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ABSTRACT

Sex differences in mortality (SDIM) vary over time and place as a function of social, health, and medical circumstances. The magnitude of these variations, and their response to large socioeconomic changes, suggest that biological differences cannot fully account for sex differences in survival. We document "stylized facts" about SDIM with which any theory will have to contend. We draw on a wide swath of mortality data, including probability of survival to age 70 by county in the United States, the Human Mortality Database data for 18 high-income countries since 1900, and mortality data within and across developing countries over time periods for which reasonably reliable data are available. We show that, in each of the periods of economic development after the onset of demographic and epidemiologic transition, cross-sectional variation in SDIM exhibits a consistent pattern of female resilience to mortality under adversity. Moreover, as societies develop, M/F survival first declines and then increases, a "SDIM transition" embedded within the demographic and epidemiologic transitions.

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Introduction

It has been long appreciated that women consistently outlive men in developed countries (Kalben 2002; Verbrugge 2012; Waldront 1976). More recently, it has become evident that not only do women have longer life expectancy from birth (LE) in such societies, but their mortality rates at every age are lower, starting *in utero* (Catalano and Bruckner 2006). So pervasive are these observations that some demographers now equate the longevity of the human *species,* at any given time and place, with the highest observed LE of women (Horton and Lo 2013; Oeppen and W.Vaupel 2002). However, sex differences in mortality (SDIM) vary widely over time and place. In this paper we explore this variation in search of insights into why women live longer. In particular, we are motivated by the hope that insight into the sources of this variation will reveal opportunities to reduce the disparity between the sexes and, thereby, the excess mortality of men.

Efforts to explain the observed sex differences in mortality are not new, with empiric and theoretical reports appearing in such diverse scientific literatures as demography, anthropology, human biology, medicine, epidemiology, economics and evolutionary biology as well as in actuarial studies and reports (Kalben 2002; Kruger and Nesse 2004; MacIntyre et al. 1996; Møller et al. 2009; Taylor et al. 2009; Waldron 1983; Waldront 1976; Yang and Kozloski 2012). Research on SDIM to date has centered on three broad themes: genetically determined biological differences; observable differences between the sexes in health behaviors; and differential “socio-biology”—differences in experiences and behavior such as child-rearing activities and social network structures whose relationship to survival advantage is postulated but not yet proved (Gorman and Read 2007; Ristvedt 2014; Umberson and Montez 2010). In the first category are salient sex differences such as the long-recognized benefit of female hormonal patterns on delay in the onset and progression of vascular disease in regions where chronic diseases dominate, i.e. high- (and increasingly middle-) income countries. Moreover, there are credible health-survey and utilization data—again drawn for recent periods of time in high income countries—documenting that while prevalence of many lethal diseases is comparable, mortality rates due to these diseases have been consistently higher for men, whether due to biologic resilience among women or behavioral differences, such as in self-care (Case and Paxson 2005; Cook et al. 2011; Rahman et al. 1994). On the other hand, the long-standing relatively higher male vs. female mortality in infancy—"when behavioral differences should be minimal"—seems more likely biologic, though it too has shown variation, increasing for many years before more recently declining (Drevenstedt et al. 2008). A recent conjecture, combining observations from infancy and later life, proffers the intriguing proposition that a possible biologic foundation for the differential survival for many important causes of death is that women are less prone to anoxic brain death from fetal life onward (Liu et al. 2014; Mage and Donner 2006).

Differential health behaviors—ranging from engaging in dangerous occupational and avocational activities, to physical risk taking and use of harmful substances—are obvious explanations for at least some of the SDIM now and historically (Concha-Barrientos et al. 2004; Cutler et al. 2011; Ezzati et al. 2008; Gabel and Gerberich 2002; Hunter and Reddy 2013; Kalben 2002; McCartney et al. 2011; Norström and Razvodovsky 2010; Tomkins et al. 2012). Although almost certainly distributed differently from one context to another, we are unaware of any large population for which women exceed men in the most lethal behaviors. The impact of these risky behaviors as determinants of higher male mortality from accidents—especially in adolescence and early adult life—demands little explanation. Likewise, differential abuse of tobacco, alcohol and other substances is both well documented and easily demonstrable as a component of SDIM, as is evident examining relative causes of mortality from lung cancer, obstructive lung disease and cirrhosis. Significantly, changes in these specific sex-differential behaviors are a frequently-cited explanation for variation in SDIM over time in various populations (Bhattacharya et al. 2012; McCartney et al. 2011; Preston and Wang 2011). If behavioral differences contribute in particular to differential decline in mortality among young men relative to young women even as longevity increases overall, then this could be one mechanism for explaining sex differences in lifespan inequality over time and across countries (Gillespie et al. 2014).

A third broad area of interest has been in socio-biologic differences in male/female behavior. Inspiration for this perspective derives form observations of relatively consistent female survival advantages among well-studied animal species, including most primates (Kohler et al. 2006). Evolutionary theory points to the potential communal benefit of surplus care-givers—grandmothers as it were—deriving from the survival pressures created at the dawn of our species when women often died of complications of repeated childbirths (Chu and Lee 2012). Such observations point to fundamental, "hard-wired" differences in the way females live compared to males that cannot be easily explained by differential exposure to (evolutionarily irrelevant) determinants of chronic diseases or biologic predisposition to chronic vascular disease due to hormonal influences. Proponents of this perspective point to the survival advantages for individuals of either sex with stronger family and other support networks for which abundant empiric evidence has been presented (Braveman et al. 2011).

In this paper we shall not attempt to weigh directly the evidence for or against each of these mutually compatible pathways. Rather, our ambition is to establish "stylized facts" about patterns of SDIM across time and place with which any theory will ultimately have to contend. We begin our investigation with the data that is of highest quality: the contemporary developed world. We then study patterns of SDIM using a wide swath of available mortality data, within and between developing and developed countries and over the time periods for which reasonably reliable data are available. We focus exclusively on *variation* in sex-specific mortality ratios. Of particular interest is the relationship between SDIM and "demographic and epidemiologic transition," that period in the history of most regions of the world when transformation of the economy occurred in close association with marked demographic changes including reduction in fertility and maternal mortality rates, better nutrition and control of infectious disease, and rapid improvements in life expectancy (Mooney 2002; Omran 1971). We adopt this perspective as a means for relating changes in SDIM in developed countries—from which almost all published work on this subject has emerged—to those presently evolving in other parts of the world, an approach that suggests the patterns we identify may constitute a more general “SDIM transition”.

Given our ambition to describe and explore SDIM variation over time and place, our approach in this paper is to present the available comparative mortality data in the simplest way, limiting explanatory analyses largely to correlations and univariate regressions to quantify associations already evident. We shall discuss in more detail below, but it warrants mention at the outset that our choices for markers of social condition within countries or regions are based entirely on availability and “generalness”; it is not our intent to quantify the relationship between SDIM and any specific causal factor, but rather to identify broad patterns that might, later, encourage precisely such exploration.

The paper is organized as follows: we begin by describing our data sources and methods, to make as clear as possible why we chose some sources and not others. Next we present our observations, dividing them into four sections. In the first we set the stage by examining current US variation in probability of survival to age 70 (S_{70}) by county, work previously presented as part of a study by two of us to explore race and geographic differences in the United States (Cullen et al. 2012) and recently extended. This section explores current cross-sectional variation in SDIM and reveals a core observation: while measured social, environmental, behavioral and medical variation from county to county largely *can* explain geographic and racial disparities within each sex subgroup, these same variables *cannot* explain the sex disparity, as men and women of each race have roughly the same social measures in each county; if anything women are slightly more “deprived” than their male neighbors, rendering women’s survival advantage even more puzzling. However, in this paper we show that the M/F survival ratio across US counties does exhibit a strong correlation with some social measures: women consistently exhibit greater survival “resilience” to social adversity. A very similar pattern characterizes the relationship between the M/F survival ratios and per capita GDP both between and within the world’s most developed countries.

In part II we explore changes in M/F mortality over time, starting with the post-World War II period. The SDIM in the US and almost all other high income countries have changed in parallel, albeit at slightly different rates: early accentuation of women's survival advantage over men—M/F declining—until some point between 1970 and 1980 when the direction of change "flipped," with men starting to catch up. Within each cross-sectional slice, however, the relationship between per capita income and M/F has remained fundamentally the same as that observed in part I—M/F is higher (men do relatively better) at higher levels of per capita income, with a strengthening of the correlation between SDIM and income (or education or other social predictor) over time.

For 18 high-income countries of Europe and North America, we then explore available data back to 1900—around the onset of epidemiologic and demographic transition. This extended time window allows observation of the pre-transition period when M/F exceeded 1: males had the survival advantage, presumably due to the combination of high fertility rates and excess maternal mortality. The historic data of the early 20th century shows the onset of epidemiologic and demographic transition and stunning turnaround in SDIM, as female survival gains exceeded those of men and M/F declined below 1. Perhaps even more strikingly, within a couple decades of the onset of transition, we also observe the cross-sectional pattern of female "resilience" to social adversity, a pattern that continues (and strengthens) thereafter through to the present.

In the third section we examine the evolution of SDIM in the contemporary developing world, drawing on the increasing availability of reasonably reliable mortality data. The data show that current middle-income countries like Argentina, Brazil, Thailand and Iran experienced a pattern of SDIM since 1970 very similar to that of the world's most developed countries decades earlier when they were developing—namely, rapidly declining M/F, with a cross-sectional pattern of female "resilience" under social adversity. It appears at least some of these countries have reached by 2000 the "inflection" point where M/F starts to rise as it had in the most developed countries 30 years before. The more recently developing countries, like India, Vietnam and

Nigeria, appear to be passing through the same pattern of change in SDIM. Examining these low-income countries can provide valuable insight about the robustness of the SDIM stylized facts, primarily because the data extend back to the onset of their epidemiologic transition. The pattern of change in their SDIM proves remarkably comparable to the beginning of the 20th century in the current high-income countries.

Part IV turns to the Former Soviet Union (FSU) and Eastern Europe to exploit the great natural experiment unleashed by Gorbachev's social investments of the late 1980's and the subsequent fall of socialist central planning, associated with unprecedented change in mortality rates over a very short period of time as per capita income plummeted in "transformational recessions." Here, too, as for western developed countries that have consistently grown richer year over year, we observe the same pattern of female "resilience"— the best explanation for why women in the former Soviet Union and Eastern Europe were largely shielded from the catastrophic and stunningly abrupt rise in mortality that afflicted men, especially in socially disadvantaged settings.

The next section draws these observations together to present a set of "stylized facts" about variation in SDIM over time and place. Linking together the threads of evidence reveals two critical conclusions: First, in each of the periods of economic development after the onset of demographic and epidemiologic transition, cross-sectional variation in SDIM exhibits a consistent pattern of female resilience to mortality under adversity. That is, at a given point in time, M/F survival is positively correlated with socio-economic conditions. Second, as societies develop over time, M/F survival tends first to decline and then to increase. The later phase of declining SDIM—when M/F asymptotes toward 1—is fully evident only thus far in the most privileged of the world's countries, but is beginning to emerge in middle-income countries as well.

We qualify these tentative conclusions by reviewing the limitations of the data used to establish them, as well as by emphasizing the need for careful subsequent causal analyses. For these two major reasons, we caution the reader to take our interpretation with a healthy dose of skepticism.

We conclude our discussion by returning to the questions that prompted our exploration of SDIM: why do women live longer than men, and what are the implications for reducing excess male mortality? We conclude, based on the patterns of change recapitulated in virtually every society once it has begun to develop, that while women enjoy some unbreachable biologic advantage, it does not account for more than a small portion of the historically observed mortality difference between the sexes. Likewise, though differential indulgence in risky and harmful behaviors is a likely important proximate cause of SDIM at every point in time, the evidence in the aggregate provides a basis for belief that there is also an underlying, universal proclivity among women towards self-preservation in the face of harm and risk, likely a hard-wired adaptation to environmental adversity usually referred to as "socio-biology." As gender roles have tended to converge in highly affluent societies, so too have mortality rates, so that the female survival advantage is compressed toward the biological minimum.

Data and methods

We chose as our metrics of mortality either survival to age 70 (S_{70}) or LE. We prefer the former because of its reliability of estimation in small populations for which rates of mortality among older age groups are unstable. However, we have yielded to the reality that for many populations and subpopulations of *a priori* interest, full sex-specific life tables were not available, only published estimates of LE, secondarily derived. As our measure of differential mortality we have chosen M/F (either M/F_{70} where possible, or M/F_{LE}) as our outcome measure. The preference for M/F as a statistic is twofold: first, it is almost uniformly between 0.6 and 1 in the data, conferring some ease of presentation; and second, it is consistent with the evolving demographic concept that in high income, low fertility societies, female mortality represents at a place and time the species longevity "gold standard," a target we would ideally hope men could emulate, i.e. that M/F_{70} or M/F_{LE} would approach unity. However, it should be noted from the outset that in other societies—particularly those plagued by poverty and high maternal mortality and/or rampant discrimination against women—a M/F_{70} or M/F_{LE} approaching or exceeding unity implies the opposite: a red flag signaling that female survival is far below potential.

Despite the noted similarities between M/F_{70} or M/F_{LE}—and the strong positive correlation between them—the two metrics are not interchangeable. We caution the reader against any direct comparison of the magnitudes of the two metrics, as the meaning of an M/F_{LE} of 0.90 is not the same as an M/F_{70} of the same numeric value: the former is about average in our LE data sets, the latter so high as to be seen only in the very wealthiest and poorest of populations.

Arguably the most challenging research decision was the choice of appropriate data, particularly historic mortality trends which are of significant interest but also of suspicious quality. We have made a few overarching choices. First, we decided for quality and practical reasons to confine our study to the last 5 decades, a time period for which reasonable mortality data, and some relevant covariate data, are available. The only exception was data from the Human Mortality Database, which enables a look back to 1900 for a group of 18 now high-income countries.

Others have previously published the average life expectancy for 187 countries by decade since 1970 (Wang et al. 2012). We grouped these countries using data from the Global Burden of Disease project (Lozano et al. 2012). Specifically, we defined five groups of countries (Group 1 most developed) based on the country's 2010 Human Development Index, modified to exclude LE as a core measure to avoid autocorrelation in our analyses, as discussed below. The decision to classify based on stage of development at the *end* of the observation period, not the beginning, was arbitrary, and was designed to facilitate observation of SDIM patterns with foreknowledge of the countries' economic/social development "endpoint" after the fact. Likewise we separated out the former Warsaw Pact countries because of their distinct survival and SDIM patterns, as will be more evident in the presentation devoted to that region below;

we designate this group as 1E. The countries classified in each of the five groups are listed in Supplemental Table 1.

A third *a priori* decision was to exclude from detailed consideration period-place combinations where we had reason to expect maternal mortality risk and its interaction with high fertility rates and infectious disease was of sufficient magnitude that women frequently died in childbirth or of closely related disorders such as rheumatic fever, influenza, etc. In societies where women are more likely than men to die between their teen years and 40, the meaning of high M/F is sharply shifted (as noted above)—a source of variation of global public health and development importance but not directly our focus. Indeed, lingering effects of this era are evident as we trace M/F over time in both developed and developing countries. In practical terms this means we have not analyzed data on M/F in any countries before 1900 or in contemporary Group 4 countries—the world's very poorest—except for presenting a single comparison with other developing countries that *have* entered transition.

Finally, despite the lure, we have largely refrained from examining cause-specific mortality data. We recognize that much of the published effort to explain sex differences in mortality has relied on such data. However, because of substantial limitations in its availability and quality going back in time, especially for the low- and middle-income countries which proved so informative to our exercise, we decided that using the fragments available—and having to choose among them which were of adequate quality—would distract from our purpose, a limitation we revisit in the discussion.

Data Sources are listed in Supplemental Table 2.

Outcome

For the US analyses of the level of state and county, we obtained S70 data using CDC/NCHS Compressed Mortality Files for the year 2010. Due to the established association between race and mortality in the US (Cullen et al. 2012) we only utilized data for non-Hispanic Whites.

For international intra-country analyses, we used country-specific census records for the latest available year to study SDIM at the region or province level (Cai 2005, 2009). Where S_{70} was not available, we used LE. We acquired mortality data for Russian oblasts for years 1978, 1988, and 1998, through the population-based HAPIEE (Health, Alcohol, and Psychosocial factors in Eastern Europe) study.

We used the Human Mortality Database (HMD) and to obtain country-level time-series S70 data for developed countries around the world for years 1900-2010.

We obtained country-level time-series LE data from the Global Burden of Disease project for all countries for years 1970-2010 (Wang et al. 2012).

Data Sources for Explanatory Variables

Except for limited purposes, we restricted our consideration of possible “explanatory variables” to the handful of measures of socioeconomic status that were 1) widely available for the different comparisons of interest; 2) generally accepted as measures of social and economic development; and 3) reasonably comparable despite differences in definitions within each historic and national context. Using these criteria we identified four metrics: per capita income or GDP; educational attainment; percent living below nationally defined poverty levels; and the Human Development Index, which we modified by excluding the LE component to avoid autocorrelation. These metrics were *not* chosen because of any strong prior belief in their importance relative to other SES measures and should not be construed as causally linked to the observed patterns of SDIM in different places and times. Additional behavioral data were collected to compare our approach with hypotheses presented previously in the literature, such as the roles of smoking and drinking in specific contexts.

We utilized numerous sources to collect these social, economic, and environmental variables. For the US analyses, we used the 2010 Behavioral Risk Factor Surveillance Surveys (BRFSS) County database to obtain county-level data on obesity, poverty, and smoking rates. We supplemented this with data from the American Community Survey on population size, high school graduation rates, and per capita income. To explore lifestyle convergence in the US, we constructed a county-level occupational similarity index, measuring the difference between the male and female distributions of occupations, treating "not in the labor force" as an occupation. The index is 1 minus the sum of the changes in the male (or female) distribution required to make the sex distributions in a county identical *(6)*.

We used other country-specific censuses to obtain Japanese income data, Sri Lankan education data, and Brazilian poverty data. We obtained data on country-level smoking prevalence for 1980-2010 through a recent study which provided the relevant data in their supplement section (Ng et al. 2014).

Per capita GDP data for 1970-2010 for countries was obtained from the World Bank. In addition to GDP, we collected maternal mortality data for each country for 1970-2008 using data collected to evaluate progress on Millennium Development Goal 5 (Hogan et al. 2010).

In each instance where we fit an OLS regression, we weighted by log population, which we obtained through country-specific censuses and the World Bank.

Part I: M/F in the US and other Group 1 Countries in 2010

The left panel of Figure 1 shows the distribution of S70 for white men and women in the US by county. The modes for the populations are 0.67 for men and 0.80 for women and the variances 0.003 and 0.001, respectively. As can be seen, women enjoy a sharp advantage and a smaller variance than men. As previously noted, within sex geographic variation in US mortality can be largely explained by a small set of social, environmental and health care-related variables, as can between-race differences (Cullen et al. 2012), but these same variables do not explain the gulf *between* the sexes. Moreover, all are less than unity—there is no US county in which males have equal or better survival than females, though there are some counties for which the ratio approaches 1.

In figure 2 A-C, we see more clearly that these ratios are not distributed randomly across the counties, illustrating one of our main points: women consistently exhibit greater survival "resilience" to social adversity. More or less identical relationships emerge with respect to percent in poverty, per capita income, or low educational attainment. Although survival is associated with each of these social measures, men are far more "elastic" in response (i.e. more vulnerable to adverse social circumstances). OLS regressions, shown in Table 1, reveal the relationships quantitatively. Though each variable is itself a potent univariate predictor of mortality, obesity and tobacco use correlate weakly with SDIM after controlling for other covariates and add little to the model's predictive power. Conditional on the other variables, M/F smoking ratios appear minimally related to M/F_{S70} (Figure S1). Counties in the 16 Southern states have lower M/F_{S70} after adjusting for the other covariates. The reader will also note substantial variation explained by the occupational similarity index, seen graphically in Figure 2D. We shall return to these observations in the discussion.

