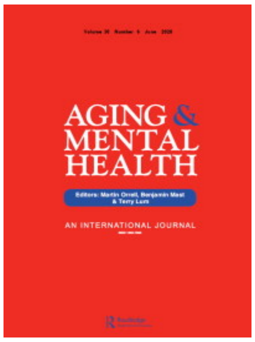

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Do ecosystem improvements enhance the cognitive function of older adults: quasi-Experimental evidence from China

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ABSTRACT

Objectives: Although growing evidence indicates that ecosystems shape human health, their effects on older adults—a group highly sensitive to environmental stressors—remain underexplored. This study examines the effect of China's National Key Ecological Function Zones (NKEFZs), a large-scale ecosystem improvement program, on the cognitive function of older adults and explores the underlying mechanisms.

Methods: Using five waves (2011–2020) of data from the China Health and Retirement Longitudinal study (CHARLS; $n = 16{,}003$), this study employs a staggered difference-in-differences design to estimate the effects of policy on cognitive health.

Results: NKEFZs significantly enhanced cognitive function and episodic memory by 0.467 and 0.372 points, respectively. Mechanism analysis identifies reductions in industrial smoke and dust emissions and a higher likelihood of using clean fuels for cooking or heating as possible channels through which NKEFZs contribute to improved cognitive health. Heterogeneity analyses indicate that the beneficial effects varied by gender, education, marital status, household size, health status, and smoking or drinking behaviors.

Conclusion: These findings highlight the role of ecosystem improvements in maintaining cognitive health and reveal disparities in the effects of such population-level interventions across individual characteristics. These insights inform other countries in developing upstream environmental strategies for dementia prevention and risk reduction.

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Ecosystem; difference-in-differences; health disparities; dementia; prevention

Introduction

Dementia is characterized by cognitive decline that interferes with daily functioning and quality of life (Finlay et al., 2022). It is the seventh leading cause of death worldwide, affecting 57 million people (WHO, 2025). Each year, nearly 10 million new cases occur, driven largely by population aging (WHO, 2025). Since dementia develops through progressive cognitive decline, maintaining cognitive health is essential to prevent dementia and reduce its risk (WHO, 2025). Modifiable factors such as smoking (Livingston et al., 2020), income (Roh et al., 2024), educational attainment (Herd & Walsemann, 2025), and social participation (Luo et al., 2019) are associated with cognitive function and may help slow its decline.

In addition to individual-level determinants, a growing body of research has highlighted the importance of social and environmental contexts in shaping cognitive health and informing upstream interventions (Finlay et al., 2022). The environment refers to the surroundings in which humans live, encompassing physical, social, organizational, and natural elements, such as air and biodiversity, that exist external to the individual (Bircher & Kuruvilla, 2014). Within this broader environmental context, ecosystems are ecological units (e.g. forest and grassland) within which living organisms, including humans, plants, and animals, interact with each other and with their physical environment (Bryce et al., 1999).

The ecological model proposed by Lawton and Nahemow (1973) is valuable for understanding how ecosystems impact the health of older adults. According to this model, individuals are embedded within their environments, and health outcomes depend on the balance between the demands of the environment (termed "environmental press") and the individual's capacity to manage those demands (referred to as "competence"). A slight excess of press over competence may promote stimulation and learning ("challenge zone"), whereas a slight deficit of press may reduce effort ("zone of maximum comfort"). In contrast, a substantial mismatch may lead to negative outcomes and maladaptive behaviors. Ecosystems shape health outcomes by modifying environmental press or by affecting individual competence. For example, ecosystem improvements, such as reduced air pollution, can enhance physical health among children by lowering environmental press (Cai et al., 2025; Naidoo et al., 2019). Similarly, ecosystem improvements can increase individual competence, as indicated by higher levels of

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instrumental activities of daily living, which in turn promote mental health among middle-aged and older adults (Liu et al., 2025).

Previous studies have investigated the effects of ecosystem improvements on health outcomes. Ecological protection has been shown to enhance physical health among children (Cai et al., 2025; Naidoo et al., 2019), middle-aged and older adults (Wang et al., 2023), and the general population (Jones et al., 2020). It has also shown to improve mental health of middle-aged and older adults (Liu et al., 2025; Wang et al., 2023). These improvements result from increased wealth, improved air quality, enhanced physical activity, and better health status (Liu et al., 2025; Naidoo et al., 2019; Tang et al., 2025).

However, few studies have examined whether and how ecosystem improvements influence cognitive function. Cognitive health, a broad concept encompassing the ability to process information, apply knowledge, and develop mental representations, may be influenced by ecosystems. Features such as biodiversity, air quality, and the availability of green space can affect cognitive health through multiple mechanisms, including depressive symptoms (Wang et al., 2023), inflammation and altered levels of dopamine (Allen et al., 2017), and behavioral pathways, such as physical activity and social cohesion, that promote mental stimulation (Burdon et al., 2019; Cai et al., 2025; Choi et al., 2023). Although Tang et al. (2025) found that ecological protection promoted cognitive function among adults aged 18 and over, evidence for older adults remains limited. Two perspectives suggest contrasting effects for older adults. The environmental docility hypothesis posits that individuals with lower competence or fewer resources are more susceptible to environmental influences (Lawton & Simon, 1968), suggesting that older adults may be particularly sensitive to ecosystems. As people age, declines in functional capacity and physiological resilience increase their vulnerability to adverse ecosystem-related stressors such as air pollution, potentially altering the magnitude and pathways through which ecosystems shape cognitive health in later life. In contrast, reduced mobility and lower levels of physical activity among older adults may reduce their exposure to challenging environments, resulting in a less pronounced effect compared with younger adults (Hartig et al., 2014; Sun et al., 2013). Additionally, it remains unclear whether ecosystem improvements have short- or long-term effects on cognitive function. Ke and Sun (2025) found that the beneficial effects of air pollution reduction policies on cognitive function increased over time, whereas Liu et al. (2025) reported that mental health benefits of policies improving physical and social environments diminished over time. Although previous studies have identified the mechanisms through which ecological policies influence health among younger people and the general population, such mechanisms remain unclear for cognitive function among older adults.

This study examines the impact of ecosystem improvements on cognitive function among older adults and explores the mechanisms underlying this relationship. The analysis focuses on China's National Key Ecological Function Zones (NKEFZs), a large-scale ecological restoration program implemented in regions facing severe environmental pollution and shrinking ecological capacity. Because cognitive health underpins daily functioning and its deterioration signals the onset of dementia, understanding whether and how ecosystems shape cognitive function among older adults is crucial for identifying upstream determinants of dementia. With the world's largest older population, China bears the highest economic costs of dementia, estimated at 2,961 billion dollars, 21% higher than in the United States and 41% higher than in Japan (Chen et al., 2024). These substantial costs highlight the importance of dementia prevention and risk reduction. Insights from China's experience are also valuable for other low- and middle-income countries facing ecological degradation and rapid population aging.

