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Dual Pathways to Relief: Local Environment Quality and External Connectivity in Rural Informal Care

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Abstract

As population aging accelerates, the mounting burden on informal family caregivers in areas lacking formal care systems threatens the sustainability of elder care. This study aims at evaluating how the rural living environment and external connectivity jointly alleviate caregiver burden and exploring whether regional accessibility serves as a substitute for local infrastructure deficits. Guided by Ecological Systems Theory, we analyzed a cross-sectional dataset of 327 matched caregiver-recipient dyads from rural China using multivariate regression and mediation models. Results indicate that a favorable local environment reduces burden both directly and indirectly through improved recipient health. Crucially, county-level accessibility moderates this relationship via a substitution effect, where the marginal relief from local environmental improvements is most potent in isolated areas but diminishes where external access is convenient. Dimension-specific analyses show that developmental and physical strains are particularly sensitive to these factors. We conclude that sustaining informal care requires a dual-pathway strategy: prioritizing local "soft" assets like community safety and cultural activities while enhancing regional connectivity to service hubs. Ultimately, this research provides empirical evidence and a theoretical framework for enhancing rural informal care sustainability through environmental optimization, thereby advancing Sustainable Development Goals regarding health, reduced inequalities, and sustainable communities.

Keywords: Informal caregiving; rural China; caregiver burden; living environment; transport accessibility; ecological systems; sustainability

1. Introduction

Increases in life expectancy and rapid population ageing have made long-term care a central policy concern worldwide [1,2]. While formal care systems are expanding, informal care—unpaid and sustained assistance with daily living, medical accompaniment, and emotional support provided by spouses, adult children, or relatives—remains the historical and functional bedrock of long-term care globally [3]. To sustain this informal care fabric, policy interventions have traditionally focused on formal service expansion [4]. However, these actions face significant structural obstacles in rural areas, including underdeveloped infrastructure, geographical dispersion of the elderly, and financial inaccessibility [5]. Consequently, traditional policy toolkits require an expansion toward broader, more scalable intervention strategies. In this study, we specifically focus on exploring the impact of improving living environment conditions on relief of informal caregivers' burden.

This globally relevant question is particularly typical and salient in rural China, where population ageing and labour out-migration intersect. According to the Ministry of Justice

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of China, by the end of 2024, the number of people aged 60 years and above had reached 310.31 million (22.0% of the total population), including 220.23 million aged 65 years and above (15.6%) [6]. Ageing is especially pronounced in rural areas, where sustained out-migration of younger workers accelerates population ageing and further strains the capacity of household-based eldercare [7].

Contrastingly, the heavier burden of aging in rural areas is paired with a significantly more fragile formal eldercare system. China has long implemented an urban-priority development strategy in terms of economic growth, infrastructure construction, and population management, which has resulted in a deep-seated urban bias and vast rural-urban disparities [8,9]. Compared with cities, service providers are sparse, travel distances are longer, and information and coordination costs are higher in rural settings, raising the effective cost of accessing and coordinating care [10,11]. On the demand side, lower household incomes and weaker old-age income security in rural areas further constrain families' ability to purchase formal services [12,13]. This prevents the spontaneous formation of an elder-care service market, even where formal long-term care insurance (LTCI) exists, its benefits may not translate into effective service use in rural areas due to limited provider supply and access barriers [11,14], and as a result, rural households are more likely to become the de facto welfare providers [15,16]. Informal care is typically unpaid and long-term care given by spouses, adult children or other relatives in informal support networks. These informal caregivers often have the following typical characteristics: a close relationship with the care receiver, no professional training, no working contract, no equivalent pay, a wide range of care giving duties, no official hours (never really off duty) and no entitlement to social rights [3]. Family-based eldercare is deeply rooted in cultural tradition; thus, informal care remains the dominant part of the long-term care provision system [15,17]. Its value is not only in satisfying the old person's daily living needs but also in its emotional support and cultural meaning that formal care services can hardly match [18,19]. Empirical studies have revealed that informal care can have a significant impact on the psychological well-being and life satisfaction of older people [20,21].

However, behind this invaluable contribution, there is a huge burden that falls on informal caregivers. Caregiver burden is a multidimensional concept that includes physical, psychological, emotional, social and economic strains [22]. Among the instruments that are used most widely in empirical research are the Zarit Burden Interview [23] and the Caregiver Burden Inventory (CBI) developed by Novak and Guest [24]. The latter assesses five dimensions, time-dependence, developmental constraints, physical strain, social strain, and emotional strain, and has shown high levels of reliability and validity [25]. Excessive caregiving demands can seriously affect the physical and mental well-being of caregivers, resulting in increased stress, depressive symptoms [26] and even in reduced paid working hours, or withdrawal from the labor market, effects often described as a "wage penalty" [27,28]. Ultimately, a heavy burden of caregiving reduces not only the quality of life of caregivers but also the quality and sustainability of the care they can provide [29].

Despite extensive research on burden determinants—including caregiver gender [30], 'sandwich generation' status [31,32], recipient limitations [33,34], and formal services [35], feasible and scalable interventions for rural areas remain under-explored. Thus, to relieve such pressure, we need to broaden the policy lens and draw on a wider toolbox of interventions.

Ecological systems theory, a foundational framework for understanding human development, offers a distinctive perspective for doing so. Ecological systems theory assumes that there are multiple, nested contexts that influence human development [36], including the microsystem of immediate interactions in living environment, the mesosystem formed

by linkages across microsystems, the exosystem that influences individuals indirectly, and the macrosystem that provides the broader cultural and institutional backdrop. The theory frames the living environment as a direct and tractable lens for intervention, making the environmental determinants of caregiver burden especially worthy of attention. Because caregiving is persistently rooted in a fixed spatial context, the local environment offers a unique opportunity to meaningfully shape the physical and mental well-being of both caregivers and recipients.

Ample empirical evidence supports the fundamental premise of Ecological systems theory—that the environment exerts a significant influence on human health and well-being. On the one hand, a vast body of literature in environmental gerontology has confirmed the profound effects of the local built environment on the physical and mental health of older adults [37,38], linking age-friendly community design to increased happiness and social inclusion [39–41]. On the other hand, research grounded in transport geography, emphasizes external accessibility as a determinant of well-being in rural settings through the lens of transport-related social exclusion (TRSE), whereby inadequate transport and the centralization of key services constrain participation in social and economic life [42,43].

However, despite strong evidence for both pathways in the broader health and well-being literature, environmental explanations for caregiver burden remain scarce. Most studies on caregiver burden focus on individual-level determinants or formal service interventions, with limited attention to how the physical and spatial environment may affect or mitigate care pressures. More importantly, the two spatial strands have largely progressed in parallel: research on age-friendly communities typically centers on local, village-level features [44], whereas TRSE research focuses on regional connectivity [43]. Consequently, although local supports and regional accessibility may exhibit complex relationships, like potential substitution [45], there has been almost no research testing effects of local environment and external connectivity on informal caregiver burden jointly. The lack of evidence on the joint effects could constrain the design of more scientifically grounded and effective integrated interventions.

To address these identified gaps, the current study, guided by ecological system theory, uses data from the China Rural Aged Care Survey (CRAS) to investigate the effect of the physical environment on caregiver burden through a dual-pathway framework. Specifically, this study aims to answer the following research questions: (RQ1) Does the quality of the local living environment significantly reduce the burden experienced by informal caregivers? (RQ2) What are the specific pathways through which the local environment influences caregiver burden, and could the care recipient's health act as a mediator in this relationship? (RQ3) To what extent does external connectivity to county centers moderate the relationship between the local environment and caregiver burden, and is there a substitution effect between these two spatial scales?

In this research article, we use the CRAS caregiver–recipient dyads, and find that improved local living environments are associated with lower caregiver burden, with care-recipient health mediating this association to some extent. More importantly, we incorporate external connectivity and show that it conditions the environment–burden link: where access is higher, the marginal relief associated with improving the local environment is smaller, whereas in more remote areas poor local environments are more strongly associated with heavier caregiver burdens—consistent with a substitution relationship between local supports and external connectivity.

By highlighting spatial and multi-scalar levers for burden relief, the implications of this study align with the global objectives of the United Nations Sustainable Development Goals (SDGs). For SDG 3 (Good Health and Well-Being), the findings suggest that improving local living environments and access conditions may reduce caregiver burden

and support the well-being of both caregivers and care recipients [46,47]. For SDG 10 (Reduced Inequalities), the results underscore how spatial disparities in environmental quality and connectivity can translate into unequal caregiving burdens, implying that targeted place-based improvements may help narrow rural–urban and within-rural gaps in access to supportive conditions [48–50]. For SDG 11 (Sustainable Cities and Communities), the study links community infrastructure and connectivity to everyday care feasibility, indicating that more age- and care-friendly built environments and transport accessibility can strengthen the sustainability of community-based living and caregiving arrangements [51,52]. While the empirical focus remains on rural China, the findings offer relevant insights for many middle-income countries in Southeast Asia, Eastern Europe, and Latin America that are experiencing similar demographic shifts, such as rapid population aging combined with the hollowing out of rural support systems due to labor migration [53–60]. Identifying sustainable infrastructural interventions thus represents a documented strategy for enhancing social sustainability in aging societies, and our findings point to a place-sensitive approach: integrated interventions that consider both local environmental conditions and broader connectivity may better target constraints faced by caregivers in remote areas [61,62].

2. Analytical Framework and Research Hypotheses

2.1. An Ecological System-Based Model of Elder Care

The ecological system theory, originally developed to explain child development, provides a powerful framework for understanding the continuous and multilayered interactions between individuals and their environments across the life course [36,63,64]. Previous studies have shown that this framework not only describes developmental trajectories but also serves as a useful tool for understanding the formation of stress and identifying potential intervention strategies [65]. In recent years, it has been increasingly applied to research on aging, daily living, and development among older adults [66]. The ecological system perspective enables us to locate the sources and dynamics of caregiver burden within a complex and enduring interplay of multilevel environmental factors.

The caregiver's role originates in the care needs of the older adult. Building on this starting point, we first construct an elder care model, and on this basis extend the analytical perspective—traditionally focused on older individuals—to a triadic structure encompassing the older adult, the caregiver, and the surrounding context. This framework highlights that caregivers do not operate in isolation but are embedded within multilayered relational systems. The structure of the care recipient's needs, the distribution of family and community resources, and the environmental and institutional provisions at the regional level jointly shape the costs and pressures of the caregiving process.

Within this model, caregivers and care recipients maintain long-term, regular, and bidirectional interactions. Merçon-Vargas emphasize that such proximal processes play a central role in the functioning of ecological systems. Accordingly, sustained daily interactions may shape the accumulation of caregiving stress over time [67]. In the eldercare context, proximal interactions encompass basic personal care, health management, medical accompaniment, facilitation of social participation, and emotional support. These interactions are influenced not only by the characteristics of both caregivers and care recipients but also by broader contextual factors such as environmental accessibility and the availability of formal institutional support.