The variation in M/F among and within other Group 1 countries reveals comparable relationships between SDIM and indicators of SES. Switching to M/F_{LE}, Figure 3 shows that log per capita GDP is strongly correlated with M/F_{LE} across high-income countries. This same relationship appears to hold among geopolitical regions within Spain and Japan, analogous to the US data above (Figure 4). Ecologic analyses of income strata in Canada and Denmark mirror this as well (Helweg-Larsen and Juel 2000; Trovato and Lalu 2005); to our knowledge there are no counter-examples among high-income countries.

Part II: M/F in the US and other Group 1 Countries over Time

We begin our inspection of the longitudinal change in M/F after World War II, when mortality data are more robust than for earlier periods. Figure 5 shows the respective changes in M/F_{S70} for all of the Group 1 countries. Japan exhibits a distinctive downward trend, but all of the other countries show a consistent "U" with the nadir somewhere between 1970 and 1985.

This "inflection point" of SDIM in the 70's and 80's has already been the subject of considerable scrutiny, if for no other reason than actuarial application to insurance and pension schemes (Gjonça et al. 2005). Some have explained the plateau, occurring as early as the late 60's in the most developed countries and over the following decade in the rest, by the impressive change in smoking behavior over that period, namely the start of decline in active smoking among men and uptake of the habit by women (Preston et al. 2012). While this theory is compelling, given the prevalence of smoking and its lethal impact, the burden imposed on any theory is to explain the general symmetry of SDIM for both between-country and within-country data, and its consistent trend over time since at least 1950. This relatively homogenous pattern may not be easily explained by the wide diversity of smoking behavior—on average and between sexes over time—that the epidemic has produced, depicted for Group 1 countries in Figure S2, and reinforced further by evidence from Asia where historic smoking patterns are quite different.[*]

As an alternative perspective, encouraged by our initial cross-sectional observations of relative resilience of female mortality rates to socially adverse environments in Part I, we show in Figure 6 in cross-section the relationship in the US between M/F and per capita GDP (by State because of availability) at the nadir of M/F (around 1970) and forward to the present. This suggests that the "female resilience" pattern is already ensconced by 1970 and persists. Striking too, although the slopes appear to remain more or less unchanged over time, the correlation strengthens in both regressions. Indeed, comparing group 1 countries with each other during this 40-year period, depicted in Figure S3, the same pattern appears to be occurring.

[*] For example, Jiaying Zhao's analysis of mortality data in East Asia from the 1970s reveals that changes in smoking patterns are unlikely to explain the dramatic changes in cause-specific SDIM there (to oversimplify, largely because women never smoked and men always have in societies like China, Japan, and Korea) (Zhao 2013).

It is instructive to investigate the pattern within Japan, perhaps the world's fastest developing country post-World War II and with a very different set of cultural norms. As seen in Figure 7, several things are apparent at a glance, notably that the growth in per capita income was remarkable, and that with growth came greater disparities among the regions of the country in mean per capita income. The evolution towards the resilience pattern observed for Japan in Figure 4 is also evident, with a hint that some prefectures are "slipping" towards lower M/F, consistent with the less marked "U" shape longitudinal pattern in Japan compared with that seen in other Group 1 countries (Figure 5).

Next we examine the data from the early 20th century to observe (available) Group 1 countries during their epidemiologic transition (Fink 2013; Omran 1971). Figure 8 reveals this was a period of steady M/F decline in the U.S. and other affluent countries for which we have data (compare Figure S4); this downward trend in M/F reflects gradually increasing relative female survival, and would appear to merge continuously into the curves depicted in Figure 5. Notably, several countries—including the United States—started the 20th century with an M/F_{LE} ratio exceeding 1.0, suggesting that during the centuries before the demographic and epidemiologic transition women suffered a mortality *disadvantage* that may hint at evolutionary origins for the later-emerging "female resilience."[†]

Figure 9, in which we (reluctantly) use average LE as the independent variable for lack of a consistent measure for GDP or human development, shows how M/F varies across a sample of Group 1 countries in each decade between 1900 and 2010. In the first two decades the *reverse* of the later resilience pattern is evident—women did relatively best in the higher LE countries—followed by a flattening of the relationship by 1920 before the familiar "resilience" pattern emerges and strengthens over time, reinforcing the picture we observed in the US (Fig. 6) and in the later decades for Group 1 countries as a whole (Fig. S3). We will return to the possible interpretations of the "flip" which occurs around 1920 after we have examined the evolving

† There is evidence from some pre-industrial societies to suggest that M/F survival ratios may have varied considerably in the past, along with fertility rates (Hollingsworth 1957)(Jones n.d.).

patterns of male and female mortality in developing countries, as the latter shed considerable intuitive light on the subject.

Part III: M/F in developing countries (LMIC's) in Groups 2, 3 and 4

Moving from developed countries to the low- and middle-income countries (LMICs), three different patterns are salient, depicted in Figure 10. In the most advanced of these (Group 2, including such countries as Brazil, Mexico, Thailand and South Africa), we see a steady decline in M/F_{LE} throughout the period 1970-2010, resembling the Group 1 countries between 1900 and 1970 with a suggestion of a "turnaround" in 2000 reminiscent of the trough in Group 1 countries 2-3 decades before. Group 3 countries, by contrast, show high levels of M/F_{LE} before the decline which appears to start around 1990-2000; M/F in Group 4 countries—the world's poorest—remains, by contrast, high throughout the period, and for a few actually exceeds 1.0 (Sub-Saharan African countries, data not shown) (Lozano et al. 2012).

Figure 11 includes regressions of the relationship between M/F_{LE} and log per capita GDP in cross-section by decade for countries in groups 2 and 3. It appears that for Group 2 countries, about a decade after the M/F begins to decline—1980 (compare with Figure 9)—the pattern of "resilience" for women begins to emerge and strengthens in extent of variation explained; by 2010 the relationship is robust. This evolution of SDIM is not unlike what was observed between 1900 and 1980 for Group 1 countries. For the Group 3 countries, the relationship remains flat through 1990, after which M/F starts to fall (Figure 10). The cross-sectional resilience pattern emerges about a decade thereafter (Figure 11), by 2010 explaining slightly less than 50% of the variance. For Group 4 countries M/F stays very high and in cross-section shows no clear relationship to GDP (data not shown) for reasons we explore further below.

Figure 12 shows recent within-country variation in cross section for two populous countries for which reasonable quality data are available. On the left panel we see Brazil, a Group 2 country now of middle income, revealing the "resilience" pattern of M/F_{LE}, here in a scatter against %

poverty, similar to the pattern which emerged in Group 1 countries several decades earlier. Sri Lanka, on the other hand, is a Group 3 country which as recently as 1963 still had sufficiently high rates of maternal mortality that *national* rates of mortality were higher for women ages 15-40 than for men (Fink 2013; Omran 1971). This pattern provides a hint that the "pre-resilience" pattern of M/F_{LE}, reminiscent of that in Group 1 countries in 1900-1910 (Figure 9), may reflect persistent excessive maternal mortality in the poorer parts of the country. This same concept would appear to explain the high M/F in the Group 4 countries as a whole, consistent with high maternal mortality, shown in Figure S5; by contrast, maternal mortality rates are detectable but low in Group 3 countries, and much lower in Groups 1 and 2 (Hogan et al. 2010).

That the lingering effects of maternal mortality may partially explain the pattern of female resilience emerging a decade or two after national rates of M/F start to fall is further suggested by modern China, a country that would have ranked as a Group 3 country as recently as 1980 but has become Group 2 (and classified as such by our schema). Figure 13 shows M/F_{70} for over 2300 county-level units in China based on county-specific life-tables calculated by Cai Yong from the year 2000 census (Cai 2005). Looking at the aggregate data (left panel) there appears to be no relationship between county log per capita GDP and M/F_{70}. Stratification by rural/urban status reveals a more nuanced picture: rural areas (middle panel) resemble the pattern observed in Sri Lanka (Figure 12), with the highest M/F among the poorest counties, in several cases here exceeding 1, consistent with China's large sex ratio at birth; whereas the urban areas (right panel) distribute more like Brazil or the US, with higher M/F_{70} in more-developed areas (although M/F_{70} exceeds 1 in a few poor urban counties in the same range of GDP per capita as rural counties). Moreover, change over time is also consistent with the patterns of M/F survival noted earlier: based on census data on LE for three of the poorest provinces (Guizhou, Qinghai and Yunnan) with data extending back to 1981, average M/F *decreased* from 0.98 in 1981 to 0.93 in 2010. By contrast, M/F life expectancy in China's wealthiest city, Shanghai, *increased* from 0.94 in 1981 to 0.95 in 2000 (Cai 2005).

Part IV: M/F in Eastern Europe and FSU (Group 1E)

The experience of Eastern European countries, including the former Soviet Union, adds a unique dimension to our understanding of sex differences in mortality. These nations display the lowest values for M/F of any group of countries in the world, based on the most current data available, evident from even cursory inspection of the map shown in Figure S6. Moreover, as shown vividly in Figure 14, the current situation is actually an *improvement* for men relative to the nadir seen two decades ago. The figure illustrates another remarkable feature not evident elsewhere in the world, which is *volatility of SDIM*, matched otherwise only in demographic disasters such as epidemics and wars (note the points off the line in Figure S4). Of course this latter observation must be viewed in the context of the enormous political change that swept this region during the 1980's and 90's, namely the liberalization of state communism during the 80's consequent to Gorbachev's policies in the USSR (associated with rapid and demonstrable improvement in the relative mortality of men), the subsequent demise of that system in the FSU and former Warsaw Pact countries and replacement with market systems in all. This was accompanied by a devastating "transformational recession" that depressed real standards of living for most of the population (Kornai 1994), associated with rapidly rising mortality for men for some years. For completeness we depict the somewhat "melded" experience of Germany (Figure 15). Like other non-FSU Warsaw pact countries, men faltered in the late 80's and even more so after the collapse of the Berlin wall, but since have followed a more typical "Group 1" pattern as part of greater Germany (Vogt and Kluge 2014).

Because of the historic heavier use of alcohol in this region of the world than any other, and the plausibility of its role as mediator for mortality rate gyrations, toxic levels of alcohol consumption have been the focus of much study (Gerry 2012; Mckee and Shkolnikov 2001; Murphy et al. 2006; Tulchinsky and Varavikova 1993; Weidner and Cain 2003; Zaridze et al. 2014; Zatoński 2011). Many analysts credit reduction in excess male mortality to one specific aspect of the Gorbachev reforms—alcohol consumption taxes—in the 80's, and blame the subsequent spike in male mortality on the elimination of those alcohol taxes after 1990 (see for example Bhattacharya et al. 2012); this account is consistent with the biphasic change in SDIM in the FSU during the 1980's seen in Figure 14, with a smoother decline in M/F in the neighboring states (including East Germany) not directly impacted by the Gorbachev alcohol controls. That said, comparative data associating male survival decline with changes in the rate of mortality from acute intoxication among the Russian Oblasts may suggest a different interpretation, or at least raise the question whether alcohol was the root cause of the rapid increase in male mortality, or only one of its mediators. As shown in Figure S7, the gyrations in SDIM in 6 of the 8 oblasts were accompanied by dramatic changes in the rate of acute alcohol-related hospital deaths (Gerry 2012; Mckee and Shkolnikov 2001; Murphy et al. 2006; Tulchinsky and Varavikova 1993; Weidner and Cain 2003; Zaridze et al. 2014; Zatoński 2011); however, comparable changes in M/F_{LE} occurred in the other two—the North Caucasus and South—with virtually no evidence of substantial acute alcohol-related death or change over the period, likely because these regions, albeit of modest comparative population size, are predominantly Muslim. This is not to suggest previous studies have inappropriately targeted the role of alcohol as a rapid and epidemic killer of (young) men, but rather to suggest the role may be better viewed as mediating a relationship between social conditions and male mortality rates—seen here as M/F_{LE}—that finds differential expression in different social and geopolitical contexts. This intuition would appear to be consistent with the fact that despite an abrupt and impressive "transformational recession" in which per capita GDP nosedived, the "resilience" patter of M/F appears moderately well preserved across the Group 1E countries, shown in Figure 16.

Discussion

From the above observations we draw a series of ten conclusions and inferences, presented roughly in the order of those least to most speculative:

1. *Sex differences in mortality (SDIM) vary over time and place as a function of social and medical conditions. The magnitude of these variations, and their abruptness in response*

to large socioeconomic changes, suggest that biological differences alone cannot fully account for observed sex differences in survival.

While many have previously observed the variation in SDIM over time and place, the assembled evidence suggests that such variation follows distinct and identifiable patterns of social change. While some of the underlying patterns are more readily explained than others (as discussed below), there would appear to be little “randomness” in M/F for any population of reasonable size to stably estimate either survival probabilities or LE (with the possible exception of the world’s poorest states, for which reliable data is lacking).

2. *A “SDIM transition” unfolds as part of the demographic and epidemiologic transitions, beginning with the emergence of the now near-universal “female survival advantage” (M/F survival<1), heralded by significant reductions in fertility and maternal mortality and associated causes of death during the reproductive years.*

It is almost certain, though data are incomplete, that there was a time in the history of all now developed (Group 1) countries, and those now developing (Groups 2 and 3), wherein female mortality exceeded that of men. In developed countries the turning point likely occurred between the late 19th century (for northern Europe and Switzerland, for example) and 1910 (see Figure S4). In Group 2 countries this change occurred later, most likely in the mid-twentieth century (although confirmation is problematic because we do not have reliable data on these countries for this time period). We observe this same SDIM transition, occurring between 1970 and 1990, in countries less far along in development (Group 3). Tragically, in some Group 4 countries M/F>1 remains true still today. Omran in his seminal presentation of the epidemiologic transition in 1971 (Omran 1971) opines this was due to maternal mortality at a time when fertility rates were high and the combination of medical knowledge and resources insufficient to prevent frequent maternal deaths from bleeding and infection in developing countries. This conclusion would appear to be reinforced by our observations of Group 2 and 3 countries as they have entered transition, and the data on maternal mortality presented in Figure S5.

Subsequently, within each of these societies, as the survival of women begins to improve, a distinctive cross-sectional pattern emerges wherein M/F is lower where development is *higher* (Figures 9, 11 and 12 (left), 13 (middle)), a pattern we have referred to above as “pre-resilience”. While we do not have sufficient local data to formally test this hypothesis, this early transition pattern likely reflects a “lag” in the decline of maternal mortality in poorer parts of newly transitioning countries.

3. *Shortly after the onset of SDIM transition, a pattern of “female resilience” emerges in which the survival advantage of women is greatest in cross-section in places where SES or development is least. In other words, M/F survival is positively correlated with SES, when M/F survival<1.*

Simultaneously, a striking and not immediately intuitive pattern emerges in cross-section: M/F becomes *positively* correlated with indices of development, i.e., the worse off a country or region within it (after taking developmental “Group” into account), the worse (proportionately) men survive and the better (proportionally) women survive. This “female resilience” pattern as we have referred to it above, illustrated in Figures 2, 3, 4, 6, 7, 9, 11, 12 (right) and S3 is a positive relationship between indices of SES and M/F that appears to persist thereafter.

This “resilience” pattern emerges within a couple of decades after the residual effects of maternal mortality as a female cause of death dissipates, as it did in the period 1900-1940 in the most developed countries (Figure 9), perhaps around 1990 for the Group 2 countries (Figure 11 upper panel), and is just beginning to emerge in the last decade in Group 3 countries (Figure 11 lower panel). That this relationship emerges so predictably as epidemiologic transition progresses—in more or less every observable culture and society (except those poorest of the Group 3 countries [Figures 11, 12] and the Group 4 countries which have not yet entered transition)—suggests that the pattern is unlikely to be best explained by any specific policy, custom, habit, medical treatment or its availability, or health behavior which vary idiosyncratically over time and place.

4. *M/F continues to decline even after the immediate contribution of declines in maternal mortality is accounted for.*

Then, what might not, *ex ante*, have seemed inevitable is observed: a decade or two after the impact of maternal mortality has largely dissipated—e.g. developed countries after 1950 or Group 2 countries after 1980—M/F *continued* to decline for some further decades (Figures 5, 8, 10). We discuss below what we can presently surmise about the causes, but note here the universality of the pattern among Group 1 counties—including Japan which is in other regards an outlier—and the initial evidence in Figure 10 that Group 2 countries are following the same pathway.

5. *At a certain point late in transition, the longitudinal pattern of declining M/F turns around—M/F rises as "men start to catch up". This inflection point in the SDIM transition is evident in almost all high-income (group 1) countries, as well as most middle-income (group 2) countries.*

Best observed presently for the most advanced (Group 1) countries, with a strong signal that Group 2 is poised to follow (Figure 9), a further change in SDIM appears to occur: men are catching up, with M/F slowly rising in the US since about 1970 and in the rest of the developed world (Groups 1 and 1E) between that time and 1990, while improvement in the survival of men appears to have begun in Group 2 countries between 2000 and the present (Figures 5, 9).

In this pattern Japan appears to represent an outlier (Figures 7, 9) in which the pattern of M/F since 1970 has first risen (like other Group 1 countries) only to decline again, reaching a second nadir around 2000; and even with evidence of small relative gains for men since that time, still

Japan has a lower M/F in 2010 than 50 years before. We speculate further on this below. It is worth noting, however, that Japan's case clearly supports our assumption that the narrowing of M/F in the wealthiest countries is not merely an artifact of approaching some biological limit on survival to age 70 (which Japan, of all countries, would be approaching rapidly) or life expectancy (Lee 2011; Oeppen and W.Vaupel 2002). Although expert opinions differ, it appears that "mortality is declining as rapidly in those countries like Japan and Sweden where it is already lowest, as it is in lagging countries like the US, suggesting that life expectancy is not yet approaching a biological limit" (Lee 2011).

6. *Over time, the female resilience pattern—the positive association of M/F with SES—strengthens, even as "men start to catch up" overall.*

Whether comparing within groups of countries (Figures S3, 9, 11) or within regions in a single country (Figures 6,7, 16), there is compelling evidence that the resilience pattern, in which women survive relatively better in circumstances of lesser advantage, strengthens over time, with the correlation (Spearman's Rho) between M/F and several measures of SES eventually reaching the range of 0.8 or higher. Noteworthy is the perpetuation of this resilience pattern after the tipping point where male survival improves relatively (approximately 1970 for Group 1 and 2000 or so for Group 2).

7. *It would appear that the patterns of SDIM observed through the epidemiologic transition for high-income (group 1) countries are being recapitulated by low- and middle-income countries (groups 2 and 3).*

Our observations would also appear to provide a new perspective on the stages of epidemiologic transition as originally defined in 1971 (Omran 1971; Fink 2013). Omran was writing, as chance would have it, at a critical historic moment that he could not have foreseen, as Group 1 countries were moving from the era of ever-improving relative survival for women into the modern era in which men have begun to catch up. At that very time, those countries we now dub Group 2 were beginning to “make their move” towards development. Omran defined the “quartet” now generally appreciated to be the cornerstones of epidemiologic transition: 1) *decline in fertility rates* with a concomitant decline in maternal mortality; 2) *rise in labor wages and productivity*, with associated social welfare benefits including better nutrition and housing; 3) *decline in malnutrition and infections as the major causes of death, with emergence of chronic diseases* as has been seen in Group 1 and now evident in groups 2 and 3 as well; and 4) despite the emergence of NCDs, *a dramatic rise in overall LE*.

