expectancy (LE) by disability state (healthy, moderately limited, severely limited), conditional on the initial disability status for individuals in the synthetic cohort being either healthy (Panel A), moderately limited (Panel B) or severely limited (Panel C).



See notes to Figure S5

Table S1: Descriptive statistics for the 2010 MLSFH study population, and comparison of the MLSFH and the IHS3 (rural) sample characteristics.

	45–64				65+			
	MLSFH 2010		IHS3 2010–11		MLSFH 2010		IHS3 2010–11	
	N	%	N	%	N	%	N	%
Demographic and Socioeconomic Characteristics								
Male	327	44.7%	1,924	48.1%	151	46.9%	785	43.2%
Any education	522	71.4%	2,483	62.1%	198	61.5%	745	41.0%
Married	605	83.4%	3,071	76.8%	192	60.8%	914	50.3%
Religion								
Christian	447	61.2%	3,319	83.0%	184	60.5%	1,418	78.0%
Muslim	156	21.4%	441	11.0%	82	27.0%	241	13.3%
Other	134	18.4%	241	6.0%	47	15.5%	158	8.7%
Metal/tile roof	184	25.4%	1,253	31.3%	85	26.9%	537	29.6%
Health Indicators								
Functional limitations and disability state								
Moderate Limitation	239	32.7%	–	–	142	44.1%	–	–
Severe Limitation	64	8.8%	–	–	93	28.9%	–	–
ADL disabled	–	–	783	19.6%	–	–	895	49.3%
Average Age (45+)	61.0		59.8					
Total	731		4,001		322		1,817	

Notes:

(1) IHS3 data description:The Integrated Household Survey is one of the primary instruments implemented by the Government of Malawi through the National Statistical Office (NSO) roughly every 5 years to monitor and evaluate the changing conditions of Malawian households. The IHS data have, among other insights, provided benchmark poverty and vulnerability indicators to foster evidence-based policy formulation and monitor the progress of meeting the Millennium Development Goals (MDGs) as well as the goals listed as part of the Malawi Growth and Development Strategy (MGDS). The Third Integrated Household Survey (IHS3) was conducted by National Statistical Office (NSO) in March 2010-March 2011 [57]. A stratified two-stage sample design was used for the IHS3. The IHS3 sampling frame is based on the listing information and cartography from the 2008 Malawi Population and Housing Census (PHC); includes the three major regions of Malawi, namely North, Center and South; and is stratified into rural and urban strata. The rural subsample of the IHS3, which is used for the above analyses, includes residents from each of the 27 districts of Malawi, except those living in the urban centers of Lilongwe City, Blantyre City, Mzuzu City, and the Municipality of Zomba, and except for residents of the island of Likoma on Lake Malawi. The sampling frame excludes the population living in institutions, such as hospitals, prisons and military barracks.

(2) Health indicators: There are no directly comparable disability/health indicators in the MLSFH and IHS3. Functional limitations and disability states for the MLSFH are defined as follows: respondents who answered "somewhat limited" on either of the two MLSFH SF-12 question about physical limitations are classified as *moderately limited*, and respondents who answered "limited a lot" on either question are classified as *severely limited* (see text for a detailed description. *ADL disabled* in the IHS3 is defined as having difficulty in any one of the following five activities of daily living (ADLs): Seeing, hearing, walking, remembering/concentrating, self-care (bathing/dressing).

(3) Comparisons between the IHS3 and the MLSFH are based on IHS3 and the MLSFH unweighted samples. All differences between the MLSFH and IHS3, except for the proportion male for 45–64 and 65+ and proportion with a metal/tile roof above 65+, are significant ($p < .05$) according to chi-square tests.

Table S2: Regression analyses for associations between disability states and income earned, pain inference with work, dissatisfaction with life, and hours worked on farm.

Logistic Regressions	Odds Ratio	S.E.	χ^2	Pr > χ^2
Do something to earn income in past week				
Healthy (ref.)	1.00	–	–	–
Mod. Limited	0.95	0.08	0.10	0.76
Sev. Limited	0.49	0.13	7.62	0.01
Pain interfered with work in past 4 weeks				
Healthy (ref.)	1.00	–	–	–
Mod. Limited	4.93	0.08	89.67	<.001
Sev. Limited	11.76	0.15	65.49	<.001
Somewhat/very unsatisfied with life				
Healthy (ref.)	1.00	–	–	–
Mod. Limited	2.55	0.13	13.40	<.001
Sev. Limited	8.88	0.17	40.90	<.001
OLS Regression	Estimate	S.E.	t	Pr > $\|t\|$
Hours Worked on Own Farm in Past Week				
Healthy (ref.)	–	–	–	–
Mod. Limited	-0.96	1.20	0.80	0.42
Sev. Limited	-5.32	1.71	3.11	<.001

Notes: Estimates control for age, age2, and gender and account for clustering of standard errors at region and village levels.

Table S3: Distribution of observed transitions between disability states (healthy/ moderately limited/severely limited) during 2006–2010 (3 MLSFH waves).

Observed distribution among disability states (healthy/moderately limited/ severely limited) and death	Number of transitions	% among all transitions
Healthy at both interviews	682	41.5%
Healthy to moderately limited	283	17.2%
Healthy to severely limited	72	4.4%
Healthy to dead	30	1.8%
Moderately limited to healthy	180	10.9%
Moderately limited at both interviews	171	10.4%
Moderately limited to severely limited	61	3.7%
Moderately limited to dead	29	1.8%
Severely limited to healthy	21	1.3%
Severely limited to moderately limited	43	2.6%
Severely limited at both interviews	55	3.3%
Severely limited to dead	18	1.1%
Total	1645	100%

Notes: See text for definition of disability states; transitions are estimated from all individuals that are observed for at least 2 MLSFH rounds during 2006–10. See also Figure 2 describing the MLSFH study population for these analyses.

Table S4: Initial gender and functional status distribution for the synthetic cohorts (N = 100,000) used in the microsimulation as based on the MLSFH.

	Age 45		Age 55		Age 65		Age 75	
	N (MLSFH)	%	*N* (MLSFH)	%	*N* (MLSFH)	%	*N* (MLSFH)	%
Female	673	55.1%	432	49.2%	211	48.2%	131	55.3%
Healthy	427	63.4%	205	47.5%	59	28.0%	31	23.7%
Moderately limited	199	29.6%	174	40.3%	97	46.0%	56	42.7%
Severely limited	47	7.0%	53	12.3%	55	26.1%	44	33.6%
Male	548	44.9%	446	50.8%	227	51.8%	106	44.7%
Healthy	451	82.3%	309	69.3%	123	54.2%	28	26.4%
Moderately limited	86	15.7%	112	25.1%	71	31.3%	46	43.4%
Severely limited	11	2.0%	25	5.6%	33	14.5%	32	30.2%

Notes: The distribution of disability states (healthy/moderately limited/severely limited) is within each gender, while the gender distribution is the fraction male (female) in the synthetic cohort. The synthetic cohort has a size of 100,000, and the *N* reported in the above table pertains to the MLSFH. Gender and functional limitation distributions are estimated from the MLSFH based on 10-year age intervals, that is, the sex and disability apportionment of the microsimulation cohort of 45-year-olds is based on the sex and limitation characteristics of individuals 45–54 in the MLSFH analysis sample.

Table S5: Microsimulation-estimated average remaining life expectancy (LE) at ages 45–75, by sex, with imputed missing data using multiple imputation by chained equations [67, 68].