Accordingly, we conceptualize the eldercare model as comprising five interrelated levels (as illustrated in Figure 1).

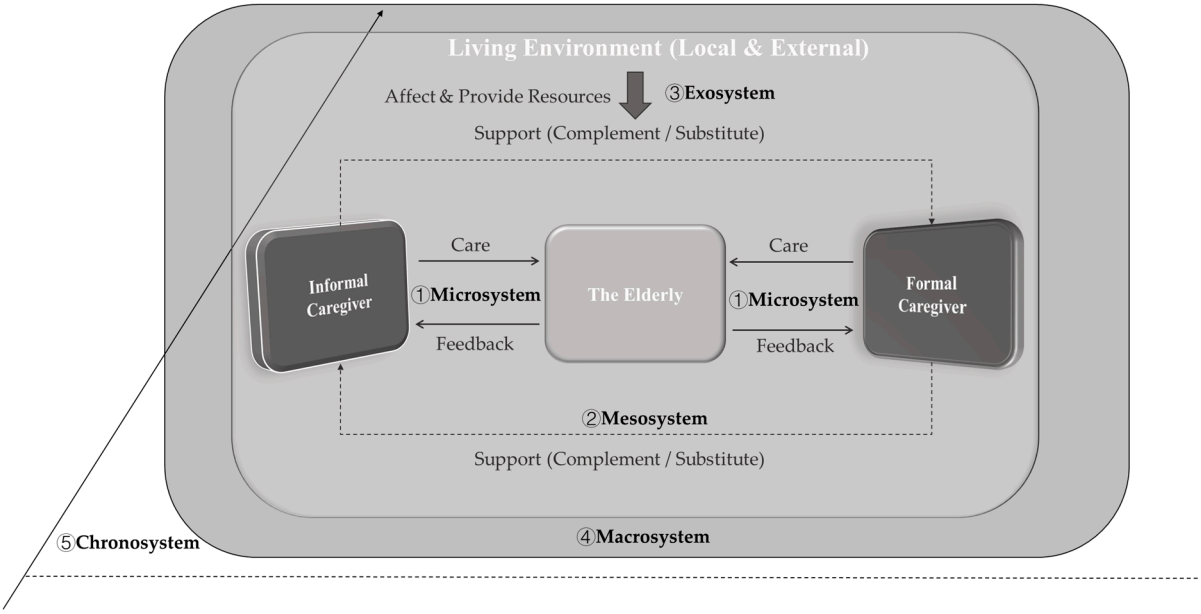


Figure 1. Ecological system Model of Elder Care.

At the microsystem level (indicated by ① in Figure 1), the model captures the direct interactions between older adults and their caregivers. This level reflects both formal and informal caregiving arrangements occurring within the family and individual domains, encompassing daily assistance, emotional support, and personal care activities. Critically, caregiving demands are imposed most directly at this level, where the day-to-day tasks of care translate into the caregiver's immediate time, physical, and emotional burdens.

The mesosystem level (indicated by ② in Figure 1) highlights the linkages, substitutions, and complementarities between formal and informal care. It concerns the degree of coordination among families, community organizations, care institutions, and primary healthcare providers, which shapes the division of caregiving responsibilities and the flow of information across systems. This mesosystem is inevitably shaped by the availability, capacity, and quality of formal care resources, which condition whether coordination and substitution can occur in practice.

The exosystem level (indicated by ③ in Figure 1) refers to the broader living environment, including transportation connectivity and road infrastructure, community safety and sanitation, and the availability of public cultural and social participation spaces. It represents the extent to which households can access livelihood opportunities and supportive resources, like services, respite, and recreational opportunities, as well as the overall convenience and friction of everyday life.

And the macrosystem level (indicated by ④ in Figure 1) represents the broader cultural context and normative expectations that shape caregiving roles and responsibilities. For example, it encompasses social norms regarding whether care responsibilities should be primarily borne by adult children or other relatives, and whether specific family members (e.g., the eldest son) are expected to carry a heavier burden [68–70]. In China, such norms are widely shaped by "Xiao Dao" (filial piety), although their salience and expression may vary across local contexts [71].

Finally, the chronosystem level (indicated by ⑤ in Figure 1) captures important historical transitions and life-course events that unfold over time and reshape other systems. Historical transitions, such as large-scale rural–urban migration and neo-familism, may impact eldercare culture and disrupt proximal interactions within the microsystem [72]. Within the context of eldercare, the most critical life-course event is the gradual onset of

disability and functional decline in older age, which generates care needs and changes the intensity and content of caregiver–recipient interactions over time.

Across these five systems, informal caregivers interact respectively with the care recipient (microsystem), formal care resources (mesosystem), and the external environment (exosystem), culturally shaped role expectations (macrosystem), and time-varying life-course and historical changes (chronosystem). Together with individual characteristics, these contextual layers constitute the primary structural factors influencing the level of caregiving burden.

Existing empirical evidence lends support to this multilevel conceptualization. Studies have shown that caregivers' personal attributes—such as gender and parental status—significantly shape their perceived burden [30–32,73]. At the microsystem level, research demonstrates that care recipients' health status and degree of functional impairment are among the strongest predictors of family caregiving stress [34,73,74]. Regarding the mesosystem, the expansion of formal medical and care services can enhance caregivers' well-being through two mechanisms: directly, by reducing household caregiving intensity, and indirectly, by improving older adults' health and functional performance, thereby lessening the caregiving load [35]. In the macrosystem, stronger filial piety norms may buffer adult children's caregiving burden by providing moral meaning, role legitimacy, and normative support for sustained caregiving commitments [75]. From a chronosystem perspective, studies emphasize how value shifts associated with modernization reshape intergenerational expectations and care arrangements over time, thereby generating new challenges for elder care in contemporary societies [71,72]. However, for the exosystem, literature shows that the living environment can play a pivotal role in shaping older adults' life experience and well-being, but further research is needed to clarify how these environmental conditions translate into caregiving processes and caregiver burden [76].

2.2. Mechanisms Linking the Living Environment (Exosystem) to Caregiver Burden

Building on the ecological system model above, the living environment may influence caregiver burden through two spatially distinct pathways: the local pathway, which structures daily caregiving within the village, and the external pathway, which reflects access to service hubs and broader resources beyond the village.

2.2.1. The Local Pathway: Direct and Indirect Effects of Within-Village Environment

Within the local pathway, the living environment is expected to shape caregiver burden through direct and indirect mechanisms. This follows from the ecological system framework: caregivers and care recipients are embedded in the same exosystem, while their sustained and regular interactions occur in the microsystem, through which environmental conditions translate into caregiving demands and stress accumulation.

For the direct effect of the within-village environment on caregiving activities, a more accessible, safer, and resource-rich community environment can reduce the time and transactional costs of caregiving, ease uncertainties associated with medical accompaniment and daily care, and alleviate emotional and psychological stress. Such environments may also provide a more pleasant and restorative daily setting, helping caregivers feel more relaxed and emotionally replenished. By providing caregivers with greater autonomy and flexibility, such environments can directly mitigate their perceived burden.

In addition to these direct effects, the local environment can operate indirectly through the health status of older adults. A supportive living environment enhances older adults' physical health and functional performance, thereby decreasing the intensity and frequency of care demands and indirectly reducing caregiver burden. High-quality medical and rehabilitation resources, smoother access to services, and abundant opportunities for social

participation help older adults maintain daily functioning and emotional stability, reducing the likelihood of sudden or high-intensity caregiving situations.

Accordingly, we expect a negative association between local environmental quality and caregiver burden, with this relationship operating through both a direct pathway and an indirect pathway mediated by the care recipient's health.

2.2.2. The External Pathway: Moderating Effects of County Accessibility

Beyond the within-village context, the scope of the exosystem is also shaped by county accessibility, which determines how easily caregivers and care recipients can reach service hubs and resources outside the village.

Poor county accessibility may increase caregivers' time and physical burdens by making routine "medical accompaniment" to county-level hospitals more costly and demanding [46,77]. It may also heighten social burden by restricting caregivers' ability to maintain social ties and access supportive networks [78,79], and impose developmental constraints by limiting opportunities for off-farm employment, education, and respite. In addition, transport barriers can lead to missed or delayed care [80], and "distance decay" in healthcare utilization [81] may worsen recipient health, thereby increasing care demands and caregiver burden.

Ecological systems theory offers a useful systems perspective for organizing multilevel environmental influences, but it can also aggregate diverse contextual forces in ways that implicitly portray individuals as largely passive recipients of environmental effects. To clarify the process through which the exosystem shapes caregiving constraints, we draw on the Sustainable Livelihoods Approach (SLA) as a complementary lens. SLA conceptualizes households as operating under a vulnerability context and pursuing well-being through livelihood strategies that mobilize different forms of capital [82]. Within this framework, caregivers are viewed as active agents who allocate and use available resources to meet caregiving needs and sustain household well-being [83]. From this perspective, both the within-village environment and county accessibility constitute key forms of physical assets—infrastructure, facilities, and connectivity that can be strategically mobilized to accomplish care and livelihood tasks [84]. Given the critical role of physical assets in sustaining rural households' livelihoods [85], caregiver burden can, to some extent, be understood as reflecting the difficulty caregivers face—under vulnerability and constraints—in effectively deploying required physical assets to overcome spatial frictions and achieve caregiving and livelihood goals. This process-oriented view makes the substitutability between external access and local environmental supports more explicit:

When external access is constrained, local living conditions may become more binding in shaping daily caregiving feasibility, time costs, and stress accumulation. By contrast, when county accessibility is higher, caregivers can more readily draw on county-level medical and care resources, markets, and supportive services. Such external access can partially compensate for deficits in the local environment by reducing transport- and coordination-related frictions and expanding feasible coping options (e.g., obtaining services, supplies, or respite outside the village). Under these conditions, improvements in the within-village environment may yield smaller marginal reductions in caregiver burden because some caregiving constraints can be alleviated through external access.

Taken together, this implies a substitution logic: county accessibility moderates the association between within-village environmental quality and caregiver burden. To be specific, we theorize that accessibility conditions the strength of the association between the local environment and caregiver burden: in remote areas with limited alternatives, local environmental conditions are expected to play a central, decisive role in shaping well-being;

whereas in well-connected areas, the marginal association of the local environment is expected to be attenuated due to the availability of external resources.