Based on our own observations, we would add to Omran’s list a fifth phenomenon: the emergence of the female survival advantage, characterized here as “resilience” from the emerging NCD epidemic. Moreover, we would speculate that the cresting of that advantage as development proceeds, now evident in all developed countries, may demarcate yet a further phase in the demographic transition, though it is too early to do more than prognosticate, as Group 2 countries as a group have just entered this phase, and Group 3 countries have yet to arrive.

Perhaps more importantly, from the perspective of SDIM, transition appears to demonstrate an impressively consistent pattern, at least based upon the data available. Viewing Figure 10 through the lens of what was learned from examination of earlier decades for Group 1 (Figures S4, 8, 9), one could readily imagine that the x-axis represents not 4 decade-markers for each of four groups of nations, but 16 “place-time” markers, structured like a classical “rondo” in which each group embarks on the transition pathway 30-40 years after the previous one, then replicates its path. Obviously it is premature to consider this empirically proved, but there is scant evidence to support an alternative prognosis.

8. *In wealthy countries, and wealthiest regions within such countries, M/F approaches—but does not reach—unity.*

From Figures 1, 2, 3, 5, 6 and S3 it is clear that some Group 1 countries as a whole, e.g. Iceland, and within highly developed nations some states or counties, such as Santa Clara California[‡], have M/F ratios that are approaching 0.96 or 0.97 for LE and 0.95 for S_{70}. We use the term "approach" with great intention, as we not only can observe these high values but also the slow assent which preceded, demarcating these settings from others—earlier in time or in poorer countries—in which identical M/F numerical values, would of course, have an altogether different interpretation.

It is equally noteworthy that we observe in this context no cases of M/F>1 as we would expect if these near-unity values represented "mean" levels around which there was random variation. In point of fact a value in excess of 1 is not encountered in a single country or sub-region of a Group 1 country, nor even in a Group 2 country (except perhaps a handful of Chinese counties, mostly rural in a unique setting for which there are other plausible explanations related to family planning policies, son preference, and their unintended social consequences). This would suggest that something around M/F_{LE} =0.97 represents an upper bound of the data at least barring any major change in causes of mortality that might uniquely impact the sexes differentially.

9. *Several sex-specific behaviors, such as smoking or alcohol consumption, have been identified in some settings as causal or contributory to the observed variation in SDIM. However, the consistency of the pattern in different countries and cultures suggests more "upstream" determinants driving the disproportionate gains in female survival over time and the strong ubiquitous "resilience" pattern that has emerged.*

What factors might underlie this phenomenon? As noted it is unlikely that maternal mortality, or other adverse health impacts associated with reproduction, play a role—even lingering—in this phenomenon that seems very robust to variation in geography, culture and ethnicity. It

[‡] from which we write

might be tempting to attribute this phase to the more rapid adoption by men than women of particular subsets of "bad behavior"—tobacco and alcohol abuse, dangerous use of motor vehicles, violence, or work in dangerous occupations, to name the more obvious contenders—or that the advantage relates to women's known greater propensity to use the health care system (Bertakis et al. 2000; Sindelar 1982; Oksuzyan et al. 2008); indeed, there is substantial evidence that each of these is a proximate cause of differential mortality between men and women in some settings (Concha-Barrientos et al. 2004; Cutler et al. 2011; Ezzati et al. 2008; Hunter and Reddy 2013; Kalben 2002; McCartney et al. 2011; Norström and Razvodovsky 2010; Tomkins et al. 2012). That said, the ubiquity of the pattern globally, after adjusting for stage of development as illustrated in Figures S1, S2, S6 and Table 1—despite differences in sex-specific behaviors in different regions, cultures and societies—suggests that the resilience of women to socio-economic adversity during the "post-maternal mortality" era of development may have a more fundamental "upstream" origin. Plausibly evolutionary pressures created a social and biological propensity for women to be resilient to other mortality causes when childbirth-related mortality was very high (during most of our species' history); according to this theory, the "smoking guns" of higher relative male mortality, such as tobacco and alcohol abuse, would be better viewed as vehicles than underlying cause.

10. *The convergence of M/F towards 1 in advanced societies appears to be associated with convergence of the lifestyles of men and women.*

It might be tempting to explain the "inflection point" in SDIM by one or another social/behavioral changes that occurred in this time frame—in some countries women began to smoke more, but also join the traditionally male sectors of the workforce or the like. However, the most parsimonious theory is that with further development, fewer and fewer of the "least developed" parts of most countries remain undeveloped. Furthermore, populations undoubtedly have migrated on average towards the economically developed parts of each country, as is so obvious with the rapid urbanization in most developing countries (e.g. Figure 12) (Fink 2013), although we have not explored the role of migration systematically.

Another way to conceptualize the phenomenon of convergence of M/F towards 1 is to consider broadly the lifestyles emerging in the richest parts of the developed world. On the one hand, women are achieving greater role parity, as legal and social barriers to their advancement in formerly male-dominated arenas such as construction and manufacturing but also business, academics, politics and the professions erode. At the same time men, now more often in marital or other relationships in which women share many of the same needs and interests as their own, are far more likely to provide child-care and other family roles formerly delegated to women. Moreover an increasing fraction of households have single or same-sex heads.

However these cultural phenomena are perceived, there can be little doubt that the formerly distinct sex roles are themselves converging in such societies; viewing this convergence as relevant to the near convergence of M/F seems inescapable. Of particular interest in this regard may be the experience of Japan, in which uniquely among Group 1 countries M/F is receding from 1 (Figures 5 and 7). Although many interpretations are plausible and research is ongoing, Figure 17 suggests some support for our claims regarding lifestyle convergence both graphically and in an ordinary least squares regression: once one controls for lifestyle differences using the “Economic Gender Equality Score” component of the 2010 “Gender Equity Index” (Hausmann and Tyson 2010), Japan is no longer an outlier in the strongly positive relationship between M/F_{LE} and GDP per capita. This theory is supported for US counties by the regression presented in Table 1 (Model 2, Full): the occupational similarity index remains a significant correlate of M/F_{S70} even when controlling for all the other predictors. Like the Group 1 country comparison, the US has “its Japan”: Alaska, despite being in the top 10% of US states by SES measures, has a low occupational similarity index and a far lower-than-expected M/F_{70} (Table 2). Arguably, the regional impact on M/F_{S70} noted in the US South, even after adjustment for occupational similarity (Table 1), may be a signal supporting a similar mechanism.

Caveats

There are of course important limitations to our approach that must be considered:

1. First, as we conceded at the outset, our effort has required use of very diverse data sets, each with quirks and opportunities for imprecision and bias. In many cases we have relied on life table analyses of others to impute sex-specific S_{70} or life expectancy. Perhaps most significantly, we have been limited to what was available; in many cases data do not extend back in time far enough nor geographically widely enough, leaving multiple empiric gaps (such as lack of evidence on Group 2 countries when M/F exceeded 1, as would appear likely from the “surrounding” data).

2. We do not consistently address over time and place the roles of sex-specific causes of death, with the exception of maternal mortality, and even that we have addressed superficially for lack of detailed data for most times and countries. Assuming that after epidemiologic transition mortality rates from cardiovascular disease (heart attack, stroke, heart failure) are at once the major causes of mortality and of its change, as well as diseases that have excessively killed men, it is tempting to explain all of the late changes in M/F by sex-differential risks related to that single disorder and its major risk factors: smoking, diet, physical inactivity, etc. Indeed, the positive correlation between M/F and SES has strengthened during the period cardio-vascular disease evolved from a disease of the relatively affluent to a disease largely afflicting poorer populations in Group 1 countries, a pattern evidently recurring in LMICs (Harper et al. 2011; Saquib et al. 2012). Nothing in our analysis can, in and of itself, disprove such a simplifying assertion. However, as noted, any theory of SDIM must be able to account for observations from myriad countries, cultures and ethnicities in which the distributions of many risks, and their timing in relationship to other developmental and medical changes, are variable. For example, there is compelling evidence that in south Asian countries women, more than men, are afflicted by inactivity, poor diet and obesity, even if they smoke far less (Saquib et al. 2013). The limited availability and quality of disease-specific mortality data has precluded our further exploration of such considerations.

3. For numerous independent covariates of *a priori* interest—e.g. differential educational attainment and career experience among men and women, differences in opportunity for managerial and professional roles for women relative to men, religious laws and customs which one might anticipate could impact or mediate some of our observations, differential access to, and quality of health care, indeed any component of the gender equity index—we had no available metric to directly test across datasets, and have refrained largely from testing in any. The importance or lack thereof for such unmeasured covariates in our analyses cannot individually or even collectively be estimated.
4. We have no way to account for yet another compelling difference well documented in many societies, namely differential health seeking behavior; women utilize approximately double the healthcare services of their male counterparts in developed societies (Bertakis et al. 2000; Oksuzyan et al. 2008; Sindelar 1982). The importance of this difference as a cause rather than a result of SDIM, outside the context of improvements in obstetric care, is impossible to assess from our data.
5. Even for those "explanatory variables" that we have tested—per capita GDP, educational attainment, percent in poverty—we lack consistent definitions and metrics over time to enjoy a high level of confidence in comparisons, even those which appear quite robust to variable choice.

Implications for pathways mediating SDIM

We return in closing to the question with which we started: why do women live longer than men? Our study aims to better understand the underlying basis of the century-long female survival advantage (in current high-income countries)—with the reminder that this has not always been true. Indeed, the *reverse* appears to have been true in even the most advanced countries until the late 19th century, and in many parts of the world until mid-late twentieth century, because of the high burden of death in women consequent from a life-course of continuous reproduction, in the absence of life-preserving health services. Regrettably, in a few of the world's poorest countries, women still have worse survival than men. That said, women in the rest of the developing and developed world *do* now enjoy an unmistakable survival advantage.

We noted in the introduction three broad theories that have received attention, and we now return to each with the benefit of our observations, with full regard for their limitations enumerated in the last section. The first notion is that women enjoy some hard-wired, *biologic* advantage, selected during human evolution. This might owe to some differential survival of Y-chromosome negative cells themselves, whose longevity is the underpinning of survival of the organism, or a systemic effect such as the impact of reproductive hormones on modification of certain pathologies (e.g. retarding the accretion of atherosclerotic plaque in our blood vessels, the cause of cardiovascular disease). It could be that the female immune system resists the decline which begins to appear in our sixth and seventh decades (Goodwin et al. 2006; Goronzy and Weyand 2012), or such benefit could be very organ-specific, such as the possibility the female human brain can withstand great stress from lack of oxygen for longer, the core idea underlying the observation that even from infancy females appear to die less frequently of assaults to their respiration (Liu et al. 2014; Mage and Donner 2006). It has recently been suggested that women are able to adapt more readily to their educational environment, based on observation in Europe between 1920 and 1950 (Weber et al. 2014). The long observed better survival of female fetuses suggests yet other evolutionary advantages (Drevenstedt et al. 2008). Owing in part because of our inability to examine specific causes of death in any universal fashion, we cannot distinguish amongst such hypotheses, nor determine to what extent such advantage might accrue owing to evolutionary pressure created by the benefit to clans of "grandmothers" to raise children in the face of high maternal mortality (Chu and Lee 2012). What we can say, however, is that there almost certainly is a biologic advantage, one that seems impervious to—indeed, becomes more evident under—environmental or social stress. How else could we explain the universality of the female survival advantage over time, culture, religion, political regime and place, once the scourge of maternal mortality has been overcome? In not one single US county, nor in any single country in Groups 1-3 including 1E, do more men survive to age 70 than women do. There would appear to be no escaping that some of the advantage is “hard”.

But despite the data limitations, we can actually infer more. For while some sex-specific difference in either S_{70} or LE appears to be constant, the magnitude is not. We have seen, with the benefit of longitudinal and cross-sectional observations, that M/F_{LE} is asymptotically approaching 0.97 and M/F_{70} is approaching 0.95, which translates to 2-3 years of extra life on average for women, or a 5% higher likelihood of survival to age 70.

So if the life expectancy difference in the Group 1-3 and 1E countries averages perhaps 6-8 years currently, and the difference in survival to 70 still exceeds 10% in many Group 1 countries, including the US, what accounts for the remainder? Differences in health behaviors beg consideration, and indeed have received a great deal, with special attention to tobacco and alcohol (Bhattacharya et al. 2012; McCartney et al. 2011; Preston and Wang 2011). Differences between the sexes in their proclivities toward violence, dangerous occupations, risky driving, and athletic behaviors are generally observed, and none can be dismissed as contributory, especially to differences in mortality rates at younger ages. On the contrary, each provides a critical pathway for intervention to improve male mortality in the appropriate context. But in the face of our observations, two thorny questions cannot be readily dismissed. First is the need to explain the universality of the pattern of female resilience to social adversity, which appears to be as true of countries like Russia and Japan as in western Judeo-Christian ones, and is emerging in the rapidly developing countries of the world—including such diverse places as Brazil, China, Iran and Thailand—in almost identical pattern. Without the ability to formally test any one of these hypotheses, we would suggest, following Popper’s famous dictum regarding hypothesis testing, that while we cannot directly observe if all swans are white, we have spotted a few possibly “black” ones, and suspect that on closer inspection others will emerge.

But even accepting that there are in almost all societies striking and lethal differences between male and female behavior choices and opportunities relating to risk and habit, the question remains as to why the different life choices arise, and why in the face of such choices women still seem to fare better, at least regarding mortality. Here we come to the third broad area of speculation—*socio-biologic differences* between the sexes, which has come to mean hereditary biologic differences whose expression is not manifest in "biology" per se but in social behavior. Most notable among these behaviors are nesting and family-protecting roles, in which sex differences appear common throughout human society and also in lower primates—indeed, observed among other animal kingdoms as well. As such one would distinguish the roles of sex hormones as mediators of pathologic changes in blood vessels from their contribution to the social planning and networking behaviors of women, which differ so markedly from men's, at least historically. How, mechanistically, such inborn differences may contribute to the remarkable resilience of women to social adversity that we have seen in every culture once epidemiologic transition takes hold is of course is something about which we can only speculate.

To this end it may be worth more closely examining the "advanced phase" of epidemiologic transition in which men have started to catch up. True, we can presently only observe this period in the most developed countries, hence it would be premature to assume that this, like the earlier phases, will be recapitulated fully by Group 2 and 3 countries over the coming decades. Nevertheless, the narrowing sex difference in survival does not owe to any obvious worsening in female survival; to the contrary, female survival continues to improve (Figure 8). Rather, the narrowing SDIM stems from a relative change in rates of improvement, with a relative acceleration of improvement for men. This "turn around" in diverse countries and contexts could be attributed to simultaneous improvements in male decision making regarding behavior, such as less smoking or improved health care. The decline in cardiovascular mortality consequent to treatment for hypertension and hyperlipidemia would stand out, along with widespread use of aspirin and impacts of interventional cardiology, albeit to greater degrees in some countries than others. But it would seem not unreasonable to speculate that this late phase in development represents, overall, a period of societal "feminization", in which the lives of men and women, historically divergent in even the most liberal western societies, have begun increasingly to converge. And while more women work outside the home, relatively more smoke, and some like guns, the net effect of “social welfare societies” would appear consistent with the rising dominance of women’s superior—at least from a survival perspective—socialization, auguring an era in which only the (modest) female genetic advantage should prevent men from achieving survival parity.

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Table 1. Regression Table

Table cells: *Regression Coefficient / Beta Coefficient*

	Outcome: M/F S70					Outcome: Male S70	Outcome: Female S70
Predictors	**Univariate (n=3,059)**	**Model 1, Limited (n=3,059)**	**Model 2, Full (n=3,059)**	**Model 3a, South (n=1,112)**	**Model 3b, NonSouth (n=1,938)**	**Model 4a, Full (n=3,059)**	**Model 4b, Full (n=3,059)**
% Poverty	-0.005 / -0.657***	-0.002 / -0.297***	-0.003 / -0.354***	-0.004 / -0.405***	-0.003 / -0.348***	-0.001 / -0.195***	-0.000 / -0.095**
Log Income PC	0.154 / 0.650***	0.117 / 0.459***	0.059 / 0.323***	0.081 / 0.387***	0.043 / 0.319***	0.091 / 0.437***	0.012 / 0.172***
% Lower Edu /<12 Yrs)	-0.003 / -0.541***	-0.001 / -0.119***	-0.000 / -0.088**	-0.001 / -0.092**	-0.000 / -0.081*	0.000 / 0.004	-0.000 / -0.152***
Occupational Similarity Index	0.437 / 0.643***		0.276 / 0.320***	0.289 / 0.337***	0.272 / 0.316***	0.202 / 0.270***	0.020 / 0.058*
Male Smoke	-0.002 / -0.251***		0.000 / 0.007	-0.000 / -0.007	0.000 / 0.014	-0.000 / -0.015	
Fem Smoke	-0.003 / -0.279***		-0.001 / -0.012	-0.000 / -0.010	-0.001 / -0.013		-0.001 / -0.010
Male Obesity	-0.006 / -0.419***		0.001 / 0.010	0.001 / 0.019	0.001 / 0.007	-0.000 / -0.012	
Female Obesity	-0.006 / -0.444***		0.000 / 0.022*	0.001 / 0.072*	0.000 / 0.005		-0.000 / -0.070**
South	-0.042 / -0.449***		-0.013 / -0.135***			-0.006 / -0.097***	0.000 / 0.060*
R^2		0.628	0.720	0.575	0.602	0.709	0.548

Inference: *P<0.05, **P<0.01, ***P<0.001

Data from the 2006-2010 NCHS's Compressed Mortality Files and US Census Bureau's 5-Yr 2010 ACS at the county level.

Data restricted to Non-Hispanic Whites in counties with >100 Non-Hispanic White deaths under age 70 between 2006-2010.

