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Human Capital Investment Helps Mitigate Family Caregiving Challenges in Aging China

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Conflict of Interest

The authors declare no competing interests.

Data Availability

The data that support the findings of this study are publicly available from the following sources:

- United Nations World Population Prospects: `https://population.un.org/wpp/`
- Wittgenstein Centre Data Explorer: `https://www.wittgensteincentre.org/dataexplorer`
- China General Social Survey (CGSS): `http://cgss.ruc.edu.cn/`

Abstract

Objective: Population aging and shrinking family structures in China are placing unprecedented strain on traditional family-based systems of old-age support. This study develops and applies a capital-based caregiving framework that integrates human capital with the structural dimension of social capital (i.e., kinship networks) to assess the caregiving dynamics within families. We provide the first long-term projection of family caregiving dynamics in China, modeling how rising education–by improving health–can simultaneously enhance caregiving capacity and moderate care needs amid declining kin availability.

Methods: We used formal demographic kinship models to project the number and age composition of a broad range of kin for older adults in China from 1950 to 2100, capturing kinship structure as the structural dimension of social capital. Educational attainment and education-specific health gradients were then integrated to model the human capital of each kin member. These dimensions were synthesized into novel health-adjusted kin-dependency ratios to assess caregiving dynamics over time.

Results: We find that while the number of working-age kin declines substantially across cohorts, rising education and health among both working-age and older kin enhance caregiving capacity and reduce care needs. Under a rapid educational expansion scenario, the health-adjusted kin-dependency ratio is projected to be approximately 10% lower by 2100 compared to a stalled education scenario, indicating a substantial buffering effect of human capital on aggregate caregiving burdens.

Conclusions: Human capital investment, particularly in education, serve as a powerful, though partial, demographic buffer against the family caregiving challenges posed by population aging and shrinking family size. These findings demonstrate that overlooking the human capital composition of kin leads to overly pessimistic assessments of family caregiving capacity. The capital-based framework developed here offers a new perspective for integrating demographic and resource-based approaches to family support, with implications for aging societies beyond China.

Key Words:

Family Caregiving, Education, Health, Human Capital, Social Capital, Population Aging

Highlights:

- A capital-based framework integrates human capital with kinship networks.
- Novel health-adjusted kin-dependency ratios are developed and applied.
- Rising education among kin enhances care capacity while reducing care needs in China.
- Educational expansion in China is expected to lower health-adjusted care burdens by approximately 10% by 2100.

Introduction

Population aging is a pressing global issue with profound social, economic, and policy implications (Lee 2002; Bloom et al. 2010; Tuljapurkar et al. 2010; Harper 2014). China exemplifies this transformation with extraordinary speed and scale. Over just a few decades, fertility rates plummeted due to rapid socioeconomic development and the enforcement of the one-child policy, while life expectancy increased sharply (Peng 2011; Chen et al. 2019; Feng and Mason 2007). Such rapid transitions have fundamentally changed the number and age of kin (Jiang et al. 2025), leading to an unprecedented "4-2-1" family configuration, where a single child supports two parents and four grandparents (Zhang and Goza 2006; Verdery 2019).

Beyond demography, China's case holds particular analytical value for understanding caregiving in aging societies due to its unique combination of cultural, institutional, and socioeconomic characteristics. On one hand, the principle of filial piety, deeply rooted in Confucian tradition and legally mandated by Chinese law (e.g., Constitution of the PRC, Article 49; Civil Code, Article 26), firmly designates the family as the primary provider of old-age support (Jiang 1995; Lei 2013). On the other hand, a massive expansion in higher education—from 1.08 million new university students in 1998 to 6.08 million in 2008 (Huang et al. 2022)—has dramatically increased the human capital of younger cohorts. This intersection of demographic constraints, enduring filial obligations, and a surge in educational attainment, creates a rich empirical context for reassessing family caregiving dynamics. Furthermore, China's experience offers comparative relevance to other East and Southeast Asian societies, such as South Korea, Japan, and Vietnam, which share similar cultural traditions around filial responsibility but vary in the pace and structure of demographic transitions.

Despite growing recognition of these processes, existing metrics for care burdens, such as age-based dependency ratios, remain limited. These conventional indicators treat individuals as homogeneous units, failing to capture heterogeneity in caregiving needs and capacities driven by differences in human capital and social capital, such as education, health, and relational cohesion (Lee 2016; Loichinger et al. 2017; Skirbekk et al. 2022). Moreover, most population-level indicators do not adequately reflect how family size and structure have fundamentally changed under rapid demographic transitions that produce smaller kin networks and increasingly complex caregiving demands. Recent studies have begun to incorporate socioeconomic characteristics into family network research to better analyze kin availability. For example, Margolis et al. (2024) shows that higher socioeconomic status (SES) individuals tend to have fewer descendants but benefit from better-educated kin, while lower SES individuals typically have larger families with younger kin. While this work represents an important advance, most existing studies are based on cross-sectional survey data focusing narrowly on immediate family members, thereby failing to capture the long-term dynamics of broader kinship structures.

To address these gaps, this study develops and applies a capital-based caregiving framework that combines two powerful theoretical concepts: human capital and social capital. Human capital, defined as the stock of knowledge, skills, and health an individual possesses (Schultz 1961; Goldin 2024), determines individuals' capacity to provide care and the timing of their own needs. Complementing this, social capital, defined as the resources embedded within social networks, including trust, norms, and obligations (Coleman 1988; Bourdieu 2018; Lin 2002; Putnam 2015), provides the relational infrastructure through which caregiving support is mobilized.

Within this framework, we conceptualize caregiving dynamics through the specific pathways of each form of capital. For human capital, we focus on a critical pathway: higher educational attainment is robustly associated with better health outcomes (Ross and Wu 1995; Ross and Wu 1996; Grossman 1997; Zajacova et al. 2012; Zajacova and Lawrence 2018). This education-driven health improvement shapes caregiving by increasing individuals' capacity to provide care while delaying their own care needs. We therefore operationalize caregiving capacity as the number of healthy working-age kin (15–64) and care needs as the number of unhealthy older kin (65+). For social capital, our framework focuses on its structural foundation: the network of available family members who form a kinship reservoir–the pool of kin who may be activated to provide or receive care (Cullati et al. 2018; Sauter et al. 2023). This focus on the kinship reservoir is a pragmatic and necessary choice for a long-term demographic model. While we acknowledge that other dimensions of social capital, such as the relational quality of ties (e.g., trust) and the cognitive norms governing obligations (e.g., filial piety), are crucial for the actualization of care, these qualitative aspects are exceedingly difficult to quantify and project. By operationalizing social capital as a measurable kinship reservoir, our framework captures the essential demographic potential of family networks to provide informal support.

This integrated framework enables us to address a central question for aging societies: As the number of available kin declines, can the concurrent rise in their human capital—in terms of both education and health—offset the growing demographic pressure on family care systems? By explicitly linking caregiving capacity and need to both kin availability (structural social capital) and human capital (education and health of kin), this framework extends prior demographic approaches by enabling an analysis of the full landscape of extended kin over a long historical period, moving far beyond the narrow subsets of kin relations previously examined.

Empirically, we move beyond simple counts of kin to estimate and project the caregiving dynamics of family networks in China across multiple generations. First, we use formal demographic kinship models (Caswell 2022) to project the full landscape of kinship networks in China from 1950 to 2100, estimating the number and age of available kin across the individual life course. Second, we incorporate the human capital of kin by integrating educational attainment and its associated health gradients, allowing us to model both caregiving capacity and need within kinship networks. Finally, we synthesize these dimensions into adjusted kin-dependency ratios, which provide a more nuanced assessment of how demographic transitions and educational expansion jointly reshape caregiving capacity by altering both the size and human capital composition of family networks over time.

In the following section, we detail our data sources, methodological steps, and key measures, showing how adjustments for education and health yield a refined understanding of the family support dynamics—one that accounts for not only the size, but also the support capacity and demand of kin. We then present our main results, followed by a discussion of their implications for theory, policy, and future research in the context of navigating aging with limited kin in China and potentially in other societies facing similar demographic prospects.

Data and Methods

Data

Table 1 offers an overview of the data sources, key indicators, time coverage, and underlying assumptions of our analysis. The table summarizes the four major categories of data—demographic, educational, economic, and health-related—highlighting the primary variables and projections applied in the analysis. This overview serves as a foundation for the subsequent detailed discussion of each dataset and its role in the modeling framework. For the purposes of this study, all data have been aggregated into five-year age groups, and key indicators are extracted at five-year intervals from 1950 to 2100.