2.2.3. Research Hypotheses

Building upon the theoretical mechanisms discussed in the preceding sections, this study formally proposes the following hypotheses for empirical testing:

Hypothesis 1 (H1). *A favorable local living environment is negatively associated with the burden experienced by informal caregivers.*

Hypothesis 2 (H2). *The negative association between the local living environment and caregiver burden is partly mediated by the health status of care recipients.*

Hypothesis 3 (H3). *Higher county accessibility weakens the marginal association between local environmental quality and caregiver burden.*

3. Materials and Empirical Methods

3.1. Data Source and Sampling Design

To test the above hypotheses and answer the research question, this study employs the data obtained from the China Rural Aged Care Survey (CRAS), a large-scale survey of adults aged 65 and above conducted in rural China. The CRAS was commissioned by the Asian Development Bank, and designed and implemented by the Center for Aging and Health Research at Zhejiang University. The authors participated as members of the research team involved in organizing and implementing the fieldwork and preparing the analytical dataset for research use.

CRAS adopted a stratified, multistage sampling design, using probability proportional to size (PPS) sampling in the earlier stages and equal-probability sampling at the final stage. Specifically, one representative province was selected from each of China's eastern, central, and western regions. Within each sampled province, three counties (or county-level districts) were selected; within each county, three townships (or subdistricts) were selected; and within each township, three villages were selected. At the final stage, eligible rural older adults aged 65 years and above were sampled with equal probability and interviewed through face-to-face surveys. Prior to the interviews, all participants were explicitly informed that their participation was entirely voluntary and that they reserved the right to withdraw from the study at any stage without providing a reason. Given this design, the data constitute a probability sample of rural adults aged 65+ within the sampled provinces, with deliberate coverage of China's three major regions. However, because only one province was selected per region, the sample is not intended to be nationally representative of all rural older adults in China, and generalization beyond the sampled provinces should be made with caution.

To ensure high data quality, CRAS implemented standardized field protocols and multiple layers of quality assurance. Interviewers recruited from universities were required to complete structured training covering questionnaire logic, interview techniques, and field protocols, followed by a mandatory assessment; only those who passed were permitted to conduct field interviews. Each field team was supervised by at least one senior researcher with a relevant professional background. Local community staff provided practical support by organizing interview logistics and facilitating dialect communication when needed to ensure accurate information exchange with older rural respondents. Using these procedures, CRAS obtained 3150 valid questionnaires from rural adults aged 65 years and above.

A distinctive feature of this project is its simultaneous collection of information on informal caregivers, including a dedicated module measuring caregiver burden. Such matched caregiver–care recipient data remain rare in China, particularly in the context of home-based eldercare in rural areas, and thus provide valuable empirical support for identifying the determinants of caregiving burden from the caregivers' perspective.

The present study focuses on informal caregivers who provide continuous care. From the total sample, we identified households with family caregiving and complete data on key variables, resulting in 327 valid observations for empirical analysis. Although modest in size, this subsample is highly targeted: it allows one-to-one matching between older adults and their caregivers, thereby reflecting the real caregiving burden within rural household settings.

A comparative analysis between the full sample and the caregiving subsample underscores the extreme vulnerability of the study population (see Table 1). Older adults requiring informal care are significantly older (mean age of 77.95 vs. 73.04) and face acute economic deprivation, with an average annual income of only 8.77 thousand Yuan, compared to 39.40 thousand Yuan in the broader sample. Furthermore, health metrics reveal substantial physical and mental decline in the subsample: ADL (85.83 vs. 96.68), IADL (24.43 vs. 36.14), and cognitive scores (9.10 vs. 11.49) are all markedly lower, indicating a high concentration of disability and cognitive impairment. Geographically, the Central Region accounts for a disproportionately large share of the caregiving subsample (40.06% compared to 33.21% in the full sample), reflecting a higher concentration of older adults with intensive care needs in this territory. These disparities underscore that informal caregivers in rural China are the primary providers for those with the most intensive needs, highlighting the profound empirical and policy relevance of supporting these caregiver-receivers dyads.

Table 1. Comparison of Key Characteristics between the Full Sample and the Caregiving Subsample.

Variable	Full Sample (N = 3150)	Caregiving Subsample (N = 327)
Age (Mean)	73.04	77.95
Gender: Female (Percent)	50.85%	50.15%
Annual Income (1000 Yuan)	39.40	8.77
ADL Score (Mean)	96.68	85.83
IADL Score (Mean)	36.14	24.43
Cognitive Score (Mean)	11.49	9.10
Eastern Region (Percent)	33.11%	35.47%
Central Region (Percent)	33.21%	40.06%
Western Region (Percent)	33.68%	24.46%

Notes: The analytical sample consists of 327 matched pairs of older adults and their primary informal caregivers, extracted from a broader survey of 3150 individuals in rural China. Functional impairment is defined based on the Activities of Daily Living (ADL) and Instrumental Activities of Daily Living (IADL) scales. Across ADL, IADL and Cognitive scores, higher scores indicate superior functional and cognitive status.

3.2. Variables and Descriptive Statistics

Dependent Variable. The dependent variable in this study is caregiver burden, measured using the Caregiver Burden Inventory (CBI) developed by Novak and Guest [24] and its validated Chinese version adapted by Chou et al. [25]. Compared with other scales designed for specific patient groups—such as the Zarit Burden Interview (ZBI) for dementia caregivers, the ABC-16 for stroke patients, or the Burden Index of Caregivers (BIC) [23,86,87]—the CBI is more suitable for caregivers of the general older population. It captures the multidimensional structure of caregiver burden through 24 items across five dimensions: time-dependence, developmental constraints, physical strain, social strain, and emotional strain.

Each item assesses the frequency of negative caregiving experiences (0 = never, 1 = rarely, 2 = sometimes, 3 = often, 4 = always). To ensure data quality, we performed

rigorous reliability and validity tests (see Table 2). The results indicate excellent internal consistency, with Cronbach's α for the overall scale reaching 0.93 and sub-dimension values ranging from 0.77 to 0.90. Construct validity was confirmed by the Kaiser-Meyer-Olkin (KMO) measure (0.91 for the overall scale) and a highly significant Bartlett's test of sphericity ($X^2 = 5111.25$, $p < 0.001$). Therefore, the total score for each dimension is computed as the sum of item scores within that dimension, and the five-dimension scores are further aggregated to represent the overall caregiver burden.

Table 2. Reliability and Validity of the Caregiver Burden Inventory (CBI).

Scale Dimensions	Items	Cronbach's α	KMO	Bartlett's Test (χ^2)	p-Value
Overall Scale	24	0.93	0.91	5111.25	<0.001
Time-Dependence	5	0.90	0.88	986.23	<0.001
Developmental Constraint	5	0.90	0.87	941.77	<0.001
Physical Strain	4	0.90	0.81	860.80	<0.001
Social Strain	4	0.77	0.74	342.23	<0.001
Emotional Strain	6	0.84	0.83	893.17	<0.001

Notes: The table presents the reliability and validity metrics, calculated using Cronbach's alpha and exploratory factor analysis, for the 24-item caregiving burden scale and its five sub-dimensions.

Table 3 presents the descriptive statistics for the primary variables. The average overall caregiver burden score is 18.55, with the scores spanning a broad range from 0 to 80. As illustrated in Figure 2, the total burden score exhibits a moderate positive skew; with a larger share of caregivers reporting relatively low-to-moderate burden levels and a smaller tail of high-burden cases, providing substantial variation for regression modeling. Across the five sub-dimensions, the mean scores are 8.31 (time-dependence), 3.92 (developmental constraints), 3.66 (physical strain), 1.49 (social strain), and 1.18 (emotional strain). On average, time-dependence burden is the highest, while emotional strain is the lowest. This disparity indicates that the most significant pressure on rural caregivers stems from constrained personal time and limited opportunities for self-fulfillment. Such findings underscore the critical role of a convenient living environment, as it can directly alleviate the daily logistical demands and time-pressures faced by caregivers. Detailed histograms for the five sub-dimensions, further illustrating these distribution patterns, are provided in Appendix A (see Figures A1–A6).

Core Independent Variable. The core independent variable is satisfaction with the living environment. We assess the favorability of the local living environment based on the subjective ratings provided by the care recipients (older adults). Respondents rated their satisfaction on a five-point Likert scale, with higher scores indicating a more favorable environment. This measurement choice is motivated by endogeneity concerns: Using care recipients' assessments, rather than caregivers' own ratings, is motivated by endogeneity concerns: by implementing the separation of measurement sources, potential reverse causality caused by caregivers' negative affect projected onto their surrounds can be moderated. As illustrated by the distribution in Figure 3 and reported in Table 3, the sample exhibits a high level of environmental contentment, with a median score of 4 and a mode of 5, indicating that the majority of older adults are satisfied or very satisfied with their local living conditions. Thus, even a slight shift toward lower satisfaction levels represents a significant departure from this normative baseline. In such a context, minor deteriorations in environmental quality may not merely be incremental changes but could act as critical stressors that disproportionately escalate the physical and emotional toll on caregivers.

Table 3. Descriptive Statistics.

		Mean/Median/Frequency	SD/Mode/Percent
Caregiver Burden	Caregiver Burden	18.55	16.54
	---Time-Dependence	8.31	6.29
	---Developmental Constraints	3.92	5.07
	---Physical Strain	3.66	4.43
	---Social Strain	1.49	2.76
	---Emotional Strain	1.18	2.75
Living Environment	County Accessibility (1 = High) *	230	70.34%
	Satisfaction with Living Environment #	4	5
	---with Sports Facilities #	4	4
	---with Recreational and Cultural Activities #	3	3
	---with Residential Safety #	4	4
	---with Sanitary Conditions #	4	4
	---with Barrier-free Environment #	3	1
Caregiver Characteristics	Age	60.56	12.52
	Weekly Caregiving Hours	63.50	57.29
	Gender (1 = Female) *	187	57.19%
	Working Status (1 = Work) *	150	45.87%
	Health Status #	4	4
Care Recipient Characteristics	Age	77.95	8.58
	ADL Score	85.83	20.64
	IADL Score	24.43	14.86
	Cognitive Function Score	9.10	5.05
	Elderly Income (1000 Yuan)	8.77	14.42
	Gender (1 = Female) *	164	50.15%
	Health Status #	3	2
Formal Care Resources	Elder Care Services	0.52	1.20
Region	Eastern	116	35.47%
	Central	131	40.06%
	Western	80	24.46%

Notes: Table reports descriptive statistics based on 327 observations, using measures appropriate to variable type. Continuous variables are summarized by mean and standard deviation (SD). Dichotomous variables are summarized by frequency (N) and percentage (%) and are marked with a superscript *. Ordinal variables (Likert-scales) are summarized by the median and mode and are marked with a superscript #.

