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Mapping environmental risk profiles of mental disorders among children and adolescents in Yunnan: constructing nature-integrated spaces for resilience

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1. Introduction

Mental disorders are a serious public health problem worldwide. The number of individuals with mental disorders increased 48.1 % from 654.80 million to 970.1 million from 1990 to 2019(Ferrari, 2022), and the economic burden of mental disorders was estimated to be over 4 trillion dollars every year(Arias et al., 2022). The number of children and adolescents(< 20 years old) with mental disorders was estimated to be 230 million in 2019(Piao, 2022). Because mental disorders often last for a long time, their early onset in childhood and adolescence may hinder the transition to a healthy adulthood and pose a direct threat towards an individual's future health and well-being. Mental disorders are linked to various negative outcomes, including poor educational performance, substance abuse, unemployment, and increased crime rates. If remain untreated, mental disorders could generate negative social and economic consequences, including decreased economic productivity, elevated high school dropout rates, homelessness, and incarceration(Erskine, 2015; Kieling, 2024). As such, a better understanding of factors influencing mental disorders among children and adolescents is of great public health significance.

Research on youth's mental health has expanded from biological and social dimensions in recent decades, from physiological mechanisms (Tarokh et al., 2016), violence exposure (particularly sexual violence and bullying)(Martinez, 2024; Jang et al., 2024), parenting styles(Tang et al., 2021), and major socioeconomic factors(Torche et al., 2024) to environmental determinants(de Figueiredo, 2021). Current studies of environmental factors focus primarily on green and blue spaces in residential areas(White, 2021; Helbich, 2019). Many cross-sectional and longitudinal studies have shown that exposure to vegetation enhances mental health via several pathways. These pathways include natural

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visual relief from stress and mental fatigue(Dzhambov et al., 2018; Triguero-Mas, 2017); encouragement of physical activity(van den Berg, 2019), filtration of harmful pollutants such as particulate matter and noise,(Rey Gozalo et al., 2018; Klingberg et al., 2017) and improvement of social cohesion within neighborhoods(de Vries et al., 2013). However, the environmental influences on mental health exhibit multidimensional characteristics that were not fully explained by vegetation coverage alone. Recent research has begun to focus on additional environmental factors, such as altitude and humidity. The unique hypoxic conditions at varying altitudes may produce distinct neurophysiological effects. While acute severe hypoxia exposure was shown to lead to neurological disorders and cognitive impairment(Daulatzai, 2015); intermittent mild hypoxia can induce cellular and physiological adaptations that increase resistance to subsequent hypoxic damage(Burtscher et al., 2021; Navarrete-Opazo and Mitchell, 2014). In existing animal studies, mild to moderate hypoxia has produced significant antidepressant-like effects in multiple rodent models(Zhu, 2010). However, current adult studies have only demonstrated correlations, and corresponding validation in pediatric and adolescent populations remains lacking. In recent years, how humidity influences health outcomes has attracted growing research attention. As another critical environmental factor, humidity is directly related to individuals' comfort. Studies indicate that low humidity levels can exacerbate mucosal symptoms, including eye dryness and fatigue, thereby impairing cognitive performance and inducing mood disturbances(Wolkoff et al., 2021). However, the specific mechanisms through which humidity affects mental disorders in children and adolescents require further clarification. Although environmental research has established positive impacts of vegetation(Helbich, 2019; Ulrich, 1984), current studies have not adequately examined the complex interactions between the normalized difference vegetation index (NDVI, a widely used metric derived from remote sensing data that quantifies the health and density of vegetation), humidity, and altitude on children and adolescents. We correlate NDVI, relative humidity and altitude to visual naturalness, microclimate comfort and multisensory experience to study the effects of nature on adolescent mental health. According to Ulrich's stress-recovery theory, humans possess an evolutionarily shaped biophilic inclination toward natural landscapes. When individuals are exposed to non-threatening natural settings, they tend to experience positive emotional states(Ulrich, 1983). Existing research indicates that exposure to relevant natural landscapes can reduce subjective stress in children and adolescents, a specific demographic. The direction of this effect aligns with predictions from the stress recovery theory, though evidence remains more fragmented compared to studies involving adults. Subsequent research has extended the application of stress recovery theory to this demographic to validate its generalizability, analyzing this association from the perspective of sensory experiences(Korpilo, 2024; Zhang, 2024). First, several investigations have highlighted the visual influence of natural environments(Brown et al., 2013). In this context, naturalness is commonly used to describe the degree to which a landscape approximates an unmodified natural state, whereas visual naturalness denotes the extent to which a scene visually resembles pristine nature(Purcell and Lamb, 1998; Roth, 2006). Second, scholars have examined microclimatic comfort, defined as the state of thermal satisfaction experienced by the human body within a small-scale climatic environment(Guo and Liu, 2022); this comfort is typically governed by wind speed, humidity, and temperature. Third, a growing body of work assesses environmental impacts from a multisensory perspective, exploring how settings shape vision, touch, smell, and other sensory modalities simultaneously(Qu and Ma, 2024). Despite these advances, existing research remains fragmented: few studies have integrated microclimatic comfort and multisensory experience into a unified spatial framework, and biophilic design—that is, the deliberate incorporation of humans' innate affinity for nature—has yet to be systematically applied.

Yunnan, a southwestern border province of China, possesses significant altitudinal gradients and ecological representativeness. This study investigated youth mental disorders in Yunnan Province through school-based two-stage PPS randomized whole-cluster sampling, resulting in multicenter cross-sectional data. We then developed gradient models incorporating five key factors that influence mental health: sociodemographic characteristics, family environment, social support, lifestyle behaviors, and educational settings. These models systematically characterized the environmental influences on mental disorders within different dimensional frameworks. A unique contribution of this study was the simultaneous inclusion of NDVI, humidity, and altitude as key environmental variables. Our analysis explored the combined effects of these multidimensional environmental factors on various mental health outcomes. We further analyzed the heterogeneous impacts of the NDVI levels, different humidity ranges and altitude zones on the psychological well-being of youth. Building upon the stress recovery theory, this research conceptualized optimal mental microenvironments through three critical dimensions: visual naturalness, microclimate comfort, and multisensory experiences (Fig. 1). This study aims to provide scientific evidence for mental health screening protocols tailored to children and adolescents living in specific environmental exposure regions.

2. Methods

2.1. Study design, data sources and study population

A prospective study was conducted in Yunnan Province, China, to examine the impact of complex environmental features on youth mental health. Yunnan Province showcases a diverse range of environmental conditions, featuring a variety of tropical, subtropical, temperate, and cold-temperate vegetation. It has complex topography with karst landscapes in the east and deep canyons in the west.