Age	45		55	
	LE	95% CI	LE	95% CI
Female				
Life Expectancy	**25.93**	(23.45–30.77)	**20.24**	(18.16–24.46)
Healthy	**10.36**	(9.23–12.23)	**6.43**	(5.45–7.87)
Mod. Limited	**10.21**	(8.82–12.79)	**8.64**	(7.36–10.84)
Sev. Limited	**5.35**	(4.21–6.83)	**5.17**	(4.01–6.65)
Male				
Life Expectancy	**23.29**	(21.30–26.58)	**18.38**	(16.60–21.34)
Healthy	**11.64**	(10.53–13.21)	**7.57**	(6.63–8.83)
Mod. Limited	**7.68**	(6.59–9.26)	**6.79**	(5.75–8.35)
Sev. Limited	**3.97**	(3.07–5.24)	**4.01**	(3.05–5.34)
Age	**65**		**75**	
	LE	95% CI	LE	95% CI
Female				
Life Expectancy	**14.71**	(13.29–19.61)	**9.00**	(8.30–14.63)
Healthy	**3.87**	(3.08–5.18)	**2.27**	(1.66–3.43)
Mod. Limited	**6.25**	(5.23–8.87)	**3.79**	(3.03–6.93)
Sev. Limited	**4.58**	(3.59–6.25)	**2.93**	(2.36–4.53)
Male				
Life Expectancy	**13.62**	(12.33–16.05)	**8.52**	(7.74–13.60)
Healthy	**4.91**	(4.11–5.98)	**2.75**	(2.05–3.94)
Mod. Limited	**4.98**	(4.11–6.39)	**3.36**	(2.58–6.29)
Sev. Limited	**3.72**	(2.83–4.95)	**2.40**	(1.85–3.76)

Notes: Estimates were obtained from synthetic cohorts of 100,000 45-, 55-, 65-, and 75-year olds created via microsimulation, based on observed transition rates from 2006–2010 MLSFH data. Missing values were imputed using multiple imputation by chained equations [67, 68]. The multiple imputation models included fixed effects for region and village, the full set of SF-12 questions, and data on income, time use, age, ethnicity, religion, gender, number of children, HIV status, and education. 20 datasets with imputed functional status and mortality outcomes for attrittors were generated. The multiple imputation analyses in this table provide results that are in close agreement with those obtained without multiple imputation (Table 2), with the primary difference being that the multiple-imputation models estimate a slightly shorter healthy life expectancy for males at age 45 and 55, and a slightly shorter total life expectancy for both sexes at age 45. None of these differences affect the substantive conclusions obtained from our analyses.

Table S6: Microsimulation-estimated average remaining life expectancy (LE) at ages 45–75, by sex, using a 2-level classification of disability (healthy vs. limited).

Age	45		55	
	LE	95% CI	LE	95% CI
Female				
Life Expectancy	**27.47**	(24.54–30.43)	**20.83**	(18.33–22.87)
Healthy	**14.56**	(12.99–15.92)	**8.95**	(7.63–10.10)
Limited	**12.91**	(11.00–14.85)	**11.88**	(10.07–13.82)
Male				
Life Expectancy	**25.03**	(22.02–28.23)	**19.06**	(16.44–21.34)
Healthy	**16.24**	(14.61–18.32)	**10.65**	(9.24–12.05)
Limited	**8.79**	(6.76–10.77)	**8.41**	(6.70–10.43)
Age	**65**		**75**	
	LE	95% CI	**LE**	95% CI
Female				
Life Expectancy	**14.61**	(13.01–16.29)	**8.72**	(8.09–9.94)
Healthy	**4.54**	(3.50–5.62)	**2.62**	(1.98–3.64)
Limited	**10.07**	(8.71–11.91)	**6.11**	(5.45–7.61)
Male				
Life Expectancy	**13.55**	(11.57–15.73)	**8.22**	(7.36–9.49)
Healthy	**6.06**	(4.80–7.21)	**3.50**	(2.74–4.21)
Limited	**7.49**	(6.24–9.36)	**4.72**	(3.97–5.90)

Notes: Estimates were obtained from synthetic cohorts of 100,000 45-, 55-, 65-, and 75-year olds created via microsimulation, based on the observed transition rates from 2006-2010 MLSFH data. Disability classification is based on MLSFH questions (*i*) "Do you have any health problems that limit you in carrying out moderate activities?" and (*ii*) "Do you have any health problems that limit you in carrying out strenuous activities?", with each question providing a list of moderate/strenuous activities and response categories being "not limited", "limited a little" and "limited a lot". Individuals who indicate that they had no functional limitations in either set of activities are classified as *healthy*, those who respond "limited a lot" or "limited a little" on *moderate activities* or "limited a lot" on strenuous activities are classified as *limited*.

Table S7: Microsimulation-estimated average remaining life expectancy (LE) at ages 45–75, by sex, using a classification of disability based on pain interfering with daily work activities.

Age	45		55	
	LE	95% CI	LE	95% CI
Female				
Life Expectancy	**27.44**	(24.66–38.47)	**22.17**	(18.74–34.91)
Healthy	**9.75**	(8.50–13.21)	**6.40**	(4.83–9.56)
Mod. Limited	**11.80**	(10.11–17.28)	**9.61**	(7.90–15.63)
Sev. Limited	**5.88**	(5.04–8.45)	**6.08**	(4.78–9.41)
Male				
Life Expectancy	**25.75**	(23.01–31.76)	**20.62**	(17.58–27.28)
Healthy	**13.02**	(11.43–15.37)	**9.07**	(7.47–11.49)
Mod. Limited	**9.24**	(7.65–12.63)	**7.95**	(6.46–10.79)
Sev. Limited	**3.49**	(2.49–5.04)	**3.57**	(2.51–5.43)
Age	**65**		**75**	
	LE	95% CI	LE	95% CI
Female				
Life Expectancy	**14.50**	(13.18–27.81)	**8.55**	(8.12–16.61)
Healthy	**3.40**	(2.49–6.23)	**1.70**	(1.16–2.91)
Mod. Limited	**6.39**	(5.33–13.12)	**3.68**	(2.93–7.42)
Sev. Limited	**4.71**	(4.07–8.39)	**3.18**	(2.82–5.81)
Male				
Life Expectancy	**14.07**	(12.44–22.00)	**8.32**	(7.61–15.09)
Healthy	**5.51**	(4.44–8.02)	**2.58**	(1.77–4.13)
Mod. Limited	**5.44**	(4.45–9.46)	**3.47**	(2.77–6.98)
Sev. Limited	**3.13**	(2.40–4.91)	**2.26**	(1.71–3.9)

Notes: Estimates were obtained from synthetic cohorts of 100,000 45-, 55-, 65-, and 75-year olds created via microsimulation, based on the observed transition rates from 2006-2010 MLSFH data. Disability classification is based on the MLSFH question "During the past 4 weeks, how much did pain interfere with your normal work (including both work outside the home and housework)?" Individuals who reported no limitations on work caused by pain in the past 4 weeks are categorized as *healthy*, individuals who report "a little bit" or "moderate" limitation are categorized as moderately limited, individuals reporting that pain limited their work activities "quite a bit" or "extremely" are categorized as *severely limited*.

Table S8: MLSFH study population 1998–2010.

	1998	2001	2004
Number of respondents	2,602	2,548	3,298
Age range (females)	15–49	18-52	15–55
HIV prevalence	—	—	6.4%
Attrition rate	—	14.9%	21.6%
Attrition due to:			
–migration	—	75.6%	58.4%
–mortality	—	13.0%	10.4%
–other factors	—	11.4%	31.2%
	2006	**2008**	**2010**
Number of respondents	3,669	4,052	3,790
Age range (females)	17–57	17–92	20–89
HIV prevalence	7.4%	8.9%	—
Attrition rate	19.8%	23.6%	25.6%
Attrition due to:			
–migration	62.5%	57.9%	56.0%
–mortality	6.3%	7.5%	8.8%
–other factors	31.2%	34.6%	35.0%

Notes: Number of respondents is the number of successfully completed MLSFH survey interviews. HIV prevalence in this table is calculated by starting with all HIV positive respondents in the current wave and imputing HIV positive respondents from a prior wave if the HIV positive respondent didn't accept HIV testing in the current wave. HIV positive respondents are significantly more likely to refuse HIV testing in future waves. The attrition rate is the percentage of MLSFH respondents who were successfully interviewed in the previous wave but not interviewed in the current wave. Migration is the most common reason for attrition among MLSFH respondents.