Conceptual framework

Based on the model of climate changes and dementia risk proposed by Zuelsdorff and Limaye (2024), a conceptual framework was developed as a guide to examine how NKEFZs, as an ecosystem improvement strategy, affect cognitive function among older adults (Figure 1). Ecosystems shape both the physical and social environments in which older adults live, thereby influencing their cognitive health (Finlay et al., 2022; Zuelsdorff & Limaye, 2024). Four potential pathways are identified: built environment (e.g. housing and environmental contaminants), social environment (e.g. social cohesion and financial stability), interpersonal and individual processes (e.g. health behaviors and social networks), and biomedical disorders (e.g. hypertension and depressive symptoms) (Zuelsdorff & Limaye, 2024).

> H1(a): The implementation of NKEFZs enhances older adults' cognitive function compared with areas without such a program.

Cognitive health comprises multiple components that respond differently to environmental factors. Among these, episodic memory and mental intactness capture distinct aspects of cognition and are not interchangeable (Herd & Walsemann, 2025; Luo et al., 2019). Episodic memory refers to the ability to recall past experiences and typically declines with age (Greene & Naveh-Benjamin, 2023). Its

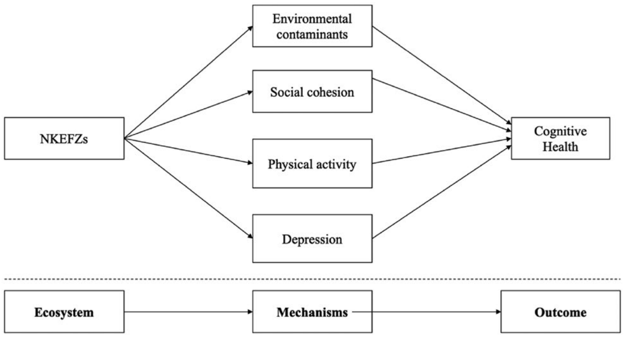

Figure 1. Conceptual framework for assessing the effect of ecosystem improvements on cognitive health.

performance is closely related to fluid intelligence, which involves reasoning and information processing and is shaped by individual behaviors and environmental contexts (Rudebeck et al., 2012). In contrast, mental intactness encompasses elements of both fluid and crystallized intelligence (Luo et al., 2019). Because crystalized intelligence reflects learned knowledge and tends to stabilize in later life, ecosystems exert weaker effects on mental intactness than on episodic memory. Although these two components are correlated and collectively contribute to overall cognitive health, they represent distinct cognitive domains and are measured separately. Therefore, this study examines overall cognitive function using a composite measure while analyzing episodic memory independently, aligning with evidence that episodic memory is more responsive to ecosystem changes.

> H1 (b): The implementation of NKEFZs has a positive effect on episodic memory compared with areas without such a program.

According to the environmental docility theory, the effects of ecosystems on cognitive health are likely to be heterogeneous across individual characteristics (Lawton & Simon, 1968). Ecological protection may yield more pronounced benefits for individuals with favorable socioeconomic and health conditions, reflecting differences in financial resources, educational attainment, functional status, and gendered life course experiences, such as stereotypes linking women to family roles and limited employment opportunities (Qing, 2020). For example, Tang et al. (2025) found that NKEFZs improved cognitive function, with stronger improvements observed among younger adults compared with older adults and among higher-income individuals compared with lower-income individuals. These patterns reflect declining neuroplasticity with age, which may reduce the extent to which older adults benefit from ecosystem improvements, and greater leisure time and opportunities to interact with nature among higher-income individuals. Similarly, Cai et al. (2025) reported that ecological protection improved health outcomes for boys relative to girls and for rural children relative to urban children, with stronger effects among younger than older children. They suggested that these differences reflect greater sensitivity to environmental improvements in these groups, resulting in more health benefits.

> H2: The effects of NKEFZs implementation on cognitive function among older adults are heterogeneous, with more pronounced benefits for individuals with more favorable socioeconomic and health characteristics.

Previous studies have demonstrated the detrimental effects of environmental contamination on cognitive health (Allen et al., 2017; Lee et al., 2023). Exposure to pollutants such as sulfur dioxide (SO_2) and particulate matter ($PM_{2.5}$ and PM_{10}) can impair brain health by inducing systemic inflammation and oxidative stress, which damage the cardiovascular and nervous systems and ultimately weaken brain cells and memory and thinking ability (Allen et al., 2017; Zuelsdorff & Limaye, 2024). Additionally, ecosystem improvements can reduce air pollution, including the emissions of carbon, SO_2, $PM_{2.5}$, and nitrogen dioxide (NO_2) (Cao et al., 2021; Greenstone & Hanna, 2014; Ke & Sun, 2025).

> H3: The implementation of NKEFZs reduces environmental contamination compared with areas without such a program, contributing to improved cognitive function.

Ecosystem improvements can strengthen social cohesion, defined as the perceived trust, reciprocity, and sense of belonging within a community (Choi et al., 2023; Jones et al., 2020). By bringing people together to manage shared resources and by creating more favorable neighborhood environments, ecosystem improvements increase trust among stakeholders (Burdon et al., 2019) and strengthen the sense of safety through reduced crime rates (Hartig et al., 2014). As a form of social capital, social cohesion promotes positive social interactions and encourages health-promoting behaviors such as regular physical activity, which in turn buffers cognitive decline (Choi et al., 2023; Luo et al., 2019).

H4: The implementation of NKEFZs promotes social cohesion compared with areas without such a program, leading to improved cognitive health.

Physical activity represents another pathway through which ecosystems affect cognitive health. Favorable ecological features provide safe and suitable spaces for outdoor activities (Hartig et al., 2014). For example, reductions in air pollution can lead people to choose walking or cycling instead of driving or using public transport (Cai et al., 2025). Extensive evidence shows that regular physical activity bolsters cognitive health (Livingston et al., 2020; WHO, 2025). The underlying physiological pathways include reduced inflammation, improved insulin sensitivity, and enhanced cardiovascular function (Finlay et al., 2022).

H5: The implementation of NKEFZs increases physical activity compared with areas without such a program, contributing to improved cognitive function.

Ecological protection can help alleviate depressive symptoms (Jones et al., 2020; Wang et al., 2023). This occurs through two pathways: by reducing exposure to adverse environmental stimuli such as noise and crowding, and by restoring adaptive capacities through opportunities for relaxation and aesthetic appreciation (Hartig et al., 2014). Although the mechanisms linking depression and cognitive function are complex, prior research suggests that depression degrades cognitive function through genetics and biological processes, as well as by limiting social interactions, which are essential for mental stimulation (Khalaila, 2026; Khalaila et al., 2024).

H6: The implementation of NKEFZs alleviates depressive symptoms compared with areas without such a program, contributing to improved cognitive function.