Structured mental disorders questionnaires were collected from 44,153 children (aged 9–14) and adolescents(aged 14–19) from 16 cities and towns in Yunnan Province from October 2023-June 2024 using school-based two-stage PPS randomized whole-cluster sampling. After excluding participants with missing addresses and missing data, the final study sample includes 37,343 participants and geocoded participants' residential addresses at baseline. The study protocol received approval from the Institutional Review Board of the First Affiliated Hospital of Kunming Medical University (Approval No. 2023-L-210).

2.2. Mental health

Participants completed four mental health questionnaires, including the PHQ-9 scale(Spitzer et al., 1999), the GAD-7 scale(Spitzer et al., 2006), the Colombian Suicide Severity Rating Scale(Posner, 2011), and the MDQ scale(Hirschfeld, 2000). The PHQ-9 (9 items, each assessing a symptom of depression based on the DSM-5 criteria) and GAD-7 (7 items, each assessing a symptom of generalized anxiety) scales assessed the occurrence of depression and anxiety in the past two weeks, with responses including not at all (0), a few days (1), more than half the time (2), and almost every day (3). The score greater than or equal to 10 indicates that the participant had moderate or severe depression or anxiety. The suicidal behaviors part of Colombian Suicide Severity Rating Scale assesses the participant's situation regarding life and death in the past month, with responses including yes (0) versus no (1), and a score greater than or equal to 3 suggests a positive screen for suicidal behavior severity. The MDQ scale is a 13-item assessment scale used to identify bipolar disorder (BD), with responses including yes (0) versus no (1). BD is considered if the subjects answer ' yes ' to seven or more questions in F1-F13, or answer ' yes ' to F14 and answer ' moderate disorder ' or ' severe disorder ' to F15.

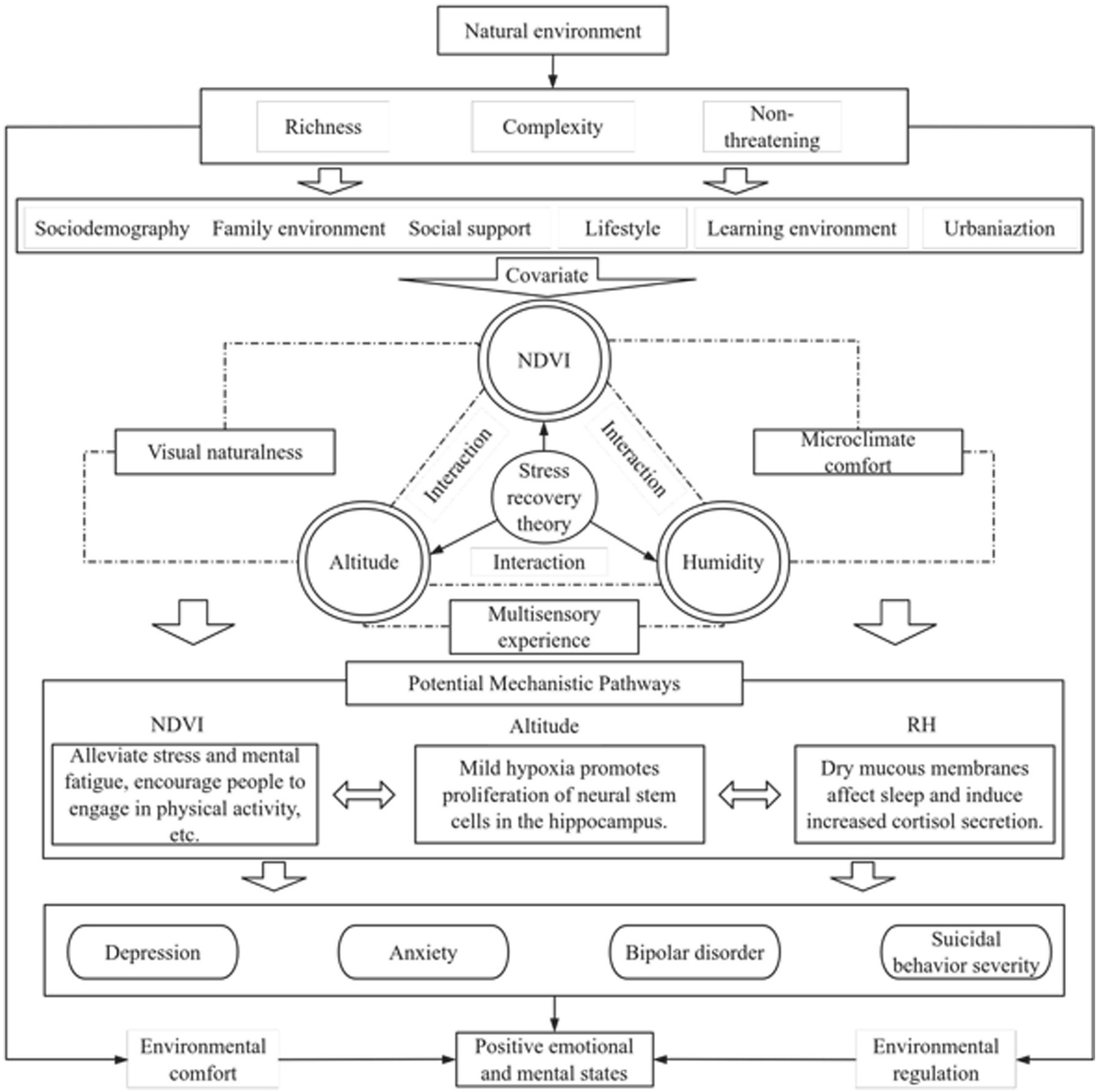

Fig. 1. Environmental impact mechanism map based on the stress recovery theory.

2.3. Environmental exposure assessment

The study collected and geocoded the addresses of participants' home residences. The average annual exposure of vegetation coverage, humidity, and altitude in the circular Euclidean buffer zone (500 m, 1000 m) was evaluated, centered around the geocodes of participant's residential address. Due to the potentially time-cumulative and delayed impact of environmental factors, environmental data were measured in the year before the baseline survey. The level of vegetation coverage was assessed based on the Normalized Difference Vegetation Index (NDVI), a greenness indicator based on surface albedo. This index ranges from −1.0 to 1.0, with values closer to 1 indicating higher vegetation density. Humidity levels around individuals were measured using relative humidity (RH), which is the ratio of absolute humidity to saturated absolute humidity under the same temperature and pressure conditions. Altitude were measured using a digital elevation model, with height measures removing building and tree height bias(Hawker, 2022). Data sources and resolutions are shown in the Appendix Table S2. Based on the 15-minute community concept, we selected environmental exposure levels within a 5- to 10-minute walking distance (500 m) as our main analysis indicator. Data processing was performed using ArcGIS software (version 10.8.1), ArcGIS pro software (version 3.1.6) and Python (version 3.12).