Additional Text:

Text S1. MLSFH sampling methods and related relevant data collection procedures

MLSFH Project Description

The ***Malawi Longitudinal Study of Families and Health*** (MLSFH) is a collaboration of the University of Pennsylvania with the College of Medicine and Chancellor College at the University of Malawi. The MLSFH continues earlier research under the ***Malawi Diffusion and Ideational Change Project*** (MDICP). The goal of the MLSFH is to (1) *collect longitudinal data* in rural Malawi that provide a rare record of more than a decade of demographic, socioeconomic and health conditions in one of the world's poorer countries, and (2) *analyze* these data to investigate the multiple influences that contribute to HIV risks in sexual partnerships, the variety of ways in which people manage risk within and outside of marriage and other sexual relationships, the possible effects of HIV prevention policies and programs, and the mechanisms through which poor rural individuals, families, households, and communities cope with the impacts of high AIDS-related morbidity and mortality. For this purpose, the MLSFH has collected longitudinal social science and biomarker data for individuals, families and households on *household structure and family change* (longitudinal household/family rosters, marriage and partnership histories), *human capital* (health, schooling, nutritional status), *sexual behaviors* (sexual relations, HIV/AIDS risk behaviors and prevention strategies), *subjective expectations and well-being* (SF12 module, subjective well-being, HIV risk perceptions, probabilistic expectations about mortality and HIV infection risks), *household production and consumption* (standard of living, time use, migration and remittances, productivity), and *social capital* (social networks, intrafamilial/intergenerational and community transfers, social participation) and *mortality and migration* of MLSFH participants and family members. The MLSFH has conducted repeated *HIV testing and counseling (HTC)*, and has collected data on *anthropometrics* (height, weight and BMI) as well as selected biomarker-based indicators of health (CRP, HDL, LDL and others). Since 2004 the MLSFH data are geocoded. MLSFH data also include linkages between spouses

(updated at each round), parent-children linkages, and longitudinal linkages of children listed on the family and household roster. The data collection and research conducted by MLSFH has been approved by the IRB at the University of Pennsylvania and, in Malawi, by the College of Medicine Research Ethics Committee (COMREC) or the National Health Sciences Research Committee (NHSRC). The initial sampling for the MLSFH, and the repeated refreshments of the MLSFH sample are described below, as are some essential fieldwork procedures relevant for this study. The present study is based on the subset of mature adults in the MLSFH, ie., the subset of MLSFH participants who are age 45 and older.

MLSFH Study Areas: The MLSFH is based in three districts in rural Malawi that have been the study sites since 1998: Rumphi in the north, Mchinji in the center, and Balaka in the south. In all of these three regions, the primary source of livelihood for MLSFH respondents is subsistence agriculture, augmented with small-scale trade of agricultural products and other goods. Transportation networks are relatively rudimentary with paved primary roads and generally unpaved secondary roads. Marriage is relatively universal in these rural Malawian regions, with more than 96% of women having ever married by age 25–29, and more than 95% of men having ever married by age 30–34 [1]. While the broad demographic, socioeconomic and epidemiological conditions are fairly similar across the three MLSFH study regions, and also across other parts of rural Malawi, some noteworthy differences across the MLSFH regions include the following. Rumphi District, located in the northern region of the country, follows the patrilineal system of kinship and lineage where residence is ideally patrilocal, inheritance is traced through sons, and parents of a groom pay bridewealth. The northern district, inhabited primarily by Tumbukas, is predominantly Protestant. Mchinji District, located in the central region, follows a less rigid matrilineal system whereby residence may be matrilocal or patrilocal. The Center is primarily inhabited by Chewas, with almost equal proportions of Catholics and Protestants. Balaka District, which is located in the southern region, is primarily inhabited by Lomwes and Yaos and has the highest proportion of Moslems. The region follows a matrilineal system of kinship and lineage system where

residence is ideally matrilocal, although it is not uncommon for wives to live at least some period of time in their husband's village. The Balaka region also exhibits a lower age of sexual debut and larger numbers of lifetime sexual partners than the other MLSFH study regions, and residents tend to be less educated and poorer than those living in the north, leading to higher levels of migration. HIV/AIDS prevalence in the southern region is significantly higher than in the northern and central region.

Initial MLSFH Sample: The original 1998 MLSFH target sample was 500 ever-married women age 15–49 in each district, plus their husbands (for additional information, see http://malawi.pop.upenn.edu/malawi-documentation-sampling). The sampling strategy adopted for the three districts differed in order to permit comparison with earlier surveys. In Mchinji and Rumphi districts the sample was designed to cover Census Enumeration Areas (CEAs) included in the 1988 Traditional Methods of Child Spacing in Malawi (TMCSM) survey. However, since the TMCSM sampled women regardless of their marital status, the CEAs included in the TMCSM survey had fewer ever-married women than the MDICP target sample of 500 women in each district. Three neighboring CEAs covered by the 1988 survey were thus added to the MLSFH Round 1 sample. In each district a cluster sampling strategy was used in all villages in the selected CEAs. Household lists of those normally resident in those villages were compiled during the week prior to fieldwork, and a sample of eligible women was then randomly selected. Since villages varied in size, sampling fractions were inversely proportional to village populations, such that a higher proportion of eligible women in the smaller villages was sampled. In Balaka district, a somewhat different procedure was followed to allow the evaluation of a Community Based Distribution (CBD) initiative that was conducted in this area at the time, following an earlier baseline survey conducted by the German aid agency GTZ with 1098 women and men in 1993. A random subset of 4/7 of the CBD villages and 5/11 of the non-CBD villages from this study were selected as MLSFH study villages. A random 1 in 4 sample of women of reproductive age (1549) and their husbands was then drawn from these villages to yield a target sample of 500 women and

their husbands. To further increase the number of MLSFH respondents who participated in the 1993 GTZ survey, an additional 260 women and 125 men were randomly drawn from the GTZ sampling lists (divided equally between the CBD and non-CBD areas) and enrolled in the MLSFH. In total, across all three regions, the MLSFH Round 1 in 1998 enrolled a sample of slightly more than 1,500 ever-married women aged 15–49 and close to 1,100 of their spouses residing in about 120 study villages (Table S8).

MLSFH Respondent follow-up, migration and vital status: The MLSFH returned to the study areas in 2001, 2004, 2006, 2008 and 2010 to reinterview the MLSFH study population. For this purpose, the MLSFH maintained a respondent database that contained previously collected identifying information for each respondent (respondents name, compound name, village name and GPS coordinates, etc.). Using this existing identifying information, MLSFH interviewers attempted to contact and reinterview MLSFH participants in each of the follow-up years. If MLSFH participants were absent at the first interviewer visit, up to two additional follow-up visits were made. Except for a migration follow-up study in 2007, which is not part of the present analyses, MLSFH respondents were not followed if they had migrated outside of the MLSFH study villages. However, they remained in the MLSFH sampling frame, and were interviewed at subsequent MLSFH waves if they returned to the MLSFH study villages (as is common since a significant amount of migration is labor-related and thus temporary). On average, the MLSFH succeeded in re-interviewing between about 75–85% of the respondents interviewed at the previous MLSFH waves (Supplemental Materials Table S8). When a MLSFH participant could not be found and contacted for a MLSFH follow-up interview, the MLSFH conducted a short interview with family members and/or neighbors to obtain essential information about the vital status and migration of the MLSFH respondent. Based on this information, the respondent's status in the MLSFH was recorded as classified as *dead*, *migrated*, *refused*, *hospitalized*, *temporarily absent*, *other*, and *unknown*. Conditional on successfully contacting a MLSFH respondents, refusals to participation in the MLSFH have been very low across all MLSFH waves (< 3% up to 2008, and < 5% in 2010).