Institutional background

To address the growing environmental challenges and improve ecosystem quality, the Chinese government introduced the National Major Function-oriented Zones Plan in December 2010. Officially released in June 2011, this plan designated NKEFZs as regions characterized by ecological fragility, limited resources and environmental capacity, and the lack of conditions necessary for large-scale and intensive industrial and urban development. The initial implementation covered 436 counties/districts, home to about 110 million residents and representing 40.2% of China's land area. In September 2016, the central government expanded the NKEFZs program to an additional 240 counties/districts. In total, the two phases involved 676 counties/districts, accounting for 53% of China's terrestrial area (Wang et al., 2023).

The primary goals of NKEFZs are to protect and restore ecosystems while promoting sustainable economic and social development. To achieve these objectives, local governments have implemented several initiatives, such as promoting the use of clean fuels, raising industrial entry thresholds, and imposing stricter controls on land development to minimize ecological disturbance, limiting resource extraction and infrastructure construction, and upgrading existing industrial areas to more resource-efficient and low-emission operations (Shen et al., 2025; Tang et al., 2025). Additionally, areas designated as NKEFZs are supervised by and receive financial support from the central government. The Ministry of Environmental Protection oversees the evaluation of ecological protection performance (H. Zhang & Tang, 2025). As of May 2024, the central government has allocated approximately CNY 900 billion (USD 126.28 billion) to support the implementation of NKEFZs (China News, 2024). Overall, these measures are designed to expand green spaces, enhance air and water quality, and preserve biodiversity.

Methods

Data

To enhance transparency and reproducibility, the analytical code used to generate all results is publicly available on GitHub (https://github.com/JZ3863/NKEFZpaper-Replication). This study utilized longitudinal data from the China Health and Retirement Longitudinal Study (CHARLS), a nationally representative survey of adults in China aged 45 and older. The CHARLS, harmonized with the Health and Retirement Study (HRS) in the United States, adopts a probability-proportional-to-size (PPS) sampling technique. It collects a rich set of information on the social, economic, and health circumstances of community-dwelling residents, including their demographics, family structure, and health status and functioning.

This study used five waves of data collected between 2011 and 2020. Among the 25,882 respondents (n=97,413) interviewed in the CHARLS over this nine-year period, this study focused on individuals aged 60 and older who completed at least two interviews. The final analytic sample comprised 16,003 person-wave observations collected from 3,553 respondents, with an average of approximately 4.5 waves per respondent. Of these, 1,053 respondents (n=4,725) were in the treatment group, and 2,500 respondents (n=11,278) were in the control group. The study sample selection process is reported in Supplementary Figure S1. Additionally, this study retrieved information about prefectural-level characteristics, such as population size and air pollutant emissions, from the China City Statistical yearbook (2011, 2013, 2015, 2018, and 2020), corresponding to the CHARLS data used in the analysis. Data on policy implementation was collected from government official documents (see Supplementary Table S1).

Measurement

Dependent variables

The outcome variables in this study were cognitive function, episodic memory, and mental intactness. Based on the Telephone Interview of Cognitive Status (TICS) used in the HRS, the CHARLS assessed cognitive function with five components: computation, drawing, immediate memory, delayed memory, and time orientation (Luo et al., 2019). For the computation, the respondent was required to successively subtract 7 from 100 for five times (range: 0–5). For the drawing score, respondents were asked to redraw a previously displayed figure (range: 0–1). The immediate and delayed memory scores were based on the number of correct responses to word recall tests. Respondents were required to listen to 10 words and recall as many as possible immediately and again after a four-minute delay. Each score ranged from 0 to 10. The time orientation score was calculated based on respondents' correct answers to questions regarding the current year, month, date, season, and day of the week, with a score range of 0 to 5. The overall cognitive function score was constructed by summing all five of these components, with a possible range of 0 (worst) to 31 (best).

Following previous studies (Luo et al., 2019; Zhao et al., 2024; Zong, 2025), this study measured cognitive function using two separate domains: episodic memory and mental intactness. Episodic memory was assessed using immediate and delayed recall tests, with a total score ranging from 0 to 20. Additionally, mental intactness is defined as individuals' mental state and cognitive integrity (Zhao et al., 2024). It was measured using the computation, drawing, and time orientation items, with a total score ranging from 0 to 11.

Independent variable

The independent variable was the timing of the implementation of NKEFZs. To capture the spatial and temporal variation in the policy rollout and to distinguish short- and long-term effects, a variable was constructed to capture the relative time of policy exposure. First, each of the five CHARLS waves was assigned a relative time value from 1 to 5, corresponding to waves 1 through 5. Second, based on the official implementation years of the NKEFZs (see Supplementary Table S1), this study created a variable to align the policy initiation time with the CHARLS survey waves. For example, Lanzhou city launched the NKEFZs in June 2011, while respondents there were interviewed in August 2011. Their relative policy exposure was coded as 2 because the policy effects could only be observed in the subsequent wave when survey data were available.

Notably, this study measured the implementation of NKEFZs at the prefectural level for theoretical and practical reasons. First, ecosystems are abstract entities that are difficult to define spatially (Bryce et al., 1999). Although NKEFZs were implemented at the county/district level, they had beneficial spillover effects on adjacent counties/districts, such as increased vegetation carbon sink (T. Zhang et al., 2022) and enhanced green development (R. Zhang & Zhong, 2023). Measuring implementation at the prefectural level allows these spillover effects to be partially captured. Additionally, county/district-level identifiers are not publicly available in CHARLS, making prefectural-level measurement a practical alternative.

Mechanism variables

This study explored four potential mechanisms through which ecosystem improvements may influence older adults' cognitive function: environmental contaminants, social cohesion, physical activity, and depressive symptoms. The first mechanism, environmental contaminants, was assessed using industrial and household air pollutant emissions. Industrial air pollution was measured at the prefectural level, including the emission of industrial SO_2 and industrial smoke and dust. The use of clean energy was used as a proxy for household air pollution. A dichotomous variable was constructed to indicate whether respondents used clean fuels—electricity, gas, solar, and central heating—for either cooking or heating (Ke & Sun, 2025; Zong, 2025). While gas is a fossil fuel, it generates substantially lower levels of air pollutants than coal or petroleum products. Consistent with previous studies (Xu et al., 2023; Yang & Chen, 2024), this study therefore classified gas as a clean fuel.

The second mechanism, social cohesion, was measured by individuals' participation in and frequency of social activities in the last month (Bradley et al., 2020). These activities were categorized into two domains: altruistic activities and collective recreational activities. These activities capture social cohesion because they involve active participation in and contribution to community life, rather than merely spending time with existing friends. Altruistic activities contribute to social cohesion by enhancing intergroup contact and promoting inclusivity (Horsham et al., 2024). Collective recreational activities refer to community-based activities that are organized on a group basis and are mainly recreational and help build or maintain social networks within neighborhoods (Bradley et al., 2020). Altruistic activities included three options: 1) performing voluntary or charity work, 2) providing help to family, friends, or neighbors who do not live with the respondent, and 3) caring for a sick or disabled adult who does not live with the respondent. The second dimension also encompassed three options: 1) playing Ma-jong, chess, or cards, or going to community club, 2) attending a sport, social, or other kind of club, and 3) participating in a community-related organization. For each activity in which respondents participated, the frequency was reported and coded as 1 (never), 2 (not regularly), 3 (almost every week), or 4 (almost daily). Two variables were then constructed to capture social cohesion. The first was a dichotomous variable coded 1 if respondents participated in any collective recreational or altruistic activity, and 0 otherwise. The second was an ordinal variable representing the frequency of social activities, defined as the maximum frequency reported across all six activities, ranging from 1 (least frequent) to 4 (most frequent).