2.4. Covariates

All covariate data were derived from the variables recorded in the initial section of the questionnaire. We included five-dimensional covariates to capture real-world influences outside of the natural environment that may affect youth mental health. The covariates included: socio-demographic characteristics (age, sex, ethnicity, household income, and school grade level); family environment (whether parents were alive, parental education levels, quality of the inter-parental relationship, marital status of parents, relationship between the individual and parents, and whether the individual was the only child); social support (relationship with others, whether participants had someone to talk to, and the number of people available for support); lifestyle and behavioral characteristics (smoking, drinking, physical activity ability, frequency of physical activity, and physical health status); learning environment (whether participants lived at school and their academic performance); and urbanization level (population density).

2.5. Statistical analysis

Descriptive analyses of covariates and environmental exposure variables were performed for all subgroups of participants who screened positive for mental disorders. We used logistic models to estimate associations between environmental exposures and mental health outcomes. We used mental disorders screening results (positive screening) as the outcome variable in our model. RH was included in the study as a continuous variable, and NDVI and altitude were included as categorical variables by natural breakpoint method (Appendix Table S3). Based on a priori theoretical assumptions about the relationship between covariates and health outcome variables, we developed six models for stepwise inclusion. Model 1 included core environmental explanatory variables (NDVI, RH, and altitude). Model 2 adjusted for sociodemographic factors. Model 3 adjusted for family environmental factors. Model 4 incorporated social support factors. Lifestyle and behavioral factors were adjusted in Model 5. Learning environment factors were adjusted in Model 6, and urbanization level factor in model 7. In addition, interaction terms were introduced in the fully adjusted models to estimate the potential interactive influences of NDVI, RH and altitude levels on mental health. Finally, a cross-stratified analysis of heterogeneity in core environmental factors was conducted.

In sensitivity analyses, we explored the association between NDVI, RH, and altitude exposure in the 1000 m living circle and participants' mental health and examined the covariance of all environmental variables at the 500 m and 1000 m buffer thresholds. To avoid the influence of potential confounding association, we fitted bi-exposure and triple-exposure models to assess the role of environmental exposure factors on mental health. Additionally, we incorporated different vegetation types into Model 8 and included nighttime light levels as a negative control in the analysis to avoid confounding effects from varying vegetation types and potential urbanization. Finally, an analysis of the severity of mental disorder in relation to the level of environmental exposure was conducted to understand the environmental exposure impact on disease severity. All analyses were performed in R software (version 4.4.3) and Stata software (version 17.0).

3. Results

3.1. Demographic characteristics

A total of 37,343 children and adolescents were included in this study, of which 48.64 % were children and 51.36 % were adolescents. The baseline information of all participants was presented based on the results of mental illness screening. The overall positive detection rate of was 23.1 % for depression, 14.5 % for anxiety, 1.4 % for BD, and 11.3 % for suicidal behavior severity (Appendix Table S4).

3.2. Environmental distribution and positive detection rate by city in Yunnan Province at the municipal level

At the municipal level in Yunnan Province, the distribution of NDVI, RH and altitude is intermixed between regions, and the positive detection rate of mental disorders also showed regional differences. Overall, the positive detection rate of mental disorders in Nujiang, an area with the high altitude(1861.22–3484.46), low NDVI(0.15–0.59) and moderate RH(71.94,81.57), is much higher than that in other areas. Specifically, the positive detection rates of depression, anxiety, bipolar disorder and suicidal were 45.59 %, 33.3 %, 4.98 % and 19.54 %, respectively in Nujiang area. Additionally, Lincang, Baoshan and Dehong, which are located in the moderate and low altitudes (108.28–2400.32) with moderate and high NDVI(0.53–0.78) and RH (66.70–81.57), also exhibited higher detection rates of mental disorders, with distribution primarily concentrated in western Yunnan. By contrast, Zhaotong, an area with low and moderate altitude (108.28–1861.22) with moderate and high NDVI(0.53–0.78) and RH (66.70–81.57), showed low mental health detection rates: 14.79 % for depression, 9.13 % for anxiety, 0.64 % for BD, and 6.2 % for suicidal behavior severity. Additionally, Lijiang and Dali, two areas with moderate and high altitudes(1399.74–3484.46), NDVI(0.53–0.78), and moderate RH(66.70–76.50), showed lower rates of mental disorders. The remaining areas had similar overall rates of mental disorder detection. (Fig. 2).

3.3. Distribution of environmental factors

Participants with positive detections of mental disorders under different environmental factors showed differential distributions. The NDVI distribution was mainly concentrated between 0.2 and 0.65, with depression, anxiety and suicidal behavior severity reaching a peak at 0.45. The overall distribution was approximately normal. At different altitudes, the positive mental disorders were mainly concentrated between 0.25–0.6 and peaked at 0.52 (1870 m above sea level), showed an overall near-normal distribution. By contrast, under different RH, the distribution of mental disorders was concentrated between 0.6–0.8 and peaked at 0.69, and overall showed a skewed distribution with multiple peaks (Fig. 3).

3.4. Association between environmental factors and mental disorders

Regression models with stepwise inclusion of covariates showed a partially significant association between environmental factors and mental disorders (Fig. 4, Appendix Table S6). Specifically, individuals living in areas with NDVI levels above 0.47 had a lower risk of depression and suicidal behavior severity compared with areas with NDVI levels below 0.47, with the OR values of 0.895 (0.826–0.970) and 0.821 (0.740–0.912), respectively. Increased vegetation cover was not negatively associated with depression in areas with NDVI less than 0.47, suggesting a potential risk threshold for the effect of low NDVI levels. Regarding RH levels, individuals exposed to higher ambient RH had a reduced risk of depression, BD, and suicidal behavior severity compared with those in drier environments, with the OR values of 0.988 (0.982–0.994), 0.976 (0.959–0.994), and 0.976 (0.969–0.984), respectively. Regarding altitude, the risk of depression, anxiety, and suicidal behavior severity was lower at moderate altitude relative to low altitude, with fully adjusted OR values of 0.887 (0.810–0.971), 0.835 (0.754–0.925), and 0.788 (0.702–0.884), respectively. However, after adjusting for lifestyle and behavioral factors, the relationship became non-significant at higher altitudes. This suggests that socio-demographic factors, family environment, and social support attenuate the relationship between altitude and mental disorders to some extent.

3.5. Association between interactive environmental factors and mental disorders

Based on the bivariate and trivariate results (Appendix Table S7, S8), no significant changes in the coefficients were found, as such we performed an interaction analysis (Fig. 5, Appendix Table S9). In the interaction between NDVI and RH, the risk of depression (OR = 0.98,0.97–1.00) and suicidal behavior severity (OR = 0.98,0.96–1.00) showed by NDVI below 0.47 was lower in a higher humidity environment. NDVI levels above 0.47 were no longer significant in reducing the risk of depression and suicidal behavior severity, suggesting that high levels of NDVI and humidity have a saturating effect on mental disorders. The combination of altitude and NDVI synergistically reduced the risk of anxiety and suicidal behavior severity. The protective association of medium altitude and high RH with depression, anxiety and suicidal behavior severity was relatively weak, with ORs of 0.96 (0.94–0.99), 0.94 (0.91–0.97), and 0.96 (0.93–0.99), respectively.