For demographic data, we use sex- and age-specific mortality, fertility, and population age structure from 1950 to 2100, as provided by the World Population Prospects 2024 version (United

Table 1: Overview of Data Sources and Assumptions

Category	Data Source	Indicators	Time Range	Assumptions
Demography	World Population Prospects (United Nations 2024)	Mortality, fertility, population age structure	1950–2100	Medium scenario for future projections from 2025
Education	Wittgenstein Centre (Lutz et al. 2018)	Educational attainment distribution	1950–2100	SSP1-3 scenarios for future projections from 2020
Health	Chinese General Social Survey (CGSS) (Bian and Li 2012)	Proportions of individuals classified as healthy by education	2010–2021	Constant education-specific proportions post-2021

Nations 2024). We rely on the "Medium" scenario from the standard projection for future demographic rates.

For educational attainment, we use sex- and age-specific distributions from 1950 to 2100 from the Wittgenstein Centre (Lutz et al. 2018). For future projections, we consider three scenarios, developed as part of the Shared Socioeconomic Pathways (SSPs). The SSPs are a set of alternative socioeconomic development narratives, defined within the IPCC's Sixth Assessment Report, which were specifically designed to assess the socioeconomic challenges for climate change mitigation and adaptation (O'Neill et al. 2017). In our analyses we include SSP1 (Sustainability/Rapid Social Development), which combines rapid education expansion (SDG education scenario) with rapid fertility and mortality decline; SSP2 (Middle-of-the-Road/Continuation), which includes medium fertility and mortality assumption with the Global Education Trend (GET) scenario; and SSP3 (Fragmentation/Stalled Development), which integrates stalled school enrolment rates (CER education scenario) with slow fertility and mortality decline. Details of the educational attainment distribution are shown in Figure C.1.

For health data, we collect sex-, age-, and education-specific proportions of being healthy also from the Chinese General Social Survey (CGSS) 2010 to 2021. The self-rated questionnaire covers three health categories: (1) overall health dichotomized into healthy (very healthy, relatively healthy, and average) and unhealthy (relatively unhealthy, and very unhealthy); (2) physical health measuring responses to the question "In the past four weeks, how often has your work or other daily activities been affected because of health issues?" dichotomized into unhealthy (always, often, and sometimes) and healthy (rarely, and never); (3) mental health measuring responses to the question "In the past four weeks, how often did you feel depressed or upset?" dichotomized into unhealthy (always, often, and sometimes) and healthy (rarely, and never). Health indicators tend to follow a more stable and predictable trend, typically showing consistent improvement over time. Due to the limited number of observations within each stratum defined by sex, age, and education, especially among older age groups and those with the highest educational attainment, we employ logistic regression models stratified by sex and health category, including age (grouped in 5-year intervals from 15 to 80+), educational attainment, and survey year as independent variables. This approach allows us to incorporate a year variable to capture historical improvements in health (Batljan et al. 2009) while achieving more stable estimates. For the dependent variable, we use the proportion of individuals classified as healthy from each panel between 2010 and 2021, establishing a basis for future projections. Although this historical trend suggests that health status will continue to improve, for simplicity, we assume that the education-related disparities in health remain at the 2021 level through to 2100. This straightforward approach enables us to focus on analyzing the effects of changes in educational structure on health outcomes, without introducing additional complexities, offering a clearer understanding of the role of education in shaping health dynamics. Age profiles of health are shown in Figures C.2.

Kinship Model

We use the time-varying two-sex kinship model, as developed by Caswell (2022) and implemented using the `DemoKin` R package (Williams et al. 2021), to estimate the expected number of living kin for an average individual (the focal individual) in the population. These estimates are disaggregated by the sex and age of both the focal individual and their kin. The model uses a matrix projection approach, treating each type of kin (e.g., children, parents, siblings) as a distinct population and projecting their dynamics over time by incorporating fertility and survival components, analogous to the cohort-component method in demographic projections (Heuveline et al. 2001). Details about this model can be found in Appendix A.1. Due to limitations in male fertility data, this study assumes that males have the same fertility rates as females, following Alburez-Gutierrez et al. (2023).

Measures

We employ several key measures to analyze the composition of kinship networks and the family caregiving dynamics.

First, we obtain the expected number of working-age (15–64) and old-age (65+) kin for an "average" old woman (focal ages 65+) from the kinship model.

Second, we calculate the education-specific numbers of working-age (15–64) and old-age (65+) kin by assigning educational attainment (primary or less, middle school, or high school and above) to each relative based on age-sex-specific distributions of educational attainment from the Wittgenstein Centre. This profile quantifies the expected number of working-age and old-age kin within each education category from 1950–2100.

Third, we attach health status to kin by combining the education-specific kin counts from step two with age-, sex-, and education-specific probabilities of being healthy estimated from the CGSS. This linkage lets us examine how human capital (education) shapes caregiving capacity, proxied by the health status of working-age kin, and care demand, proxied by the health status of old-age kin.

Finally, we construct two measures on caregiving dynamics. The age-based kin dependency ratio is defined as the number of old-age kin divided by the number of working-age kin, while the health-adjusted kin dependency ratio compares the number of unhealthy old-age kin to the number of healthy working-age kin to capture potential care demand relative to available supply.

Detailed measurement constructions are provided in Appendix A.2.

Main Results

Dynamics of Kinship Networks and Support Burden

We start by analyzing the changes in kinship networks for an average older female (65+ years old) in China over time, without considering educational attainment. A significant decline in the number of working-age kin (aged 15–64) is observed starting around 2000 (upper panel in Figure 1A). This decline is primarily due to the sharp reduction in fertility rates after the 1980s, largely resulting from the implementation of the one-child policy. In contrast, the number of older kin (aged 65+) increases until around 2040 before gradually declining (lower panel in Figure 1A).

By focusing on the year 2020 (Figure 1B), we gain insight into how the kinship structure varies across ages. The upper panel shows a marked decline in the number of working-age kin for older focal individuals, especially for individuals older than 70. This is primarily due to cousins and siblings transitioning out of the working-age bracket. Meanwhile, the lower panel reveals a modest rise in older kin among these focal individuals, mainly because nieces or other slightly younger relatives are "aging up" into the 65+ category. These patterns reveal growing constraints on the pool of available working-age kin to support older adults. The contraction of lateral kin relationships, in particular, contributes to greater vulnerability in family-based care provision.

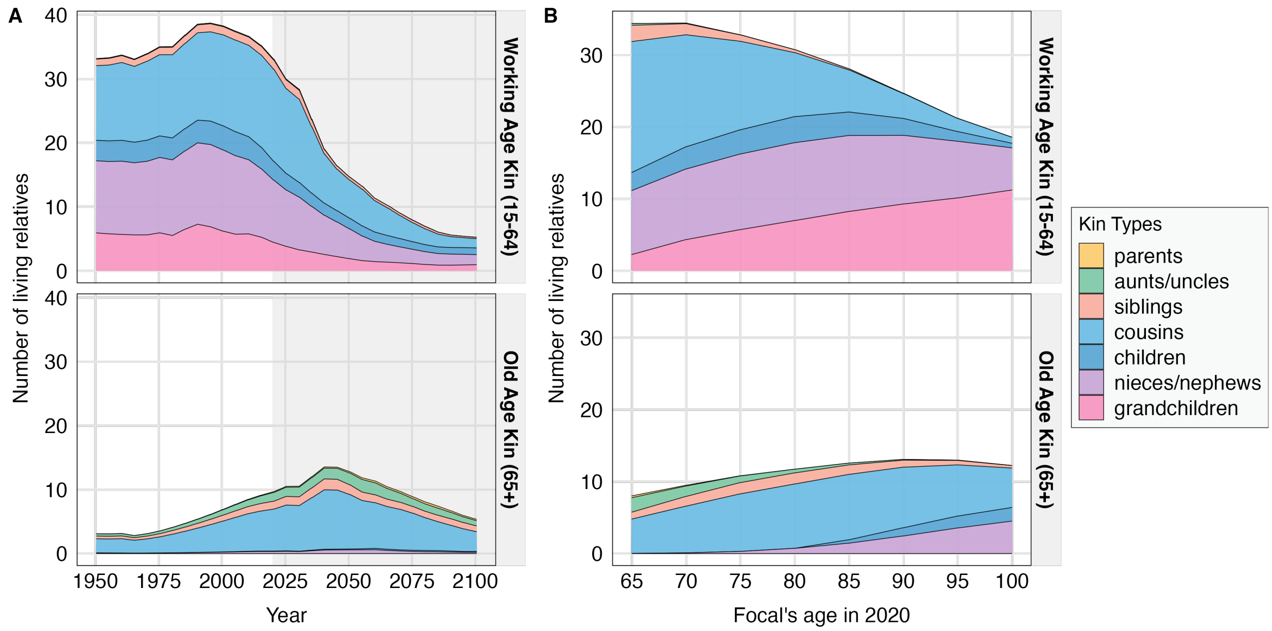

Figure 1: Expected number of living relatives for an average old-age focal individual (65+ years old) across time (Panel A) and expected number of living relatives for focal individuals at different ages in 2020 (Panel B). The educational attainment is under SSP2 educational projection scenario. Rows show number for relatives in different age groups: Working Age (15-64) and Old Age (65+). The areas represent accumulated numbers for each type of relative, indicated by different colors. The shaded area shows the results using projected demographic rates. Data source: Kinship network is calculated by authors using kinship models (Caswell 2022) and WPP2024 demographic data (United Nations 2024).