MLSFH Sample Additions: Additions to the MLSFH have occurred primarily through three mechanisms: new spouses, the 2004 adolescent sample, and the 2008 parent sample. We discuss these three mechanisms in turn. ***New spouses:*** The initial MLSFH sample in 1998 included 1,541 ever-married women aged 15–49 and their spouses. Up to the 2004 round of data collection, the MLSFH attempted to re-interview all of these initial MLSFH respondents and their current spouses; that is, if a MLSFH respondent divorced and remarried, or in the case of polygamous men, added an additional wife, the MLSFH added the current wife (all current wives) of the initial MLSFH participants. However, spouses who were not part of the initial MLSFH sample were not followed and retained in the MLSFH if they divorced or their spouses died. Starting with the 2006 MLSFH, the study retained all MLSFH study participants; that is, from 2006 onward, once an individual was interviewed for the MLSFH once, for instance after being enrolled as a new spouse, the MLSFH made an attempt to re-interview the respondent at all subsequent waves. ***2004 Adolescent Sample:*** In 2004, to compensate for the aging of the initial MLSFH sample and the underrepresentation of unmarried individuals at adolescent and young adult ages, the MLSFH added an adolescent sample in 2004 (N = 998). For this purpose, two household rosters were collected in each sampled community as part of the 2004 MLSFH data collection. The first was collected from all households in the sampled villages—that is, MLSFH and non-MLSFH households—during a household listing interview in which all members of all households in the MLSFH were enumerated along with basic demographic characteristics. The second household roster was incorporated into the primary MLSFH survey instrument administered to all female MLSFH participants to enumerate all eligible adolescents who are part of existing MLSFH households. To allow for intergenerational analyses, all adolescents aged 15–25 listed as members of the existing MLSFH households and residing in the MLSFH study villages were enrolled into the MLSFH adolescent sample, constituting about 1/3 of the total N of the adolescent sample. The remaining members of the MLSFH adolescent sample were selected from the household listing conducted for non-MLSFH

households using a age-stratified sampling strategy that adjusted for the differential ages at marriage between gender and MLSFH study regions (for additional information, see http://malawi.pop.upenn.edu/malawi-documentation-sampling. ***2008 MLSFH Parent Sample:*** To increase the suitability of the MLSFH to study intergenerational aspects and the health of older individuals in Malawi, a parent sample was added to the MLSFH in 2008. This new sample of parents of MLSFH respondents was drawn from family listings from MLSFH respondents in 2006 (because of the respondents' young age, parents of MLSFH respondents in the 2004 adolescent sample were not included). All living biological parents who resided in the same village as the respondent were included in the 2008 MLSFH new sample of parents. Based on this approach, parents of MLSFH respondents living in the MLSFH study villages were added to the 2008 MLSFH sample (N = 549). As a result of this enrolling older individuals who were not necessarily captured by the earlier MLSFH sampling frame, the age range covered by the MLSFH was substantially extended by (Supplemental Materials Table S8). Among approximately 3,800 respondents interviewed in the 2010 MLSFH, 44.1% were from the original MLSFH sample drawn in 1998, 19.5% were from the 2004 adolescent sample, 12.5% from the 2008 parent sample, and the remainder (23.9%) were new spouses that have been added during 2001–2010.

Comparisons of the MLSFH with national representative samples: While the initial sampling strategy of the MLSFH was not designed to be representative of the national population of rural Malawi, the initial sample characteristics closely matched the characteristics of the rural population of the 1996 Malawi Demographic and Health Survey (DHS) [2]. After three rounds of longitudinal data collection, despite attrition and the enrollment of new subjects, the 2004 MLSFH sample continues to be in close agreement in observable characteristics with the nationally-representative 2004 Malawi DHS (rural sub-population) [3]. After three additional rounds of MLSFH follow-up, the 2010 MLSFH mature adult population— i.e., the study population that is used for the analyses here—continues to closely match the rural subsample in the national-representative IHS3 (Table S1) in key

observable characteristics.

References

1. Malawi National Statistical Office, ICF Macro (2011) Malawi Demographic and Health Survey 2010: final report. Calverton (Maryland): ICF Macro. Available: http://www.measuredhs.com/publications/publication-fr247-dhs-final-reports.cfm. Accessed 25 March 2013.
2. Watkins S, Behrman JR, Kohler HP, Zulu EM (2003) Introduction to “research on demographic aspects of HIV/AIDS in rural Africa”. Demogr Res Special Collection 1: 1-30.
3. Anglewicz P, Adams J, Obare F, Kohler HP, Watkins S (2009) The Malawi Diffusion and Ideational Change Project 2004–06: data collection, data quality and analyses of attrition. Demogr Res 20: 503-540.

Aging in the Americas: Disability-Free Life Expectancy among Adults Age 65 and Older in the United States, Costa Rica, Mexico, and Puerto Rico.

Appendix Materials:

Tables:

Table S1: Paramater Estimates from Equation 1

	CRELES (CR)	MHAS (MX)	PREHCO	HRS (US)
From Disability-Free:				
To ADL Disabled				
Age	0.071	0.060	0.044	0.054
	(0.006)	(0.008)	(0.008)	(0.002)
Male	-0.237	-0.241	-0.210	-0.178
	(0.055)	(0.083)	(0.074)	(0.022)
Intercept	-7.776	-7.370	-6.460	-6.917
	(0.480)	(0.564)	(0.594)	(0.162)
To Dead				
Age	0.090	0.080	0.085	0.095
	(0.011)	(0.009)	(0.008)	(0.003)
Male	0.121	0.153	0.097	0.203
	(0.089)	(0.110)	(0.081)	(0.027)
Intercept	-10.268	-9.441	-9.767	-10.635
	(0.863)	(0.652)	(0.678)	(0.235)
From ADL Disabled				
To Disability-Free				
Age	-0.064	-0.048	-0.041	-0.031
	(0.011)	(0.009)	(0.012)	(0.002)
Male	0.111	-0.129	0.084	-0.018
	(0.102)	(0.111)	(0.107)	(0.031)
Intercept	2.916	2.000	0.489	0.282
	(0.880)	(0.599)	(0.852)	(0.176)
To Dead				
Age	0.060	0.043	0.074	0.065
	(0.009)	(0.016)	(0.011)	(0.003)
Male	0.139	-0.115	0.339	0.213
	(0.078)	(0.178)	(0.113)	(0.029)
Intercept	-6.924	-5.323	-8.244	-7.136
	(0.749)	(1.231)	(0.864)	(0.254)

Note: Standard errors are reported in parenthesis below parameter estimates.

Table S2: Microsimulation Estimated Disability-Free and Total Life Expectancy for Males and Females Age 65, 75, and 85

	CRELES (CR)	MHAS (MX)	PREHCO (PR)	HRS (US)
Female				
Age 65				
Disability-Free	12.94	14.96	13.92	15.01
95% CI	(12.01 - 14.19)	(13.39 - 16.85)	(12.4 - 15.66)	(14.62 - 15.4)
Total	20.11	19.24	20.37	20.52
95% CI	(18.84 - 21.86)	(17.43 - 21.48)	(18.53 - 22.28)	(20.09 - 20.92)
Age 75				
Disability-Free	6.98	8.37	8.74	8.62
95% CI	(6.32 - 7.69)	(6.9 - 10.12)	(7.7 - 9.96)	(8.29 - 8.94)
Total	13.15	12.49	13.70	13.29
95% CI	(12.13 - 14.19)	(10.84 - 14.63)	(12.32 - 15.32)	(12.97 - 13.62)
Age 85				
Disability-Free	3.27	3.39	4.24	3.64
95% CI	(2.82 - 3.78)	(2.17 - 4.85)	(3.21 - 5.32)	(3.35 - 3.96)
Total	8.11	7.20	8.62	7.51
95% CI	(7.37 - 8.92)	(5.71 - 9.35)	(7.46 - 10.19)	(7.25 - 7.82)
Male				
Age 65				
Disability-Free	14.55	15.18	14.62	14.91
95% CI	(13.42 - 16.06)	(13.52 - 16.98)	(13.43 - 15.86)	(14.51 - 15.28)
Total	19.01	18.43	18.08	18.14
95% CI	(17.79 - 20.79)	(16.28 - 20.68)	(16.62 - 19.4)	(17.69 - 18.55)
Age 75				
Disability-Free	8.38	9.05	9.25	8.61
95% CI	(7.58 - 9.22)	(7.78 - 10.65)	(8.35 - 10.18)	(8.27 - 8.93)
Total	12.29	12.23	11.80	11.36
95% CI	(11.34 - 13.35)	(10.51 - 14.35)	(10.95 - 12.7)	(11.02 - 11.69)
Age 85				
Disability-Free	4.10	3.56	4.93	3.98
95% CI	(3.51 - 4.7)	(2.24 - 5.13)	(3.86 - 5.91)	(3.64 - 4.28)
Total	7.31	7.28	7.12	6.24
95% CI	(6.61 - 8.08)	(5.74 - 9.69)	(6.35 - 7.98)	(5.95 - 6.53)