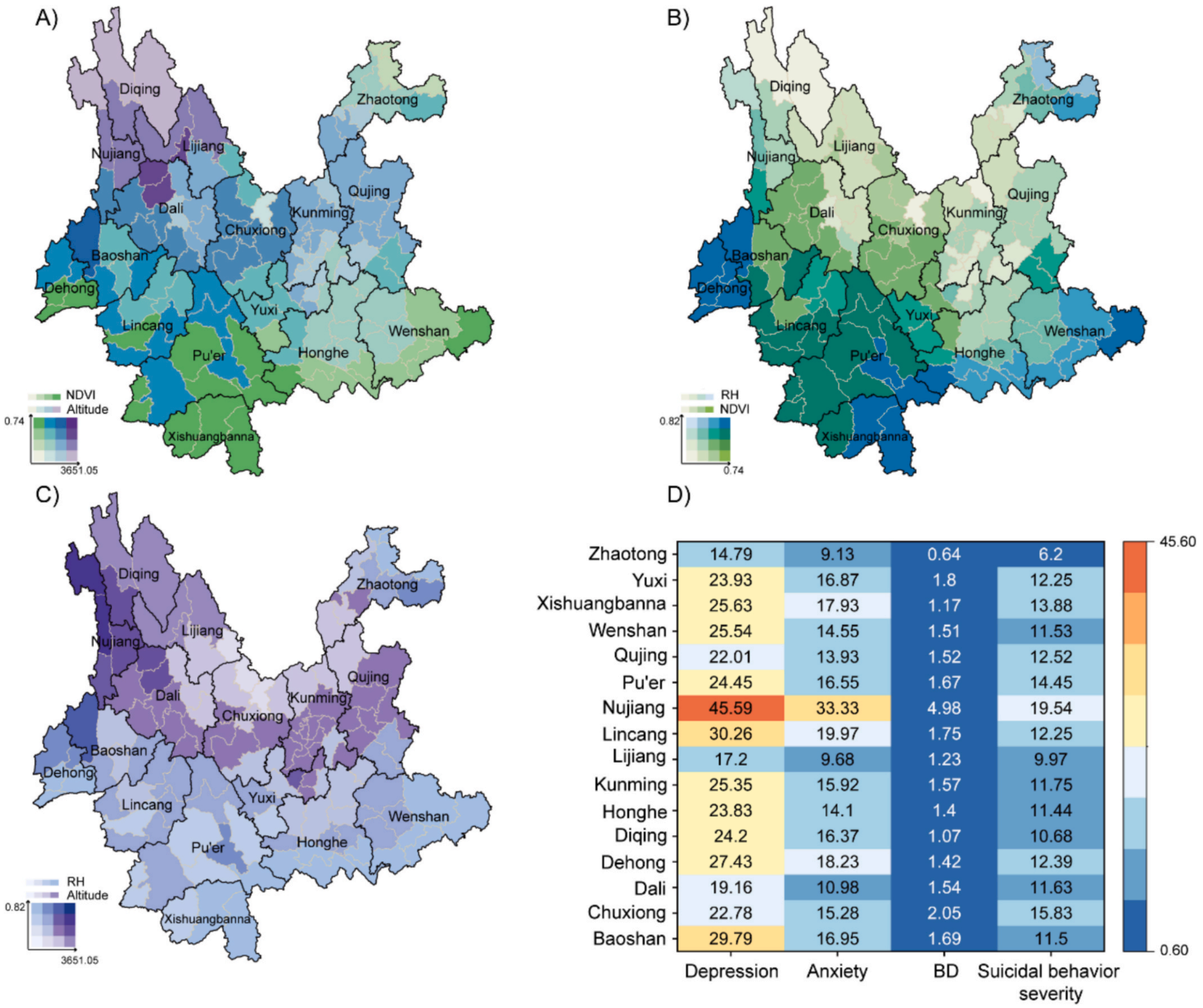

Fig. 2. The distribution of the bivariate environmental map in Yunnan Province, as well as the detection rates of mental disorders in various cities. Figure A shows a bivariate map of NDVI* Altitude. Figure B is a bivariate map of RH*NDVI. Figure C is a bivariate map of RH*Altitude. Figure D shows the screening rate of depression, anxiety, BD and suicidal behavior severity by municipality.

3.6. Heterogeneity analysis

The hierarchical model revealed marked heterogeneity in the effects of greenness (Fig. 6; Appendix Table S10). Within moderately green areas (NDVI 0.37–0.47), higher RH consistently correlated with lower probabilities of mental disorders. This effect was particularly pronounced for depression and suicidal behavior severity, while anxiety showed a smaller but similarly directional reduction. Conversely, when NDVI $\geq$ 0.47, the additional reduction in depression or anxiety disappeared with increasing RH, consistent with diminishing marginal returns observed under high RH and high NDVI conditions. Additionally, at NDVI values of 0.37–0.47, middle altitude areas exhibited stronger protective associations compared to low altitude areas. Conversely, in environments with low vegetation cover (NDVI $<$ 0.37), increasing altitude corresponded with an upward trend in suicidal behavior severity risk.

3.7. Sensitivity analysis

The sensitivity used the living circle of 1000 m instead of 500 m. The results show a general agreement in the main results (Appendix Table S13). Specifically, the protective association with higher NDVI, humidity, and moderate altitude remained robust. The ORs below the moderate NDVI still suggest the existence of a risk threshold, although not significant. We also performed a correlation analysis (Appendix Table S11) and found that buffer-scale changes in NDVI and elevation showed strong correlations, whereas humidity showed lower correlations, suggesting that RH varied more at regional scales, but its protective effect on mental disorders remained robust after regression treatment. After incorporating grassland, shrubland, and forest composition within a 500 m buffer zone (Model 8, Appendix S15), the results remained robust. NDVI continued to indicate protective effects, with effect sizes broadly comparable. As an additional check for residual urbanization confounding, we used nighttime lights as a core explanatory variable (Appendix Table S18, S19). The 500 m and 1000 m exposure results showed that nighttime lights exhibited an independent risk signal with an opposite direction, suggesting that even in the presence of residual confounding, its impact on the core conclusions of NDVI is minimal, and our main findings remain robust.