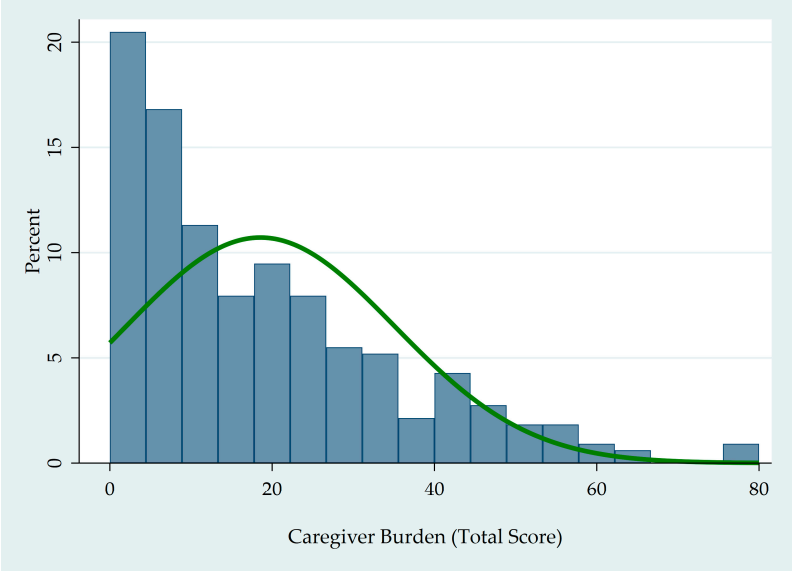


Figure 2. Distribution of Caregiver Burden Total Scores.

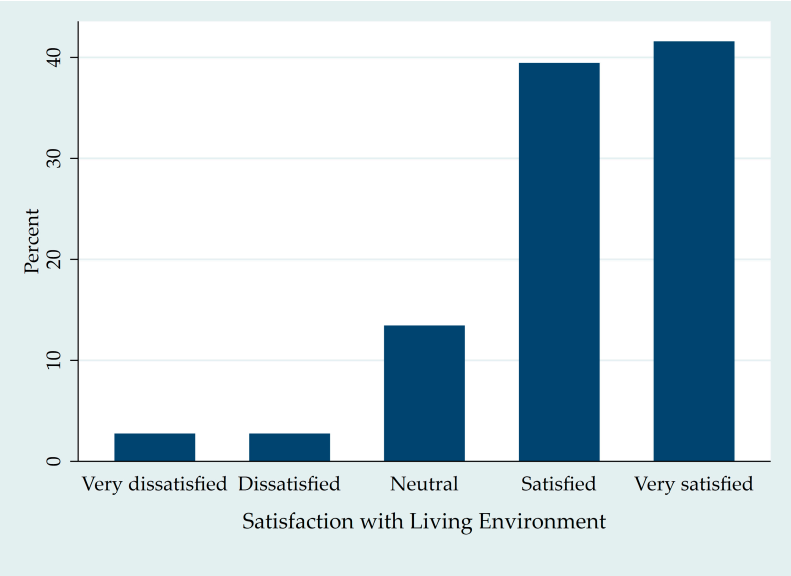


Figure 3. Distribution of Care Recipients' Satisfaction with Living Environment.

Additionally, respondents evaluated specific environmental dimensions, including satisfaction with sports facilities, recreational and cultural activities, residential safety, sanitary conditions, and barrier-free environment (each measured on the same five-point scale). According to Table 3, among different dimensions, satisfaction was notably lower for recreational and cultural activities (median = 3, mode = 3), and for barrier free environment (median = 3, mode = 1). In the main specification, we use the overall satisfaction measure as the primary indicator of within-village environmental quality, while subsequent analyses replace it with the dimension-specific measures to explore which aspects of the living environment are most strongly associated with caregiver burden. Detailed frequency distributions for each of these specific environmental sub-dimensions are provided in the Appendix A (see Figures A6–A10) to illustrate the localized variations in rural infrastructure.

Mediating and Moderating Variables. To test Hypothesis 2 (H2), we utilize the health status of the care recipient as the mediating variable, and it is measured by self-rated health on a five-point Likert scale (1 = poor to 5 = excellent). As reported in Table 3, the sampled care recipients exhibit a sub-optimal health profile, with a median self-rated health score of 3 and a mode of 2. This distribution indicates that a significant portion of care recipients perceive their health as fair-to-poor, a condition that potentially intensifies the daily care demands and the resulting psychological strain experienced by their caregivers.

To assess the contextual moderation proposed in Hypothesis 3 (H3), we include county accessibility as the moderating variable, capturing the ease with which older adults and their caregivers can access external environments and services. This variable is coded as a binary indicator of high accessibility (1 = high), and 70.34% of caregivers reside in areas classified as having high county accessibility (see Table 3).

Control Variables

Based on the eldercare model constructed above, we include controls that map onto key levels of the ecological system theory:

- Caregiver characteristics (microsystem), including gender, age, caregiving hours, self-rated health, and employment status.
- Care recipient characteristics (microsystem), including gender, age, ADL and IADL scores, cognitive ability, and personal income.

- Formal care resources (macrosystem), calculated as the sum of the products of service utilization and satisfaction scores across five core community services: home cleaning, laundry, meal delivery, health monitoring, and rehabilitation assistance. This index reflects the degree of external support the formal system provides to informal caregivers.
- Regions (macrosystem), using province fixed effects to capture broader contextual influences that may vary across provinces, including differences in how widely shared filial-care norms are interpreted and enacted, as well as other province-specific factors that could jointly shape caregiver burden and local environmental conditions.

Notably, the descriptive results reveal several characteristics of the rural caregiving landscape (see Table 3). First, caregivers are themselves relatively old (mean age = 60.56), reflecting the prevalence of "old-age caring for the old" in rural China. Second, the gender distribution is relatively balanced, with female caregivers (57.19%) only slightly outnumbering males; this may be related to the aforementioned phenomenon of mutual care between elderly spouses. Third, nearly half of the caregivers (45.87%) are "dual-tasked," juggling both employment and caregiving responsibilities, which imposes significant time-pressure. Finally, formal care support is severely lacking, with an average score of only 0.52 out of a possible 10, and a maximum observed score of only 8. These patterns underscore the heavy reliance on informal care.

3.3. Empirical Strategy

This study first estimates the total effect of the living environment on caregiver burden using the following baseline regression model:

$$Burden_i = \alpha_0 + \alpha_1 Env_i + X_i'\Gamma + \mu_p + \varepsilon_i \quad (1)$$

where $Burden_i$ represents the caregiver's burden, Env_i denotes the care recipient's environmental satisfaction, X_i' is a set of control variables, μ_p indicates province fixed effects, and ε_i is the error term. α_1 is the coefficient of interest. Prior to estimation, the environmental satisfaction variable is mean-centered to mitigate potential multicollinearity issues.

Furthermore, to examine the mediating effect, we apply the following two equations:

$$Health_i = \beta_0 + \beta_1 Env_i + X_i'\Theta + \mu_p + \epsilon_i \quad (2)$$

$$Burden_i = \delta_0 + \delta_1 Env_i + \delta_2 Health_i + X_i'\Pi + \mu_p + \xi_i \quad (3)$$

where $Health_i$ represents the health status of the care recipient. Equations (1)–(3) are used to test Hypotheses 1 and 2. Specifically, H1 is examined through α_1 in Equation (1), and H2 is assessed through β_1 in Equation (2) and δ_2 in Equation (3). β_1 provides evidence regarding the relationship between the environment and the older adult's health. The mediating effect is established only when β_1 is statistically significant. δ_1 measures the direct effect of the living environment on the caregiver's burden after controlling for the care recipient's health, while $\beta_1 \times \delta_2$ captures the indirect effect of the living environment on the caregiver's burden through the health of the older adult. We employ the delta method to examine the confidence interval and significance of the nonlinear combination of these two coefficients across the two equations.

Finally, to test the moderating effect of transport accessibility (Hypothesis 3, H3), we estimate the following moderated mediation model:

$$Burden_i = \theta_0 + \theta_1 Env_i + \theta_2 Access_i + \theta_3 (Env_i \times Access_i) + \theta_4 Health_i + X_i'\Lambda + \mu_p + \eta_i \quad (4)$$

where $Access_i$ represents the convenience of access to the county center. The moderating effect is captured by θ_3. A positive θ_3 indicates that the easier it is to access the

county center, the weaker the direct effect of the living environment on the caregiver's burden, suggesting a substitutive relationship between the local environment and external (regional) accessibility.

To more clearly illustrate these hypothesized pathways, a path diagram with directional linkages and expected coefficients is presented in Figure 4.

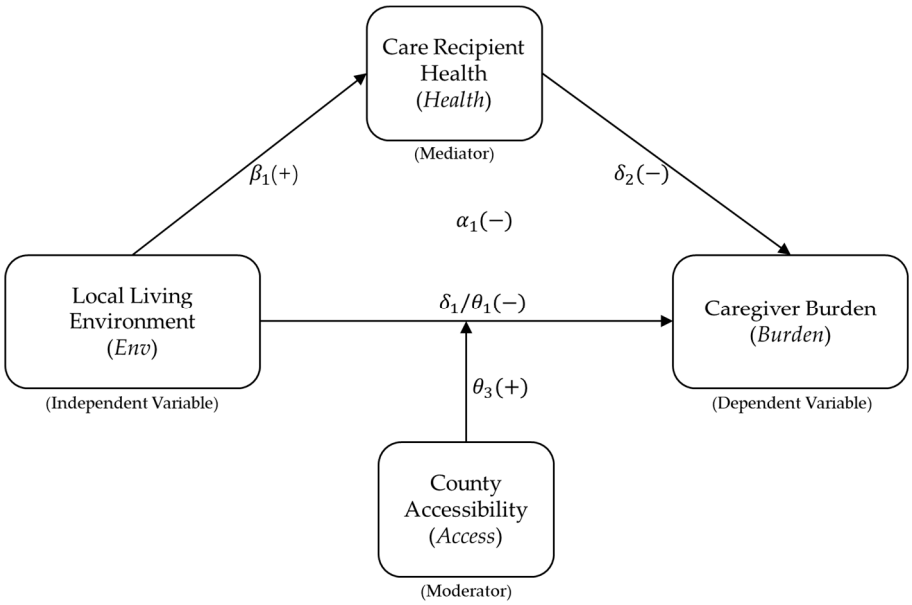


Figure 4. Path Diagram of the Empirical Model. Notes: The diagram summarizes the key variables and their relationships in the empirical model. Arrow directions indicate the hypothesized direction of influence, and each arrow is labeled with the corresponding estimated coefficient, the expected signs are shown in parentheses.

4. Empirical Results

Before examining the hypothesized relationships, we conducted preliminary diagnostics to assess bivariate associations and multicollinearity. Table 4 presents the Pearson correlation matrix for the key variables. Caregiver burden is significantly and negatively correlated with environmental satisfaction, recipient health, and county accessibility, while environmental satisfaction is positively correlated with recipient health. These correlations align with the hypothesized directions of our theoretical model and are of moderate magnitude, suggesting meaningful associations without indicating extreme linear dependence among regressors.

Table 4. Pearson Correlation Matrix for Key Variables.