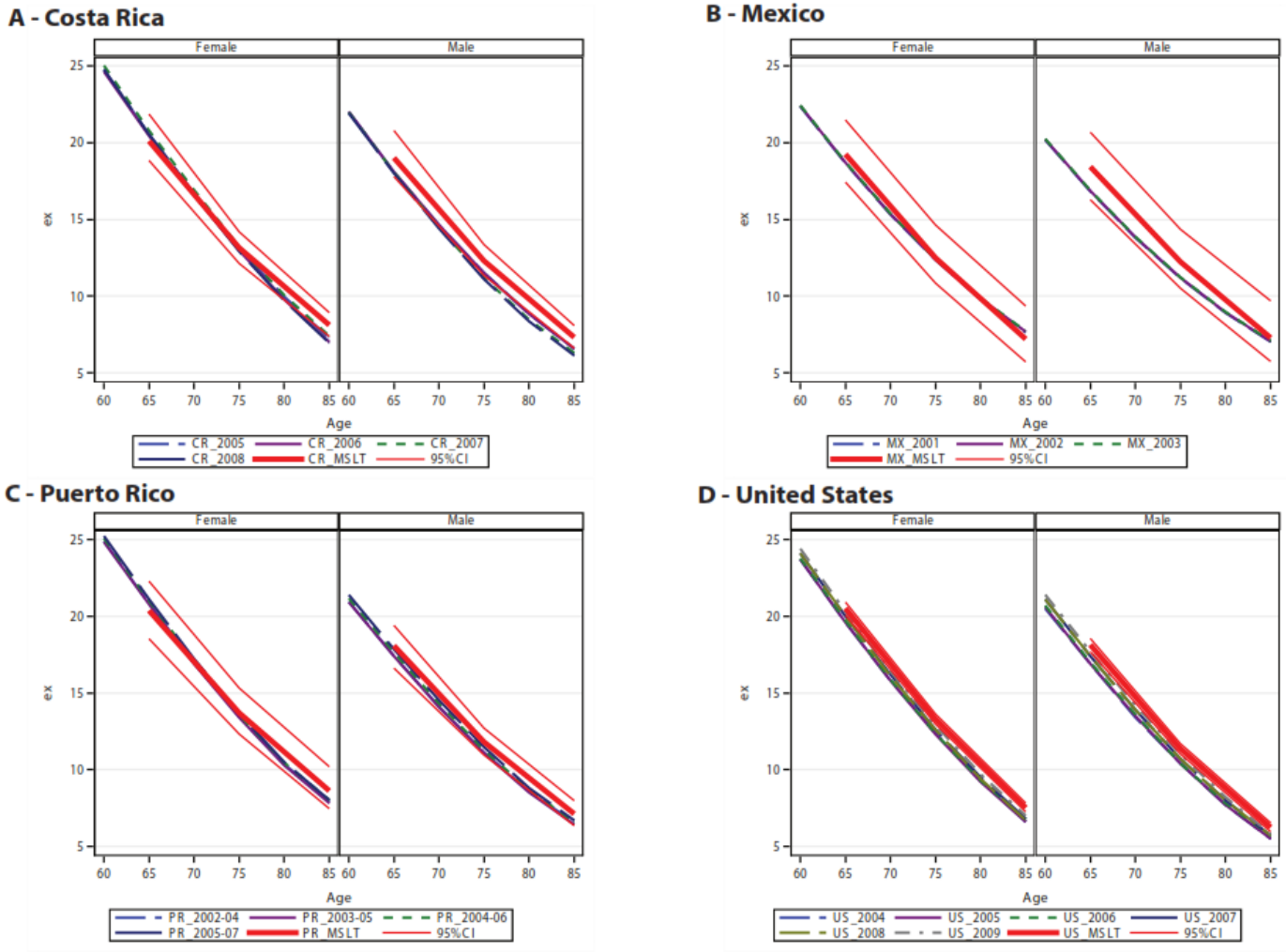
Notes:
All presented results use national-level sample weights.
Estimates were obtained from synthetic cohorts of 100,000 65-, 75-, and 85-y-olds created via microsimulation, based on observed transition rates from original data.

Table S3: Microsimulation Estimated Healthy, ADL Limited, and Total Life Expectancy for Males and Females Age 65, 75, and 85, Casewise Deletion for Missingness

	CRELES (CR)	MHAS (MX)	PREHCO (PR)	HRS (US)
Female				
Age 65				
Healthy	12.39	14.94	13.67	14.76
95% CI	(11.53 - 13.43)	(13.21 - 16.73)	(12.2 - 15.56)	(14.4 - 15.16)
ADL Limited	6.98	4.21	6.45	5.54
95% CI	(6.13 - 7.97)	(3.21 - 6)	(5.35 - 8.03)	(5.22 - 5.79)
Total	19.37	19.15	20.12	20.30
95% CI	(18.05 - 20.74)	(17.09 - 21.23)	(18.58 - 22.48)	(19.83 - 20.66)
Age 75				
Healthy	5.96	8.47	8.40	8.52
95% CI	(7.25 - 5.99)	(6.91 - 10.16)	(7.39 - 9.74)	(8.15 - 8.77)
ADL Limited	5.21	4.10	5.15	4.66
95% CI	(6.82 - 12.61)	(3.04 - 5.96)	(4.08 - 6.53)	(4.46 - 4.96)
Total	11.64	12.60	13.55	13.18
95% CI	(13.56 - 13.76)	(10.83 - 14.83)	(12.31 - 15.34)	(12.82 - 13.5)
Age 85				
Healthy	3.12	3.49	3.97	3.62
95% CI	(2.68 - 3.58)	(2.27 - 5.12)	(3.09 - 5)	(3.33 - 3.96)
ADL Limited	4.80	3.74	4.53	3.89
95% CI	(4.1 - 5.47)	(2.78 - 5.89)	(3.58 - 6.05)	(3.65 - 4.18)
Total	7.92	7.24	8.50	7.51
95% CI	(7.22 - 8.71)	(5.63 - 9.83)	(7.23 - 10.18)	(7.24 - 7.81)
Male				
Age 65				
Healthy	13.90	15.05	14.48	14.70
95% CI	(12.83 - 15.06)	(13.34 - 16.78)	(13.2 - 15.74)	(14.23 - 15.06)
ADL Limited	4.43	3.35	3.23	3.20
95% CI	(3.72 - 5.29)	(2.18 - 4.8)	(2.55 - 4.32)	(2.98 - 3.48)
Total	18.33	18.40	17.71	17.89
95% CI	(17.18 - 19.76)	(15.82 - 20.62)	(16.37 - 19.13)	(17.46 - 18.31)
Age 75				
Healthy	7.93	9.12	9.17	8.49
95% CI	(7.31 - 8.73)	(7.8 - 10.59)	(8.16 - 10.22)	(8.18 - 8.79)
ADL Limited	3.87	3.22	2.41	2.79
95% CI	(3.21 - 4.5)	(2.09 - 4.94)	(1.8 - 3.28)	(2.57 - 3.02)
Total	11.80	12.34	11.58	11.27
95% CI	(10.9 - 12.83)	(10.44 - 14.32)	(10.67 - 12.61)	(10.94 - 11.56)
Age 85				
Healthy	3.94	3.60	4.87	3.96
95% CI	(3.44 - 4.46)	(2.41 - 5.05)	(3.81 - 5.76)	(3.63 - 4.23)
ADL Limited	3.20	3.77	2.13	2.32
95% CI	(2.71 - 3.83)	(2.35 - 6.65)	(1.53 - 3.02)	(2.1 - 2.53)
Total	7.14	7.38	7.00	6.29
95% CI	(6.49 - 7.8)	(5.88 - 9.86)	(6.29 - 7.93)	(5.99 - 6.55)