Table 2: Alaska and Alaskan Counties

I. Alaska

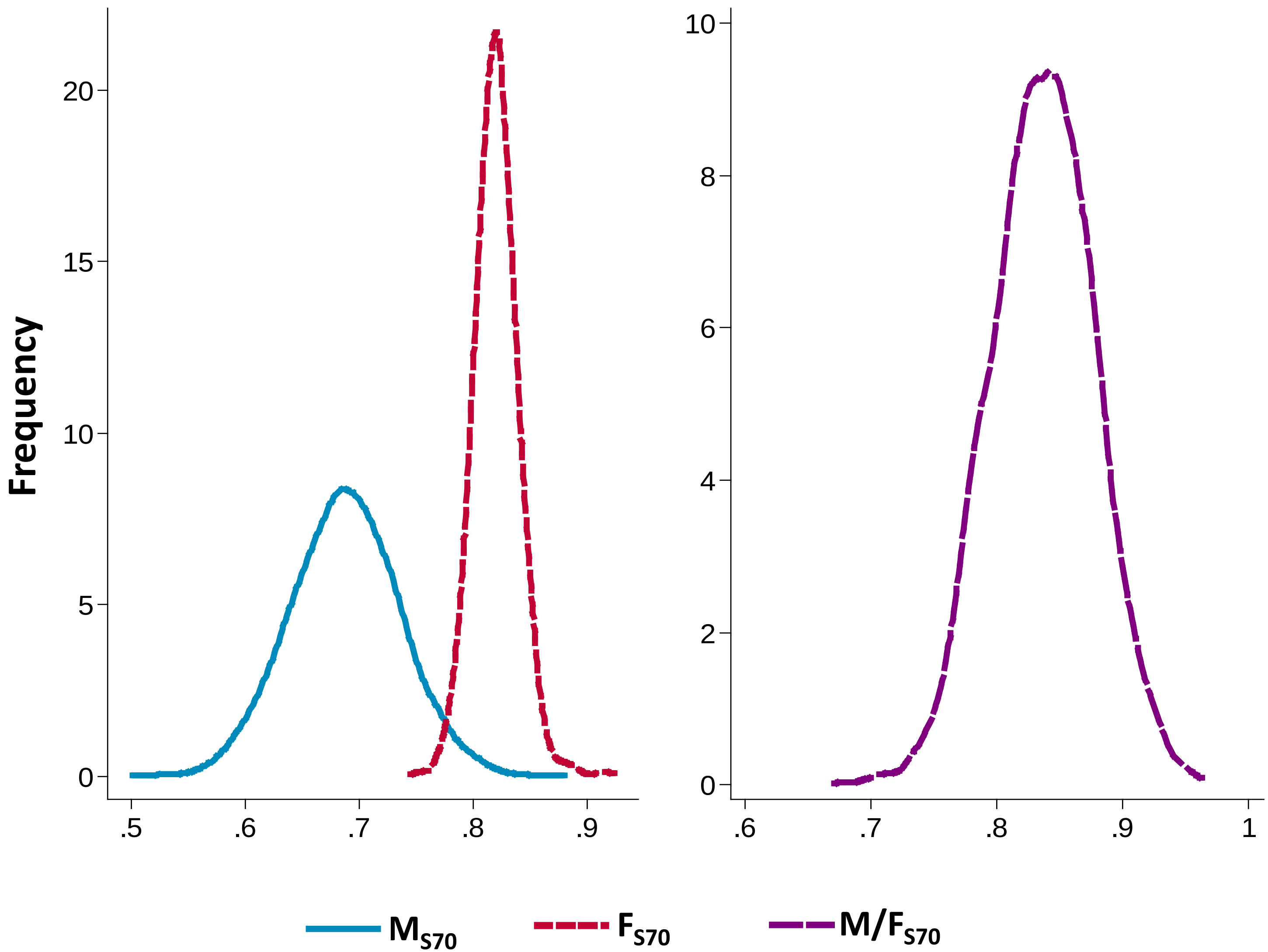
	M/F S70	Predicted M/F S70*	% Poverty	Income per Capita	% Low Education, <12 Yrs School	Occupational Similarity Index
Alaska	0.85	0.92	7.5	51,971	10.0	0.39
Mean, All States	0.90	0.90	13.2	41,948	12.3	0.51

II. Five Largest Counties in Alaska

	M/F S70	Predicted M/F S70*	% Poverty	Income per Capita	% Low Education, <12 Yrs School	Occupational Similarity Index
Matanuska-Susitna Borough, AK	0.80	0.89	7.9	56,634	14.4	0.35
Kenai Peninsula Borough, AK	0.82	0.90	8.6	57,096	12.4	0.37
Fairbanks North Star Borough, AK	0.85	0.93	5.8	58,945	7.1	0.45
Juneau, AK	0.85	0.94	5.2	70,092	6.8	0.62
Anchorage, AK	0.84	0.94	3.6	76,228	7.7	0.64
Mean, All Counties	0.84	0.82	15.2	45,308	20.7	0.56

*Predicted M/F S70 is predicted using % Poverty, Income per Capita, and % Not Graduate High School

Figure 1: Frequency Distribution of S70 for US Counties for Whites, Males and Females, and M/F_{S70}



3,059 counties with at last 100 deaths/year between 2006-2010

Figure 2 . M_{S70}, F_{S70}, and M/F_{S70} vs Poverty, Log Income, Education, and Occupation

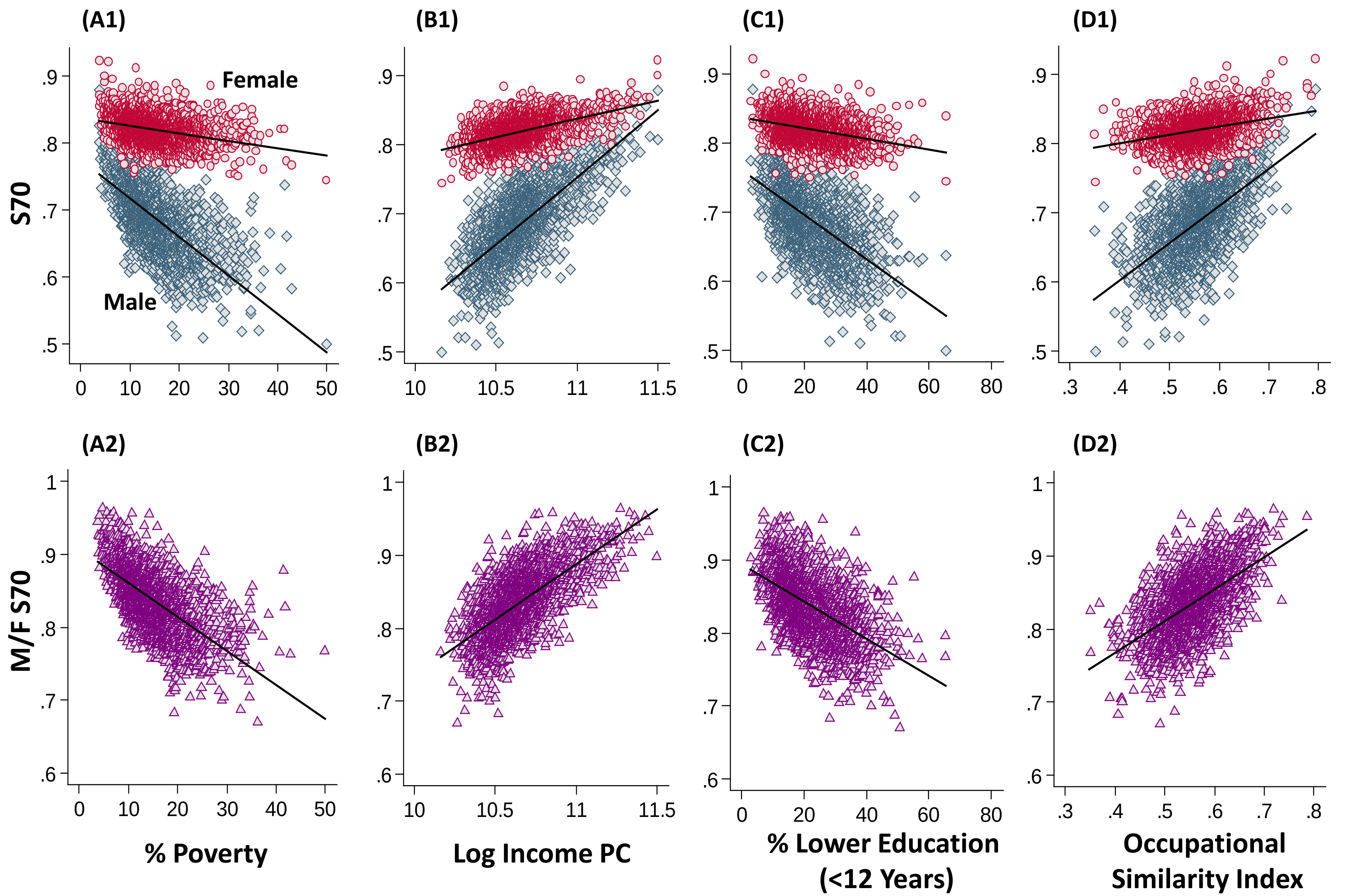
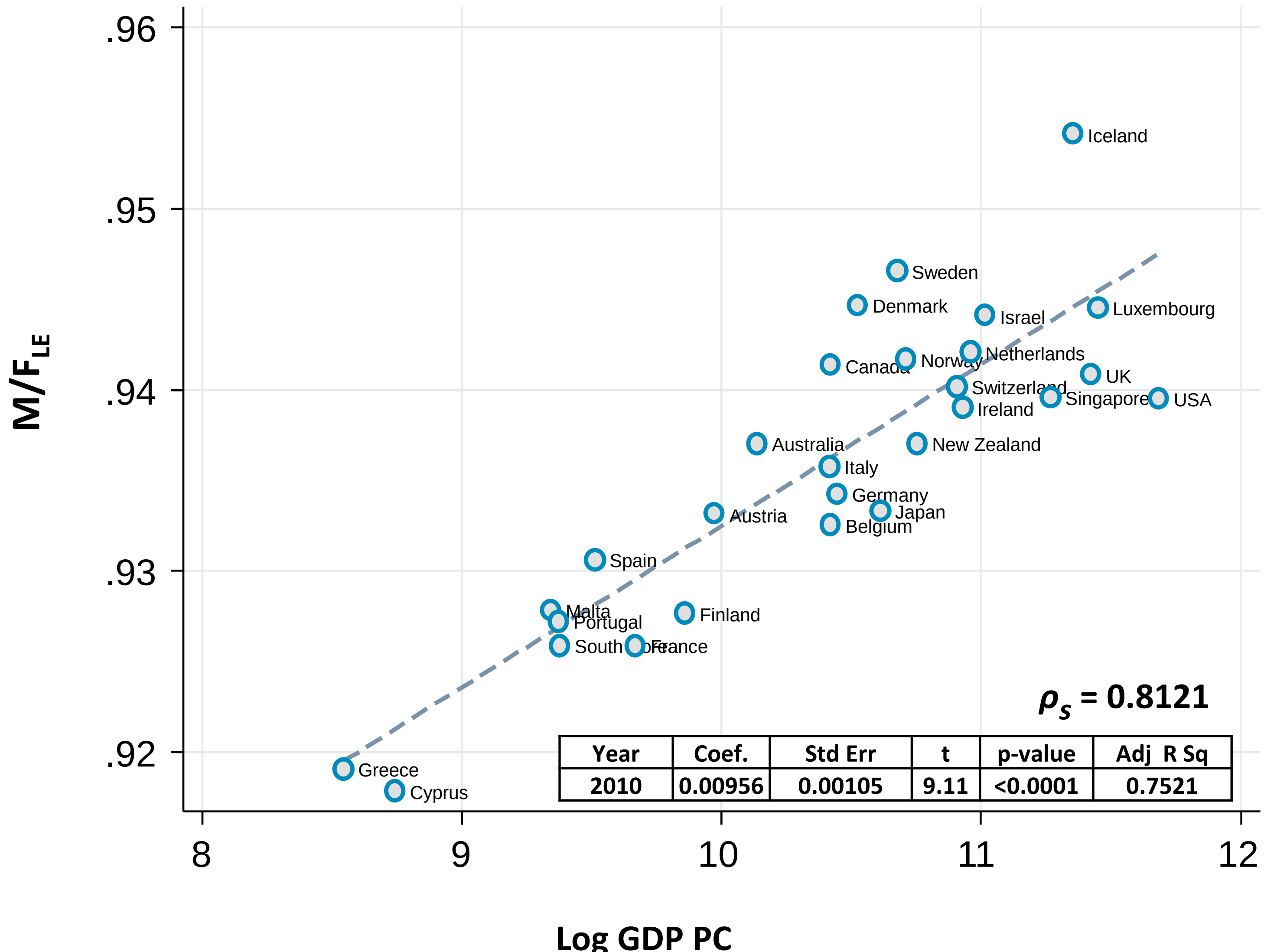


Figure 3: M/F_{LE} v. log per cap GDP for Group 1 countries, 2010



Year	Coef.	Std Err	t	p-value	Adj R Sq
2010	0.00956	0.00105	9.11	<0.0001	0.7521

Murray, Lancet

Figure 4: M/F_{s70} v. log GDP for Spain and M/F_{LE} v. log Income for Japan (2005)

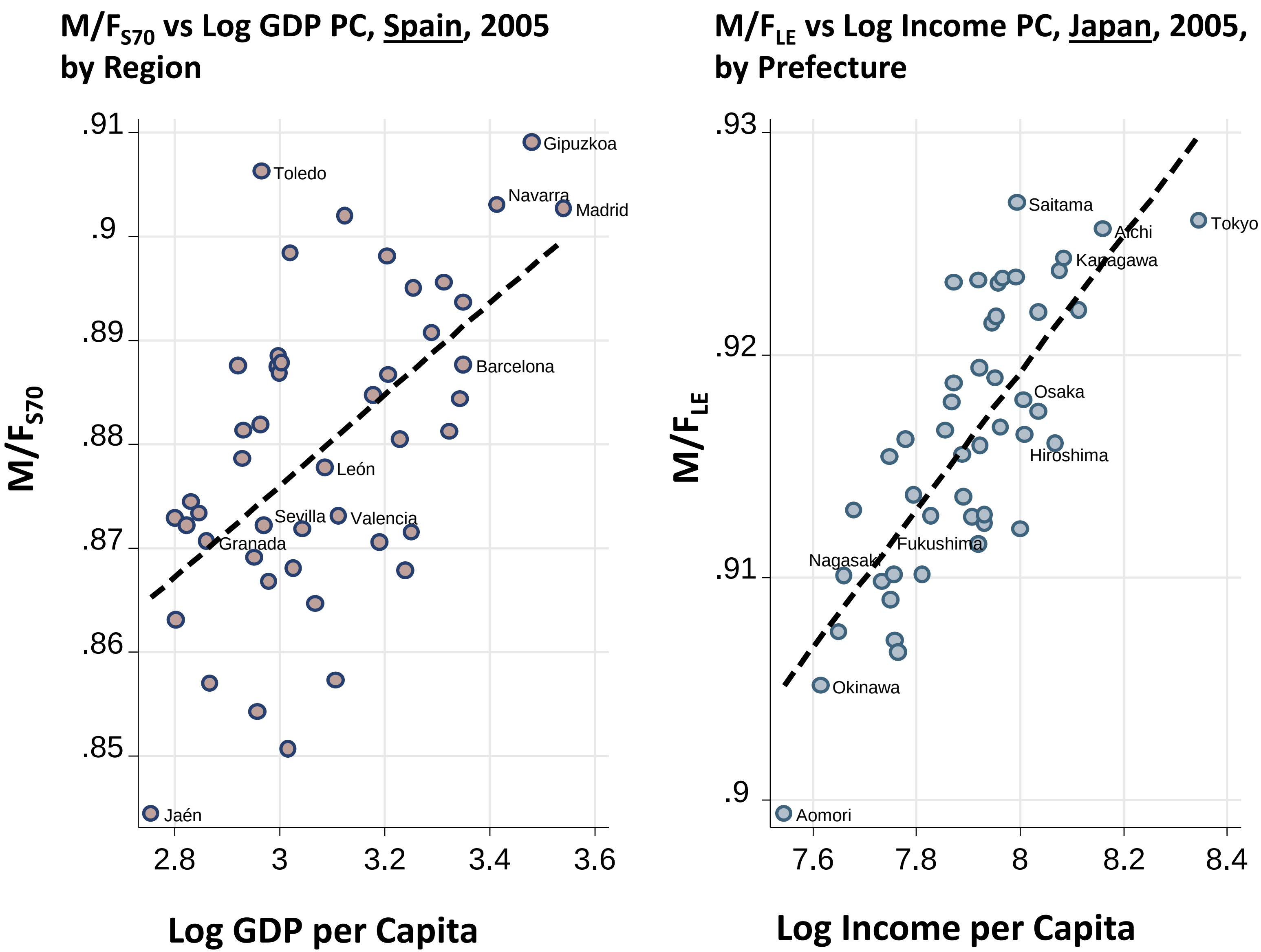
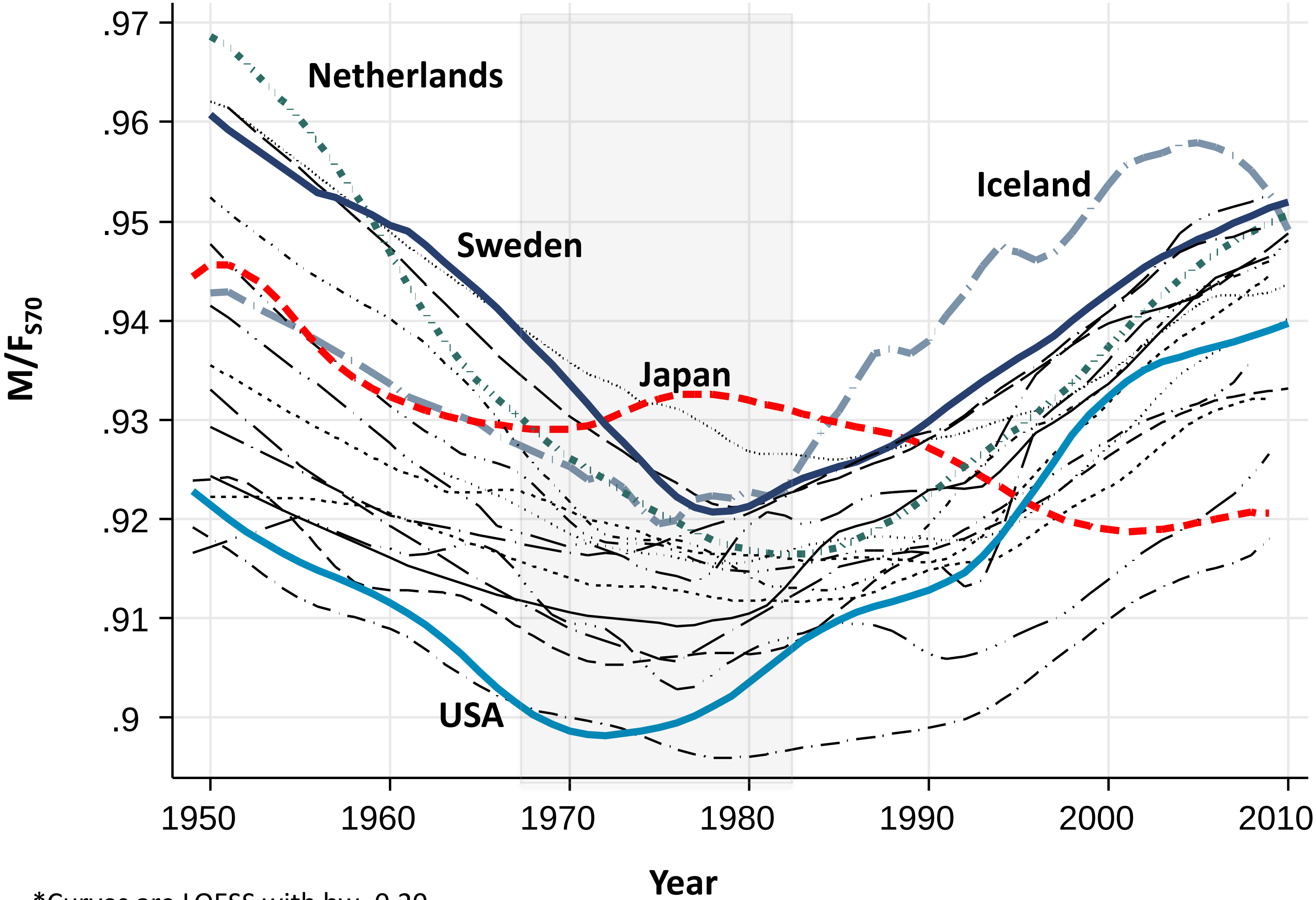
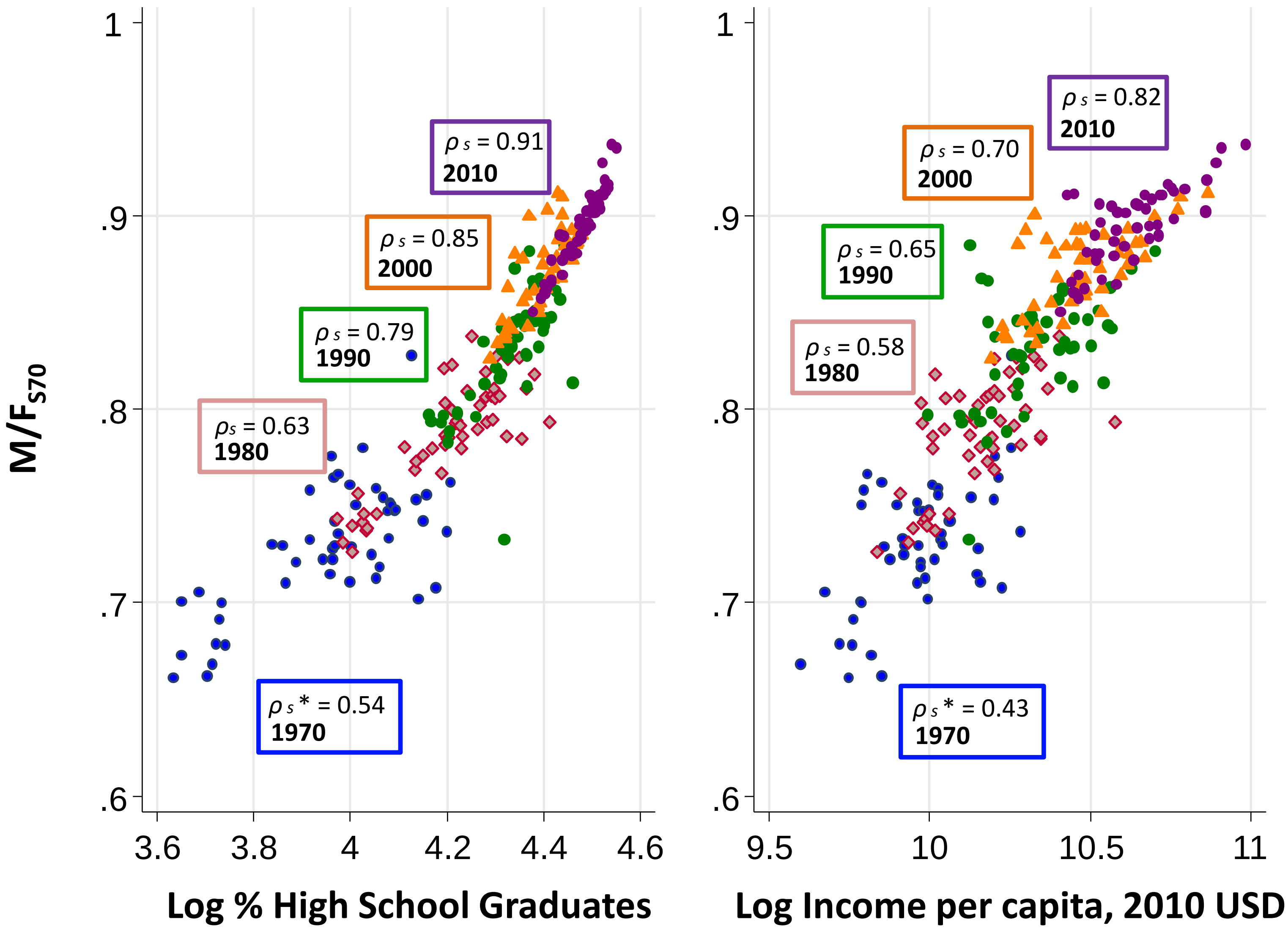