Variables	*Burden*	*Env*	*Health*	*Access*
Burden	1.0000			
Env	−0.1835 ***	1.0000		
Health	−0.4171 ***	0.1691 ***	1.0000	
Access	−0.2352 ***	0.1204 **	0.1758 ***	1.0000

Notes: *** and ** denote statistical significance at the 1% and 5% levels, respectively. Environment satisfaction is mean-centered.

To further assess multicollinearity, we calculated variance inflation factors (VIFs) based on the full moderated mediation specification in Equation (4). The mean VIF is 1.77, and individual VIF values range from 1.16 to 3.24, which are well below conventional thresholds, providing no evidence of problematic multicollinearity. Table 5 reports the VIF statistics for the key variables.

Table 5. Variance Inflation Factor (VIF) Results for Key Variables.

Variables	VIF	1/VIF
Env	3.24	0.309
Health	1.29	0.778
Env × *Access*	3.10	0.322
Access	1.18	0.845
Mean VIF	1.77	

Notes: Results are estimated based on the full moderated mediation specification in Equation (4). Control variables include caregiver characteristics (gender, age, caregiving hours, self-rated health, and employment status), care recipient characteristics (gender, age, ADL/IADL scores, cognitive ability, and income), formal eldercare services, and province fixed effects.

4.1. Baseline Model

The results of the baseline regression analysis are presented in Table 6. Column (I) reports the relationship between the living environment and caregiver burden without controlling for additional covariates, while Column (II) further includes control variables and province fixed effects. The main conclusion remains robust.

Table 6. Basic Model Results.

	(I)	(II)	(III)	(IV)
	Burden	***Burden***	***Health***	***Burden***
Env	−3.22 ***	−2.66 ***	0.16 **	−2.21 **
	(1.18)	(0.92)	(0.06)	(0.89)
Health				−2.84 ***
				(0.69)
Caregiver Controls	No	Yes	Yes	Yes
Care Recipient Controls	No	Yes	Yes	Yes
Formal Care Control	No	Yes	Yes	Yes
Regional Fixed Effects	No	Yes	Yes	Yes
Mediating Effect				−0.45 **
				(0.21)
Direct Effect				−2.21 **
				(0.87)
Total Effect				−2.66 ***
				(0.90)
Adjusted R-squared	0.031	0.379	0.181	0.412
Prob > F	0.007	0.000	0.000	0.000
Root MSE	16.287	13.033	1.078	12.688
Observations	327	327	327	327

Notes: Columns (I), (II), and (IV) use caregiver burden (*Burden*) as the dependent variable, while Column (III) uses older adults' health (*Health*) as the dependent variable. Key independent variable *Env* denotes the care recipient's stratification with the local living environment. Columns (II)–(IV) control for caregiver characteristics (gender, age, weekly caregiving hours, self-rated health, and employment status), care-recipient characteristics (gender, age, ADL score, IADL score, cognitive function score, and income), and formal care resources, and include province fixed effects. All regressions employ robust standard errors, with robust standard errors reported in parentheses. Column (IV) additionally presents the estimated mediated effect, direct effect, and total effect obtained using the delta method, with z-values shown in parentheses. *** and ** denote statistical significance at the 1% and 5% levels, respectively.

The estimated total effect α_1 is −2.66 and statistically significant at the 1% level, indicating that a one-unit improvement in the living environment is associated with a 2.66-point reduction in caregiver burden. This corresponds to a 14.34% decrease relative to the mean caregiver burden, thus supporting H1.

Column (III), based on Equation (2), examines the impact of the living environment on the health of older adults. The coefficient $\beta_1 = 0.16$ is positive and significant, suggesting that better living environments are significantly associated with improved health among older adults. This provides empirical support for the hypothesized mediating pathway in

H2, through which the living environment affects caregiver burden indirectly via older adults' health.

Column (IV) presents the estimation results for Equation (3). The coefficient $\delta_2 = -2.84$ is negative and statistically significant at the 1% level, indicating that better health of care recipients substantially reduces caregiver burden. Moreover, the coefficient on the living environment remains negative and statistically significant after controlling for care recipients' health, implying that the living environment continues to exert a direct effect on caregiver burden beyond its indirect health-mediated pathway. This pattern suggests that the impact of the living environment is partially, rather than fully, mediated by older adults' health. Combined with the results from Column (III), these findings confirm the presence of a mediation effect as proposed in H2.

Using the delta method to jointly test the indirect effect, we find that the mediation effect is statistically significant at the 5% level. The magnitude of the indirect effect is -0.45, indicating that a one-unit improvement in the living environment indirectly reduces caregiver burden by 0.45 units through improved health of older adults. The mediation effect thus accounts for approximately 20% of the total effect of the living environment on caregiver burden.

In terms of overall model performance, the explanatory power improves markedly once covariates and fixed effects are included, indicating that caregiver burden is shaped by multiple observed characteristics as well as contextual heterogeneity. The R-squared increases from 0.031 in the bivariate specification (Column (I)) to 0.379 in the fully controlled baseline model (Column (II)), and further to 0.412 when recipient health is included (Column (IV)). The overall model significance is confirmed by the F-test, and the Root MSE declines as additional covariates are introduced, suggesting improved fit in the controlled specifications. Nevertheless, we acknowledge that the overall fit is still modest; accordingly, the estimated associations should be interpreted with appropriate caution, and our emphasis is placed on the direction, consistency, and robustness of the key relationships rather than on predictive performance.

We also examine the estimated associations for the control variables, which map onto key components of the elder-care ecological system model (detailed coefficients are reported in Appendix B Table A1). First, caregiver characteristics significantly influence burden: older caregivers, those with longer weekly caregiving hours, and those with poorer self-rated health experience significantly higher levels of strain, whereas caregiver gender and employment status are not statistically significant. Second, among care-recipient characteristics, functional limitations, captured by ADL and IADL scores, are key predictors of higher caregiver burden. Finally, we do not observe a statistically significant association between formal care resources and caregiver burden in this sample, which is likely attributable to limited variation in formal care availability and generally low levels of formal support in rural settings.

4.2. Moderating Effect

To examine whether broader neighborhood environments can substitute for within-village living conditions, we introduce county accessibility as a moderating variable. The estimation results are reported in Table 7.

Starting with the model estimation of Equation (4) without including control variables or care recipients' health, Column (I) shows that the coefficient θ_3 of the interaction term is 5.63 and statistically significant at the 5% level. Because the main effect of environmental satisfaction on burden is negative, this significant positive interaction coefficient indicates that as county accessibility increases, the burden-reducing effect of local environment improve-

ments becomes substantially weaker. This finding provides direct empirical support for H3, suggesting a substitutive relationship between local conditions and regional accessibility.

Table 7. Results of the Moderating Effect.

	(I)	(II)	(III)	(IV)
	Burden	***Burden***	***Health***	***Burden***
Env	−6.48 ***	−5.71 ***	0.21 *	−5.13 ***
	(2.14)	(1.77)	(0.11)	(1.70)
Access	−7.31 ***	−2.32	0.14	−1.93
	(1.95)	(1.84)	(0.15)	(1.79)
Env × *Access*	5.63 **	4.76 **	−0.09	4.51 **
	(2.36)	(1.92)	(0.13)	(1.83)
Health				−2.72 ***
				(0.67)
Caregiver Controls	No	Yes	Yes	Yes
Care Recipient Controls	No	Yes	Yes	Yes
Formal Care Control	No	Yes	Yes	Yes
Regional Fixed Effects	No	Yes	Yes	Yes
Adjusted R-squared	0.094	0.397	0.180	0.426
Prob > F	0.000	0.000	0.000	0.000
Root MSE	15.745	12.851	1.079	12.533
Observations	327	327	327	327

Notes: Columns (I), (II), and (IV) use caregiver burden (*Burden*) as the dependent variable, while Column (III) uses older adults' health (*Health*) as the dependent variable. Key independent variable *Env* denotes environmental satisfaction, and *Access* is a binary indicator of high county accessibility (1 = high), *Env* × *Access* denotes the interaction term. Columns (II)–(IV) control for caregiver characteristics (gender, age, weekly caregiving hours, self-rated health, and employment status), care-recipient characteristics (gender, age, ADL score, IADL score, cognitive function score, and income), and formal care resources, and include province fixed effects. All regressions employ robust standard errors reported in parentheses. ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively.

After adding the full set of covariates and province fixed effects, the results displayed in Column (II) yields a similar result, suggesting that this substitution effect between local and neighboring environments is robust to the inclusion of covariates. This robustness further strengthens the evidence in favor of H3.

Column (III) uses care recipients' health as the dependent variable and reveals no significant moderating effect of county accessibility on the relationship between the living environment and older adults' health This result does not necessarily imply that county accessibility is irrelevant for health; rather, it suggests that accessibility does not materially condition the association between within-village environmental quality and health in this sample. A plausible interpretation is that for older adults with limited mobility, health is shaped primarily by immediate living conditions, so the local environment–health link is relatively stable across accessibility contexts.

Finally, Column (IV) adds older adults' health as a control variable based on the specification in Column (II), and the results remain qualitatively similar. Together, these results reinforce the robustness of the moderating effect and suggest that the substitution pattern operates mainly through the direct burden-reduction channel rather than by altering the local environment–health pathway.

Overall, the inclusion of the interaction term and covariates significantly enhances the model's explanatory power. The adjusted R-squared increases from 0.094 in the restricted specification (Column (I)) to 0.426 in the full moderated mediation model (Column (IV)). Across all specifications, the overall model significance is confirmed by the F-test, and the Root MSE decreases from 15.745 to 12.533 in the final model, indicating improved predictive precision and a robust fit.

Figures 5 and 6 provide a more intuitive visualization of H3, the moderating role of county accessibility. Figure 5 depicts the marginal effects of the local living environment

under two conditions—when travel to the county seat is inconvenient versus convenient. As shown, the local living environment exerts a substantial effect on reducing caregiver burden only when travel is inconvenient, whereas this effect diminishes markedly when county accessibility is high.