Third, physical activity was measured using the International Physical Activity Questionnaire. Respondents reported whether they had engaged in mild activities (e.g. walking for leisure, sports, or entertainment), moderate activities (e.g. bicycling, Tai-chi, or speed walking), or vigorous activities (e.g. an aerobic workout and carrying heavy stuff) for at least 10 min in a regular week. Three dichotomous variables were created to represent whether respondents engaged in each type of physical activity. The final mechanism, depressive symptoms, was assessed using the 10-item Center for Epidemiological Studies Depression Scale (CES-D-10). The total score ranged from 0 to 30, with higher scores indicating more severe depressive symptoms.

Covariates

This study adjusted for sociodemographic, health and behavioral, and prefectural-level characteristics that could confound the key estimates. Sociodemographic factors encompassed age (in years), gender (female or male), education level (less than lower secondary education, upper secondary/vocational training, or tertiary education), marital status (single or married/cohabiting), household size, residence area (rural or urban), and per capital household expenditure (quartiles). Expenditure was used instead of income for two reasons. First, according to the permanent income hypothesis, income fluctuates over time in response to temporary shocks (e.g. unemployment and bonuses), whereas expenditure remains more stable, providing a more reliable measure of well-being and economic resources available to families (Carver & Grimes, 2019; Firedman, 1957). Second, using expenditure helped maximize the analytic sample, as the analyses contained a larger proportion of missing values for income (28% of the sample) than for expenditure (23%). To preserve the sample size, observations with missing expenditure values were retained and assigned to a separate category.

Health and behavioral factors included self-rated health, a dichotomous indicator of difficulties in performing activities of daily living (ADLs), number of chronic diseases, and whether respondents reported currently smoking or drinking in the past year. Prefectural-level characteristics comprised population size (log-transformed) and whether the city implemented the Low-carbon City Pilot Program (see Supplementary Table S1), which has been shown to have beneficial effects on older adults' cognitive function (Ke & Sun, 2025). All covariates were measured at baseline, ensuring that only pre-treatment values were included in the analysis. Descriptive statistics are presented in Supplementary Table S3.

Analytic strategies

To estimate the causal effect of ecosystem improvements on older adults' cognitive function, this study exploited the doubly robust difference-in-differences (DR-DiD) estimator proposed by Callaway and Sant'Anna (2021). This method offers two advantages for estimating the average treatment effect on the treated (ATT). First, DR-DiD does not impose homogeneity restrictions across subgroups (e.g. individuals differing by age, gender, or physical impairments) and over time (e.g. short- and long-term effects), a condition that rarely holds in practice (Baker et al. 2026). For example, Wang et al. (2023) found that NKEFZs produced greater improvements in depressive symptoms among individuals without physical impairments than among those with impairments, demonstrating the presence of treatment heterogeneity. Second, DR-DiD is less susceptible to model misspecification because it combines regression adjustment and inverse probability weighting, requiring only one of the two models to be correctly specified (Callaway & Sant'Anna, 2021). For this study, the treatment group includes respondents living in cities that implemented NKEFZs in 2016, while the control group comprises respondents residing in cities that did not implement NKEFZs during the study period (see the Analytical Strategies Section in Supplementary Material for details).

Results

Effects of NKEFZs on older adults' cognitive function

Table 1 presents the aggregated ATT estimates and dynamic treatment effects using the DR-DiD models (see Supplementary Figure S2 for the event-study visualization). Across all outcomes, none of the pre-treatment coefficients were statistically significant at the 5% level, supporting the validity of parallel trends assumption and indicating that there is no evidence of anticipation effects. Furthermore, the standardized differences in covariates between the treatment and control groups are presented in Supplementary Figure S3. Before applying the weighting, six covariates, such as marital status and residence areas, exhibited standardized differences exceeding the threshold of 0.1. After weighting, the standardized differences for all covariates fell below 0.1, with further reductions observed for many covariates such as age, gender, and education level. These results indicate that the parallel trends assumption was not violated.

Regarding the aggregated ATT, NKEFZs significantly increased older adults' cognitive function by 0.467 points, which supports H1(a). The estimated short-term (2018) and longer-term (2020) effects were similar in magnitude, at 0.465 and 0.469, respectively. NKEFZs were associated with a 0.372-point improvement in older adults' episodic memory, whereas the effect on mental intactness was positive but not statistically significant (supporting H1(b)). Event-study estimates further show that NKEFZs significantly enhanced older adults' episodic memory in the short term, with a marginally significant effect persisting in the longer term ($p = 0.078 < 0.1$).

Mechanism analysis

Table 2 shows the results of the mechanisms analysis for the four channels of NKEFZs (see Supplementary Figures S4-S6 for the event-study visualization). Since industrial SO_2 and smoke and dust were measured at the prefecture level, the individual-level covariates were aggregated to the prefecture level to ensure consistency in the unit of analysis and to capture the overall demographic and socioeconomic characteristics of each prefecture. NKEFZs significantly reduced emissions of smoke and dust, whereas the effect on SO_2 was not statistically significant. At the individual level, NKEFZs significantly increased the probability of using clean fuel by 4.4 percentage points on average, with a stronger long-term effect of 4.8 percentage points. These results indicate that NKEFZs improved older adults' cognitive function through

Table 1. Effect of NKEFZs on cognitive function.

	Cognitive function		Episodic memory		Mental intactness	
ATT	0.467**	(0.176)	0.372**	(0.143)	0.068	(0.088)
Pre-trends	0.007	(0.163)	0.151	(0.132)	0.011	(0.082)
2011 (t − 3)	−0.268	(0.212)	0.150	(0.172)	−0.105	(0.101)
2013 (t − 2)	0.282	(0.182)	0.151	(0.147)	0.128	(0.095)
2018 (t)	0.465*	(0.204)	0.440*	(0.173)	0.014	(0.100)
2020 ($t+1$)	0.469*	(0.212)	0.304	(0.172)	0.121	(0.109)
n	16,003		14,830		15,948	

Note. All models adjusted for covariates. Robust standard errors were reported in parentheses. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

Table 2. Potential mechanisms of the impact of NKEFZs on cognitive function using DR-DiD estimators.