Increasing Proportion of Highly Educated Kin

When we incorporate the educational attainment of kin, a noticeable shift emerges in both the absolute numbers and educational distribution among relatives of older focal individuals. Figure 2 presents area plots showing the number of kin by educational attainment alongside lines tracking the proportion of highly educated kin over time. More detailed information about the educational distribution can be found in Figure C.3.

Results show that while the total number of working-age kin decreases across all scenarios, this decline is not uniform across educational categories. Particularly in SSP1 and SSP2, the number of working-age kin with high school education and above decreases more slowly than those with lower educational attainment. For instance, in SSP1, as primary-educated working-age kin practically disappear by 2075, the highly-educated segment continues to comprise a substantial portion of the remaining working-age kin. For older kin, the pattern is even more striking—the number of highly educated older kin actually increases before beginning to stabilize or decline around 2075. This trend reflects the aging of better-educated cohorts who benefited from China's educational expansion in recent decades.

The overlaid lines confirm these structural changes, showing that the proportion of highly educated kin (high school and above) is projected to rise in the future. Under SSP1, which assumes rapid educational expansion, the share of working-age kin with high school education or above climbs from around 35% in 2025 to 75% by 2050 and to over 90% by 2100. By 2075, even among the old-age kin, this proportion approaches 75% under SSP1. Meanwhile, SSP2 presents a more moderate trajectory, eventually converging toward SSP1 levels after 2050. By contrast, SSP3 indicates a much slower progression, with less than 60% of working-age kin attaining high school or higher degrees by 2100.

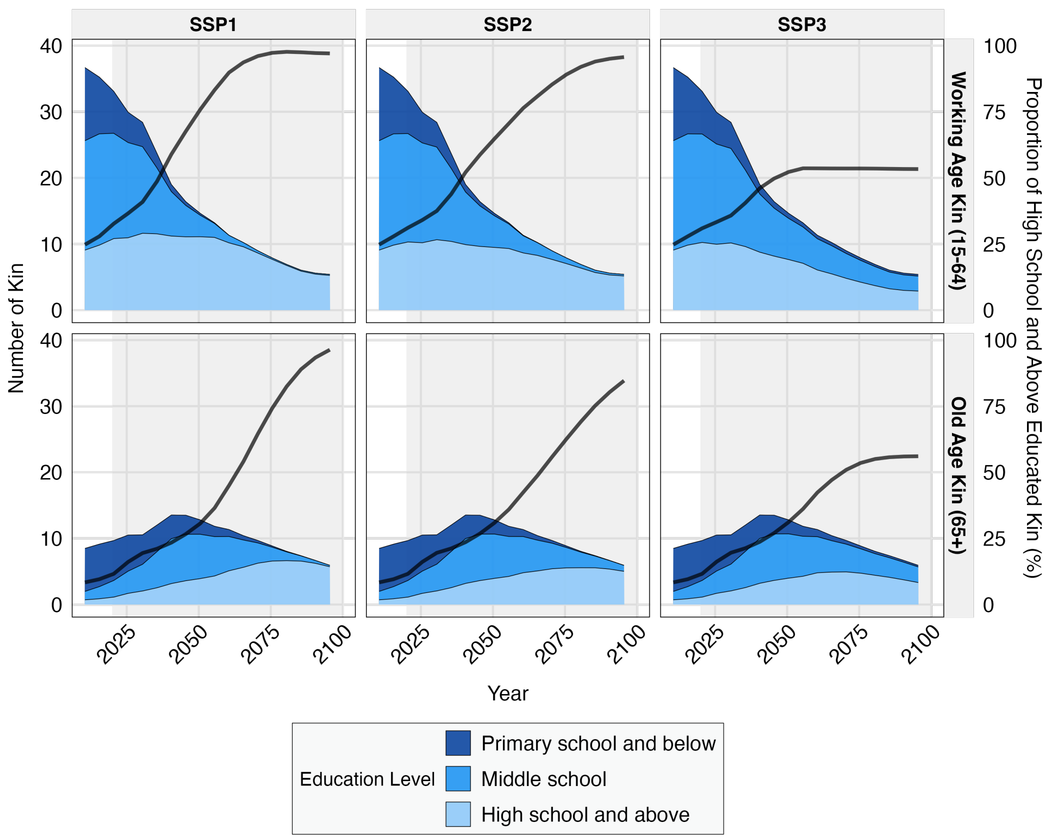

Figure 2: Number of living relatives with different educational attainment distribution (shown as stacked areas of different colors with y-axis on the left side) and the proportion of high school and above-educated kin among all living relatives (shown as black lines with y-axis on the right side) for average old-age focal individuals (65+ years old). Columns indicate different educational projection scenarios, and rows show relatives of different age groups. The shaded area shows the results using projected demographic rates. Data source: Educational attainment distribution is from Wittgenstein Centre (Lutz et al. 2018)

Health Status of Kin Due to Educational Change

In this section, we extend our analysis to the health status of kin, an important factor that is related to education and mediates caregiving capacity. Figure 3 shows the proportion of healthy relatives, considering physical health, mental health, and overall health, across different years.

For working-age kin, the proportion of individuals with good physical health is higher under SSP1 compared to SSP3, indicating that higher educational attainment produces better health outcomes. This trend is consistent across all health dimensions—physical, mental, and overall health. In SSP1, the proportion of physically healthy working-age kin approaches around 84% by 2100, while mental health and overall health also show significant improvements over time.

In contrast, for older-age kin, there is a noticeable decline in health status over time, regardless of the educational scenario. However, SSP1 still presents a relatively higher proportion of healthy older individuals compared to SSP3, underscoring a cumulative advantage effect of long-term educational benefits. By 2100, the proportion of physically healthy older kin under SSP1 is around 45%, whereas it is around 40% under SSP3.

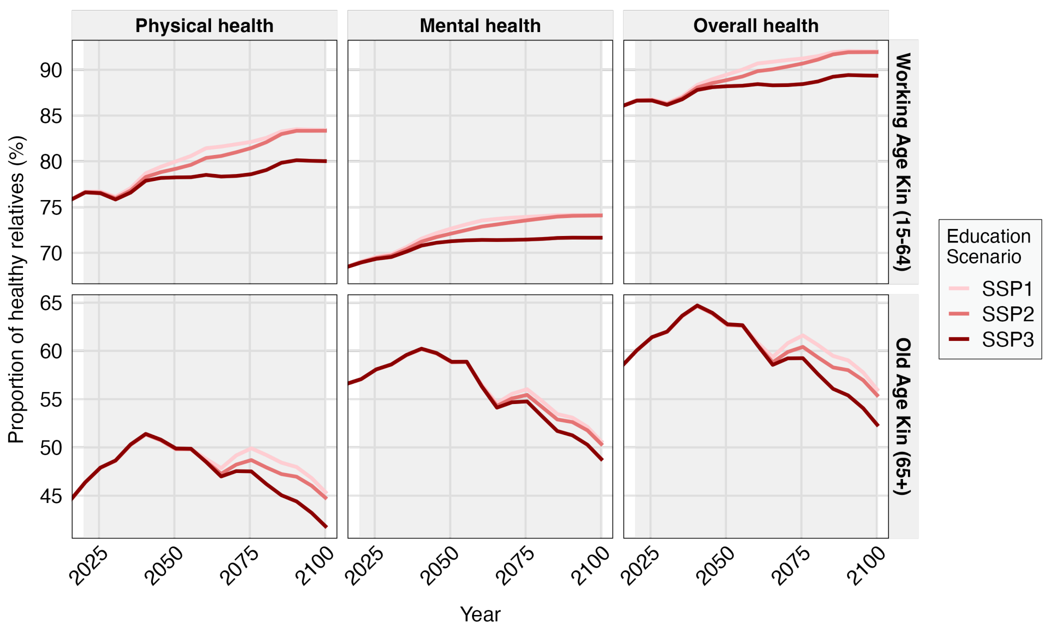

Figure 3: Health status (proportion of being healthy, %) of living relatives for average old-age focal individuals (65+ years old) across time. Columns show different health categories, and rows show different ages. Colors show different education projection scenarios. The shaded area shows the results using projected demographic rates. Data source: Health status is from Chinese General Social survey (2010-2021).

Kin Dependency Ratios: From Age-Based to Health-Adjusted

Finally, we summarize the changing caregiving dynamics through two kin dependency ratios: age-based and health-adjusted.