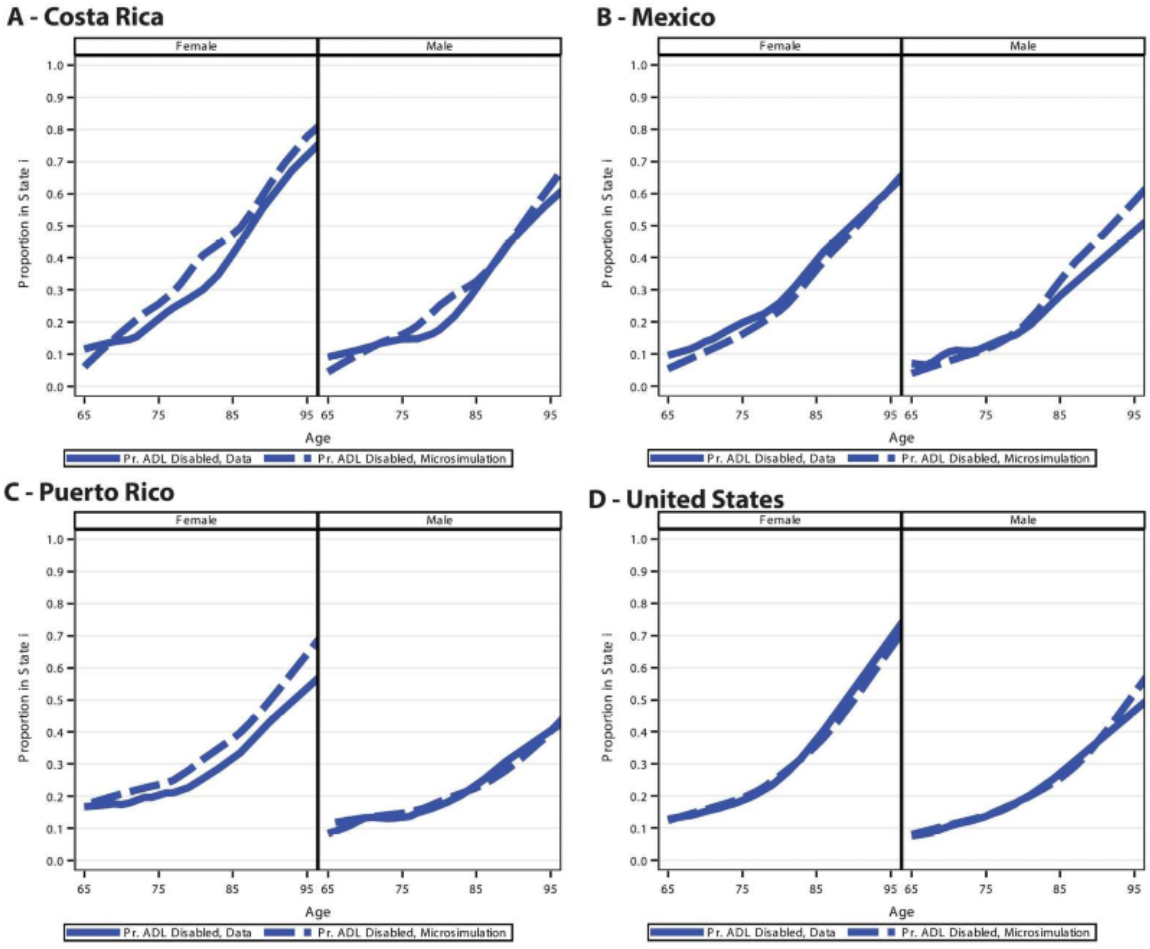
Figures:

Figure S1: Comparisons of e_x Between Multi-State Life Tables and Various Country Life Tables



Sources: Costa Rican National Institute of Statistics and Censuses Life Tables, Commonwealth of Puerto Rico Department of Health Life Tables for Puerto Rico, National Council of Population, Mexico, Basic Demographic Indicators 1990-2010, Centers for Disease Control National Vital Statistics Reports 56, 58, 59, 61, 62.

Figure S2: Proportion ADL disabled in source dataset and microsimulation cohort, by sex, for Costa Rica (Panel A), Mexico (Panel B), Puerto Rico (Panel C), and the United States (Panel D).



The Population-Level Impact of ART Rollout on Adult Health and Mortality in Rural Malawi

Appendix Materials:

Figures:

Figure S1: Study locations in Malawi

Fig S2: LE at age 15, including 2004-2006 sample

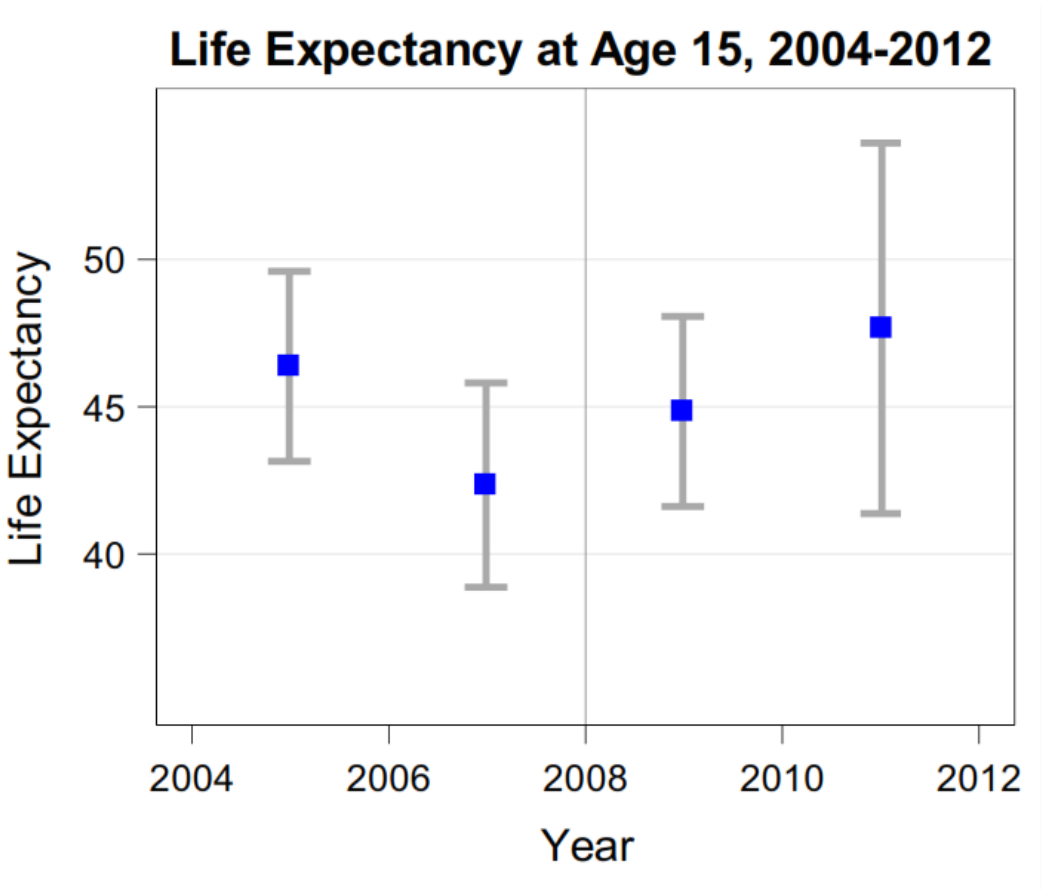
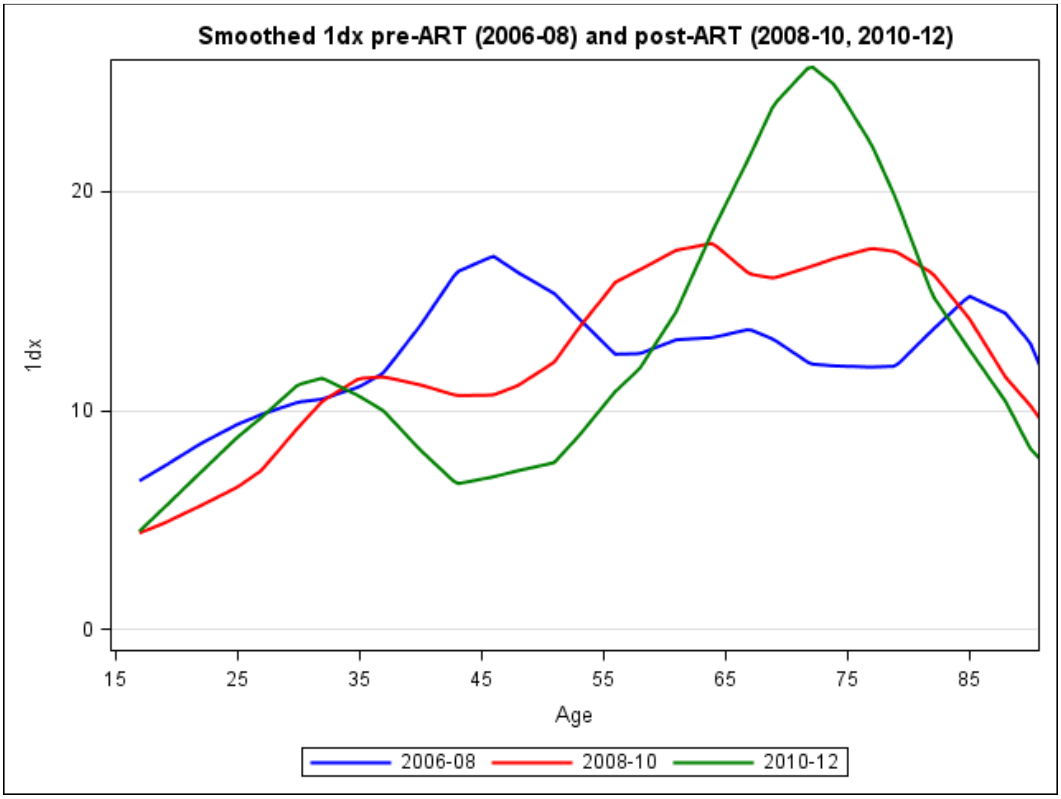