Panel A	Smoke and dust		SO_2		Clean fuel	
ATT	−0.202*	(0.092)	−0.114	(0.084)	0.044*	(0.020)
Pre-trends	−0.113	(0.065)	0.060	(0.079)	0.021	(0.017)
2011 (t − 3)	−0.121	(0.065)	0.091	(0.146)	0.030	(0.018)
2013 (t − 2)	−0.105	(0.069)	0.030	(0.039)	0.013	(0.021)
2018 (t)	−0.142	(0.081)	−0.092	(0.074)	0.041	(0.022)
2020 ($t+1$)	−0.262*	(0.111)	−0.137	(0.104)	0.048*	(0.046)
n	408		406		16,003	
Panel B	**Social cohesion (dichotomous)**		**Social cohesion (continuous)**		**Mild physical activity**	
ATT	0.006	(0.019)	0.023	(0.042)	−0.048	(0.028)
Pre-trends	−0.012	(0.017)	−0.048	(0.040)	0.009	(0.041)
2011 (t − 3)	−0.012	(0.018)	−0.079	(0.047)	0.002	(0.048)
2013 (t − 2)	−0.011	(0.020)	−0.016	(0.044)	0.016	(0.053)
2018 (t)	0.012	(0.021)	0.047	(0.048)	−0.018	(0.031)
2020 ($t+1$)	0.000	(0.022)	−0.000	(0.048)	−0.079*	(0.034)
n	15,984		15,984		5,981	
Panel C	**Moderate physical activity**		**Vigorous physical activity**		**Depressive symptoms**	
ATT	−0.028	(0.035)	−0.021	(0.030)	0.171	(0.236)
Pre-trends	−0.027	(0.050)	−0.054	(0.041)	0.085	(0.221)
2011 (t − 3)	−0.061	(0.058)	−0.017	(0.049)	0.263	(0.277)
2013 (t − 2)	0.008	(0.063)	−0.091	(0.049)	−0.092	0.237
2018 (t)	−0.005	(0.038)	0.000	(0.033)	−0.060	(0.271)
2020 ($t+1$)	−0.051	(0.042)	−0.041	(0.036)	0.403	(0.294)
n	5,984		5,994		15,934	

Note. All models adjusted for covariates. Robust standard errors were reported in parentheses. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

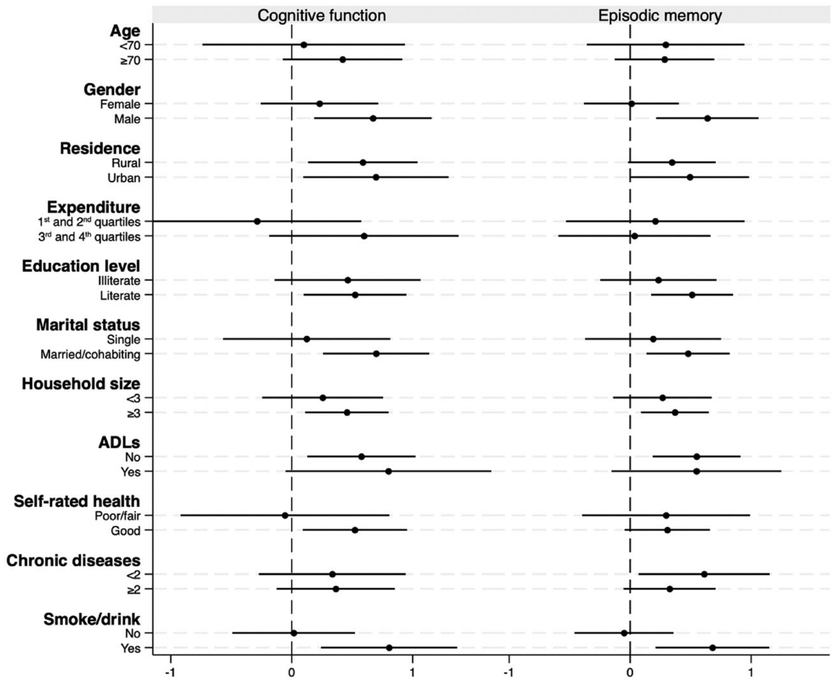

Figure 2. Heterogeneous treatment effects on cognitive function and episodic memory.
Note. Points indicate the overall ATT for each subgroup, calculated by aggregating short-term and long-term effects. Horizontal lines represent 95% confidence intervals.

reducing environmental contaminants and enhancing air quality (supporting H3).

NKEFZs, however, did not affect cognitive function through the other three mechanisms: social cohesion, physical activity, and depressive symptoms. Specifically, while NKEFZs showed positive associations with depressive symptoms and both dichotomous and continuous measures of social cohesion, and negative associations with mild, moderate, and vigorous physical activity, none of these relationships reached statistical significance at the 5% level.

Heterogeneous effects

Given the positive effects of NKEFZs on cognitive function and episodic memory, further analyses were conducted to examine the heterogeneous treatment effects across individual characteristics. Figure 2 shows the overall ATT for each subgroup by aggregating both the short-term and long-term effects. The patterns of heterogeneity were largely consistent across cognitive function and episodic memory. The beneficial impacts were more pronounced among males, those who were literate, those who were married or cohabitating, those living in larger households (three members of more), individuals without limitations in ADLs, and those who reported current smoking or drinking behaviors. For episodic memory, stronger positive effects were also observed among individuals living in urban areas and those with fewer chronic diseases (< 2). In contrast, individuals reporting good self-rated health benefited more from NKEFZs in terms of cognitive function compared with those rating their health as poor or fair. No significant heterogeneity was found by age group or expenditure level, as the subgroup estimates for these characteristics were not statistically significant at the 5% level. These results support H2. Several robustness tests were conducted, and the results align with the main findings (see the Robustness Check Section in the Supplementary Material).

Discussion

Using a staggered DiD design, this study examined the effect of NKEFZs on cognitive function among older adults. The results indicate that NKEFZs improved older adults' cognitive function and episodic memory by reducing environmental contamination. The positive effects were more pronounced among individuals with favorable socioeconomic characteristics (e.g. higher education level) and health conditions (e.g. fewer physical impairments). These findings highlight the role of upstream environmental interventions in dementia prevention and risk reduction. They also underscore the need for targeted interventions to support older adults with limited resources and lower socioeconomic status.

NKEFZs enhanced cognitive function among older adults. This finding aligns with a growing body of literature emphasizing the critical role of ecosystem improvements in shaping human health (Cai et al., 2025; Ke & Sun, 2025; Tang et al., 2025; Wang et al., 2023). This study further complements and extends this evidence in two ways. First, NKEFZs exerted positive effects on cognitive health in both the short and long term. This suggests that the benefits of ecological protection persist beyond immediate adjustments—an important consideration for policymakers designing effective interventions to prevent dementia. Second, this study distinguishes the heterogeneous effects of NKEFZs across cognitive domains. The positive impact was more evident for episodic memory, suggesting that NKEFZs influenced cognition primarily through physiological pathways, such as reduced inflammation, rather than through experiential processes underlying mental intactness, which depend on accumulated knowledge. This finding points to the importance of incorporating domain-specific measures of cognition into policy evaluation and advancing the understanding of how environmental factors influence cognitive health.