Kin dependency ratios measure the dynamics of family support within households, focusing on the availability of working-age kin relative to non-working age kin. In this study, we specifically focus on the old-age dependency ratio and examine the kinship networks of older individuals aged 65 and above (referred to as focal individuals). These networks include family members such as parents, aunts/uncles, siblings, cousins, children, nieces and nephews, and grandchildren. Figure 1 (A) illustrates the family networks for older individuals over time, including the number and type of working-age and older kin. Since the kinship network is defined around a focal individual, changing the age range of the focal naturally alters the composition of the kin network. For instance, the siblings of an older focal individual are more likely to also be older, while the siblings of a working-age focal are more likely to fall within the working-age range.

(1) Age-Based Kin Dependency Ratio

The age-based kin dependency ratio is a baseline measure that calculates the number of older kin relative (red area in Figure 4A) to the number of working-age kin (blue area in Figure 4A) within the family network of an average Chinese female aged 65 and above. This ratio, shown as the solid line in Figure 4A, provides a straightforward indicator of the caregiving burden borne by working-age family members from the perspective of an older individual. Overall, figure 4A shows how the dramatic decline in working-age kin (from approximately 36 in 2020 to about 5 by 2100) coupled with the initial increase and later decrease in old-age kin, directly translates into a rising kin dependency ratio. To be specific, the age-based ratio rises steadily from about 0.25 in 2020, crosses the threshold of 1.0 around 2060, and peaks at approximately 1.2 by 2080, before slightly declining toward 2100. This trajectory suggests a fundamental inversion of the family support structure, where, for the first time in history, old adults may have more old-age dependents than working-age relatives available.

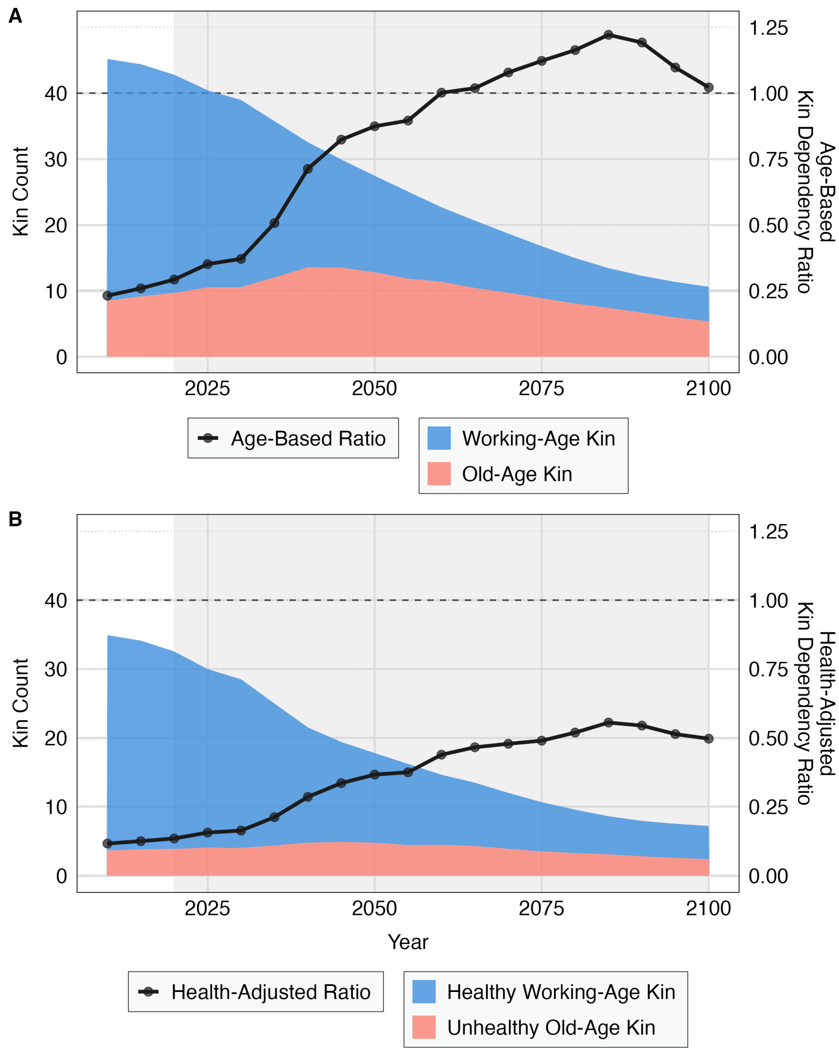

Figure 4: Kin dependency ratio for average old-age focal individuals above 65 years old (shown as black lines with y-axis on the right side) and the denominator and numerator of the dependency ratio (shown as stacked areas of different colors with y-axis on the left side) across time under SSP2 educational projection scenario. Upper panel shows the age-based ratio and lower panel show the health-adjusted ratio (for overall health). The horizontal dashed line in the background indicates a reference line of kin dependency ratio as 1, meaning that for every (unhealthy) old-age relative, there is one (healthy) working-age relative available within the family. The shaded area shows the results using projected demographic rates.

(2) Health-Adjusted Kin Dependency Ratio

We extend this analysis by incorporating health status, showing the number of healthy working-age kin (blue area in Figure 4B) and unhealthy old-age kin (red area in Figure 4B), alongside the resulting health-adjusted dependency ratio (solid line in Figure 4A). This measurement acknowledges that caregiving needs primarily arise when older relatives experience poor health, while the capacity to provide support is greatest among healthier working-age kin. Results show that when health status is considered, the dependency ratio follows a similar trajectory to the age-based ratio but at a lower level. Starting from approximately 0.15 in 2020, it will grow to around 0.5 by 2100, indicating that for every unhealthy old-age kin, there will be roughly two healthy working-age kin available within the family. The relatively slow increase in health-adjusted ratio suggests that, despite demographic pressures, accounting for the better health of both care providers and care recipients paints a less severe, though still challenging, caregiving landscape.

(3) Comparison Across Scenarios (SSP1, SSP2, SSP3)

We further compare the age-based and health-adjusted dependency ratios across the three educational scenarios (SSP1, SSP2, SSP3) in Figure 5. We find that while the age-based dependency ratios (dashed lines) show no difference across all three educational scenarios, the health-adjusted dependency ratios (solid lines) vary across scenarios.

Under SSP1, where educational attainment improves most rapidly, there are fewer unhealthy older kin relative to healthy working-age kin, leading to a lower overall support burden. By contrast, SSP3—characterized by slower educational progress—sees a larger share of unhealthy older individuals. By 2100, the health-adjusted dependency ratio under SSP1 is approximately 0.49, compared to 0.547 under SSP3. This indicates that rapid educational expansion is expected to reduce the burden on healthy working-age kin supporting less healthy older kin by approximately 10% in 2100, compared to the stalled education development scenario.

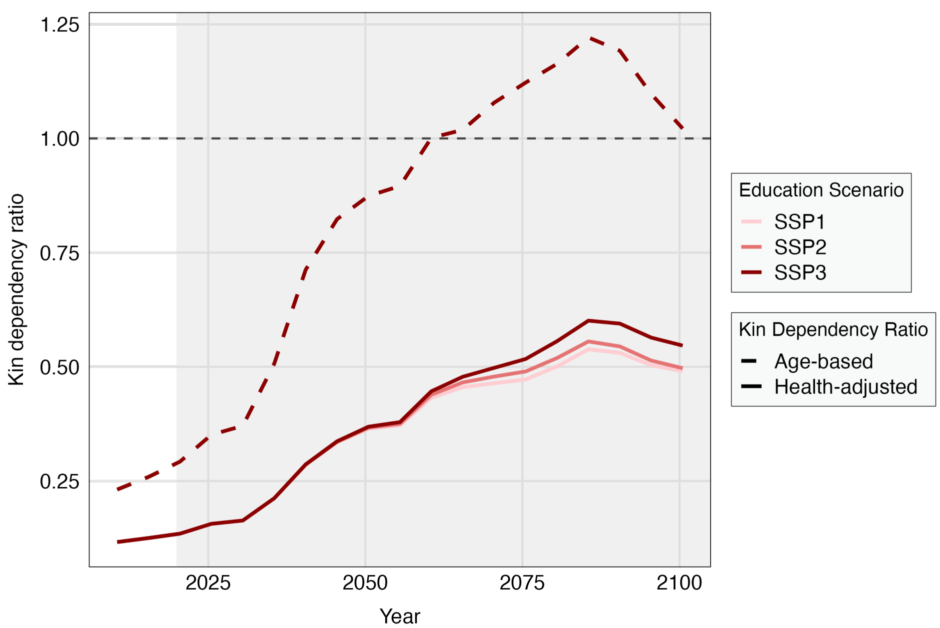

Figure 5: Kin dependency ratio for average old-age focal individuals (65+ years old) across time under different educational projection scenarios. Colors show different education projection scenarios. Dashed lines show age-based kin dependency ratio while solid lines show health-adjusted kin dependency ratio. Here we only consider overall health among three health categories. The horizontal dashed line in the background indicates a reference line of kin dependency ratio as 1, meaning that for every unhealthy old-age relative, there is one healthy working-age relative available within the family. The shaded area shows the results using projected demographic rates.