Fig S3: Smoothed 1dx pre-ART (2006-08) and post-ART (2008-10, 2010-12)



Notes: Figure S.3 displays the number of deaths between exact ages x and x+1 in life-table populations (radix=1000) generated for each survey period separately ($_1d_x$ in conventional lifetable notation). This standardization allows for a direct comparison across sample waves, accounting for possible differences in the age-distribution of the study population at each time period. We see that the distribution of deaths is substantially more right-skewed after the introduction of ART in 2008, with a larger proportion of deaths occurring at later ages. Reductions in deaths post-ART are evident in late middle age, from approximately ages 40-55y, but there is little evidence for an effect of ART in earlier life (15-35y). $_1d_x$ values smoothed using PROC LOESS in SAS 9.4.

Tables:

Table S1: Selected Characteristics of the analysis sample

	2006 %	2008 %	2010 %	2012 %
A. Age				
15-29	39.1	36.7	37.5	42.4
30-44	21.9	21.1	21.5	20.4
45-59	20.5	20.8	18.7	17.0
60-74	14.0	15.2	15.3	11.4
75+	4.6	6.2	7.1	8.8
B. Percent female by age				
15-29	53.0	52.9	53.1	51.9
30-44	57.0	55.5	55.3	50.9
45-59	53.7	54.7	56.8	62.4
60-74	50.0	49.7	50.5	51.2
75+	42.6	42.4	46.7	54.5
C. Percent with 5+ years education by age				
15-29	69.2	69.3	66.8	63.1
30-44	57.0	56.8	57.6	60.9
45-59	48.8	48.6	50.7	50.2
60-74	34.8	36.1	37.5	32.2
75+	28.2	27.6	27.9	20.9
D. General health				
Excellent	26.1	29.3	30.5	34.3
Very good	37.2	36.2	36.1	34.3
Good	29.0	29.4	29.1	26.8
Poor	7.4	4.6	3.9	4.1
Very poor	0.3	0.5	0.5	0.4
E. Percent in poor/very poor health by age				
15-29	3.3	3.3	3.1	2.3
30-44	5.5	5.7	5.1	5.5
45-59	10.2	10.4	9.2	6.8
60-74	22.7	18.7	17.8	20.2
75+	35.9	35.9	31.2	41.8

Table S1: Selected Characteristics of the analysis sample (continued)

	2006 %	2008 %	2010 %	2012 %
F. Relationship to primary respondent				
Respondent	24.4	20.5	19.7	14.4
Spouse	17.5	16.4	15.2	10.2
Child/child-in-law	26.8	29.2	36.2	62.8
Parent/parent-in-law	29.1	32.4	27.8	11.4
Other	2.2	1.5	1.1	1.2
G. Where individual usually lives				
Same HH	55.6	46.1	44.4	37.8
Same compound	13.2	14.7	14.9	18.2
Same village	5.1	6.2	7.3	5.1
Same TA	9.7	12.5	13.1	13.6
Same district	7.6	7.5	8.6	8.7
Elsewhere	8.8	12.9	11.7	16.6
H. How individual matched				
First round	98.8	97.8	98.7	99.1
Second round	0.3	1.1	0.3	0.3
Hand matched	0.9	1.1	1.0	0.6
N observations	7,481	8,883	7,913	3,733
N primary respondents	1,822	1,821	1,557	526

Table S2: Match rate for analysis sample by selected characteristics

	2006 %	2008 %	2010 %	2012 %
Overall match rate	75.9	80.9	82.2	92.5
A. Age				
15-29	75.6	79.9	84.6	92.9
30-44	83.1	85.6	89.0	97.3
45-59	78.1	81.5	79.0	91.9
60-74	67.9	80.1	74.4	89.3
75+	62.4	77.4	75.8	85.0
B. Relationship to Respondent				
Respondent	96.9	98.0	98.0	97.7
Spouse	85.0	85.6	83.8	81.3
Child/child-in-law	77.5	83.5	92.1	96.1
Parent/parent-in-law	66.8	75.8	69.9	86.0
Other	12.0	22.3	21.3	42.3
C. Where individual usually lives				
Same HH	84.3	85.6	86.0	90.1
Same compound	70.1	79.9	83.3	95.4
Same village	65.1	78.4	76.0	93.2
Same TA	69.4	73.8	75.7	93.4
Same district	65.0	80.0	80.9	95.0
Lilongwe	60.6	78.1	83.3	92.4
Blantyre	74.2	71.8	90.0	91.7
Elsewhere	64.7	74.7	77.5	92.8
D. Sex				
Male	75.2	80.3	80.1	90.5
Female	76.5	81.4	84.2	94.5
E. General health				
Excellent	80.3	80.7	84.4	93.4
Very good	76.9	82.5	82.4	92.4
Good	73.1	79.9	80.1	92.4
Poor	71.2	81.6	83.0	92.1
Very poor	72.0	86.0	84.2	82.4

Table S3: Adult Life Expectancy and Median Length of Life by Sex

A. Adult Life Expectancy

Period	Years	95% CI	
Male			
2006-2008	40.3	36.4	44.1
2008-2010	43.0	39.6	46.5
2010-2012	45.2	40.7	49.7
Post ART (2008-2012)	43.7	40.9	46.4
Female			
2006-2008	47.2	43.6	50.9
2008-2010	47.0	43.4	50.5
2010-2012	47.6	41.9	53.3
Post ART (2008-2012)	48.2	45.2	51.1

B. Median Length of Life

Period	Years	95% CI	
Male			
2006-2008	39	34	45
2008-2010	45	41	49
2010-2012	49	40	53
Post ART (2008-2012)	45	42	49
Female			
2006-2008	48	42	55
2008-2010	50	44	56
2010-2012	55	45	58
Post ART (2008-2012)	50	46	56

Note: Data were truncated at age 95 when dividing the sample by gender due to small samples at older ages. We close the survival function by exponentially extending the survival curve to zero.