The effect of NKEFZs implementation on cognitive function among older adults (0.077 standardized deviation = 0.467 ÷ 6.1) appears larger than that reported by Tang et al. (2025) for the general population aged 18 and older (0.052 standardized deviation = 0.0993 ÷ 1.9003), although differences in outcome measures limit direct comparison. This pattern is consistent with theories highlighting the vulnerability of older adults to ecosystem changes. Compared with younger individuals, older adults experience age-related deterioration in physiological processes and a higher prevalence of chronic conditions such as coronary artery disease (Shumake et al., 2013), both of which increase susceptibility to environmental stressors. From a neurobiological perspective, aging is characterized by reduced neural plasticity, weakened immune response, decreased resilience to oxidative stress, and diminished capacity to compensate for environmental stressors (Geller & Zenick, 2005). These age-related changes limit older adults' ability to buffer environmental stressors but may also increase their responsiveness to improvements in ecological conditions. Consequently, ecosystem improvements may produce more pronounced cognitive effects in older adults than in the general population.

Reductions in environmental contaminants were a potential mechanism through which NKEFZs improved cognitive function. Consistent with previous studies (Allen et al., 2017; Cai et al., 2025; Ke & Sun, 2025; Zong et al., 2025), this study highlights the importance of air pollution in shaping cognitive health, as poor air quality triggers inflammation and oxidative stress. The pronounced effects of NKEFZs on episodic memory further support this mechanism, suggesting that ecological protection may promote cognitive health by reducing exposure to environmental contaminants. However, after performing multiple sensitivity analyses with alternative mechanism variables, this study found that NKEFZs did not improve cognitive function through social cohesion, physical activity, and depressive symptoms.

This study found heterogeneous treatment effects of NKEFZs on cognitive function and episodic memory. Individuals who were male, literate, or married/cohabiting, lived in larger households or urban areas, reported better health, and had fewer chronic diseases and physical impairments were more likely to benefit from ecosystem improvements. These results support the environmental docility hypothesis, which posits that personal competence and resources buffer the influence of environmental stressors on health outcomes (Lawton & Simon, 1968). These findings also align with existing evidence showing that social, cultural, and health capital can be mobilized as resources to buffer the adverse consequences of environmental stressors (Pelling & High, 2005; Tang et al., 2025; Zong et al., 2025). However, the positive effect of NKEFZs was statistically significant among older adults who reported current smoking or drinking, but not among those without such behaviors. The mechanisms underlying these heterogeneous effects are still not fully understood and may reflect differences in baseline cognitive function or in the quantity and frequency of tobacco and alcohol use. In contrast, those who smoked or drank likely exhibited lower baseline cognitive function, allowing greater potential for improvement as their ecosystems improved. Future research could explore why ecosystem improvements yield heterogeneous effects across these subgroups.

Limitations

This study has some limitations. First, although the conceptual framework proposed by Zuelsdorff and Limaye (2024) was adopted to explore the mechanisms linking ecosystem improvements to cognitive health, not all potential pathways could be examined due to data constraints. For example, the CHARLS lacks detailed biological indicators such as inflammatory markers and contextual information on housing conditions, including power outages. Future research could use complementary datasets containing such information to test additional mechanisms. Second, the non-significant effect of NKEFZs on physical activity should be interpreted with caution. In contrast to the measurement of cognitive health, questions on physical activity were asked only among half of the respondents in waves 1 to 3 of the CHARLS, resulting in a smaller analytic sample that may not adequately reflect the true policy impact. Third, due to the lack of publicly available county-level data in CHARLS, this study assessed NKEFZs implementation at the prefectural level. While this approach partially captures spillover effects between adjacent counties, it does not account for policy variations within prefectures. Future studies could use granular data to further validate these results. Lastly, given the spillover effects of NKEFZs on neighborhood cities, respondents in areas classified as untreated but bordering NKEFZ cities may experience cognitive benefits, potentially underestimating the true effect of NKEFZs. Therefore, the estimated treatment effects are conservative and represent a lower bound of the positive impact of NKEFZs.

Theoretical and practical implications

This paper makes several contributions. First, using a staggered difference-in-differences design, it provides causal evidence on the relationship between ecosystem changes and cognitive health among older adults, a topic that has largely been examined through correlational analyses (Naidoo et al., 2019; Wang et al., 2023). The findings show that NKEFZs have pronounced effects on episodic memory, a modifiable aspect of cognitive function that is particularly responsive to environmental stressors. Second, drawing on Zuelsdorff and Limaye (2024) framework, this paper extends previous research on the mechanisms linking ecological conditions to cognitive health (Ke & Sun, 2025; Liu et al., 2025; Tang et al., 2025; Wang et al., 2023). It provides evidence that both individual- and macro-level environmental contaminants are potential mechanisms through which ecosystem changes influence cognitive function. Third, this study uncovers heterogeneous treatment effects of ecosystem changes across individual characteristics. The findings lend support to the environmental docility hypothesis, suggesting that older adults with greater resources, including being male, literate, married or cohabitating, living in larger households, and with fewer physical impairments, benefit more from ecosystem improvements than their counterparts. Lastly, this paper contributes to the literature on the effectiveness of ecosystem protection policies, which has primarily focused on their economic and environmental outcomes, such as local GDP and industrial air pollution (Cao et al., 2021; Shen et al., 2025). The results indicate that ecological protection contributes not only to macro-level improvements but also to downstream benefits for cognitive health among older adults.

This study offers important practical implications. First, the findings highlight the effectiveness of environmental policies in preventing cognitive decline and dementia. Given the substantial economic and societal burden of dementia, policymakers should systematically assess the cost-effectiveness of ecosystem policies, considering not only their environmental benefits but also the potential cost savings associated with reduced dementia. Second, as population-level interventions, ecosystem improvements disproportionately affect individuals. To mitigate health disparities, policymakers could adopt complementary strategies targeting individuals with lower health conditions (e.g. poorer health and more ADL limitations) and fewer resources (e.g. living alone or in rural areas). Finally, with more than 60% of the global dementia population living in low- and middle-income countries (WHO, 2025), China's experience provides valuable insights into how large-scale ecosystem interventions can promote cognitive health in aging societies.

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Ethical approval

This manuscript reports secondary analyses of fully de-identified data from publicly available sources. No new data were collected, no intervention was administered, and there was no contact with study participants.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Code availability statement

All code used to generate the results reported in this manuscript is publicly available on GitHub (https://github.com/JZ3863/NKEFZpaper-Replication).

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Data availability statement

Data for the China Health and Retirement Longitudinal Study are publicly available at http://charls.pku.edu.cn/.