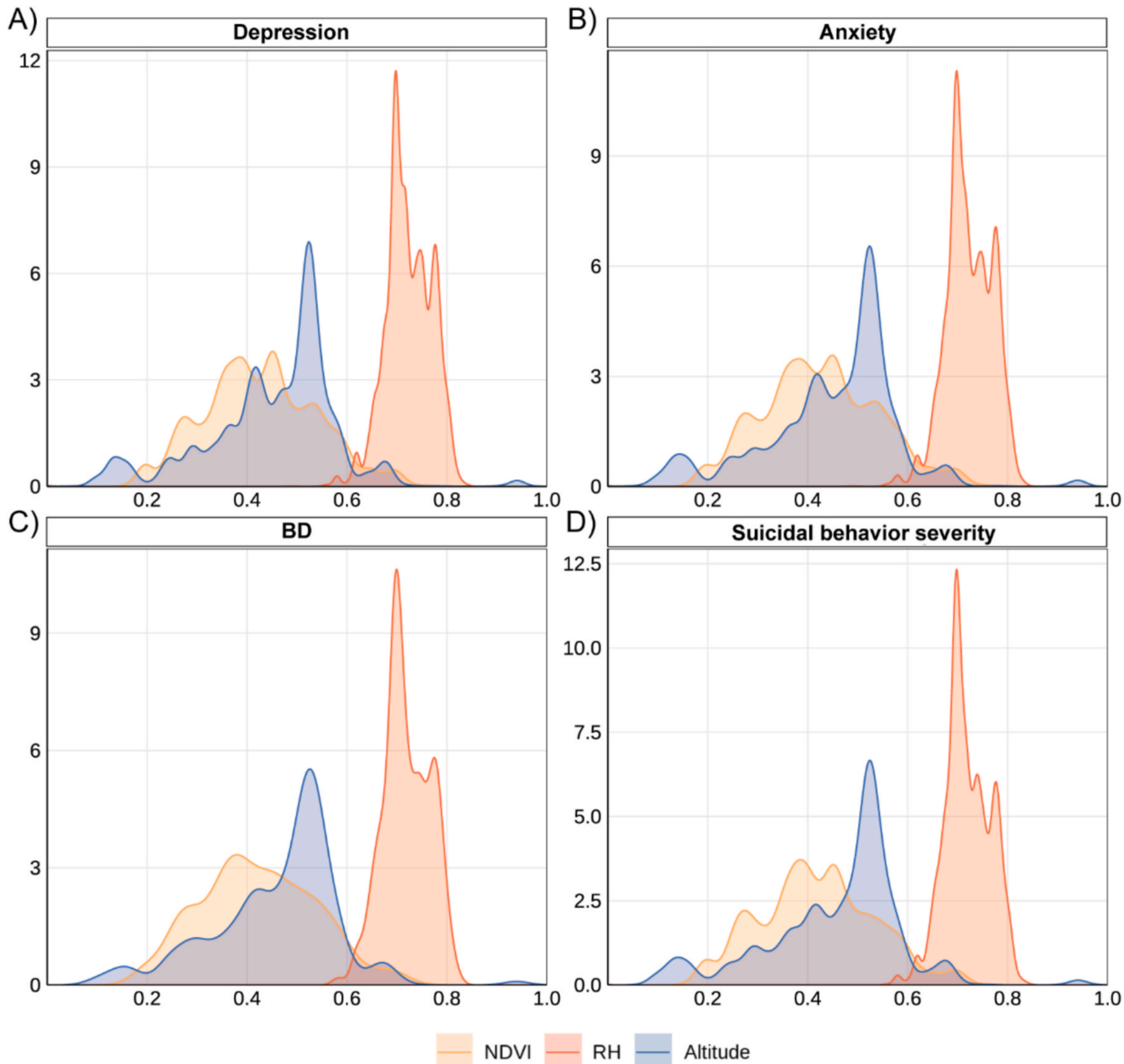

Fig. 3. The distribution of the positive detection rates of different mental disorders under varying environmental factors.

4. Discussion

This study combines stress recovery theory with visual naturalness, microclimate comfort, and multisensory experience to explore the pathophysiological mechanisms of NDVI, humidity, and altitude on mental health in children and adolescents in Yunnan. This study created an environmental feature map of the risk of mental disorders for this vulnerable group. The key findings are: First, the association between NDVI and depression in children and adolescents was stronger in the NDVI range of 0.37–0.47 than in the range of 0.15–0.37. When NDVI increased beyond 0.47, however, the relationship shifted toward a stronger inverse (protective) association with depression. This indicates a nonlinear pattern between NDVI and mental disorders. Second, environments with high RH and high NDVI did not show a stepwise increase in protection. Instead, the data suggest diminishing marginal returns. Finally, an altitude of 1180–1730 m, together with high NDVI, was associated with a lower risk of mental disorders.

4.1. Risk of mental disorders in children and adolescents with different environmental exposures

Children and adolescents are susceptible to psychological crises because their central nervous system is in a vulnerable developmental window relative to adults. So any stressful challenges that occur at this time can trigger short- and long-term physiological responses, cognitive and behavioral impairments(Danese, 2009). Previous studies on NDVI in children and adolescents have shown that high NDVI reduces the risk of depression, which is consistent with the results of this study (OR:0.895, 95 % CI:0.826–0.970). However, the results in our study show that an increase in NDVI levels when NDVI levels were below 0.47 did not show a single linear protective effect for depression (OR:1.112, 95 % CI:1.035–1.194). Compared with the NDVI levels of 0.37–0.47, the levels of 0.15–0.37 showed a protective association(Banay, 2019; Liu, 2023).

In general, NDVI levels in the range of 0.15–0.37 were dominated by open meadows and sparse forests. These environments typically feature more abundant sunlight, better air circulation, and expansive views. Adequate sunlight exposure inhibits vitamin D synthesis-a key factor in depression, as low vitamin D levels are a significant contributor to the condition. This type of environment offers better sunlight, improved air circulation and a broader view, which can help reduce the risk of mental illnesses like depression by hindering vitamin D synthesis and other mechanisms(Alfredsson, 2020). However, dense and low shrubs (0.37–0.47 levels) pose a potential environmental threat to children, and their sharp branches are likely to cause physical harm, and sometimes even lead to lasting psychological trauma to youth.