Table S4: Adult life expectancy and median length of life for alternative definitions of the study population

	Years	95% CI	
A. Coresident with primary respondent			
Adult LE			
2006-08	42.3	38.7	45.9
2008-10	44.8	41.5	48.1
2010-12	47.7	41.3	54.1
Post	46.6	43.7	49.4
Median age at death			
2006-08	58	51	65
2008-10	67	59	69
2010-12	68	58	74
Post	67	64	70
B. All available observations			
Adult LE			
2006-08	42.7	40.7	44.7
2008-10	43.4	41.7	45.2
2010-12	45.2	43.0	47.5
Post	44.1	42.7	45.5
Median age at death			
2006-08	58	55	62
2008-10	60	59	62
2010-12	65	60	68
Post	61	60	64
C. Matched in first round of matching			
Adult LE			
2006-08	45.3	42.6	48.0
2008-10	48.2	45.6	50.8
2010-12	47.5	43.6	51.3
Post	47.9	45.7	50.0
Median age at death			
2006-08	60	55	65
2008-10	66	62	69
2010-12	68	63	73
Post	67	64	69
D. Respondent, spouse, children, & parents only			
Adult LE			
2006-08	43.0	40.4	45.6
2008-10	45.2	42.7	47.6
2010-12	45.9	42.2	49.5
Post	45.1	43.1	47.1
Median age at death			
2006-08	58	54	63
2008-10	62	59	66
2010-12	67	60	70
Post	64	60	67

Notes: Panel A uses all individuals in the analysis sample who were listed as living in the same household or the same compound as the primary respondent. Panel B expands the analysis sample to all individuals listed on household rosters, including duplicate reports on the same household by spouses. Panel C uses only those individuals in the analysis sample who were matched in the first pass of the matching algorithm. Panel D limits the analysis sample to respondents, and spouses, children, and parents of respondents.

Text:

Text S1: MLSFH Household Roster Details

Beginning in 2006 and continuing in the 2008, 2010 and 2012 MLSFH waves, the MLSFH collected data on family structure. The MLSFH household and family roster included not only all individuals who currently live in the household as frequently done in other studies, but it also asked information about all parents and children independent of their survival and resident status (Box 1).

Box 1: Individuals listed in MLSFH Household/family roster
1. List the respondent 2. List name of spouse(s) of respondent. If respondent is not currently married, list name of most recently deceased or divorced spouse. For polygamous men: list all wives. If never married proceed to instruction 3, below. 3. List name of respondents parents (list names even if parents are deceased) 4. [if R is married or widowed] List name of spouses parents (list names even if parents are deceased; for polygamous men: list parents of all wives) 5. List the names of all children of the respondent (children ever born; include children who are no longer alive or do not live in respondents household) 6. List the names of any other children who usually live in this household (including non-biological children, grandchildren, nieces & nephews). 7. List the names of all other persons who slept in this household last night 8. List the names of all other persons who usually sleep in this household, but did not last

night

9. List the names of all non-related children who are under your care but not living in the household (for example, anyone you have helped with school fees in the last 5 years).

The questionnaire asked about each individual's selected demographic, socioeconomic, and health characteristics and health as known to/perceived by the respondent (Box 2).

Box 2: Information about each person listed on the MLSFH household/family roster

Q2	What is [name's] relationship to you?
Q3	Is [name] male or female?
Q4	Is [name] alive? If [name] is dead, when did he/she die? (*Note:* Questions Q5–16 were not asked for persons who had died)
Q5	How old is [name]? Or, in what year was [name] born?
Q6	Where does [name] usually live?
Q7	Did [name] sleep here last night?
Q8	If a person does not regularly live here: when did [name] move to this place?
Q9	Has [name] been ill in the past 12 months? If yes, for how long?
Q10	How would you rate [name's] health in general?
Q11	How would you compare [name's] health to other people in your village who are the same age and sex?

Q12	What is [name's] current marital status?
Q13–14	What is the highest level of schooling name completed? How many grades (in years) did [name] complete at that level?
Q15	If age > 10: What is [name's] main way of earning money?

For persons who were reported as having died during the previous two years on the MLSFH household/family roster, the MLSFH also asked more detailed information about when the death occurred, how old the person was when he/she died, the level of schooling and the marital status of the diseased person, the health prior to the dying, and the likelihood (as perceived by the respondent) that the death was due to AIDS.

Supplemental Text 2: The Matching Process and Diagnostics

We developed a probabilistic matching algorithm that generated longitudinal links between individuals on the household rosters across rounds of data collection. Individuals are matched based on name, age, sex, and familial relationship to respondent. To illustrate the matching process, let us take matching two waves of data, Wave A and Wave B as an example. As a first step, we sort each dataset by primary respondent, and within each primary respondent by the listed members of the household. We then generate a dataset of all possible permutations of Wave A to Wave B matches within each primary respondent (that is, a file with one data line for each possible combination of individuals reported on the household roster within each primary respondent).

At this point, we generate a weighted match score based on first and last names (with gradations of match scores based on a generalization of the Levenshtein edit distance), age (with gradations of match scores based on proximity of ages between waves), sex, and relationship to respondent (respondent, spouse, child, parent, grandchild, grandparent, sibling, uncle/aunt, other related, or other non-related).

At the end of this process, each combination of individuals reported on a household roster has a match score ranking the match quality. Within each primary respondent, we rank the match scores of each listed individual in Wave B to all listed individuals in Wave A, generate a ranking variable, and re-rank the match scores of each listed individual in Wave A to all listed individuals in Wave B. A match is counted as strong if the same individual is ranked first in each ranking (that is, the match has the highest score of all matches for each individual) and has a match score of over 65%. Lower-ranking matches (between 50% and 65%, or not ranking first across the same individual) are then set aside, cleaned of individuals with a strong match, and re-matched using a higher threshold of 70%. This

second match accounts for 1% or fewer of matched individuals. At this point, individuals with a match score of over 60%, or those who had a match score of over 50% but are missing information on one of the variables used in matching, are set aside for hand coding. These hand coded matches also represent only about 1% of the final analysis sample and are generally cases where there were obvious mistakes in the data entry (such as an individual listed as the respondent's grandparent being 77 years old in one wave, but listed as 7 years old two years later).

Table S1 displays selected characteristics of the analysis sample. In the 2006-2012 rounds of data, few differences are evident on age composition, percent female, or education. The 2006 to 2010 waves of MLSFH data collection visited all available respondents from the MLSFH study population. In 2012, only primary respondents over the age of 45 were interviewed. This has little effect on the age composition of the sample (Panel A), though individuals on the household roster are more likely to be the children of respondents and somewhat less likely to be parents of the main respondent (Panel F). This higher proportion of children in the sample may also account for the slight increase in the proportion of listed individuals living within the same compound as the primary respondent, and the commensurate decrease in the proportion living in the same household (Panel F). Percent female (Panel B), percent with 5+ years of education (Panel C), general health (Panel D), and method of matching (Panel H) show fairly small fluctuations across waves.

Table S2 presents the match rates of individuals listed on the household rosters of the analysis sample by selected characteristics in 2006-2012. For the 2006-2010 rounds, match rates varied between 76% (for 2006) to 84% (for 2010). In the 2012 round of survey collection, the household roster questionnaire was pre-filled with names of spouses, children, and parents, from the previous wave, which resulted in a higher overall match rate of over 92%. However, this increase in match rate does not appear to have affected sample

characteristics (Table S1). Match rates were similar in all age groups, though rates for the 60+ population in the 2006 wave lag the other waves somewhat. However, these ages are outside the prime ages where we would expect the effect of ART, and thus a differential in match rates in unlikely to bias our estimates. Match rates were generally higher for individuals who are closely related to the primary respondent (Panel B) and living geographically closer to the primary respondent (Panel C). Rates are comparable by sex (Panel D) and health status (Panel E). Overall, it does not appear that any systematic biases arise during the matching process, and the small variations in match rate that are observed occur in age ranges that are unlikely to affect our primary outcomes. Our findings on the increase in adult LE post-ART are also robust to a number of alternative sample parameterizations (Table S4).

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