References

Allen, J. L., Klocke, C., Morris-Schaffer, K., Conrad, K., Sobolewski, M., & Cory-Slechta, D. A. (2017). Cognitive effects of air pollution exposures and potential mechanistic underpinnings. *Current Environmental Health Reports*, *4*(2), 180–191. https://doi.org/10.1007/s40572-017-0134-3

Baker, A., Callaway, B., Cunningham, S., Goodman-Bacon, A., & Sant'Anna, P. H. C. (2026). Difference-in-differences designs: A practitioner's guide. *Journal of Economic Literature*, *64*(2), 498–557. https://doi.org/10.1257/jel.20251650

Bircher, J., & Kuruvilla, S. (2014). Defining health by addressing individual, social, and environmental determinants: New opportunities for health care and public health. *Journal of Public Health Policy*, *35*(3), 363–386. https://doi.org/10.1057/jphp.2014.19

Bradley, E., Chen, X., & Tang, G. (2020). Social security expansion and neighborhood cohesion: Evidence from community-living older adults in China. *Journal of the Economics of Ageing*, *15*, 100235. https://doi.org/10.1016/j.jeoa.2019.100235

Bryce, S. A., Omernik, J. M., & Larsen, D. P. (1999). Environmental review: Ecoregions: A geographic framework to guide risk characterization and ecosystem management. *Environmental Practice*, *1*(3), 141–155. https://doi.org/10.1017/S1466046600000582

Burdon, D., Potts, T., McKinley, E., Lew, S., Shilland, R., Gormley, K., Thomson, S., & Forster, R. (2019). Expanding the role of participatory mapping to assess ecosystem service provision in local coastal environments. *Ecosystem Services*, *39*, 101009. https://doi.org/10.1016/j.ecoser.2019.101009

Cai, J., Li, Y., & Coyte, P. C. (2025). The impact of China's low-carbon city pilot program on the health of children. *Social Science & Medicine (1982)*, *369*, 117823. https://doi.org/10.1016/j.socscimed.2025.117823

Callaway, B., & Sant'Anna, P. H. C. (2021). Difference-in-differences with multiple time periods. *Journal of Econometrics*, *225*(2), 200–230. https://doi.org/10.1016/j.jeconom.2020.12.001

Cao, H., Qi, Y., Chen, J., Shao, S., & Lin, S. (2021). Incentive and coordination: Ecological fiscal transfers' effects on eco-environmental quality. *Environmental Impact Assessment Review*, *87*, 106518. https://doi.org/10.1016/j.eiar.2020.106518

Carver, T., & Grimes, A. (2019). Income or consumption: Which better predicts subjective well-being? *Review of Income and Wealth*, *65*(S1), S256–S280. https://doi.org/10.1111/roiw.12414

Chen, S., Cao, Z., Nandi, A., Counts, N., Jiao, L., Prettner, K., Kuhn, M., Seligman, B., Tortorice, D., Vigo, D., Wang, C., & Bloom, D. E. (2024). The global macroeconomic burden of Alzheimer's disease and other dementias: Estimates and projections for 152 countries or territories. *The Lancet. Global Health*, *12*(9), e1534–e1543. https://doi.org/10.1016/S2214-109X(24)00264-X

China News. (2024). China has invested nearly 900 billion yuan to advance the development of the National Key Ecological Function Zones. *China News Service*, https://www.chinanews.com.cn/gn/2024/05-13/10216184.shtml

Choi, J., Han, S. H., Ng, Y. T., & Muñoz, E. (2023). Neighborhood cohesion across the life course and effects on cognitive aging. *The Journals of Gerontology. Series B, Psychological Sciences and Social Sciences*, *78*(10), 1765–1774. https://doi.org/10.1093/geronb/gbad095

Finlay, J., Esposito, M., Langa, K. M., Judd, S., & Clarke, P. (2022). Cognability: An Ecological Theory of neighborhoods and cognitive aging. *Social Science & Medicine (1982)*, *309*, 115220. https://doi.org/10.1016/j.socscimed.2022.115220

Firedman, M. (1957). The permanent income hypothesis. In *A Theory of the Consumption Function*. (pp. 20–37) Princeton University Press. https://www.nber.org/books-and-chapters/theory-consumption-function

Geller, A. M., & Zenick, H. (2005). Aging and the environment: A research framework. *Environmental Health Perspectives*, *113*(9), 1257–1262. https://doi.org/10.1289/ehp.7569

Greene, N. R., & Naveh-Benjamin, M. (2023). Adult age-related changes in the specificity of episodic memory representations: A review and theoretical framework. *Psychology and Aging*, *38*(2), 67–86. https://doi.org/10.1037/pag0000724

Greenstone, M., & Hanna, R. (2014). Environmental regulations, air and water pollution, and infant mortality in India. *American Economic Review*, *104*(10), 3038–3072. https://doi.org/10.1257/aer.104.10.3038

Hartig, T., Mitchell, R., de Vries, S., & Frumkin, H. (2014). Nature and health. *Annual Review of Public Health*, *35*(1), 207–228. https://doi.org/10.1146/annurev-publhealth-032013-182443

Herd, P., & Walsemann, K. M. (2025). Underestimating the relationship: Unpacking both socioeconomic resources and cognitive function and decline in midlife to later life. *Journal of Health and Social Behavior*, *66*(3), 299–320. https://doi.org/10.1177/00221465241276818

Horsham, Z., Abrams, D., Davies, B., & Lalot, F. (2024). Social cohesion and volunteering: Correlates, causes, and challenges. *Translational Issues in Psychological Science*, *10*(1), 51–68. https://doi.org/10.1037/tps0000387

Jones, N., Graziano, M., & Dimitrakopoulos, P. G. (2020). Social impacts of European protected areas and policy recommendations. *Environmental Science & Policy*, *112*, 134–140. https://doi.org/10.1016/j.envsci.2020.06.004

Ke, J., & Sun, F. (2025). The effect of the low-carbon city pilot program on the cognitive function of older adults: Quasi-experimental evidence from China. *The Gerontologist*, *65*(7), gnaf131. https://doi.org/10.1093/geront/gnaf131

Khalaila, R. (2026). The moderation effect of cognitive reserve on the longitudinal association between depression and cognitive performance among older adults. *Aging & Mental Health*, *30*(1), 142–151. 10. https://doi.org/10.1080/13607863.2025.2545360

Khalaila, R., Cohn-Schwartz, E., Shiovitz-Ezra, S., & Lawlor, B. (2024). A prospective association between social isolation and cognitive performance among older adults in Europe: The role of loneliness and poor oral health. *Aging & Mental Health*, *28*(8), 1162–1168. https://doi.org/10.1080/13607863.2023.2299968

Lawton, M. P., & Nahemow, L. (1973). Ecology and the aging process. In C. Eisdorfer & M. P. Lawton (Eds.).*The Psychology of Adult Development and Aging*, pp. 619–674. https://doi.org/10.1037/10044-020

Lawton, M. P., & Simon, B. (1968). The ecology of social relationships in housing for the elderly. *The Gerontologist*, *8*(2), 108–115. https://doi.org/10.1093/geront/8.2.108