Figure 5: M/F$_{S70}$ over Years 1950-2010, 20 Wealthiest OECD Countries



*Curves are LOESS with bw=0.20

Figure 6: M/F$_{S70}$ vs Average HS Grad Rate and Average Income, by Decade, US States



*Spearman Correlation Coefficients

Figure 7: M/F$_{LE}$ vs Income, by Japanese Prefecture

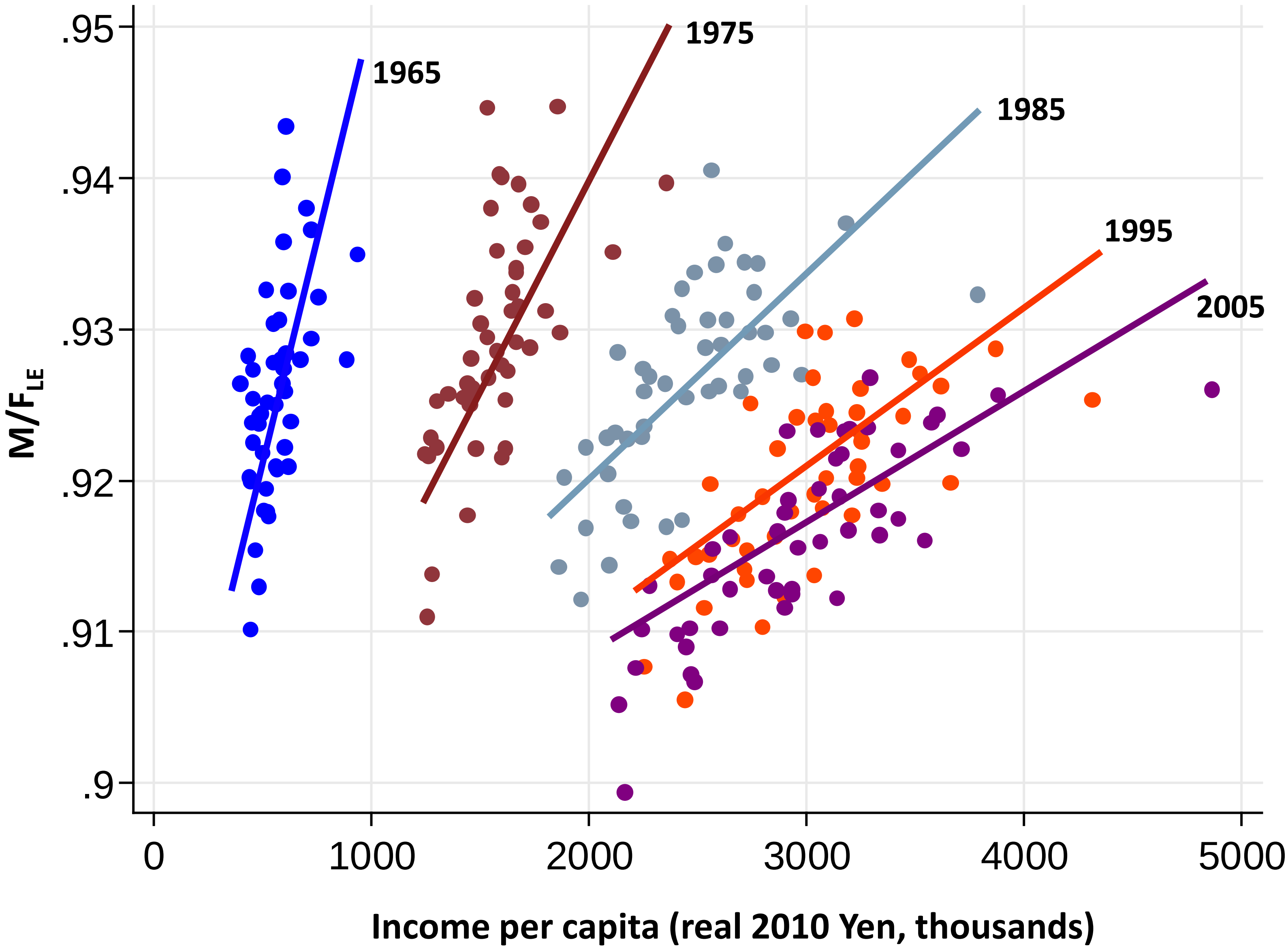


Figure 8: Male and Female LE and M/FLE over Years for USA (Top Row) and Other Developed Countries (Bottom Row), 1900-2010

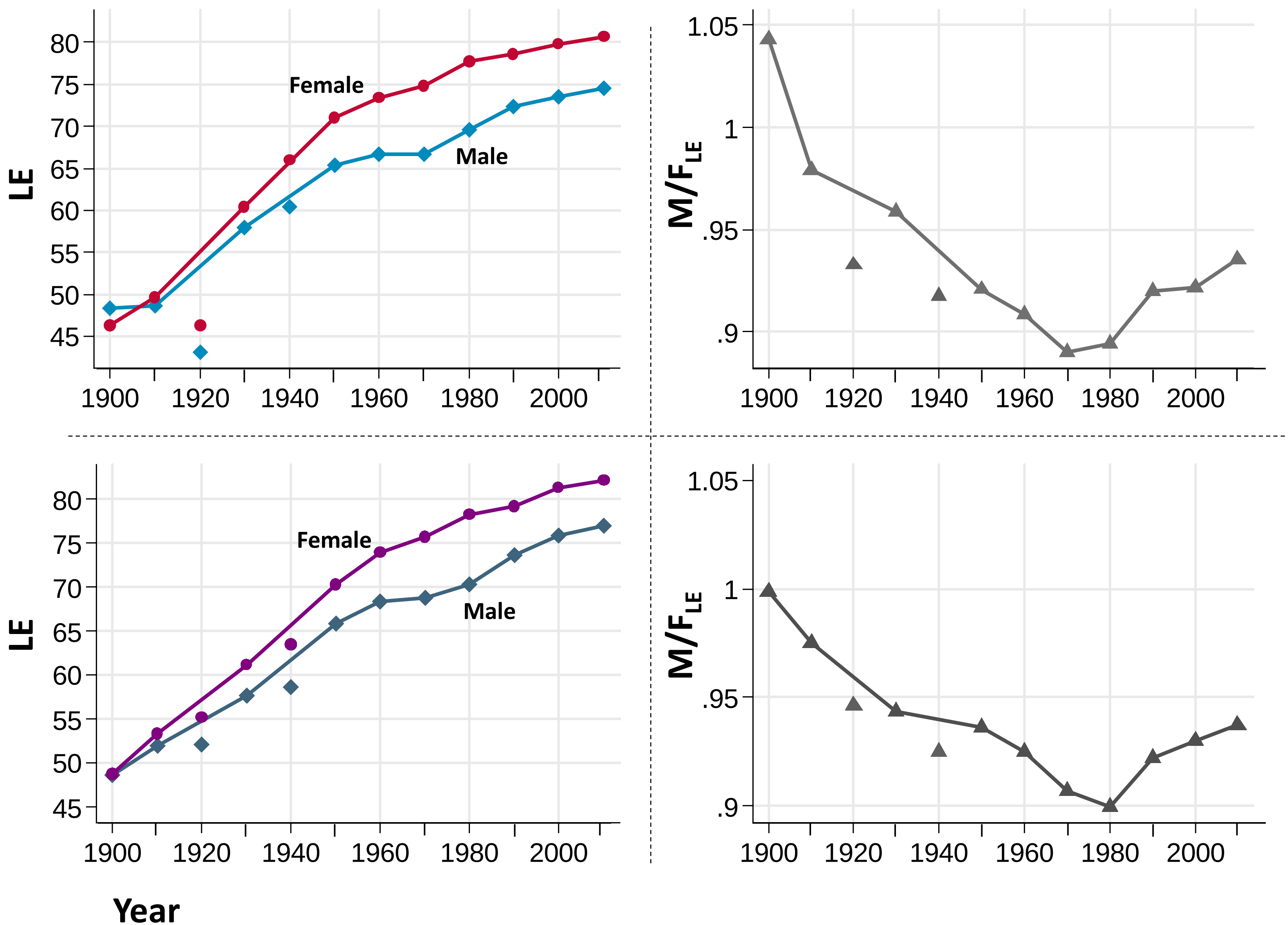


Figure 9: M/F_{LE} vs Average LE for 18 Group 1 Countries, by Decade, 1900-2010

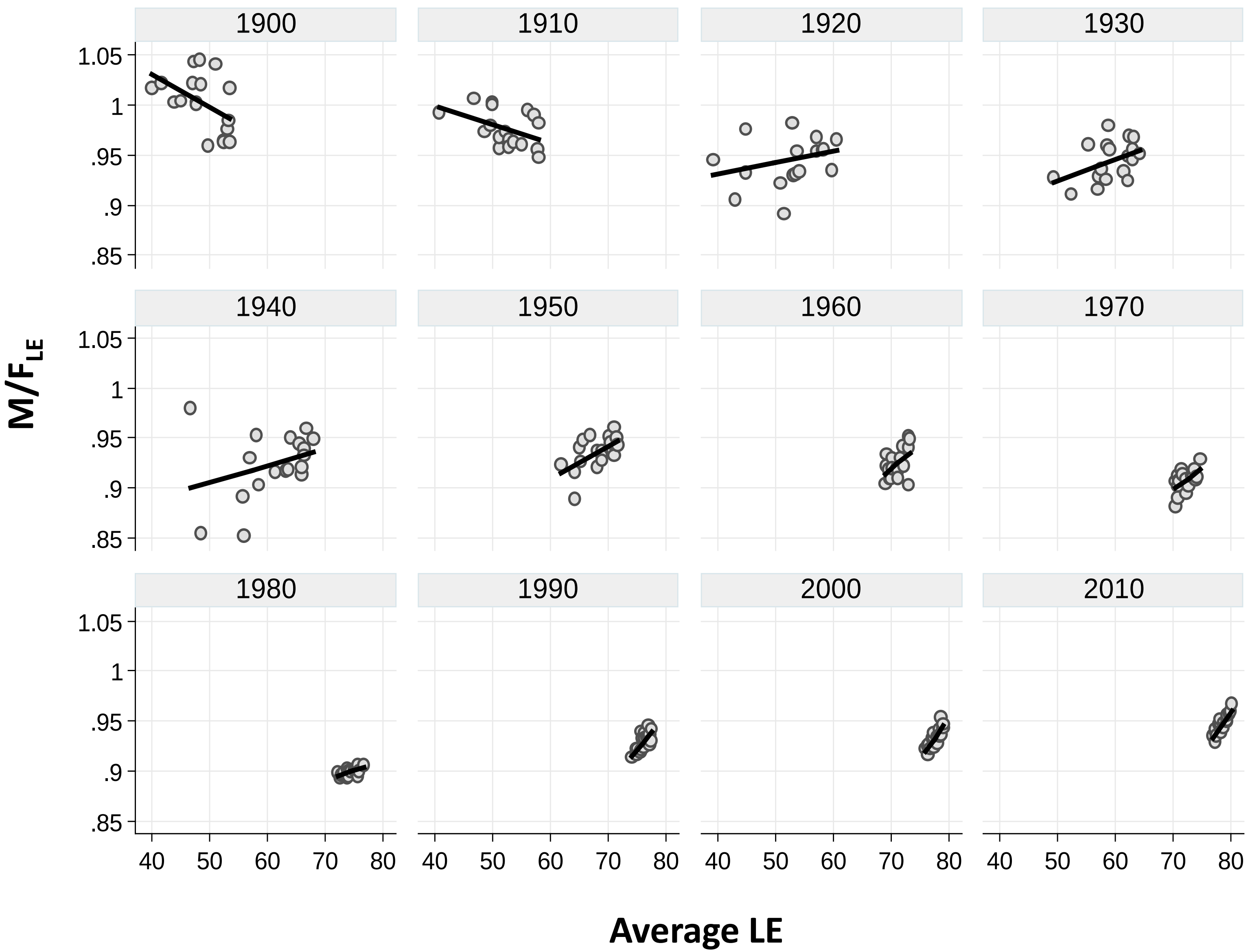
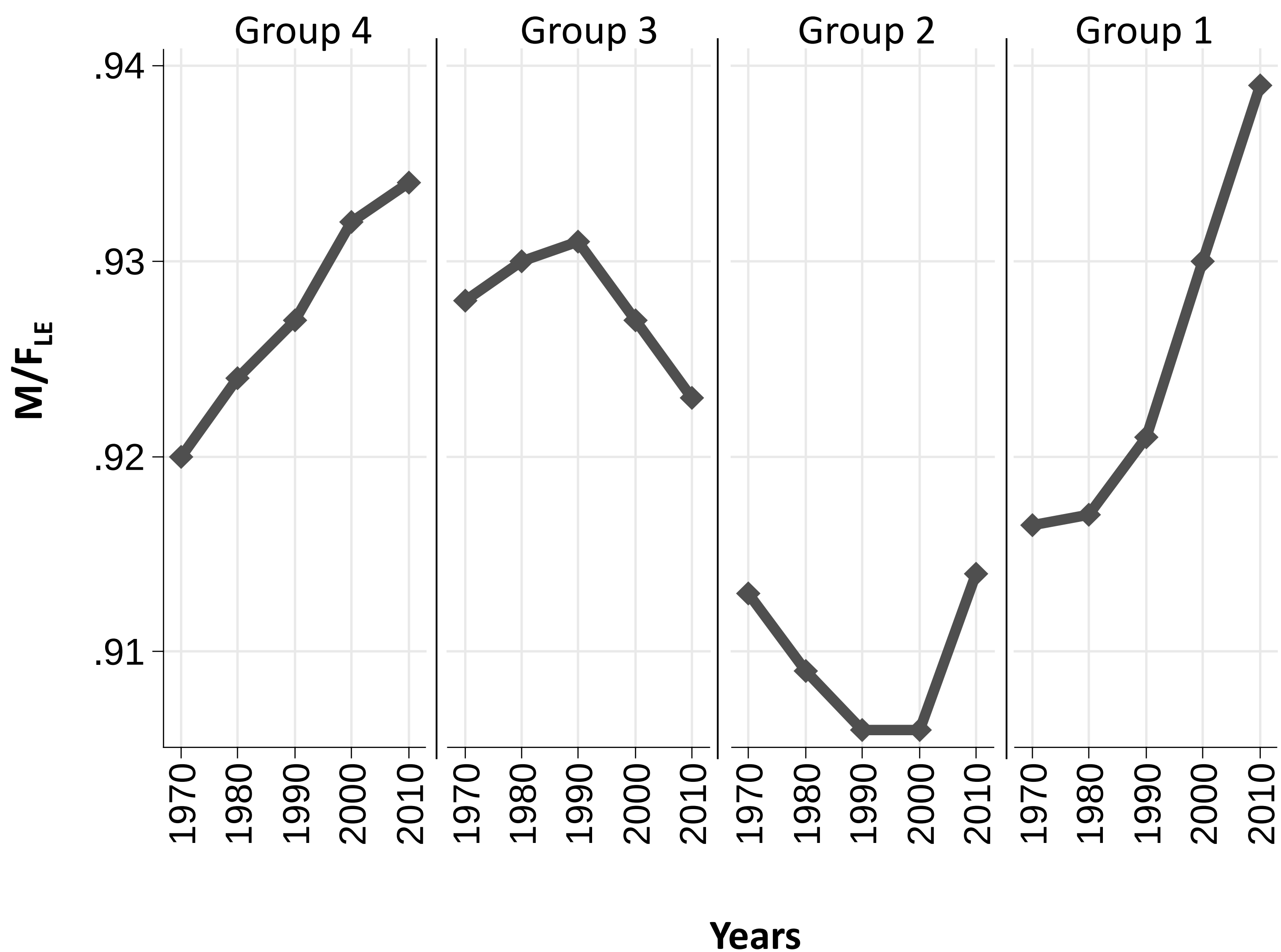
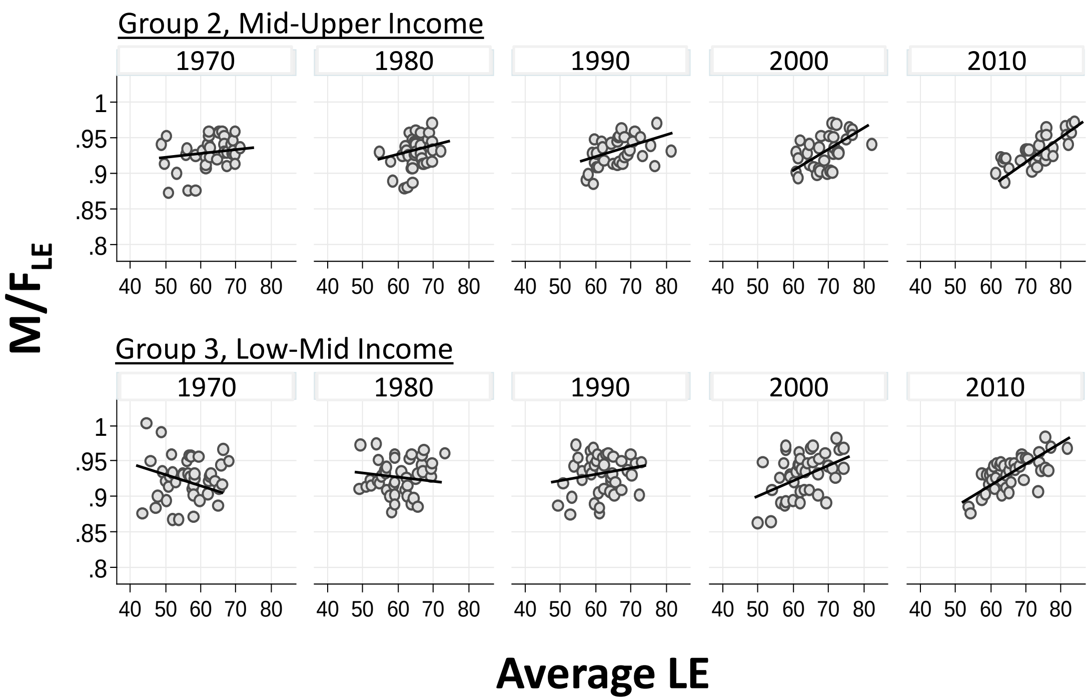