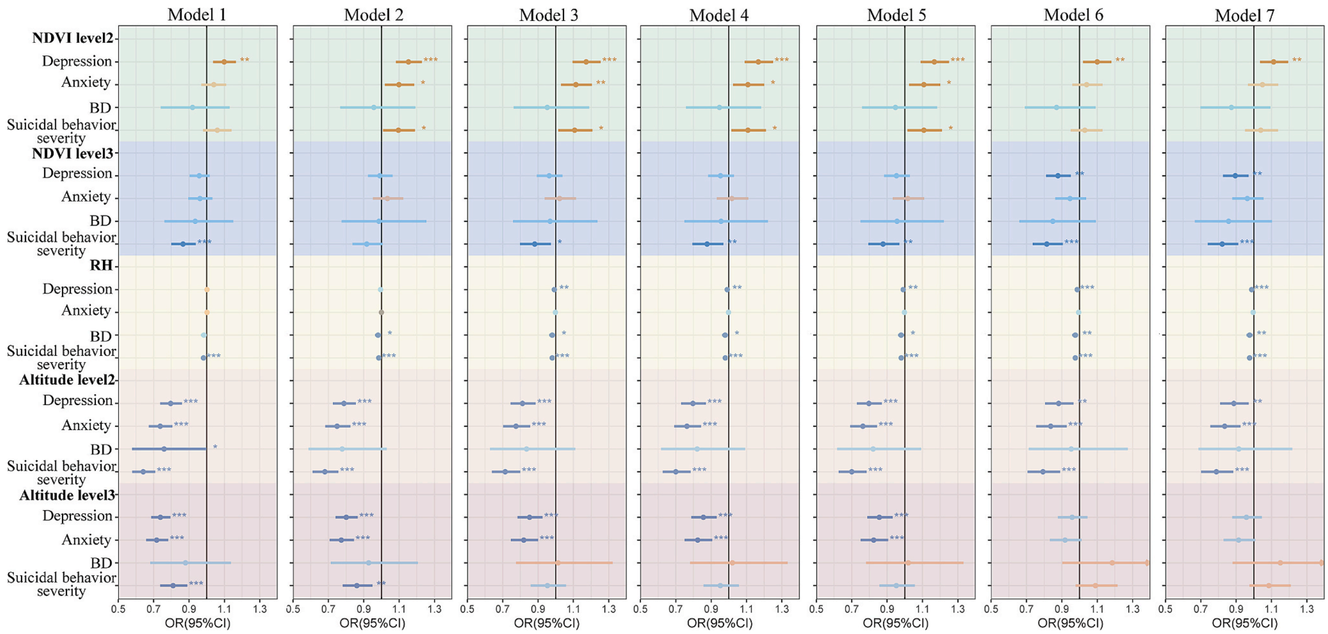

Fig. 4. The relationships between NDVI, RH, altitude and diagnoses of mental disorders in models with different covariate sets and fully adjusted models. Model 1 included the core environmental explanatory variables (NDVI, RH and altitude). Model 2 was adjusted by adding socio-demographic factors. Model 3 was adjusted by adding family environment factors. Model 4 was adjusted by adding social support factors. Model 5 was adjusted by adding lifestyle factors. Model 6 was adjusted by adding learning environment factors. Model 7 was adjusted by adding urbanization level factors.

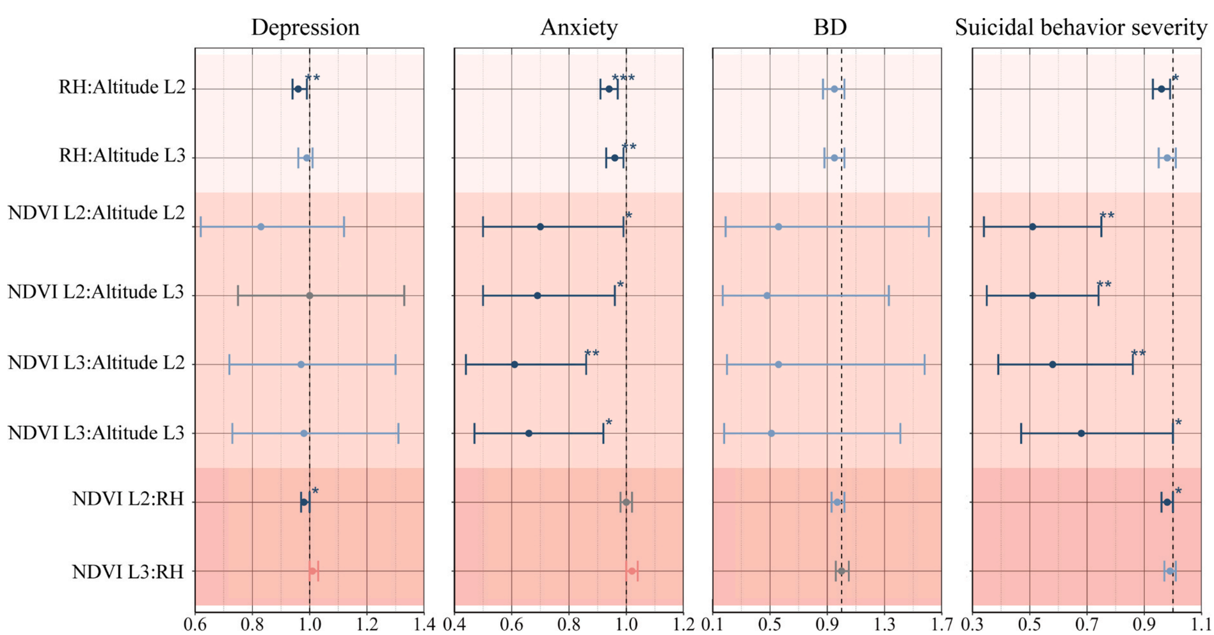

Fig. 5. The OR of the interactive model of environmental factors associated with the severity of depression, anxiety, BD, and suicidal behavior severity.

In previous studies on altitude, it was found that individuals living at altitudes above 4000 m have a significantly higher prevalence of mental disorders than those at lower altitudes due to cold and dry climates, hypoxic conditions, strong winds, and intense UV exposure(Li, 2000).In studies related to low and medium altitudes, it was found that mild hypoxic stimuli can cause physiological adaptations in individuals, which can make them more resistant to subsequent hypoxic or ischemic injuries. This process may involve the brain-derived neurotrophic factor (BDNF) mediating increased neural stem cell proliferation in the hippocampus (the brain's emotional memory center), thereby reducing the risk of depression(Burtscher, 2022; Khalil, 2024; Weisstaub and Santarelli, 2003). Our study validated that altitude gain below 1730 m elevates children and adolescents' resistance to cope with depression (OR:0.887,95 % CI: 0.810–0.971), anxiety (OR:0.835,95 CI %:0.754–0.925), and suicidal behavior severity (OR:0.788,95 CI %:0.702–0.884). However, the protective effect of the altitude range of 1730–3500 m on mental disorders was partially explained by socio-demographic factors, family environment, and social support, which may be due to the fact that the culture of living in a group at high altitude makes people more resistant to hypoxia or ischemic injury(da Silva et al., 2022). This may be due to the fact that the culture of living in groups at high altitude makes people more inclined to a slower pace of life and collective collaboration, and the mutual support of the group counteracts the negative impacts of the harsh climate on mental health.