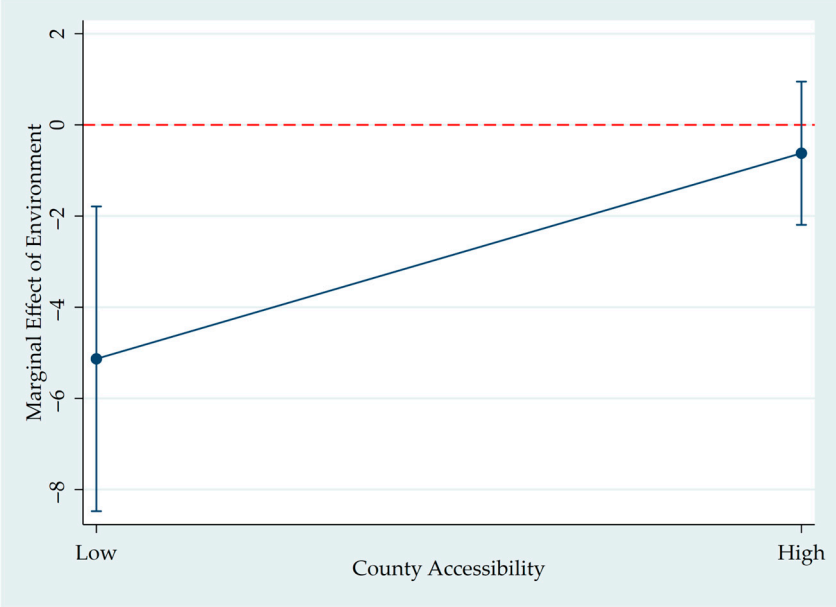


Figure 5. Marginal Effects of Living Environment under Different Levels of Accessibility. Notes: Marginal effects are estimated consistent with column (IV) of Table 7, with all other variables set to their means, 95% confidence intervals are shown.

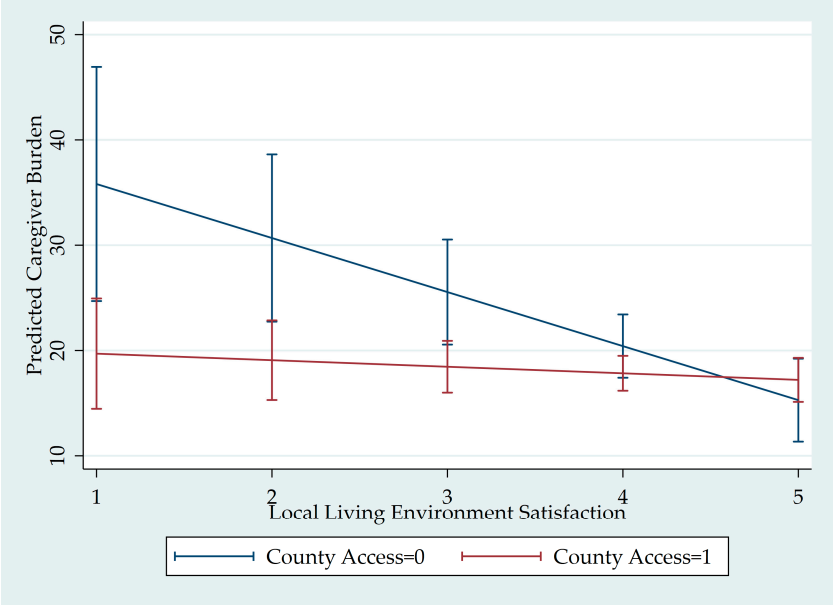


Figure 6. Predicted Caregiver Burden under Different Levels of Accessibility. Notes: Predicted scores are estimated consistent with column (IV) of Table 7, with all other variables set to their means, 95% confidence intervals are shown.

Building on the estimation results from Equation (4), we further predicted caregiver burden across different levels of living environment quality under varying degrees of accessibility, and visualized the results in Figure 6. When county accessibility is high predicted caregiver burden varies only modestly with local environmental quality, with

only narrower confidence intervals—indicating that in better environments, caregiver burden becomes more concentrated but not significantly reduced. By contrast, when accessibility is low, caregiver burden decreases noticeably as the quality of the local living environment improves, highlighting the critical role of local environmental conditions in less accessible areas.

4.3. Further Analysis

4.3.1. Dimensions of Caregiver Burden

When caregiver burden is disaggregated into five dimensions—time-dependence, developmental constraints, physical strain, social strain, and emotional strain—the association between the living environment and caregiver burden shows clear heterogeneity. As reported in Table 8, we observe the most consistent evidence for the hypothesized substitution logic (H3) in developmental constraints and physical strain. Specifically, when county accessibility is low (i.e., travel to the county seat is inconvenient), the marginal association between environmental satisfaction and caregiver burden is significantly negative in these two dimensions (−1.43 and −1.64, respectively), both statistically significant at conventional levels. However, when county accessibility is high, these marginal associations attenuate and approach zero. Consistent with this pattern, the interaction terms are positive and statistically significant, indicating that improved external connectivity weakens the association between local environmental satisfaction and caregiver burden in these dimensions—suggesting that county accessibility can substitute for local environmental supports in alleviating constraints on caregivers' personal development and reducing physical strain. In addition, the main effects of county accessibility are negative (though not statistically significant once controls are included), aligning with the idea that better access to county-level resources may ease these burdens directly.

Table 8. Relationship between Living Environment and Different Dimensions of Caregiver Burden.

	(I)	(II)	(III)	(IV)	(V)
	Time-Dependence	**Developmental**	**Physical**	**Social**	**Emotional**
Env	−0.62	−1.43 ***	−1.64 ***	−0.46	−0.98
	(0.50)	(0.50)	(0.38)	(0.47)	(0.69)
Access	−0.89	−0.16	−0.35	−0.31	−0.23
	(0.70)	(0.58)	(0.49)	(0.36)	(0.34)
Env × *Access*	0.31	1.64 ***	1.66 ***	0.12	0.79
	(0.62)	(0.57)	(0.45)	(0.49)	(070)
Health	−0.85 ***	−0.76 ***	−0.45 **	−0.37 ***	−0.29 **
	(0.27)	(0.22)	(0.19)	(0.13)	(0.14)
Caregiver Controls	Yes	Yes	Yes	Yes	Yes
Care Recipient Controls	Yes	Yes	Yes	Yes	Yes
Formal Care Control	Yes	Yes	Yes	Yes	Yes
Regional Fixed Effects	Yes	Yes	Yes	Yes	Yes
Adjusted R-squared	0.376	0.321	0.410	0.135	0.091
Prob > F	0.000	0.000	0.000	0.000	0.006
Root MSE	4.970	4.176	3.405	2.569	2.624
Observations	327	327	327	327	327

Notes: Columns (I)–(V) use specific sub-dimensions of caregiver burden (*Time-Dependence*, *Developmental*, *Physical*, *Social*, and *Emotional*) as the dependent variables. The key independent variables are *Env* (within-village living environment satisfaction), *Access* (county accessibility), and their interaction *Env* × *Access Health* denotes the care recipient's self-rated health. All models control for caregiver characteristics (gender, age, weekly caregiving hours, self-rated health, and employment status), care-recipient characteristics (gender, age, ADL score, IADL score, cognitive function score, and income), and formal care resources, and include province fixed effects. All regressions employ robust standard errors reported in parentheses. *** and ** denote statistical significance at the 1% and 5% levels, respectively.

In contrast, the main and interaction effects of the environment and accessibility are statistically insignificant in the time-dependence, social, and emotional dimensions. This suggests that these aspects of burden are more likely shaped by mechanisms such as intra-household time allocation, social support, and emotional adjustment, where the marginal short-term benefits of infrastructure or external service connectivity are relatively limited. Notably, care recipients' health remains consistently and significantly associated with lower caregiver burden across all five dimensions, indicating that the health-related pathway is robust and operates broadly across different forms of caregiving strain.

4.3.2. Dimensions of the Living Environment

Based on available survey data, we further examine the effects of five specific dimensions of the living environment—recreational facilities, cultural and entertainment activities, residential safety, sanitation conditions, and barrier-free environment—on caregiver burden. The results are reported in Table 9. It is important to note that, unlike the caregiver burden scale, the overall environmental satisfaction score is not a linear aggregation of these individual dimensions. Therefore, these indicators may not capture all aspects of how residents evaluate their surroundings; rather, their analytical value lies in identifying which types of rural environmental improvements yield the greatest marginal benefits for reducing caregiver burden. In particular, this dimension-level decomposition helps translate a broad "environment" construct into more actionable policy levers, while also revealing potential heterogeneity in which components matter most for different facets of burden.

Table 9. Associations between Dimensions of Living Environment and Caregiver Burden.

	(I)	(II)	(III)	(IV)	(V)
	Sports Facilities	**Cultural Activities**	**Residential Safety**	**Sanitary Conditions**	**Barrier-Free**
Env (*Different Aspects*)	−0.67	−2.00 *	−2.81 **	−2.98	−1.46
	(1.20)	(1.12)	(1.18)	(2.09)	(1.01)
Access	−2.42	−1.89	−2.02	−2.47	−2.79
	(1.88)	(1.86)	(1.83)	(1.83)	(1.85)
Env (Different Aspects) ×*Access*	−0.06	1.08	2.01	3.84 *	0.69
	(1.29)	(1.25)	(1.36)	(2.30)	(1.08)
Health	−2.93 ***	−2.77 ***	−2.79 ***	−2.98 ***	−2.94 ***
	(0.71)	(0.71)	(0.69)	(0.69)	(0.70)
Caregiver Controls	Yes	Yes	Yes	Yes	Yes
Care Recipient Controls	Yes	Yes	Yes	Yes	Yes
Formal Care Control	Yes	Yes	Yes	Yes	Yes
Regional Fixed Effects	Yes	Yes	Yes	Yes	Yes
Adjusted R-squared	0.376	0.321	0.410	0.135	0.091
Prob > F	0.000	0.000	0.000	0.000	0.006
Root MSE	4.970	4.176	3.405	2.569	2.624
Observations	327	327	327	327	327

Notes: Columns (I)–(V) use caregiver burden (*Burden*) as the dependent variable. Key independent variable *Env* denotes the specific dimension of the living environment being tested (*Sports Facilities, Cultural Activities, Residential Safety, Sanitary Conditions, and Barrier-free Environment*, respectively). All models control for caregiver characteristics (gender, age, weekly caregiving hours, self-rated health, and employment status), care-recipient characteristics (gender, age, ADL score, IADL score, cognitive function score, and income), and formal care resources, and include province fixed effects. All regressions employ robust standard errors reported in parentheses. ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively.

5. Discussion

Rapid population aging and persistent rural–urban disparities have made informal family caregiving a central pillar of elder care in rural areas, yet caregivers often face substantial multidimensional burden in settings where formal services and supportive

environments remain limited. This study explores feasible ways to reduce caregiver burden. Specifically, we investigate whether, and how, the rural living environment alleviates informal caregiver burden, and whether external connectivity—captured by county accessibility—conditions such effects.

Empirically, three findings stand out. First, a more favorable local living environment is robustly associated with lower caregiver burden, and this relationship operates through both a direct pathway and an indirect pathway mediated by care recipients' health, supporting H1–H2. Second, county accessibility moderates this relationship in a substitution pattern: where access to the county seat is high, the marginal burden relief from local environmental improvements is significantly attenuated, supporting H3. Third, heterogeneity matters: the substitution effect concentrates in developmental constraints and physical strain, while the health-mediated pathway is consistently meaningful across dimensions. Taken together, our results suggest that rural caregiver burden can be mitigated through dual pathways to relief: improving local living environment quality and strengthening regional connectivity.