Lee, Y., Yoon, S.-J., Yoon, S. H., Kang, S. W., Jeon, S., Kim, M., Shin, D. A., Nam, C. M., & Ye, B. S. (2023). Air pollution is associated with faster cognitive decline in Alzheimer's disease. *Annals of Clinical and Translational Neurology*, *10*(6), 964–973. https://doi.org/10.1002/acn3.51779

Liu, N., Wang, Z., & Li, Z. (2025). The impact of the healthy cities pilot policy on mental health and its inequalities among urban middle-aged and older adults. *Cities*, *158*, 105688. https://doi.org/10.1016/j.cities.2024.105688

Livingston, G., Huntley, J., Sommerlad, A., Ames, D., Ballard, C., Banerjee, S., Brayne, C., Burns, A., Cohen-Mansfield, J., Cooper, C., Costafreda, S. G., Dias, A., Fox, N., Gitlin, L. N., Howard, R., Kales, H. C., Kivimäki, M., Larson, E. B., Ogunniyi, A., … Mukadam, N. (2020). Dementia prevention, intervention, and care: 2020 report of the lancet commission. *Lancet (London, England)*, *396*(10248), 413–446. https://doi.org/10.1016/S0140-6736(20)30367-6

Luo, Y., Pan, X., & Zhang, Z. (2019). Productive activities and cognitive decline among older adults in China: Evidence from the China health and retirement longitudinal study. *Social Science & Medicine (1982)*, *229*, 96–105. https://doi.org/10.1016/j.socscimed.2018.09.052

Naidoo, R., Gerkey, D., Hole, D., Pfaff, A., Ellis, A. M., Golden, C. D., Herrera, D., Johnson, K., Mulligan, M., Ricketts, T. H., & Fisher, B. (2019). Evaluating the impacts of protected areas on human well-being across the developing world. *Science Advances*, *5*(4), eaav3006. https://doi.org/10.1126/sciadv.aav3006

Pelling, M., & High, C. (2005). Understanding adaptation: What can social capital offer assessments of adaptive capacity? *Global Environmental Change*, *15*(4), 308–319. https://doi.org/10.1016/j.gloenvcha.2005.02.001

Qing, S. (2020). Gender role attitudes and male-female income differences in China. *The Journal of Chinese Sociology*, *7*(1), 12. https://doi.org/10.1186/s40711-020-00123-w

Roh, S., Lee, Y.-S., Moon, H., Steele, J. S., Warne, D. K., & Lee, J.-A. (2024). Cognitive impairment and social determinants of health among indigenous women. *The Gerontologist*, *64*(8), gnae072. https://doi.org/10.1093/geront/gnae072

Rudebeck, S. R., Bor, D., Ormond, A., O'Reilly, J. X., & Lee, A. C. H. (2012). A Potential spatial working memory training task to improve both episodic memory and fluid intelligence. *PloS One*, *7*(11), e50431. https://doi.org/10.1371/journal.pone.0050431

Shen, H., Zhang, Y., Wang, M., & Lei, Y. (2025). Unlocking the dual benefits: Economic and ecological impacts of China's national key ecological function areas. *China Economic Review*, *90*, 102365. https://doi.org/10.1016/j.chieco.2025.102365

Shumake, K. L., Sacks, J. D., Lee, J. S., & Johns, D. O. (2013). Susceptibility of older adults to health effects induced by ambient air pollutants regulated by the European Union and the United States. *Aging Clinical and Experimental Research*, *25*(1), 3–8. https://doi.org/10.1007/s40520-013-0001-5

Sun, F., Norman, I. J., & While, A. E. (2013). Physical activity in older people: A systematic review. *BMC Public Health*, *13*(1), 449. https://doi.org/10.1186/1471-2458-13-449

Tang, J., Ni, C., Lu, S., Xiong, J., & Wang, M. (2025). The cognitive benefits of ecosystem improvement: Evidence from China's national key ecological function zones. *Social Science & Medicine (1982)*, *381*, 118149. https://doi.org/10.1016/j.socscimed.2025.118149

Wang, M., Huang, H., Xiong, J., Yuan, Z., & Zeng, K. (2023). Impact of ecological reserves on the local residents' health: Evidence from a natural experiment in China. *Social Science & Medicine (1982)*, *336*, 116186. https://doi.org/10.1016/j.socscimed.2023.116186

WHO. (2025). *Dementia*. World Health Organization. https://www.who.int/news-room/fact-sheets/detail/dementia

Xu, T., Ye, X., Lu, X., Lan, G., Xie, M., Huang, Z., Wang, T., Wu, J., Zhan, Z., & Xie, X. (2023). Association between solid cooking fuel and cognitive decline: Three nationwide cohort studies in middle-aged and older population. *Environment International*, *173*, 107803. https://doi.org/10.1016/j.envint.2023.107803

Yang, K., & Chen, R. (2024). Association between cooking fuel exposure and respiratory health: Longitudinal evidence from the China health and retirement longitudinal study (CHARLS). *Ecotoxicology and Environmental Safety*, *275*, 116247. https://doi.org/10.1016/j.ecoenv.2024.116247

Zhang, H., & Tang, Y. (2026). The impact of local government preferences on environmental regulation: Evidence from China's national key ecological function zones. *Applied Economics Letters*, *33*(11), 1847-1852. https://doi.org/10.1080/13504851.2025.2450284

Zhang, R., & Zhong, C. (2023). The establishment of the national key ecological functional zone and the county's ecological green development. *Frontiers in Ecology and Evolution*, *11*,1144245. https://doi.org/10.3389/fevo.2023.1144245

Zhang, T., Hou, M., Chu, L., & Wang, L. (2022). Can the establishment of national key ecological function areas enhance vegetation carbon sink? A quasi-natural experiment evidence from China. *International Journal of Environmental Research and Public Health*, *19*(19), 12215. https://doi.org/10.3390/ijerph191912215

Zhao, Q., Del Ponte, A., Hilal, S., & Seow, W. J. (2024). Effect of particulate matter on cognitive function among middle-aged and older adults in China: An instrumental variable approach. *Social Science & Medicine (1982)*, *362*, 117438. https://doi.org/10.1016/j.socscimed.2024.117438

Zong, X. (2025). The long arm of childhood: The association between early-life indoor air pollution exposure and cognitive performance in later life. *Social Science & Medicine*, *387*, 118662. https://doi.org/10.1016/j.socscimed.2025.118662

Zong, X., Guan, M., Zhang, Y., & Dong, G. (2025). Railways to better minds: The influence of high-speed rail on cognitive health inequalities. *Social Science & Medicine (1982)*, *385*, 118624. https://doi.org/10.1016/j.socscimed.2025.118624

Zuelsdorff, M., & Limaye, V. S. (2024). A framework for assessing the effects of climate change on dementia risk and burden. *The Gerontologist*, *64*(3), gnad082. https://doi.org/10.1093/geront/gnad082