Discussion

Key Findings

This study set out to examine how the interplay between kinship structure and human capital reshapes family caregiving dynamics under conditions of rapid population aging and shrinking kin networks in China. Specifically, we asked: as family sizes decline and caregiving demands rise, to what extent can investments in human capital, manifested as higher educational attainment and better health among kin, compensate for the declining number of family caregivers and effectively mitigate the nation's growing care burden? Using a capital-based caregiving framework that integrates both the structural dimension of social capital (kin availability) and human capital (education and health of kin), we provide long-term projections of family caregiving dynamics across multiple generations. A short answer to our research question is: Yes, investment in human capital can mitigate family caregiving challenges in aging societies, such as China.

Our findings highlight four key patterns. First, the ongoing decline in working-age kin underscores the demographic pressures confronting traditional family-based old-age care systems. This aligns with concerns raised by previous research (Verdery 2019; Zhou et al. 2019) that shrinking family sizes and increased risks of "kinlessness" intensify the caregiving responsibilities borne by a smaller number of working-age relatives. In particular, lateral kin—such as siblings, cousins, and nieces—who historically provided distributed caregiving across extended families, are increasingly scarce. This erosion of extended kin ties amplifies caregiving vulnerabilities, especially for older adults with fewer or no direct descendants. In this context, women often assume disproportionate caregiving responsibilities (Zhang and Goza 2006; Cong and Silverstein 2012), making older females especially vulnerable as both care providers and care recipients, especially when they face their own health or economic constraints while also caring for peers.

Second, despite shrinking kin networks, the human capital composition of remaining kin has improved substantially due to educational expansion. These shifts reflect the operation of human capital mechanisms within our capital-based caregiving framework, where rising education improves both the potential to provide care and delays the onset of care needs. In scenarios with rapid education growth (e.g., SSP1), the proportion of highly educated working-age kin continues to rise steadily, reaching over 90% by 2100. These educational improvements emerge more quickly among working-age kin, as improvements in schooling manifest more quickly in younger cohorts. Older kin, by contrast, reflect past educational policies and socio-historical conditions, thus lagging behind in achieving higher education. Consequently, any gains in caregiving capacity or health benefits derived from better education will be felt most acutely among the younger generation, reinforcing the importance of sustained educational investment.

Third, rising educational attainment contributes to improved health profiles among both working-age and older kin (Bowen and Finegan 1966; Harper 2014; Loichinger 2015). These education-induced health improvements operate through multiple pathways, such as enhanced health literacy, greater socioeconomic stability, and improved access to healthcare (Zajacova and Lawrence 2018), which accumulate over the life course (Crimmins et al. 2010). In our projections, under a rapid education expansion scenario (SSP1), the proportion of physically healthy working-age kin approaches 84% by 2100. Due to population aging, the absolute number of healthy old-age kin decreases over time, but health outcomes under SSP1 remain relatively better compared to other scenarios.

Fourth, by introducing health adjustments into the kin dependency ratio, our capital-based framework provides a more nuanced measure of caregiving dynamics than conventional age-based metrics (Lee 2016; Loichinger et al. 2017; Skirbekk et al. 2022). The health-adjusted kin dependency ratio simultaneously reflects caregiving capacity (healthy working-age kin) and care needs (unhealthy old-age kin). We find that educational expansion moderates caregiving burdens by reducing the share of unhealthy old-age kin relative to healthy working-age kin. For example, under a rapid education expansion scenario (SSP1), the health-adjusted kin-dependency ratio in 2100 is projected to be approximately 10% lower than under a stalled education scenario (SSP3), highlighting the buffering role of human capital investment in aging societies.

Conceptual, Methodological and Policy Implications

This study offers several implications that extend beyond its empirical findings. Conceptually, previous research on family caregiving has often addressed demographic transitions, such as fertility decline and kin shrinkage, and socioeconomic factors as separate contributors to caregiving vulnerability. Demographic studies have typically focused on how shrinking family size limits caregiving resources, while public health and social inequality research has examined how socioeconomic disadvantage shapes the well-being of caregivers and care-receivers. Our capital-based caregiving framework integrates these dimensions by jointly modeling kin availability (as the structural dimension of social capital) and human capital (including education and health of kin), allowing for a dynamic, multigenerational analysis of how caregiving capacity changes under demographic and socioeconomic transitions. Furthermore, our integration of kin availability into a capital-based framework echoes recent conceptualizations of the kinship reservoir, which encompasses both immediate and extended kin who may be mobilized for caregiving as needs arise (Cullati et al. 2018; Sauter et al. 2023). Human capital operates as a filtering mechanism within this reservoir, determining which kin possess the resources and health to provide effective care. This perspective allows us to capture not only shrinking family size but also the unequal distribution of caregiving capacity within evolving kin networks.

Methodologically, prior studies on family caregiving have often relied on cross-sectional data or focused on immediate family ties, limiting their ability to capture longer-term dynamics across generations (Margolis et al. 2024; Verdery et al. 2019). Our approach integrates formal demographic kinship models with education-specific health gradients to estimate and project caregiving capacity and need within extended kinship networks over a long time period. By incorporating both kin availability and the other important characteristics of kin, this capital-based framework provides a flexible tool for analyzing caregiving dynamics across diverse aging contexts.

From a policy perspective, our findings offer several crucial implications for navigating population aging, centered on the strategic value of human capital investment. First and foremost, our analysis underscores the importance of education as a long-term strategy to strengthen caregiving resilience in contexts of limited kin. By improving population health, educational attainment enhances the capacity of younger cohorts to provide care while simultaneously delaying the onset of their own care needs. Expanding access to secondary and tertiary education, especially for disadvantaged groups, is therefore a critical tool for narrowing health disparities and promoting more equitable old-age support within families.

Furthermore, the strategic importance of education transcends the specific health pathway modeled in our study. Even if the strong link between education and health were to weaken in the future, investing in human capital per child would remain a vital adaptive strategy. Broader international research supports this view. For example, recent work in Finland demonstrates that, even in the face of declining fertility, sustained investments in human capital can substantially mitigate the long-term burdens of population aging by extending healthy working lives and reducing demands on pension systems (Myrskylä et al. 2025). This suggests that in contexts of limited kin availability, strengthening per capita investments in education represents a robust strategy with multiple benefits for sustaining societal well-being under demographic pressure.

Finally, while investing in human capital strengthens the foundation of informal family care, it must be complemented by a robust formal care system. Policies that support families under caregiving strain, such as caregiver training, community-based services, telemedicine integration, and public-private care partnerships, can help supplement informal support systems. As younger, better-educated cohorts increasingly adopt alternative caregiving strategies, policymakers must anticipate evolving care preferences while ensuring equitable access to care resources for families with limited caregiving capital.

Limitations

Several limitations warrant consideration. First, our framework captures structural aspects of social capital (the number and age distribution of kin) but does not directly observe relational (trust, cohesion, norms of reciprocity) or cognitive (shared obligations and expectations) dimensions, which are critical for understanding whether available kin actually mobilize caregiving resources when needs arise, meaning our results likely represent an upper-bound estimate of actual support. Second, our model holds education-health gradients constant over time, though future changes in health technology, policy, or inequality could alter these trajectories. To assess sensitivity, we tested four alternative health scenarios (Appendix Table B.1 and Figure C.4) and calculated corresponding kin dependency ratios (Appendix Figure C.5). Results show that the caregiving burden is sensitive to whether education-related health disparities persist, narrow, or widen, underscoring the importance of addressing both educational attainment and the pathways linking education to health outcomes. Third, we do not model educational differentials in fertility and mortality, which may further influence kin availability across cohorts. This simplification could introduce competing effects, as lower fertility among the highly educated may reduce kin counts while their lower mortality could extend kin availability. Fourth, our projections do not incorporate internal migration patterns (especially from rural to urban areas), which can redistribute caregiving capacity geographically and affect physical proximity between kin. This would likely cause our national-level estimates to overstate the availability of proximate, hands-on care for older adults in rural areas. Fifth, our national-level analysis does not capture substantial sub-national heterogeneity in education, health, and kinship dynamics within China. Consequently, our findings may mask more severe caregiving deficits in vulnerable regions. Sixth, our model does not account for the clustering of education within families (i.e., assortative mating and intergenerational transmission). This simplification ignores the inequality in support networks, as we likely overestimate the human capital in kin networks of less-educated families and underestimate it for the highly-educated. Finally, while our framework estimates the potential size and human capital composition of the kinship reservoir, it does not capture the dynamic processes through which kinship ties are activated, lost, or re-engaged in response to changing family circumstances (Sauter et al. 2023). Future research incorporating longitudinal activation models could offer richer insights into how shrinking kin networks adapt to evolving caregiving needs.