Figure 10: M/F_{LE} over Years, by Development Group



Group mean weighted by ½ log population of countries within group

Figure 11: M/F_{LE} vs Average LE for Countries in Groups 2 and 3, by Decade



Dependent Var: M/F_{LE}, Independent Var: LE

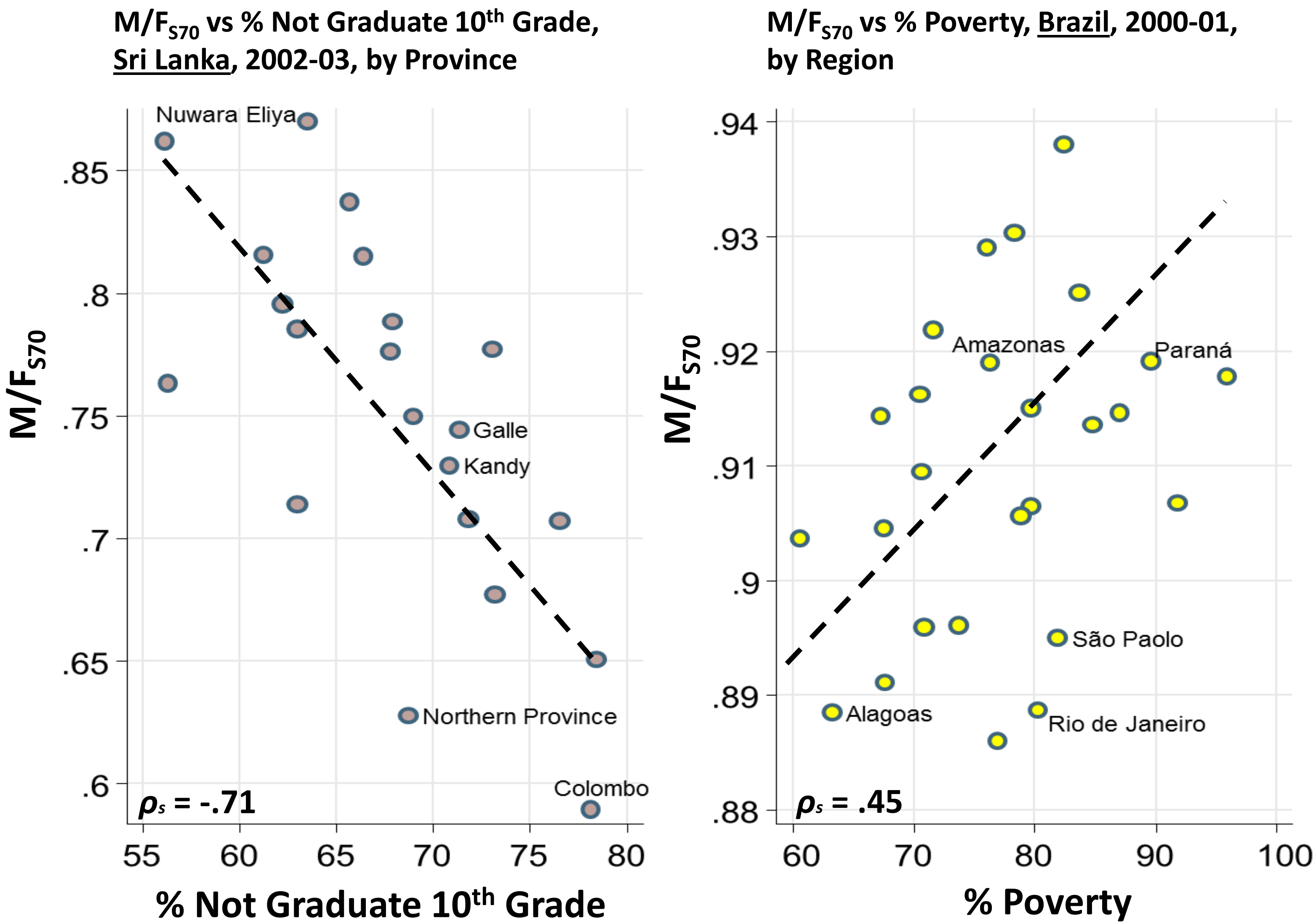
Year	Coef.	Std Err	t	p-value	ρs
1970	0.0004	0.0006	0.45	0.652	0.2300
1980	0.0006	0.0007	1.01	0.32	0.3576
1990	0.0011	0.0005	2.23	0.033	0.4178
2000	0.015	0.0005	2.93	0.006	0.5200
2010	0.0017	0.0003	5.69	<0.001	0.7810

Group 2

Year	Coef.	Std Err	t	p-value	ρs
1970	-0.0009	0.0009	-0.8	0.428	-0.0094
1980	-0.0004	0.0007	-0.45	0.655	-0.0125
1990	0.0005	0.0007	0.95	0.348	0.1122
2000	0.0011	0.0006	1.78	0.083	0.4550
2010	0.0016	0.0004	3.34	0.002	0.6877

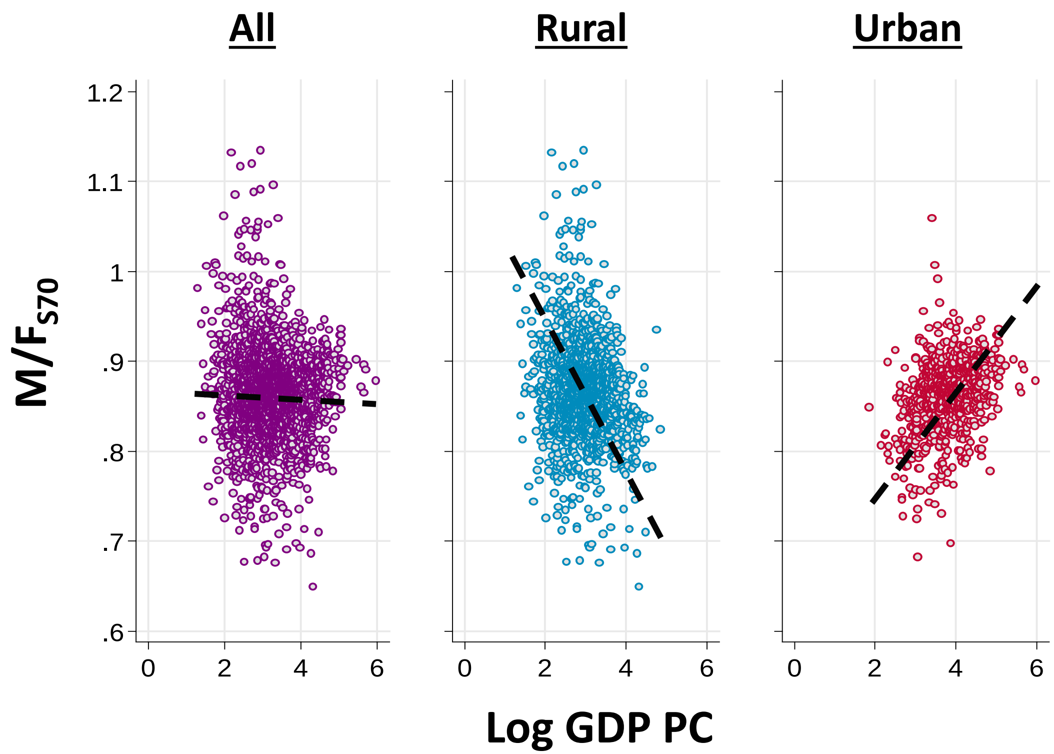
Group 3

Figure 12: M/F_{s70} v. education (% without a 10th grade graduation) for Sri Lanka (2002) and M/F_{LE} v. % in poverty for Brazil (2000)



Department of Census and Statistics District Report, Sri Lanka, 2002-03; 2000-01 Brazil Census

Figure 13: M/F_{S70} vs Log GDP per capita, China Provinces, Stratified by Urban and Rural



Outcome	N	Coef.	Std Error	p-value	ρ_s
All M/F S70	2358	-0.01	0.003	0.006	-0.0199
Rural M/F S70	1610	-0.37	0.002	<0.0001	-0.2118
Urban M/F S70	748	0.44	0.002	<0.0001	-0.4564

Figure 14: M/F_{S70} by Decade for IE Countries, 1950-2010

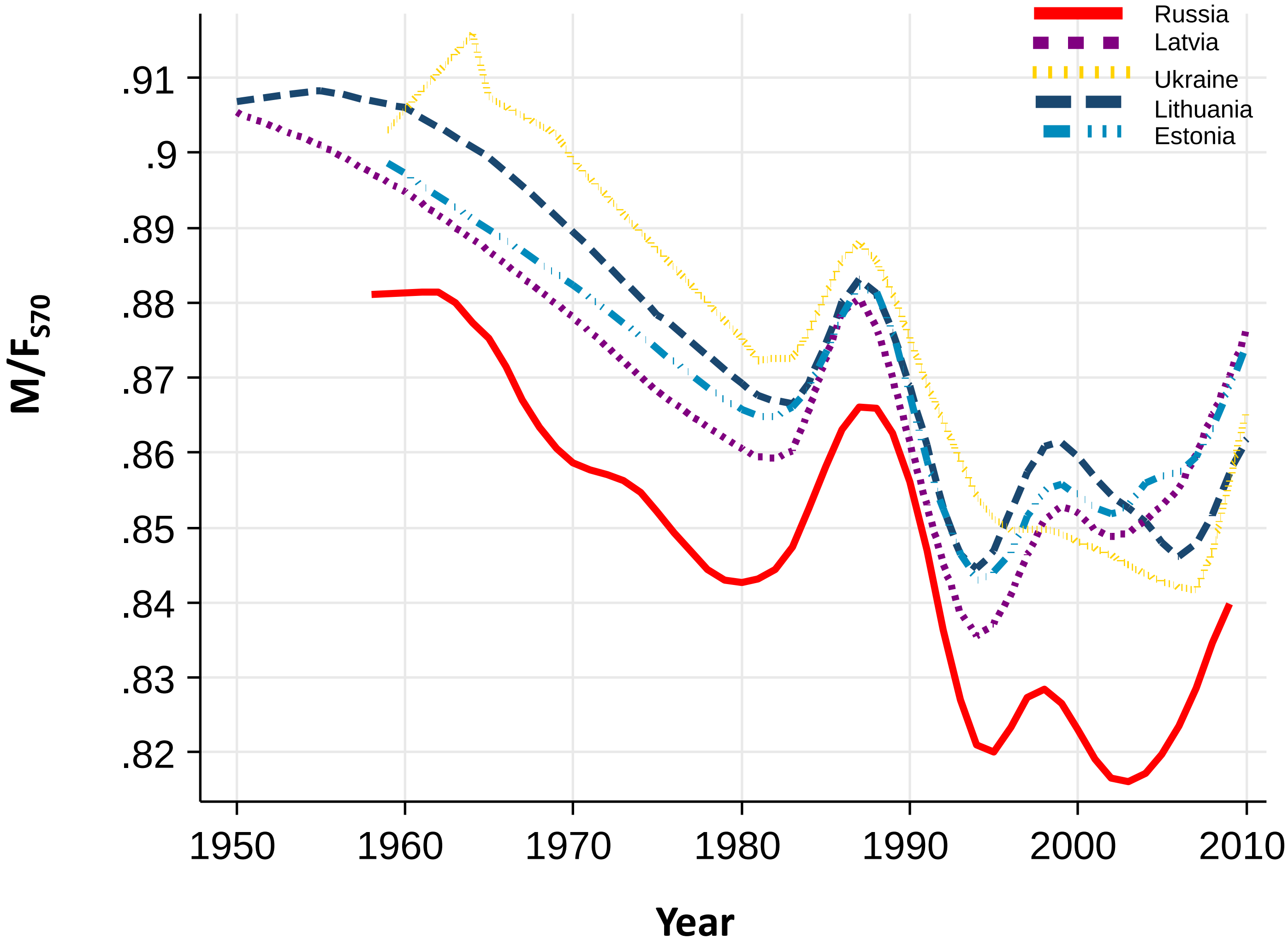
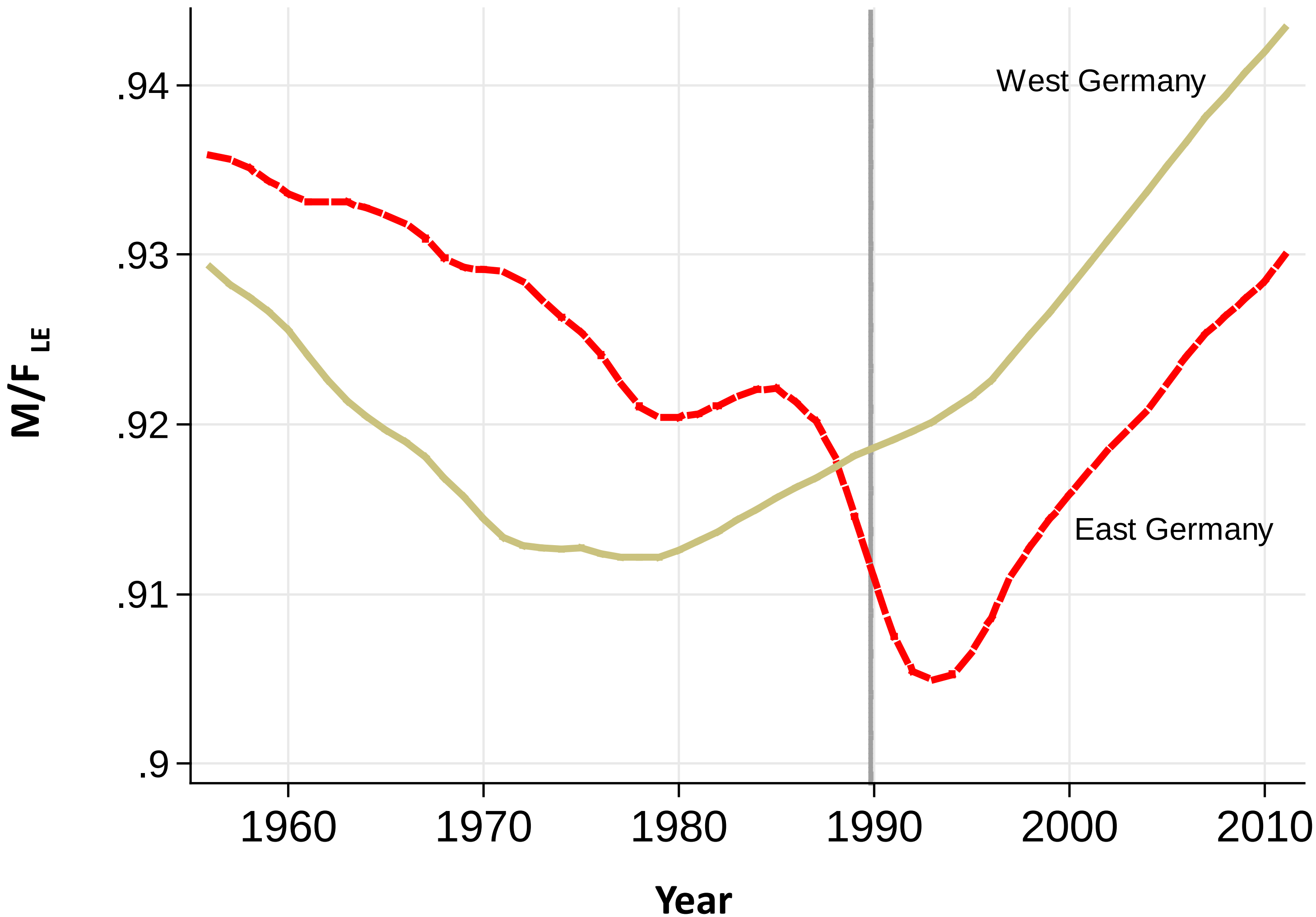


Figure 15: M/F$_{LE}$ by Year, East and West Germany, 1958-2010



Vertical line represents fall of Berlin Wall

Figure 16: M/F_{S70} vs per capita Log GDP for available Group IE Countries by Decade, 1980-2000