A primary contribution of this study is to place caregiver burden within a broader ecological system. We treat burden as a comprehensive, lived experience, rather than solely as a function of caregiving tasks. Ecological systems theory emphasizes that individual well-being is shaped by nested contexts that range from immediate daily settings to broader institutions and cultural norms [63]. Applying this perspective, we shift the focus from the traditional model of caregiving that centers on the act of care and its feedback [88–90], toward a more holistic view of the caregiver's life. In this framework, the microsystem of daily care is embedded within an exosystem, through which environmental conditions translate into well-being by reducing daily frictions and uncertainty.

This perspective bridges two research traditions that have often been discussed separately: firstly, the caregiver stress/burden literature that focuses on role demands and coping [30–35], and secondly, the environment-and-well-being literature that highlights how place-based conditions shape health and daily functioning [37,38,91–93].

Furthermore, our findings regarding county accessibility introduce a dynamic, multiscalar extension to the ecologic system theory. We emphasize that we must recognize not only the separate impacts of different ecological levels but also the joint interaction between elements within the same level. Specifically, the identified substitution effect between the local village environment and regional connectivity reveals that the exosystem can be accessed beyond immediate village boundaries.

To clarify why this substitutability emerges, we employ the Sustainable Livelihoods Approach (SLA) as a complementary lens, which conceptualizes households as active agents operating under vulnerability and constraints, assembling different forms of capital/assets to pursue well-being [82,83]. Under this lens, within-village built conditions and county accessibility can both be viewed as deployable physical assets. Caregivers are therefore not purely passive recipients of environmental influence; instead, they are active agents who navigate their spatial constraints by leveraging reachable service hubs, such as county centers, to achieve caregiving and livelihood goals. In this sense, caregiver burden is a plastic state that can be strategically modified through the expansion of a household's asset portfolio.

The observed roles of local living environments and county accessibility, especially for developmental constraints, carry direct policy implications. They suggest that both place-based environmental upgrading and connectivity-based support can strengthen the sustainability of family-based care while expanding caregivers' opportunities for respite, social participation, and continued engagement in work and other developmental activities. These findings necessitate a transition toward a Social Development Approach (SDA) in

policy-making, which views welfare improvement, such as environmental interventions, as a productive social investment, therefore enhancing people's capabilities, social inclusion, and community resilience [94]. This is heightened by the rural caregiving reality observed in our sample: caregivers are themselves older on average, and nearly half simultaneously juggle work and caregiving, while formal care support remains limited. In the rural area with a large older population base and a still-weak formal care system, reducing caregiver burden is not only a family welfare issue but also a key condition for sustaining community-based eldercare.

While this study is based on a Chinese sample, the findings have broader international relevance for many middle-income and developing countries facing rapid population aging alongside rural service scarcity [55,56,60]. Because caregiver burden is shaped not only by caregiving tasks themselves but also by the living environment, feasible services, infrastructures, and social participation options within daily reach. The findings therefore point to a dual-pathway strategy for relieving caregiver burden in resource-constrained rural areas: improving local living environments and strengthening extra-local connectivity, with the appropriate mix depending on baseline accessibility and local constraints.

First, place-based improvements should prioritize caregiver-relevant environments alongside essential infrastructure. Our disaggregated analysis specifically identifies cultural and entertainment activities and residential safety as the two dimensions most consistently associated with lower burden. These domains appear to facilitate both the recipient's functioning and the caregiver's relief, effectively addressing both the direct and health-mediated components of burden observed in our results. For instance, enhancing residential safety and designing safe walkable spaces can significantly reduce the vigilance costs of caregivers while supporting the care recipient's functional independence. Moving beyond basic physical infrastructure, governments should prioritize these "soft" assets as productive social investments. This investment does not merely compensate for risk but empowers caregivers by providing social inclusion and respite, thereby transforming caregiving from a restrictive life-trap into a sustainable role that allows for individual development and continued participation in the broader community.

Second, our discovery of the substitution effect between local environment and external accessibility offers a generalizable framework for "aging-in-place" strategies in resource-constrained settings worldwide. It suggests that where large-scale, universal infrastructure upgrades are fiscally prohibitive, strategic investment in regional connectivity can serve as an effective welfare bypass to support informal care systems. China's policy practices, such as strengthening county–town–village linkages through the development of service hubs (e.g., "central towns") [44,95] and relocating households from severely disadvantaged locations ("relocation-based poverty alleviation") [96,97] provide illustrative experiences aligned with this enabling logic: they seek to reduce spatial frictions by reorganizing access to services and opportunities, which parallels the mechanism highlighted in our results. Similar hub-and-link approaches can be considered, with careful attention to local feasibility and equity, in other countries facing geographically dispersed ageing populations and constrained care systems.

Despite these contributions, several limitations warrant caution. The analysis is based on cross-sectional survey data, which restricts causal interpretation. Although we mitigate potential reverse causality by measuring environmental satisfaction from care recipients rather than caregivers, unobserved confounding may still bias the estimates. Further, the dataset does not allow a detailed empirical examination of macrosystem- and chronosystem-specific mechanisms, such as cohort shifts in caregiving norms or long-run institutional and demographic changes shaping care trajectories. Finally, while the sampling strategy was designed to ensure representativeness of the rural older population within the sampled

provinces, CRAS does not constitute a nationally representative sample. Therefore, when extrapolating our conclusions to other regions or countries, it is important to account for contextual background conditions.

6. Conclusions

In this study, we follow the guidance of ecological system theory and build the model to improve the understanding of influence factors for caregiver burden. Using matched caregiver–care recipient survey data from rural China, we find that more favorable local living environments are robustly associated with lower caregiver burden through both a direct pathway and an indirect pathway mediated by care recipients' health. We also identify a moderating, substitution pattern in which the marginal burden-relief effect of local environmental improvements becomes weaker when county accessibility is high. These findings hold significance for both China and other middle-income and developing nations facing rapid population aging and rural service scarcity; it implies that policies can relieve caregiver burden through two complementary routes, improving within-village living environments and strengthening extra-local connectivity, with the appropriate mix depending on baseline accessibility and local constraints.

These insights speak to broader development goals. By improving functional health and reducing the multidimensional strain on family members, these interventions advance SDG 3 regarding good health and well-being for all ages. The substitution mechanism specifically addresses SDG 10 by narrowing the welfare gap for households in remote areas through enhanced regional connectivity and a spatial safety net. In practical terms, this can be implemented by strengthening county–town–village linkages and service hubs like "central towns", increasing the frequency and reliability of village-to-county public transport, and extending logistics and parcel-delivery networks to township and village node. These concrete measures reduce the time and coordination costs of reaching county-level services and enable caregivers to mobilize extra-local resources when within-village supports are constrained. Furthermore, the emphasis on creating safe, participatory, and inclusive rural spaces supports SDG 11 by ensuring that aging in place remains a viable option for rural communities within the global development agenda.

Future research should further explore environment-related determinants and heterogeneity in caregiver burden, especially given the modest overall model fit, which suggests that additional environmental factors may remain unmeasured—particularly "soft" dimensions such as digital inclusion, social trust, and opportunities for social participation, and how these operate across cultural and institutional contexts. Moreover, to strengthen causal interpretation and to better assess the effectiveness of practical interventions, longitudinal designs and quasi-experimental strategies are needed, for example to evaluate targeted transport-service expansions, or logistics-network extensions. In addition, pairing subjective satisfaction measures with objective environmental indicators (e.g., geocoded amenities, transport connectivity, safety incidents, and service availability) would provide stronger triangulation of the mechanisms through which physical and social spaces influence the life-course care system. Such efforts can help identify the most targeted and cost-effective levers for supporting ageing populations while protecting the development opportunities of informal caregivers.

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Informed Consent Statement: Informed consent for participation was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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Abbreviations

The following abbreviations are used in this manuscript:

ADL	Activities of Daily Living
BIC	Burden Index of Caregivers
CBI	Caregiver Burden Inventory
CRAS	China Rural Aged Care Survey
IADL	Instrumental Activities of Daily Living
KMO	Kaiser-Meyer-Olkin
LTCI	Long-Term Care Insurance
TRSE	Transport-Related Social Exclusion
SDA	Social Development Approach
SLA	Sustainable Livelihoods Approach
VIF	Variance Inflation Factor
ZBI	Zarit Burden Interview

Appendix A. Supplementary Figures on Variable Distributions

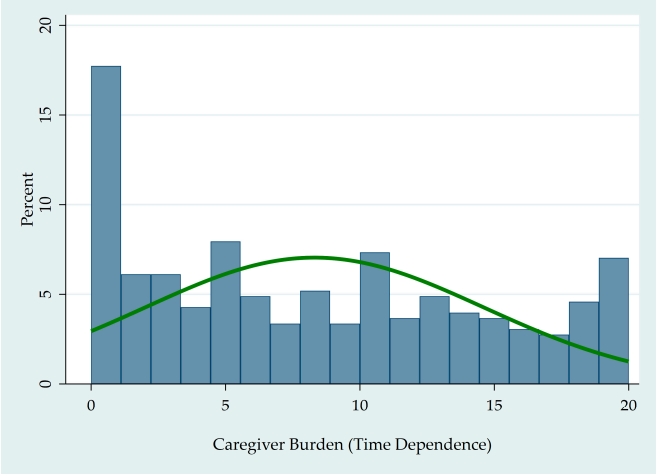


Figure A1. Distribution of Time-Dependence Burden.

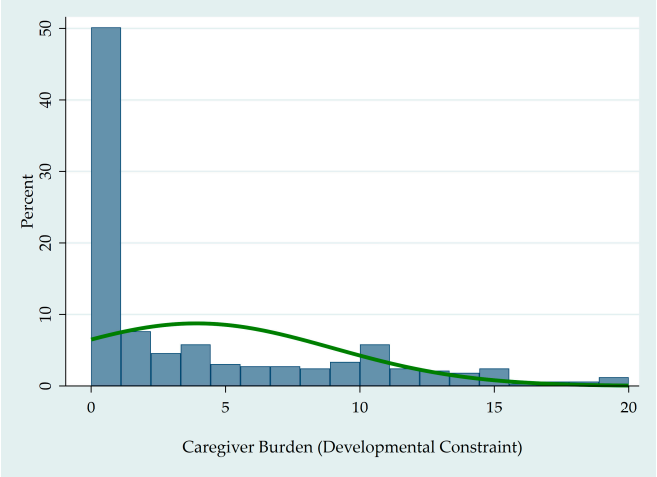


Figure A2. Distribution of Development Constrain Burden.