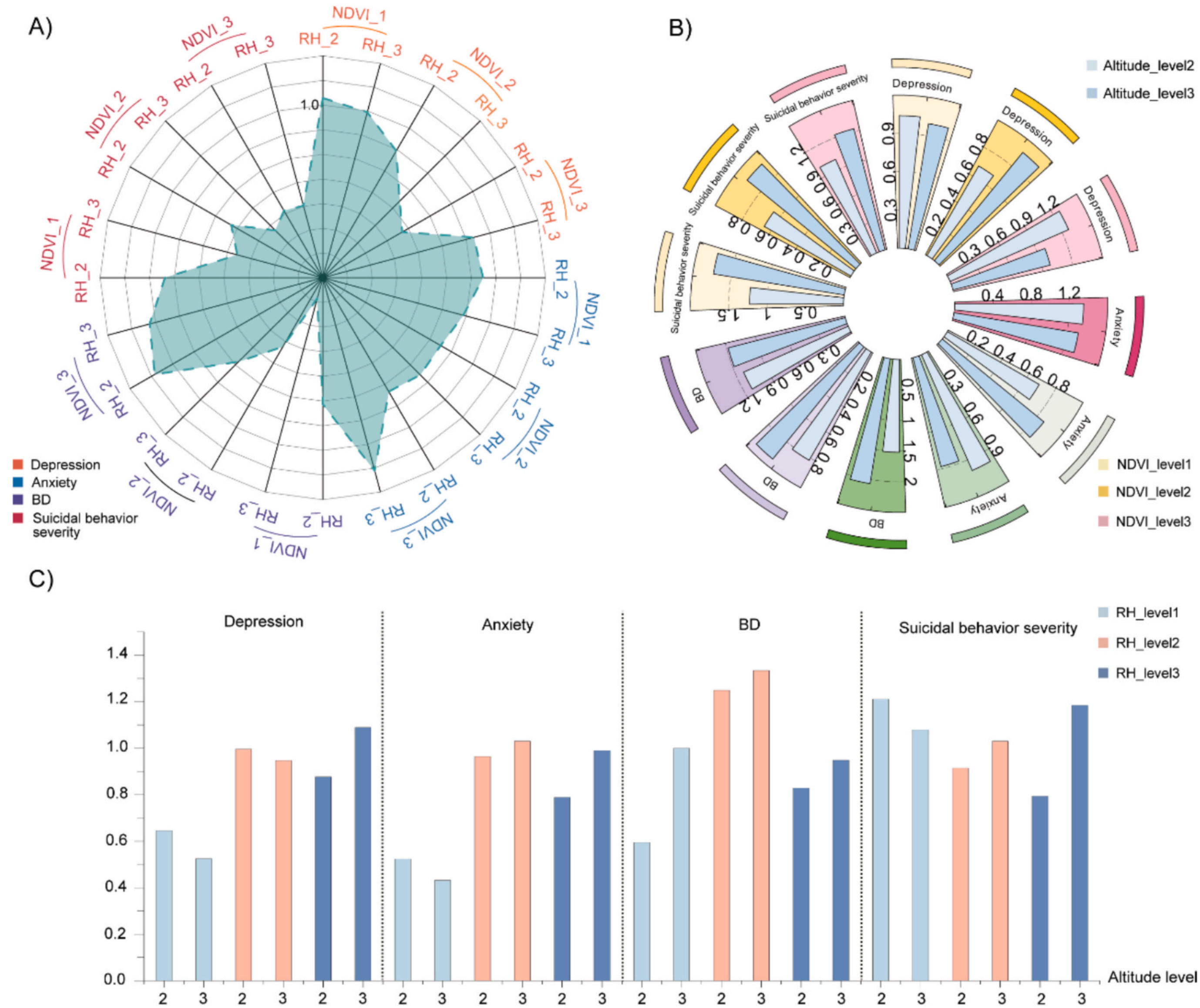

Fig. 6. Stratified analysis of positive patients with mental disorders under different environmental factors. Figure(A) represents NDVI-stratified RH effects for depression, anxiety, BD and suicidal behavior severity. Figure(B) represents NDVI-stratified altitude effects for depression, anxiety, BD and suicidal behavior severity. Figure(C) represents RH-stratified altitude effects for depression, anxiety, BD and suicidal behavior severity.

RH is a relatively minor factor compared to altitude and NDVI. Low RH reduces environmental comfort by irritating the eyes, oral mucosa, and respiratory tract. On one hand, it may exacerbate dry eye syndrome and trigger mental disorders mediated by sleep disturbances(Palagini et al., 2022; Ayaki et al., 2018). On the other hand, environmental dryness may induce increased cortisol secretion in the epidermis of diseased skin characterized by barrier dysfunction, potentially affecting mental state and systemic physiology(Takei et al., 2013).

4.2. Interaction of multidimensional environmental factors

In our interaction analysis, we found that altitude range of 1,180–1,730 m synergistically enhanced the protective association with an NDVI level of 0.37–0.47 on anxiety (OR:0.70,95 % CI:0.50–0.99) and suicidal behavior severity (OR:0.51,95 % CI:0.34–0.75). Humidity showed synergistic association with an NDVI level of 0.37–0.47 on depression and suicidal behavior severity, which might be attributed to the subtropical location and the warm and humid environment created by humidity. This may be due to the subtropical location and the warm and humid environment created by humidity, which promotes photosynthesis and the air purification efficiency of vegetation(Chia and Lim, 2022). However, at NDVI levels above 0.47, the effects of high humidity were not sustained. Mental health benefits exhibit stronger protective associations when NDVI exceeds 0.47. This may stem from higher canopy cover providing shelter, shade cooling, and noise/heat load buffering, typically yielding more stable mental health advantages(Astell-Burt and Feng, 2019). However, when greenery and environmental humidity are both high, the marginal effects of microclimate improvements diminish. In fact, negative correlations emerge due to discomfort from humid air and the proliferation of mold and insects(Zhao et al., 2020; Gatto et al., 2024). Existing research has identified harmful effects of humid environments and mold exposure on participants' mental health. A potential mechanism may involve biochemical effects from inhaled mold. A mouse study found mold exposure impaired memory and induced anxiety-like behaviors through innate immune activation (Harding, 2020). However, this mechanism remains validated only in animal experiments. Additionally, some studies have identified higher mosquito abundance in damp green spaces, potentially increasing vector-borne disease transmission risks while reducing residents' willingness to go outdoors and green space usage rates(Zhao et al., 2020). The nonlinearity of NDVI effects fundamentally reflects the perceived balance between openness and shelter, and its integrated regulation of thermal exposure and physiological stress. The combination of canopy cover and open spaces reduces mental health risks. Yet in scenarios of high NDVI coupled with high humidity, further vegetation increases do not yield proportionally greater perceptible psychological benefits, manifesting as "diminishing marginal returns".