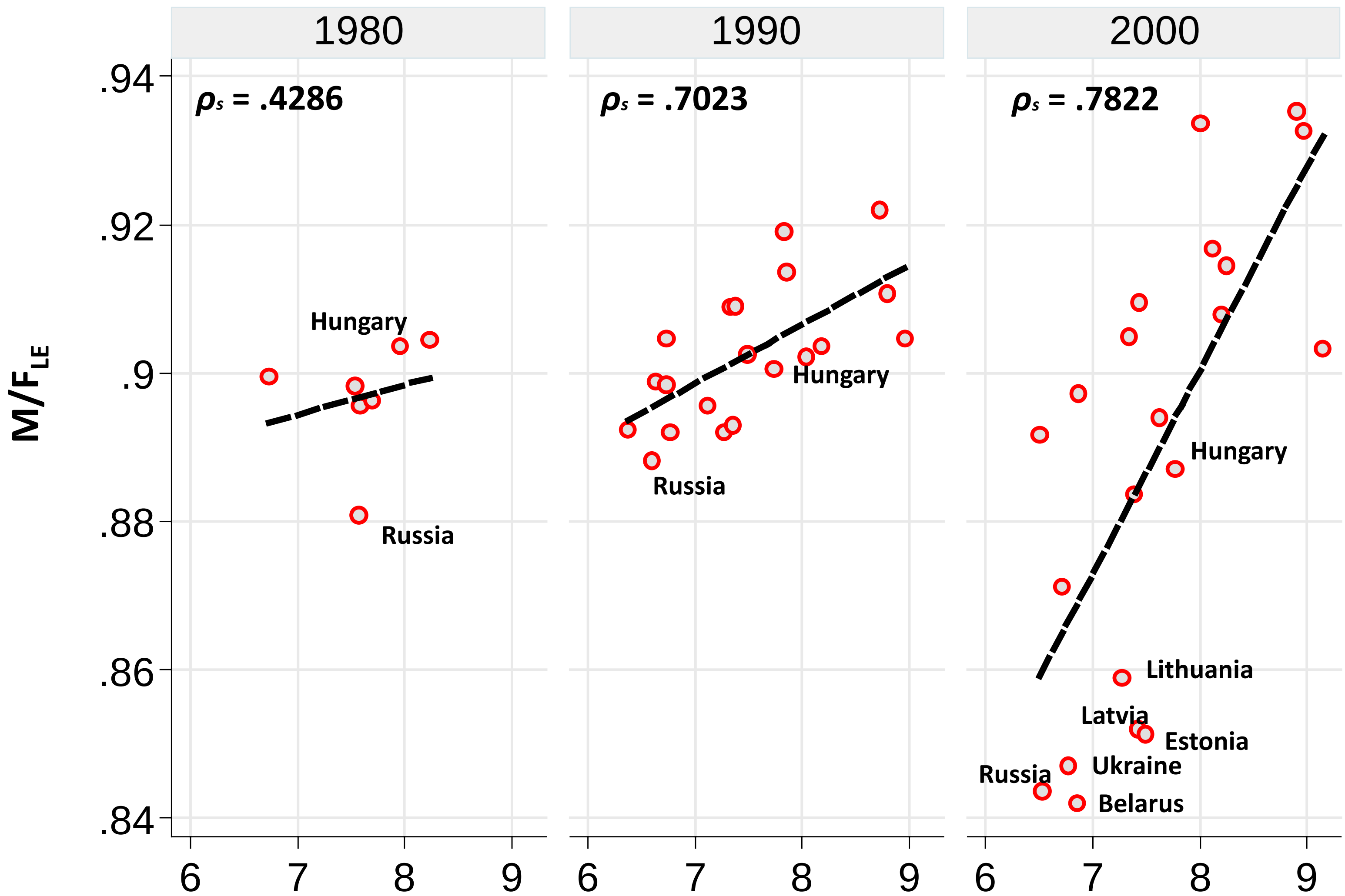
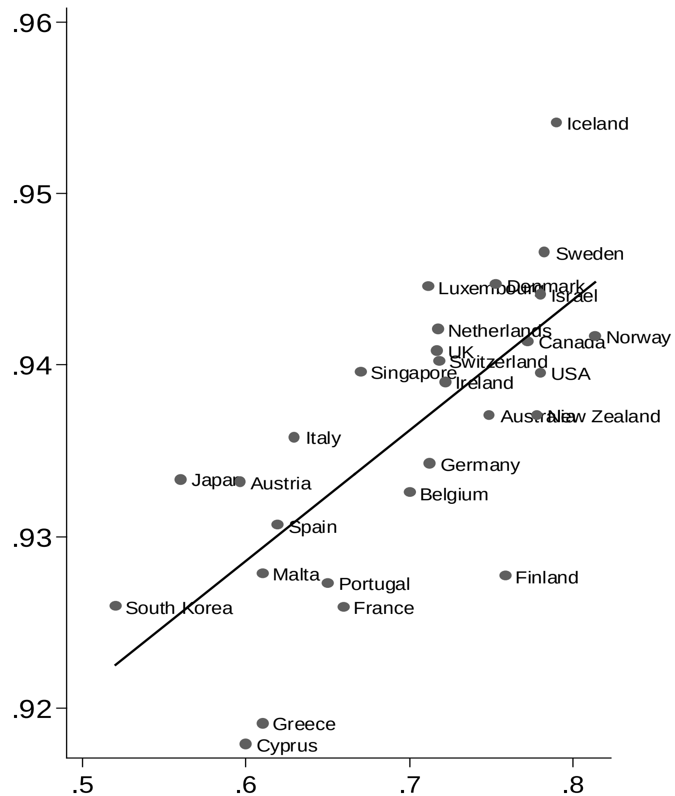
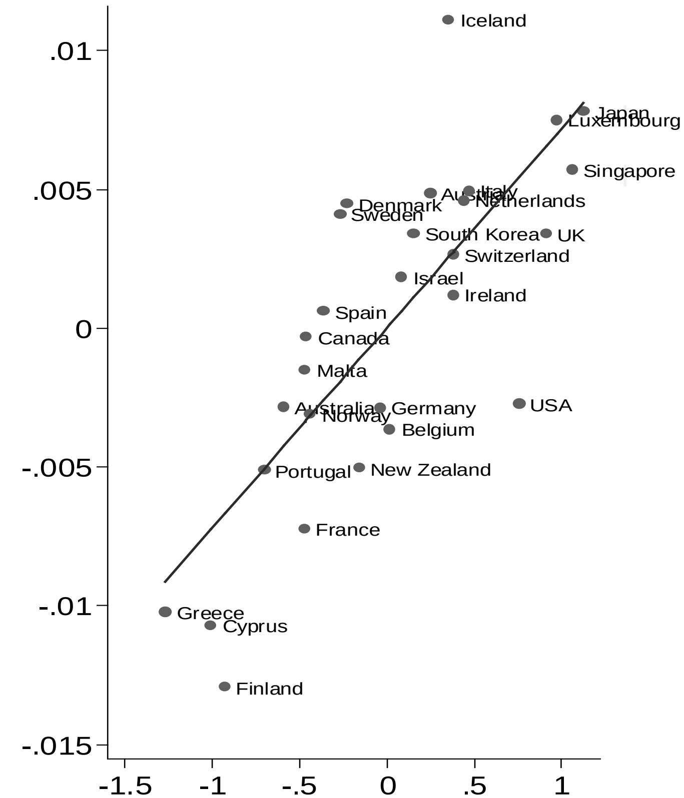


Figure 17: M/F_{LE} vs Economic Gender Equality, Group 1 Countries, 2010

M/F_{LE} vs Economic Gender Equality, Group 1 Countries, 2010



Added variable graph: M/F_{LE} vs Log GDP PC, Economic Gender Equity held Constant, Group 1 Countries, 2010



OLS Regression Diagnostics, Group 1 Countries, 2010

Outcome = M/F_{LE}

Vars	Unadjusted Spearman Correlation	Adjusted Spearman Correlation	Standardized Regression Coefficient	P-value
Econ Gender Equality	0.73	0.27	.285	0.018
Log GDP PC	0.81	0.85	.693	<0.001

Supplemental Table 1: Countries included in each of the five groups based on the Human Development Index with life expectancy removed and Eastern Europe considered separately.

	Group 4 (HDI<0.5)	Group 3 (0.5<=HDI<0.7)	Group 2 (0.7>=HDI>0.8)	Eastern Europe	Group 1 (HDI>=0.8)
1	**Afghanistan**	**Bhutan**	**Algeria**	**Albania**	**Australia**
2	**Angola**	**Bolivia**	**Argentina**	**Armenia**	**Austria**
3	**Bangladesh**	**Cameroon**	**Bahrain**	**Belarus**	**Belgium**
4	**Benin**	**Cape Verde**	**Barbados**	**Bosnia**	**Canada**
5	**Burkina Faso**	**Congo**	**Botswana**	**Bulgaria**	**Cyprus**
6	**Burundi**	**Djibouti**	**Brazil**	**Croatia**	**Denmark**
7	**Cambodia**	**Egypt**	**Chile**	**Czech Rep.**	**Finland**
8	**CAR**	**El Salvador**	**China**	**Estonia**	**France**
9	**Chad**	**Fiji**	**Colombia**	**Georgia**	**Germany**
10	**Comoros**	**Gabon**	**Costa Rica**	**Hungary**	**Greece**
11	**Congo, Dem.**	**Ghana**	**Dominica**	**Latvia**	**Iceland**
12	**Equ Guinea**	**Guatemala**	**Dominican Rep.**	**Lithuania**	**Ireland**
13	**Eritrea**	**Guyana**	**Ecuador**	**Macedonia**	**Israel**
14	**Ethiopia**	**Honduras**	**Grenada**	**Moldova**	**Italy**
15	**Gambia**	**India**	**Iran**	**Montenegro**	**Japan**
16	**Guinea**	**Indonesia**	**Jordan**	**Poland**	**Luxembourg**
17	**Guinea-Bissau**	**Iraq**	**Kuwait**	**Romania**	**Malta**
18	**Kazakhstan**	**Ivory Coast**	**Lebanon**	**Russia**	**Netherlands**
19	**Kyrgyzstan**	**Kenya**	**Libya**	**Serbia**	**New Zealand**
20	**Lesotho**	**Kiribati**	**Malaysia**	**Slovakia**	**Norway**
21	**Liberia**	**Laos**	**Mauritius**	**Slovenia**	**Portugal**
22	**Madagascar**	**Marshall Islands**	**Mexico**	**Ukraine**	**Singapore**
23	**Malawi**	**Mongolia**	**Namibia**		**South Korea**
24	**Mali**	**Morocco**	**Oman**		**Spain**
25	**Mozambique**	**Nicaragua**	**Panama**		**Sweden**
26	**Niger**	**Nigeria**	**Peru**		**Switzerland**
27	**Rwanda**	**Pakistan**	**Qatar**		**UK**
28	**Sierra Leone**	**Papua New Guinea**	**Saudi Arabia**		**USA**
29	**Somalia**	**Paraguay**	**South Africa**		
30	**Tanzania**	**Philippines**	**Suriname**		
31	**Timor-Leste**	**Samoa**	**Thailand**		
32	**Togo**	**Sao Tome**	**Trinidad**		
33	**Uganda**	**Senegal**	**Tunisia**		
34	**Zimbabwe**	**Solomon Islands**	**Turkey**		
35	**North Korea**	**Sri Lanka**	**Uruguay**		
36		**Sudan**	**Venezuela**		
37		**Swaziland**			

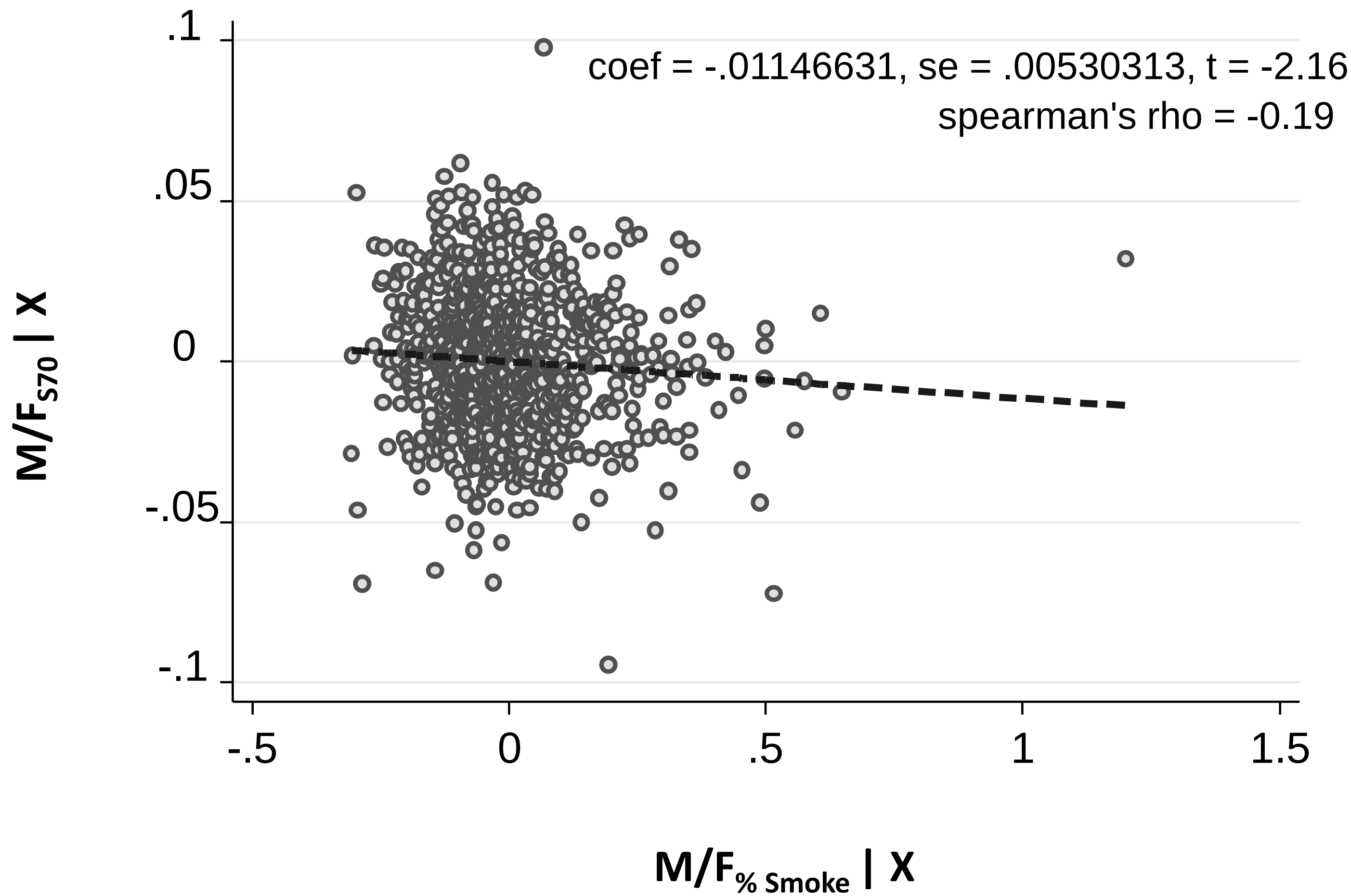
38		**Syria**			
	Group 4 (HDI<0.5)	**Group 3 (0.5<=HDI<0.7)**	**Group 2 (0.7>=HDI>0.8)**	**Eastern Europe**	**Group 1 (HDI>=0.8)**
39		**Timor-Leste**			
40		**Tonga**			
41		**Uzbekistan**			
42		**Vanuatu**			
43		**Vietnam**			
44		**Yemen**			
45		**Zambia**			

Supplemental Table 2: Data Sources

Name of Database	Umbrella Organization	Division within Organization	Location	Data Year	URL	Date accessed
2006-2010 American Community Survey 5-year estimates	US Census Bureau	Population Estimates Program (PEP)	Suitland, Maryland	2010	http://factfinder2.census.gov	03-Sep-14
2010 World development indicators – GDP per capita	World Bank	International Comparison Program		2010	http://data.worldbank.org/indicator/ny.gdp.pcap.pp.cd	18-Feb-14
Behavioral Risk Factor Surveillance System Survey Questionnaire	U.S. Department of Health and Human Services	Centers for Disease Control and Prevention (CDC)	Atlanta, GA	2010	http://www.cdc.gov/brfss/data_tools.htm	02-Jun-14
Census of Population and Housing 2003	Department of Census and Statistics (DCS)		Sri Lanka	2003	http://www.statistics.gov.lk/page.asp?page=Population%20and%20Housing	18-Feb-14
Compressed Mortality File, 2010 (machine readable data file and documentation, CD-ROM Series 20, No. 2P) as compiled from data provided by the 57 vital statistics jurisdictions)	National Center for Health Statistics	Vital Statistics Cooperative Program	Hyattsville, Maryland	2012	http://wonder.cdc.gov/cmf-icd10.html	02-Jun-14
Contabilidad Regional de España	Instituto Nacional de Estadística		Madrid, Spain	2005	http://www.ine.es/en/inebmenu/mnu_cuentas_en.htm	02-Jun-14
Demographic Census: Tabela 1.8 Esperança de vida ao nascer, segundo as Grandes Regiões e Unidades da Federação	Instituto Brasileiro de Geografia e Estatística (IBGE)		Rio de Janeiro, Brazil	2005	http://www.ibge.gov.br/home/estatistica/populacao	22-Jan-13

Human Mortality Database	University of California and Max Planck Institute for Demographic Research (Germany)		Berkeley and Rostock, Germany	2010	www.mortality.org	11-Feb-14
Life Expectancy by Prefecture	Ministry of Health, Labour and Welfare	Vital Statistics	Tokyo, Japan	2005	http://www.mhlw.go.jp/english/database/db-hw/index.html	18-Feb-14
Per Capita Income by Prefecture	Ministry of Internal Affairs and Communications	Statistics Bureau	Tokyo, Japan	2005	http://www.stat.go.jp/english/data/kakei/ct2005.htm	18-Feb-14
Prefecture income and GDP deflator data	Economic and Social Research Institute	Cabinet Office	Tokyo, Japan	2005	http://www.esri.cao.go.jp/jp/sna/kouhyou/kouhyou_top.html#d	18-Feb-14
Tablas de mortalidad de la población española.	Instituto Nacional de Estadística		Madrid, Spain	2005	http://www.ine.es/daco/daco42/idb/idb.htm	02-Jun-14
Trends in Life Expectancy by Prefectures in Japan	Ministry of Health, Labour and Welfare	Vital, Health, and Social Statistics Division	Tokyo, Japan	1999	http://www.mhlw.go.jp/english/database/db-hw/vs_8/vs0.html	18-Feb-14

Figure S1: M/F_{S70} vs Excess Male Smoking (M/F Smoking Prevalence) after adjusting for Education, Income, Poverty, and Obesity, 2010 US Counties, Whites