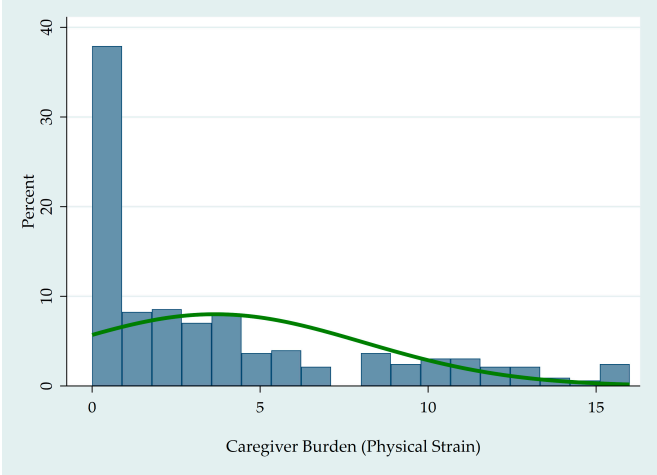


Figure A3. Distribution of Physical Strain.

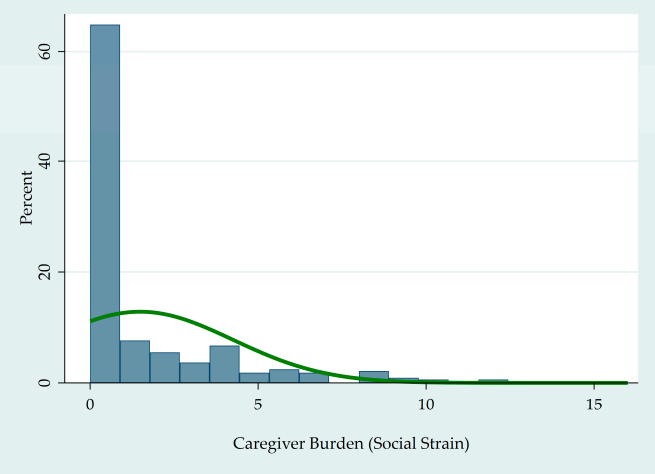


Figure A4. Distribution of Social Strain.

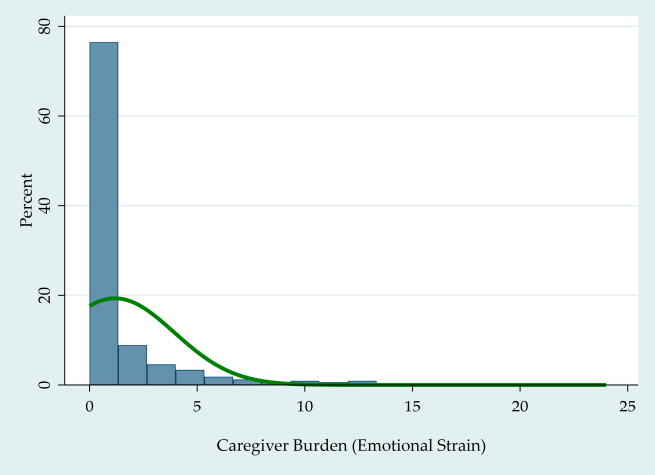


Figure A5. Distribution of Emotional Strain.

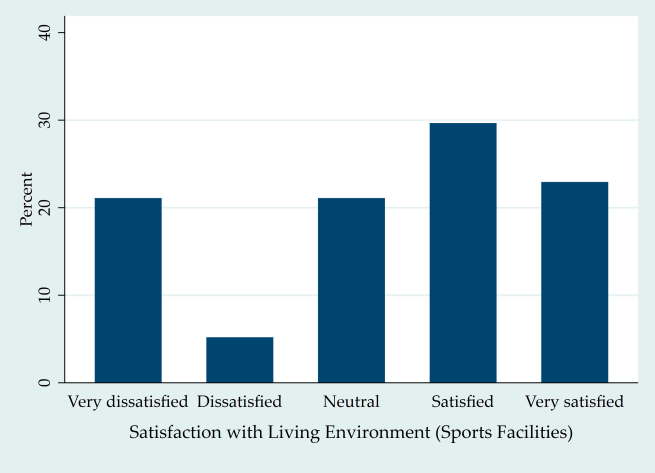


Figure A6. Distribution of Satisfaction with Sports Facilities.

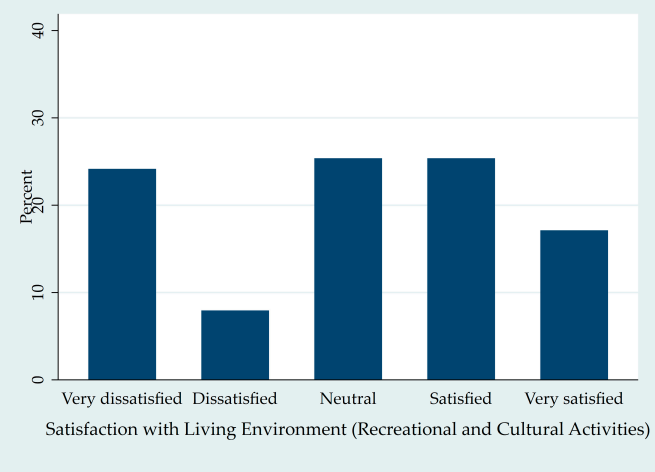


Figure A7. Distribution of Satisfaction with Recreational and Cultural Activities.

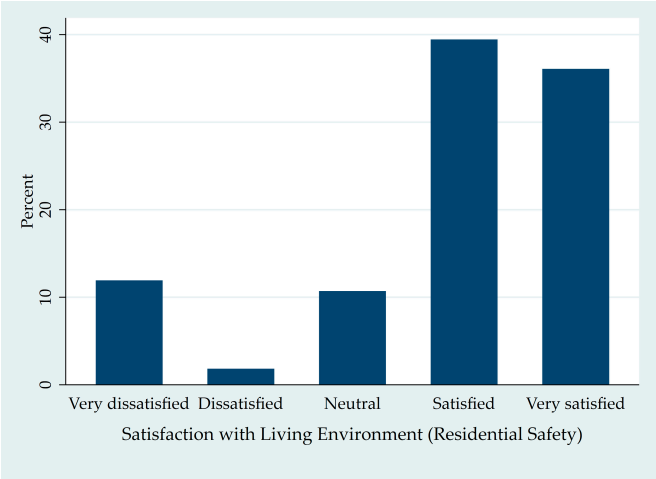


Figure A8. Distribution of Satisfaction with Residential Safety.

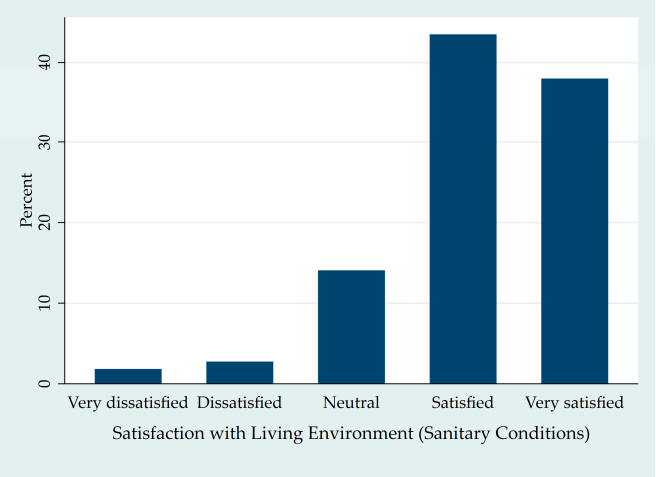


Figure A9. Distribution of Satisfaction with Sanitary Conditions.

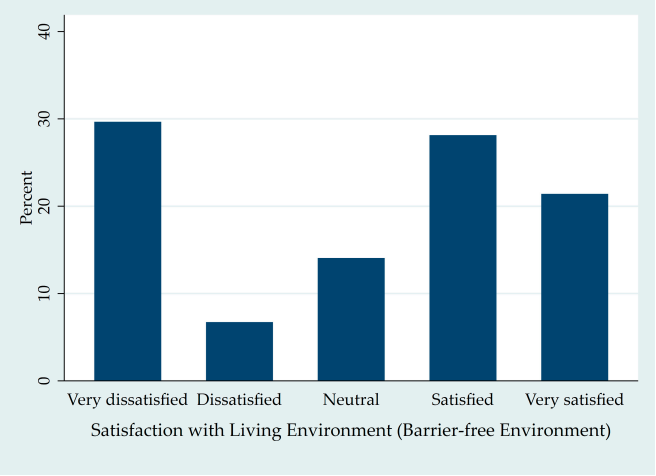


Figure A10. Distribution of Satisfaction with Barrier-free Environment.

Appendix B. Detailed Regression Results

Table A1. Detailed Basic Model Results.

	(I)	(II)	(III)	(IV)
	Burden	***Burden***	***Health***	***Burden***
Env	−3.22 ***	−2.66 ***	0.16 **	−2.21 **
	(1.18)	(0.92)	(0.06)	(0.89)
Health				−2.84 ***
				(0.69)
Caregiver Characteristics				
Female		−1.60	0.23	−0.93
		(1.76)	(0.15)	(1.66)
Age		−0.13 **	0.00	−0.12 **
		(0.06)	(0.01)	(0.06)
Work		−1.64	−0.05	−1.79
		(1.75)	(0.16)	(1.66)
Health Status		−4.65 ***	0.26 ***	−3.92 ***
		(0.82)	(0.06)	(0.82)
Weekly caregiving Hours		0.04 ***	−0.00	0.04 ***
		(0.02)	(0.00)	(0.02)
Care Recipient Characteristics				
Female		0.71	0.05	0.85
		(1.68)	(0.15)	(1.62)
Age		−0.10	0.03 ***	−0.01
		(0.10)	(0.01)	(0.10)
ADL Score		−0.23 ***	0.01 ***	−0.20 ***
		(0.05)	(0.00)	(0.05)
IADL Score		−0.26 ***	0.01 *	−0.23 ***
		(0.08)	(0.01)	(0.08)
Cognitive Score		−0.09	0.01	−0.05
		(0.20)	(0.02)	(0.20)
Elderly Income		0.03	0.01	0.05
		(0.07)	(0.01)	(0.07)
Formal Care Resources				
Elder Care Services		−0.29	0.08 *	−0.06
		(0.54)	(0.05)	(0.53)
Regional Fixed Effect				
Eastern Region		2.04	−0.08	1.82
		(2.41)	(0.21)	(2.39)
Central Region		−2.04	0.11	−1.72
		(2.04)	(0.16)	(1.97)
Mediating Effect				−0.45 **
				(−2.14)
Direct Effect				−2.21 **
				(−2.55)
Total Effect				−2.66 ***
				(−2.95)
Adjusted R-squared	0.031	0.379	0.181	0.412
Prob > F	0.007	0.000	0.000	0.000
Root MSE	16.287	13.033	1.078	12.688
Observations	327	327	327	327

Notes: ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively.

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