Conclusion

This study demonstrates how shrinking kin networks and rising human capital jointly shape family caregiving capacity under demographic transitions. As more individuals face aging with limited family ties, education-driven gains in health can help partially mitigate these challenges by improve caregiving capacity and moderating caregiving needs, though formal care systems will remain essential. The capital-based framework developed here offers a tractable tool for integrating demographic and capital-related factors into long-term caregiving projections, with relevance not only for China but for other aging societies navigating similar transitions.

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Appendix A Method in Detail

A.1 Kinship Model

We use a time-varying two-sex kinship model (Caswell 2022) to estimate the expected number of living kin for an average individual (the focal individual) in the population. The estimates are disaggregated by the sex and age of both the focal individual and their kin. The kinship dynamics are modeled using a matrix projection approach, which treats each type of kin (e.g., children, parents, and other relatives) as a distinct population. Similar to the classical cohort-component method in demographic projections (Heuveline et al. 2001), this approach projects the dynamics of each kin group over time by incorporating fertility and survival components. By accounting for time-varying demographic rates, this framework provides a robust method for analyzing changes in kinship networks, particularly in populations undergoing rapid demographic transitions or structural changes.

In the basic one-sex time-varying model (Caswell and Song 2021), let $\mathbf{k}_{x,t}$ represent the age distribution vector of a specific type of kin at time t, where x is the age of the focal individual. The projection equation is expressed as:

$$\mathbf{k}_{x+1,t+1} = \mathbf{U}_t \mathbf{k}_{x,t} + \mathbf{B}_{x,t} \tag{1}$$

where:

- $\mathbf{U}_t$: Survival matrix at time t, containing age-specific survival probabilities for both sexes.
- $\mathbf{B}_{x,t}$: Age-specific distribution of new kin recruited through reproduction. This depends on the fertility matrix at time t, $\mathbf{F}_t$ and the distribution of source kin (who give birth to the kin of projection), $\mathbf{k}^*_{x,t}$.

For the two-sex extension used in this study, the kinship projection is structured as:

$$\tilde{\mathbf{k}}_{x+1,t+1} = \tilde{\mathbf{U}}_t \tilde{\mathbf{k}}_{x,t} + \tilde{\mathbf{B}}_{x,t} \tag{2}$$

where:

$$\tilde{\mathbf{k}}_{x,t} = \begin{pmatrix} \mathbf{k}_{f,x,t} \\ \mathbf{k}_{m,x,t} \end{pmatrix}, \quad \tilde{\mathbf{U}}_t = \begin{pmatrix} \mathbf{U}_f(t) & 0 \\ 0 & \mathbf{U}_m(t) \end{pmatrix} \quad \tilde{\mathbf{B}}_{x,t} = \begin{pmatrix} \mathbf{B}_{f,x,t} \\ \mathbf{B}_{m,x,t} \end{pmatrix} \tag{3}$$

Here:

- $\mathbf{k}_{f,x,t}$, $\mathbf{k}_{m,x,t}$: Kinship vectors for female and male kin, respectively.
- $\mathbf{U}_f(t)$, $\mathbf{U}_m(t)$: Survival matrices for females and males.
- $\mathbf{B}_{f,x,t}$, $\mathbf{B}_{m,x,t}$: Kinship vectors for female and male new kin recruited through reproduction, respectively. This can be divided into several scenarios. The output depends on fertility, number and age distribution of source kin (who give birth to the kin of projection), and sex ratio at birth (where we assume there are 49 female births per 100 births). More details can be found in Caswell (2022).

The computations in this study were performed using the DemoKin R package (Williams et al. 2021), which calculates age- and sex-specific kinship distributions. Due to data limitations on male fertility, this study follows Alburez-Gutierrez et al. (2023) in assuming that males have the same fertility rates as females. We further used the female population age structure as weights to calculate the expected number of kin for average females aged 65+ (see equation (4 below).

A.2 Key Variables

In this study, we focus on the kinship network for female focal individuals. The variables used in our model are:

- $k_{x,y,t}$: The expected number of a particular type of kin in year t, where the kin is aged y and the focal individual is aged x. Derived from the kinship model output $\tilde{\mathbf{k}}_{x,t}$. We can aggregate the estimates by age of kin to obtain counts for broad age groups, such as working-age kin and old-age kin.

- $PE_{y,e,t}$: Proportion of individuals aged y in year t within educational category e. Categories include: "Primary school and below", "Middle school", and "High school and above".

- $PH_{y,e,h,t}$: Proportion of individuals aged y in year t within educational category e who are healthy in health status h. Health statuses include: "Physical health", "Mental health", and "Overall health".

Using these variables, we calculate key indicators for the focal individual at age x in year t:

- $\sum_y PE_{y,e,t} \cdot k_{x,y,t}$: Expected number of kin in educational category e.

- $\sum_{y,e} PH_{y,e,h,t} \cdot PE_{y,e,t} \cdot k_{x,y,t}$: Expected number of kin who are healthy in health status h.

To derive the kin estimate for an average focal individual aged 65 and above, regardless of age x, we weight the kin estimate using the female age structure as follows:

$$\text{Indicator}_t = \sum_{x=65}^{x=100+} \frac{\text{Indicator}_{x,t} \cdot \omega_{x,t}}{\sum_x \omega_{x,t}} \tag{4}$$

where $\omega_{x,t}$ represents the proportion of the female population at age x in year t. This indicator could be the total expected number of kin for an old age individual, or, more specifically, the expected number of kin within particular age, educational, or health status categories.

Subsequently, we use the age-based old-age kin dependency ratio and the health-adjusted old-age kin dependency ratio to analyze the family support dynamics:

$$\text{Age-Based Kin Dependency Ratio} = \frac{\text{Old-age (65+) kin}}{\text{Working-age kin (15-64)}} \tag{5}$$

$$\text{Health-Adjusted Kin Dependency Ratio} = \frac{\text{Old-age (65+) kin who are not healthy}}{\text{Working-age kin (15-64) who are healthy}} \tag{6}$$

Appendix B Tables

Table B.1: Health Scenarios For Future Trend

Health Scenario	**Assumptions**
Constant at 2020 Level	Assumes **no change** in age-sex-education-specific health levels, maintaining the health baseline of **2020** into the future.
Converge Towards High-Education Health	Assumes that health disparities among education groups **narrow** over time. The health levels of the higher-educated group follow historical trends and stabilize after 2050, while the lower-educated group gradually catches up, reaching the same level by 2100.
Converge Towards Low-Education Health	The opposite of the upward convergence scenario.
Follow Historical Trend	Projects **gradual health improvement**, continuing the trends in population health development from 2010 to 2021, and stabilizing after 2050.