By contrast, the synergistic effect of NDVI and altitude on anxiety and suicidal behavior severity was significantly elevated in the altitude interval of 1180–1730 m. Existing evidence indicates that at moderate altitudes, low-dose hypoxic stimulation can be induced, triggering proliferation of hippocampal neural stem cells and producing antidepressant-like effects. Under conditions of unobstructed green views, natural exposure may potentially promote stress recovery and attention restoration, thereby synergistically amplifying the restorative effects of NDVI.(Burtscher et al., 2021; Dzhambov et al., 2018; Huang et al., 2021) In addition, the 1180–1730 m altitude range and humidity showed weak protective effects against depression (OR:0.96, 95 % CI:0.94–0.99), anxiety (OR:0.94, 95 % CI:0.91–0.97), and suicidal behavior severity (OR:0.96, 95 % CI:0.93–0.99). This altitude range at 80 % humidity may reduce the discomfort of environmental irritants such as dust and dryness in children and adolescents, and at the same time ameliorates the risk of mental disorders due to the dryness that affects the quality of sleep in children and adolescents(Wolkoff, 2018). However, it is worth noting that the mechanistic interpretation of the aforementioned interaction effects between NDVI and humidity, as well as NDVI and altitude, currently constitutes a biologically plausible yet still unproven explanation. This interpretation is primarily based on animal experiments and indirect evidence from adult populations, with the direct causal chain in adolescent populations still lacking. Future research will need to validate these findings.

4.3. Construction of biophilic psychomicrospaces

According to Ulrich's theory of stress recovery, a spiritually restorative environment should contain enough natural elements, such as plants, bodies of water, and mountains. It should also have a specific spatial structure and focus. The natural environment should have medium depth and complexity, and there should be no threatening landscape elements in the visual environment(Ulrich, 1984). Although the diverse landscapes in Yunnan Province satisfy the natural visual diversity and multisensory experience, they still do not match the fine-grained needs of children and adolescents in their individual 500 m living spaces. Regarding vegetation, green coverage must align with the nonlinear relationship observed in NDVI. First, areas with NDVI levels between 0.37 and 0.47 require alternating coverage of shaded trees and grasslands to elevate the NDVI sub-optimal range above 0.47. This should replace dense thorny shrubbery while avoiding the enclosed spaces and oppressive feel caused by continuous tall forests. Regarding altitude, lowland residents can moderately experience mild hypoxic stimulation at mid-altitudes (1,180–1,730 m) through travel or hiking. High-altitude residents, however, must promptly seek nearby shelter from direct sunlight when encountering threatening natural conditions like strong winds or intense UV radiation. Both psychological and physiological stress must be maintained within mildly controllable ranges. To cultivate a comfortable microclimate while preventing excessive humidity, drainage systems should be installed in areas shaded by tall trees. Vegetation trimming and drainage maintenance ensure clear visibility and dry pathways. In regions with high humidity, standing water features must be avoided to prevent the breeding of disease vectors and insect pests.

The Nujiang area is the highest-altitude region in Yunnan Province with relatively low NDVI values. Its greening efforts should prioritize locally adapted mountain tree species and grasses that are cold-tolerant, wind-resistant, and possess robust root systems to elevate NDVI levels above 0.37. This approach not only accommodates the mild environmental stress and visual recovery benefits associated with high altitudes but also mitigates threats from strong winds and intense ultraviolet radiation. In contrast, Dali's mid-to-low altitude and higher NDVI levels yield diminishing returns from further NDVI increases. Thus, its planning priority is not to boost green coverage but to stabilize existing NDVI above 0.37 while creating spatial and visual continuity. This can be achieved by alternating small woodlands with open lawns to maintain the protective range of NDVI. Simultaneously, rest areas are established under tree shade, leveraging comfort and spatial continuity to consistently activate the protective effects of NDVI and altitude. In contrast, the southern regions of Xishuangbanna and Pu'er feature lower altitudes and proximity to tropical zones. Closed vegetation can trap humidity, creating damp dead zones. Thus, closed canopies should be avoided to enhance sky visibility and air circulation, while drainage systems beneath roadways ensure vapor dissipation.

4.4. Limitation

There are limitations to this study. First, as a cross-sectional study, the study could not infer a causal relationship between environmental factors and mental illness. Secondly, Ulrich's stress recovery theory has been studied mainly in adults, so the conclusions of this study should be regarded as an extension of stress recovery theory in specific situations. Third, while this study's environmental exposure assessment is based on 500 m and 1000 m European buffer zones, variations in individual activity ranges warrant further consideration. Particularly for individuals in rural and mountainous areas, terrain and road characteristics may lead to either overestimation or underestimation. Future research could incorporate GPS trajectory data to conduct more precise assessments of actual individual activity spaces. Fourth, due to limitations in data availability, this study did not include physiological measurement data. Future research may collect additional relevant indicators such as blood oxygen saturation, sleep disturbances, and biomarkers by utilizing wearable devices or on-site saliva cortisol sampling. Fifth, there may still be under-observed confounding factors in this study. Finally, future studies can be further validated in different regions to provide more sufficient evidence.

5. Conclusion

This study demonstrated that NDVI showed a non-linear relationship with depression and suicidal behavior severity, and that NDVI levels of 0.15–0.37 were more protective than NDVI levels of 0.37–0.47. The risk of depression, anxiety, and suicidal behavior severity was lower at an altitude of 1180–1730 m, whereas humidity was more conducive to suppressing depression, BD, and suicidal behavior severity at a RH of 80 %. In the interaction analysis, the effect of environment with high humidity and high NDVI on mental disorders showed a tendency of diminishing marginal returns. The altitude range of 1180–1730 m in conjunction with high NDVI was more favorable for preventing the risk of mental disorders.

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CRediT authorship contribution statement

Ye Li: Conceptualization, Writing – review & editing , Funding acquisition. **Fangqi Qu:** Visualization, Formal analysis, Writing – original draft. **Yuanxiang Shi:** Formal analysis, Writing – original draft. **Kejin Ma:** Software. **Yongqiang Lai:** Software, Methodology. **Yang Yang:** Data curation. **Lu Lu:** Data curation. **Mengyun Jin:** Data curation. **Jiangmin Chu:** Software, Data curation. **Na Li:** Data curation. **Xiufeng Xu:** Data curation. **Yongmei Wu:** Data curation. **Hongtao Lei:** Data curation. **Mengmei Liu:** Data curation. **Guanghong Yan:** Data curation. **Sifan Duan:** Data curation. **Yani Li:** Data curation. **Wenjing Xia:** Data curation. **Ying Zhao:** Data curation. **Linglin Zhou:** Data curation. **Xin Ning:** Data curation. **Fahui Chen:** Data curation. **Chang Shu:** Data curation. **Jidong Huang:** Writing – review & editing. **Yuqi Cheng:** Project administration. **Dingyun You:** Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2025.109901.

Data availability

The data that has been used is confidential.

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