X = % High School Grad, Average Income, % Poverty, % Obese, by County

Figure S2: Smoking for Group 1 countries M/F_{LE} vs. M/F Smoking Prevalence

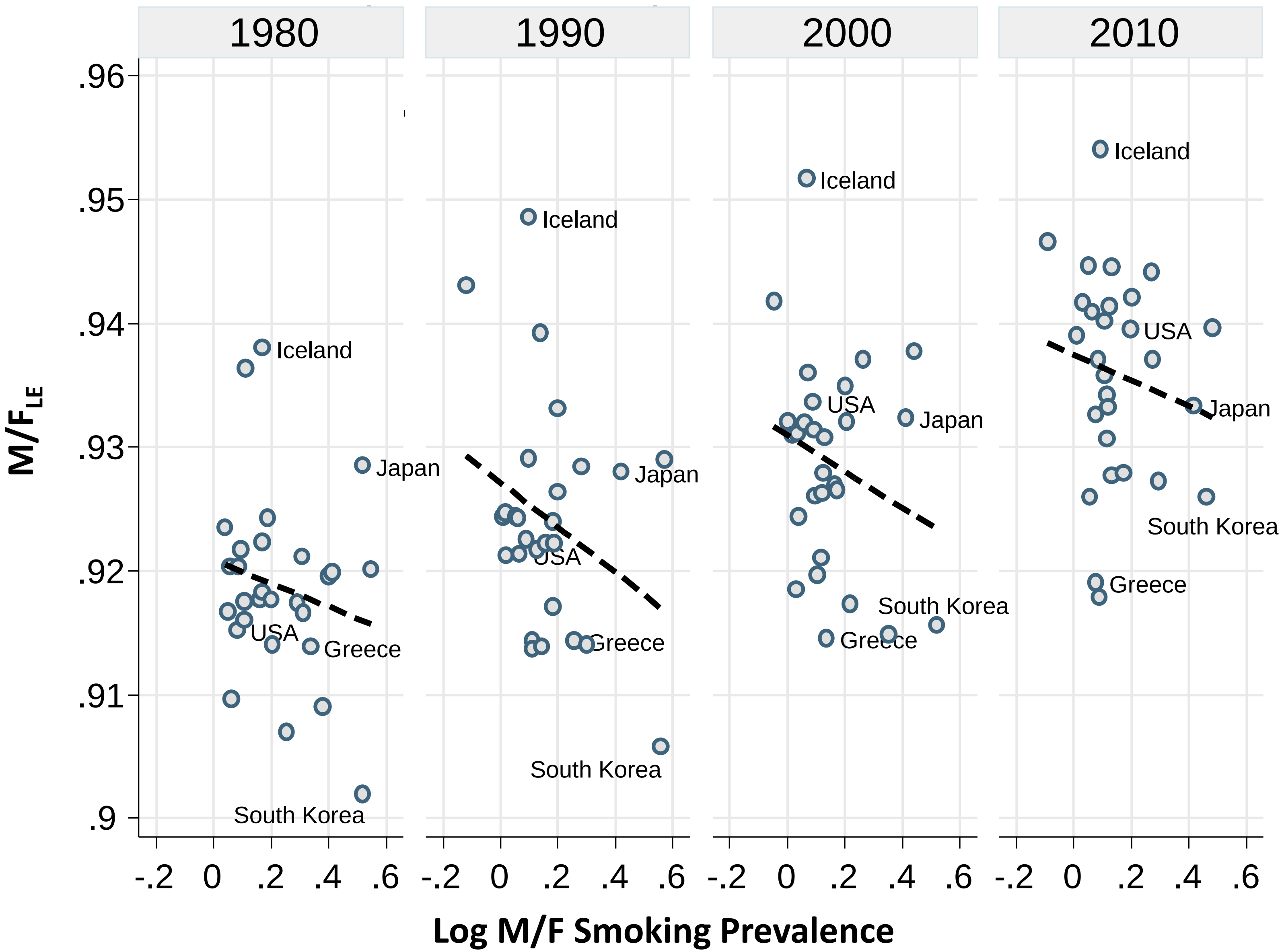
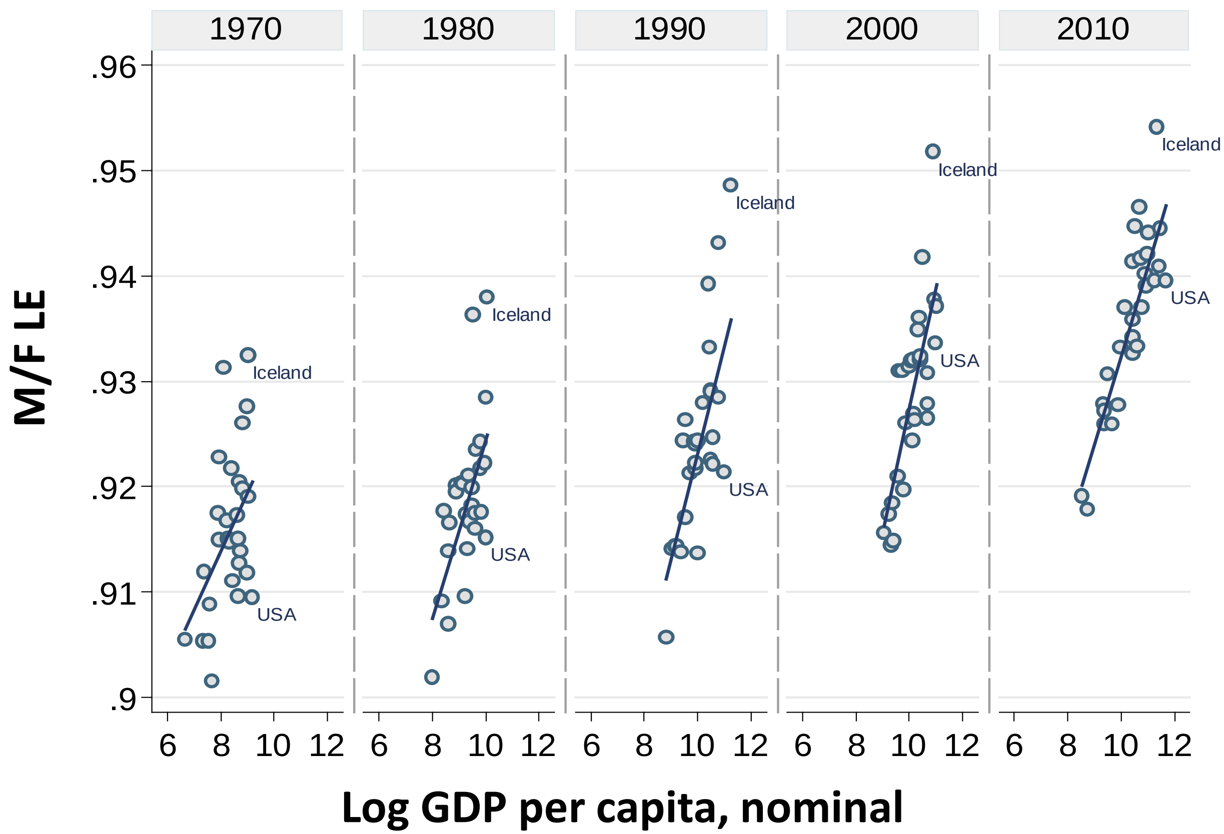
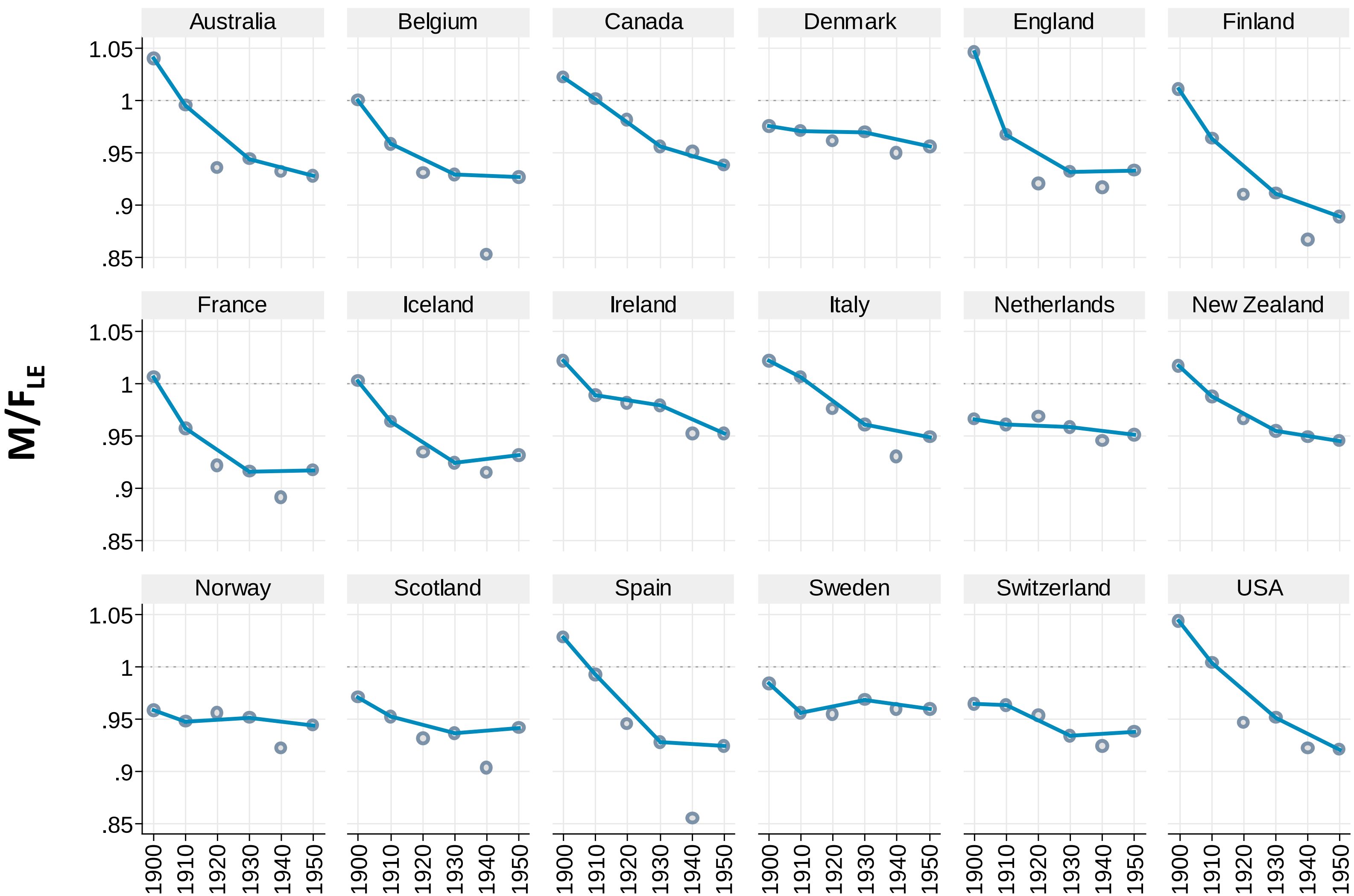


Figure S3: M/F_{LE} vs. Log PC GDP for Group 1 Countries, by Decade



	Coef.	Std Err	t	p-value	ρ_s
1970	0.0068	0.0023	2.95	0.007	0.53
1980	0.0095	0.0022	4.33	<0.0001	0.67
1990	0.0120	0.0021	5.78	<0.0001	0.71
2000	0.0128	0.0020	6.51	<0.0001	0.86
2010	0.0096	0.0011	9.11	<0.0001	0.93

Figure S4: M/F_{LE} FOR THE 18 Developed Countries, 1900-1950



Note: Line does not connect values for 1920 and 1940, as those years had Spanish Influenza and World War Two.

Figure S5: Maternal Mortality Rate over each Group, 1980-2010

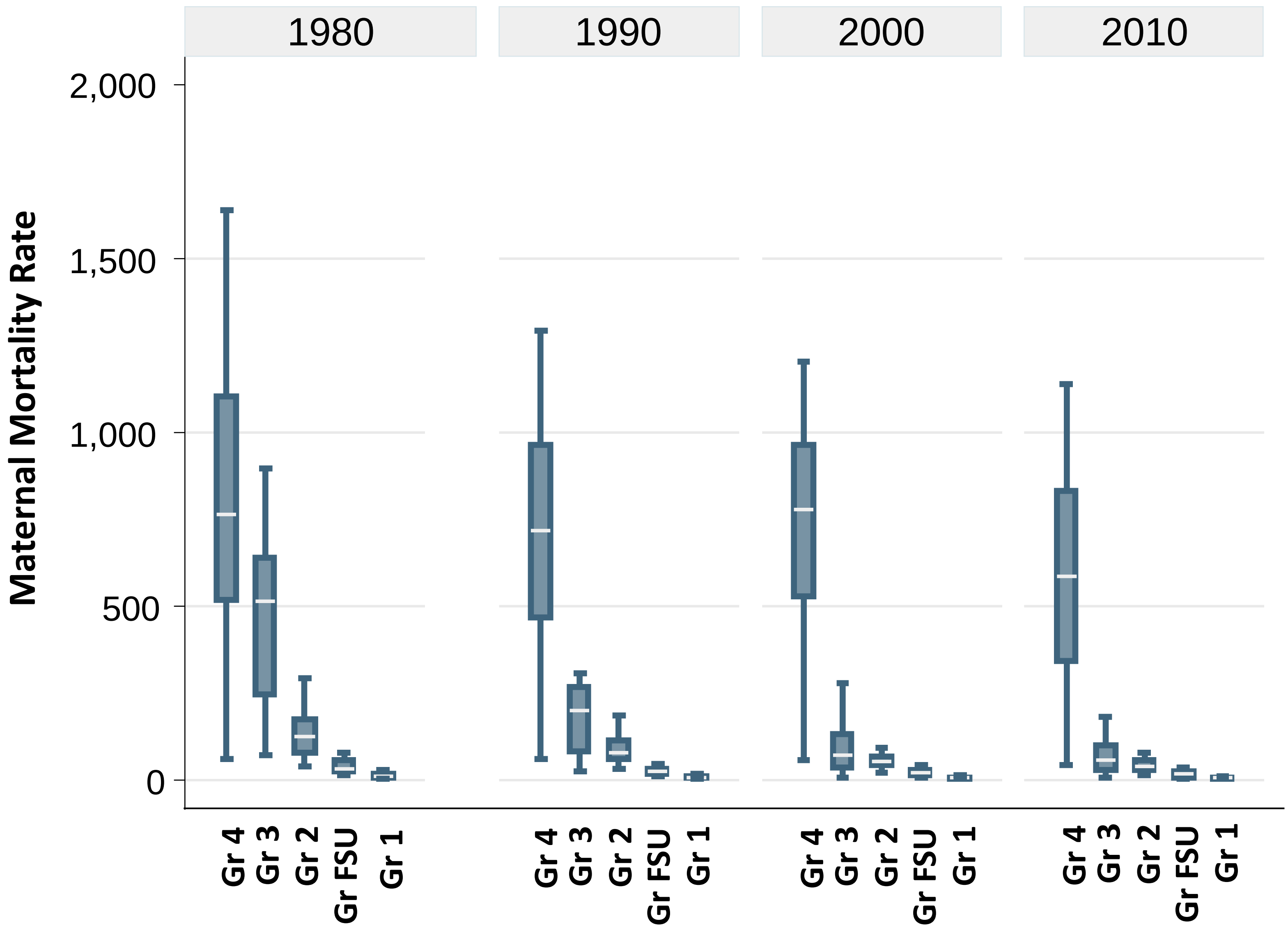
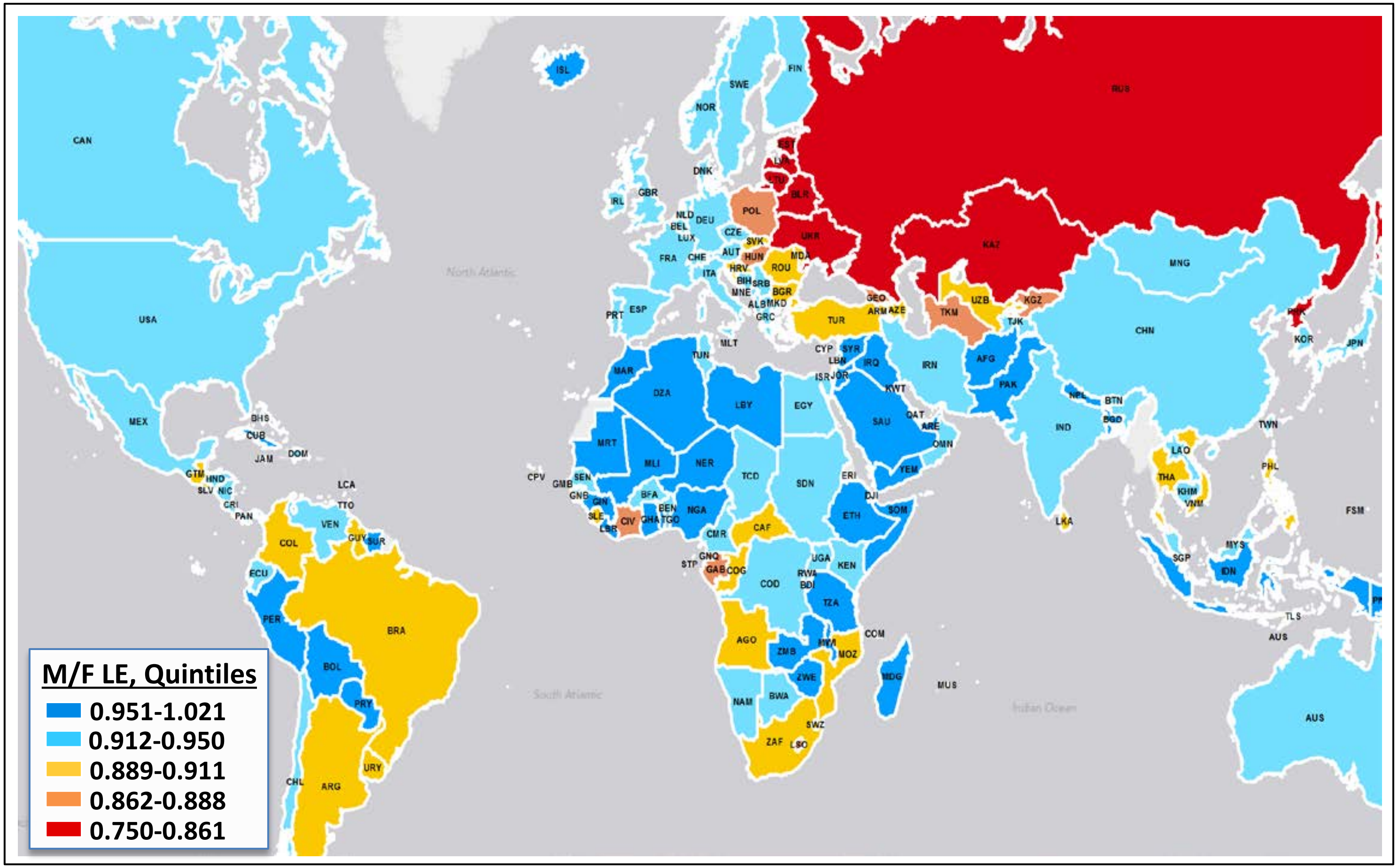
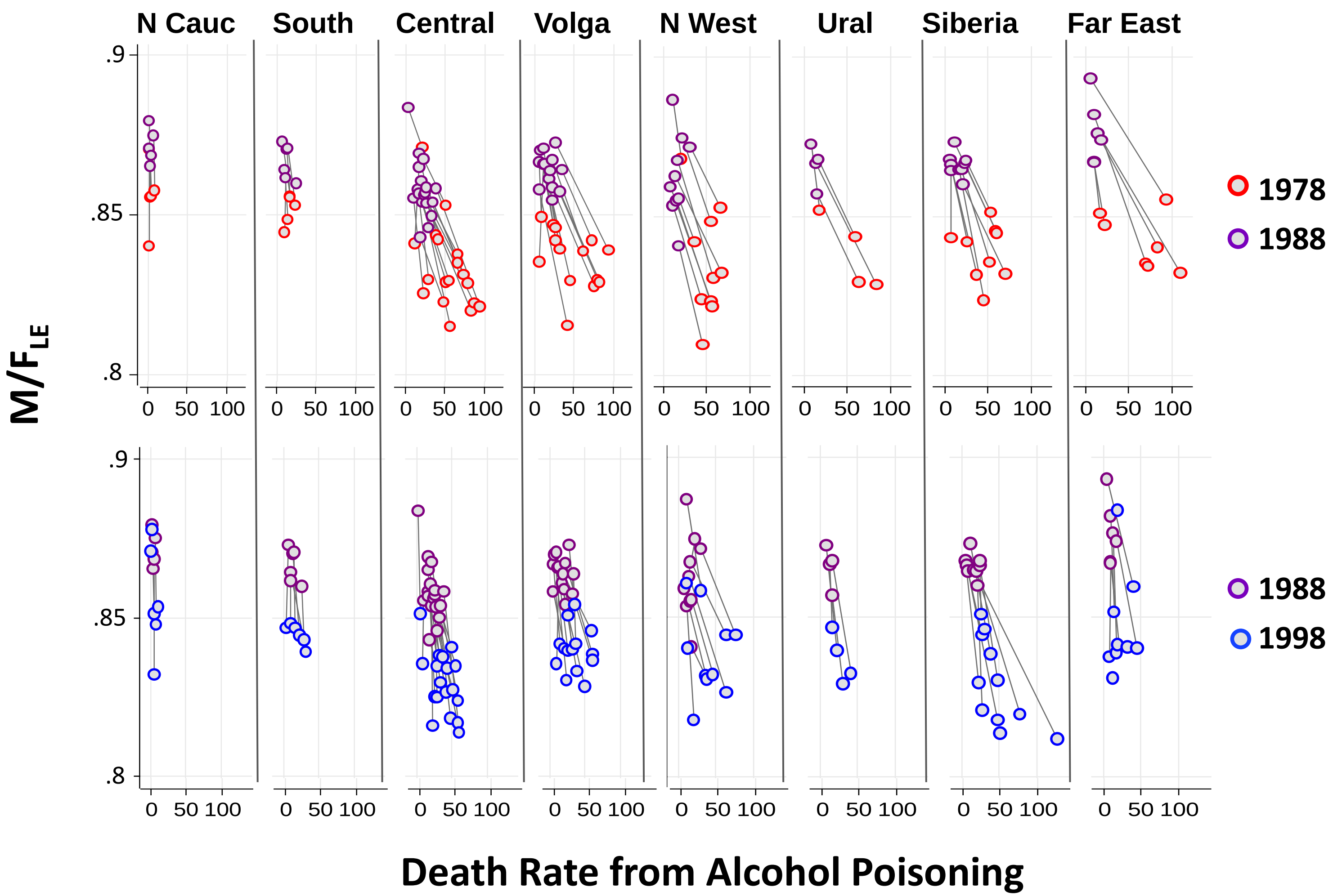


Figure S6: M/F_{LE} by Country, 2000



Supplemental Figure 7: M/F_{LE} vs Alcohol Death Rate, by Oblast and Region, 1978 to 1988, 1988 to 1998



-Death Rates, per 100,000

-Regions N Cauc and South have highest Muslim populations

-Plots are at level of oblast, by region ordered geographically from SW to NE (same a most to least Muslim by % population)