Appendix C Figures

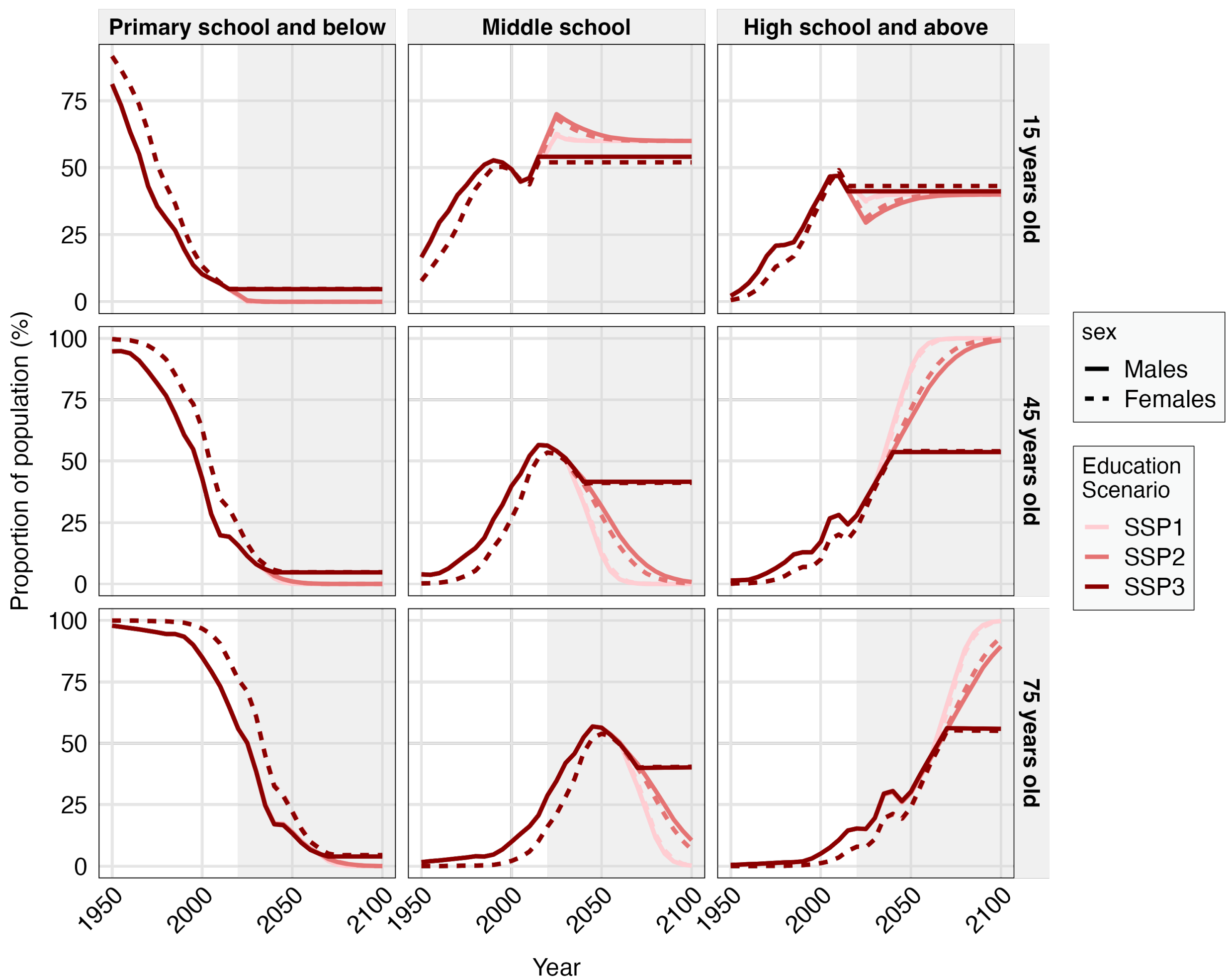

Figure C.1: Educational attainment distribution (proportion of being in a certain educational category, %) at different ages across time in China. Columns show different educational categories, and rows show different ages. Colors show different educational projection scenarios and line types show different sexes. The shaded area shows the projection horizon. Data source: Educational attainment distribution is from Wittgenstein Centre (Lutz et al. 2018)

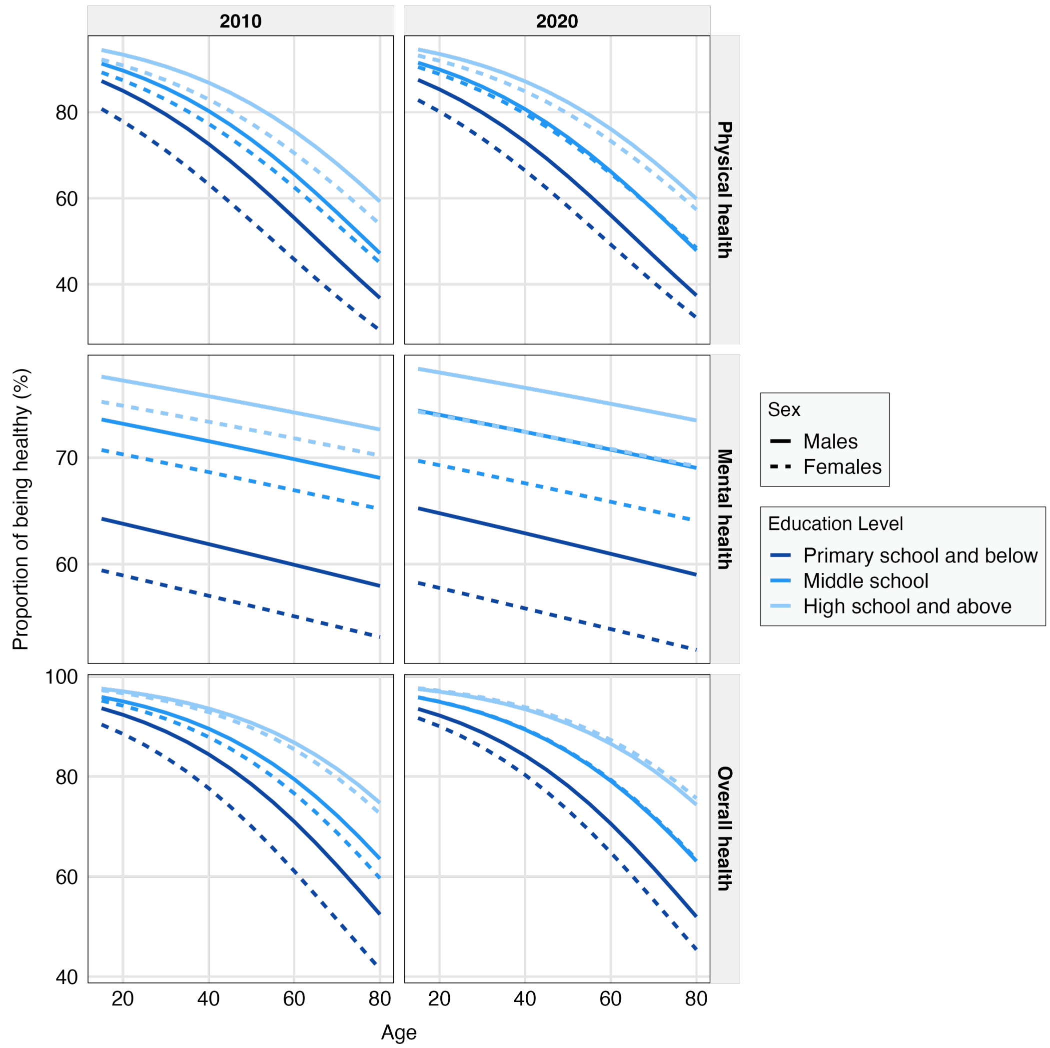

Figure C.2: Educational difference in health status (the proportion reported being healthy, %) across age. Columns show different years and rows show different health categories. Colors indicate different levels of educational attainment, whereas line types show sex groups. Data source: Health status is from Chinese General Social Survey (2010-2021).

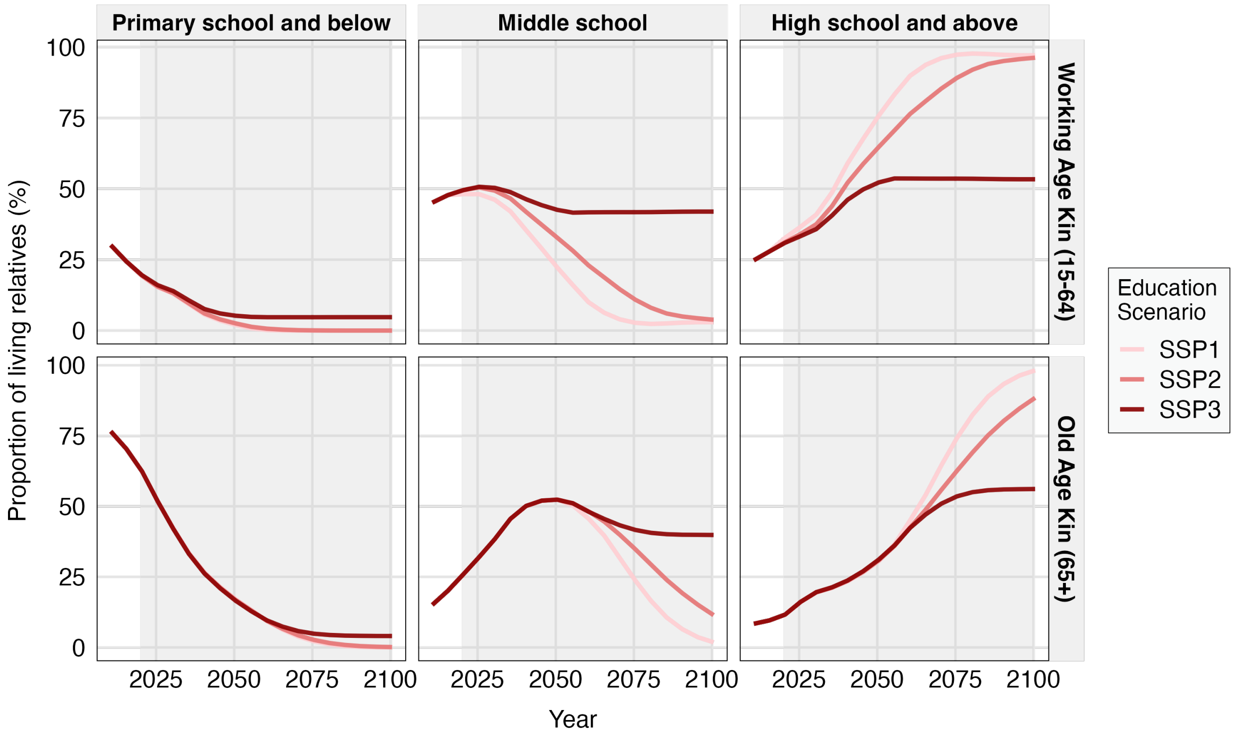

Figure C.3: Educational attainment distribution (proportion of being in a certain educational category, %) of living relatives for average old-age focal individuals (65+ years old) across time. Columns show different educational categories, and rows show different ages. Colors show different educational projection scenarios. The shaded area shows the results using projected demographic rates. Data source: Educational attainment distribution is from Wittgenstein Centre (Lutz et al. 2018)

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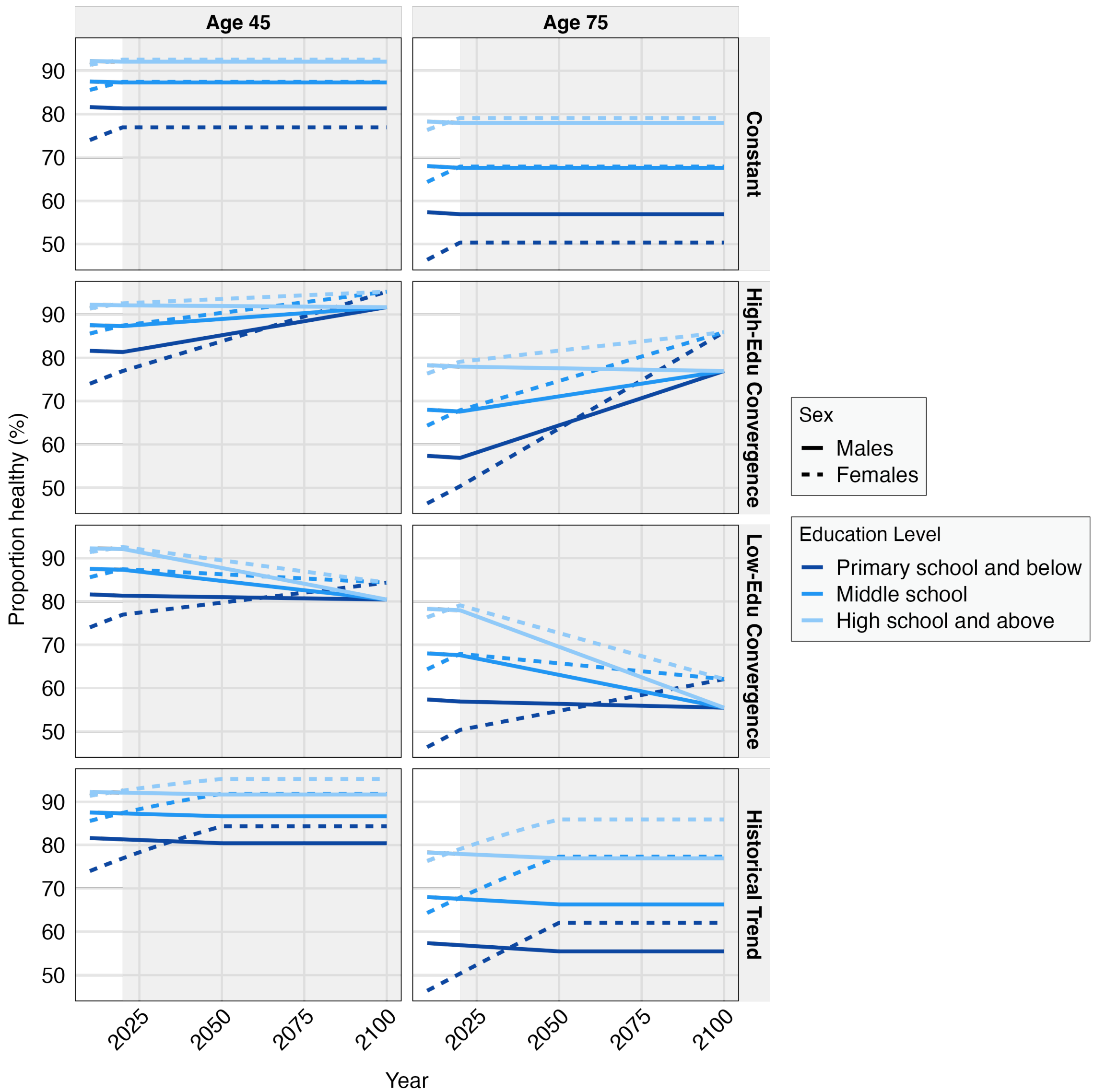

Figure C.4: Proportion of being healthy under different educational attainments over time. Colors show different educational attainments, and line types show different sexes. Columns represent the proportion of individuals of different ages, and rows represent different health projection scenarios. Here we only show overall health among three health categories. The shaded area shows the results using projected demographic rates.

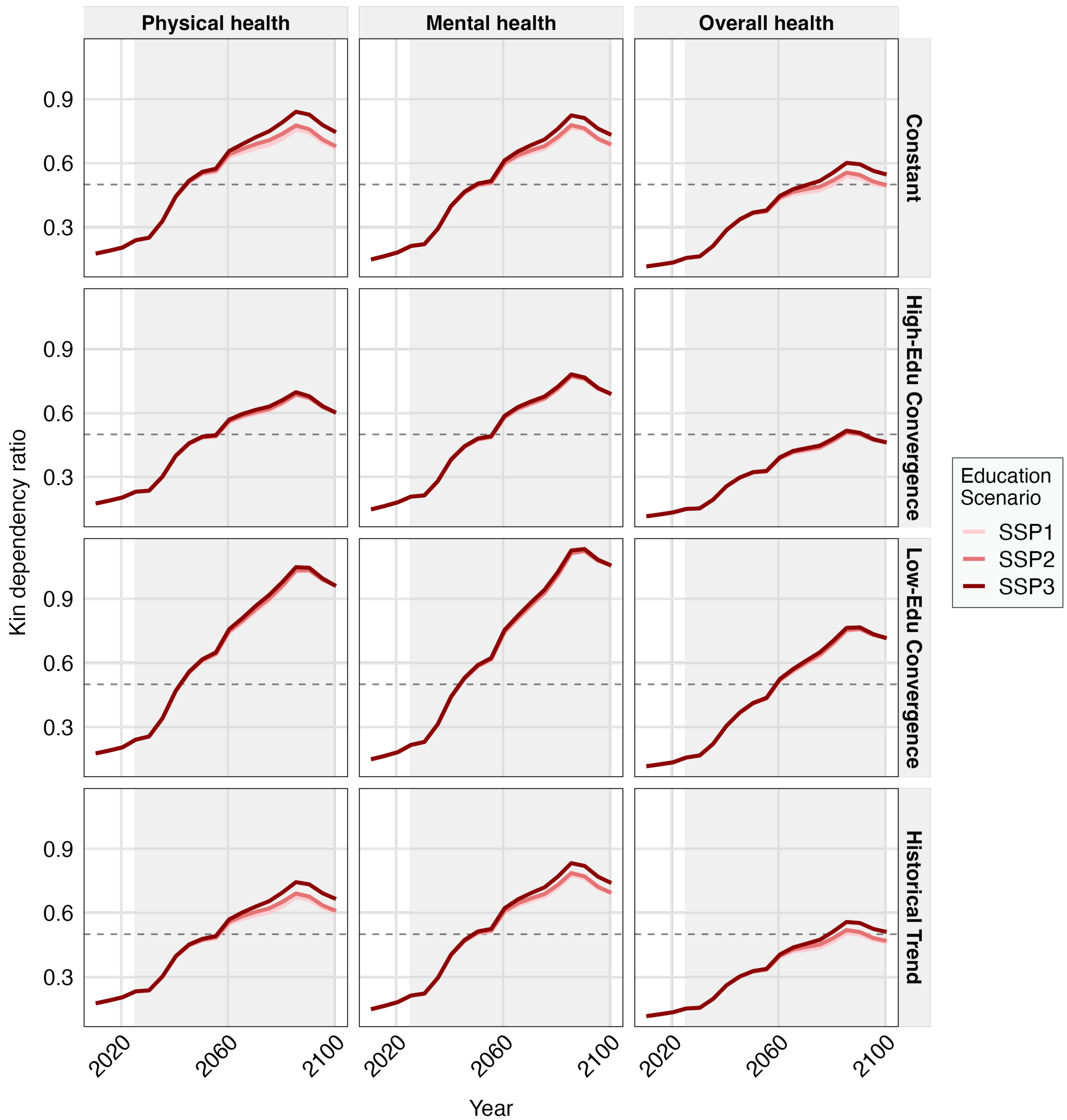

Figure C.5: Health-adjusted kin dependency ratio for average old-age focal individuals (65+ years old) across time under different educational and health projection scenarios. Colors show different educational projection scenarios. Columns show different health categories, and rows show different health projection scenarios. The horizontal dashed line in the background indicates a reference line of kin dependency ratio as 0.5, indicating that for every unhealthy old-age kin, there are two healthy working-age kin available within the family. The shaded area shows the results using projected demographic rates.