Impact of road corridors on soil properties and plant communities in high-elevation fragile ecosystems

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Abstract

Road construction constitutes a significant disruption to natural ecosystems. Globally, high-elevation regions are among the most fragile and sensitive ecosystems, while systematic information regarding the impact of road construction on soil properties and plant communities in these regions remains scarce. In this study, paired plots were established along the road route from Yunnan Province to Tibet Autonomous Region in Southwest China, with elevation ranging from 2,400 m to 4,900 m. Results revealed the restoration of soil properties post-disturbance had been a multifaceted and long-term progress. Specifically, disturbed plots exhibited a significant increase in soil pH, while soil moisture, TC, TN, TP, NH_4-N, and AK suffered substantial loss. Moreover, the strong recovery ability of shrub and herbaceous species was observed in our study, while tree communities were difficult to revert to their original state. Furthermore, the influence of elevation on vegetation restoration also varied depending on plant life forms. In light of these findings, appropriate strategies were proposed to mitigate the negative impacts and promote the ecosystem recovery after road construction in these ecologically fragile regions.

1. Introduction

Forest disturbance can cause profound impacts on the global ecosystem (Antwi et al. 2022; Thom and Seidl 2016). These disturbances include frequent natural disasters (fires, pests, and disease outbreaks) and human activities (deforestation and land use changes), which will considerably influence carbon storage, biodiversity, and result in serious damage to forest structure and degradation of ecological functions (Marzo et al. 2023; Spicer et al. 2023; Zhang et al. 2023). Road construction poses a destructive threat causing the deforestation of natural habitats (Forman et al. 2003; Zhuo et al. 2022), introduction of chemicals and heavy metals (Ma et al. 2018), alteration of hydrological processes and microclimate (Kastridis 2020; Sheridan and Noske 2007), and establishment of invasive plant species (Li et al. 2022), often with irreversible impacts on ecosystems. With the continuous advancement of urbanization and economic growth, the expansion and renovation of road networks are inevitable (Rentch et al. 2005). Globally, at least 25 million kilometers of new roads will be constructed by 2050, representing a 60% increase in the total road length compared to 2010 (Laurance et al. 2014). Although some existing studies have discussed about the negative impacts of road construction on the surrounding ecosystem (Angold 1997; Cui et al. 2009; Deljouei et al. 2018; Hansen and Clevenger 2005; Neher et al. 2013; Olander et al. 1998), there still remains a significant gap in the systematic understanding of how road construction affect soil properties and plant communities, especially in fragile ecosystems.

Globally, high elevation zones (more than 2,400 m; National Geographic Society) are among the most fragile and sensitive ecosystems characterized by unique environmental conditions such as temperature, humidity, and atmospheric pressure (Boyle and Martin 2015; Körner 2007; Mesquita et al. 2020). These special environmental factors intricately shaped the distinct vegetation structure and soil physio-chemical properties in such areas (Backes et al. 2021; Hamid et al. 2021; Han et al. 2022). Consequently, these ecosystems offer valuable avenues for biodiversity, climate change, carbon dynamics, ecosystem services, and conservation research. However, these regions are particularly vulnerable to human-induced disturbances due to their delicate ecological balance and limited resilience (Boucher and Grondin 2012; Kumar and Ram 2005). For example, Bisht et al (2022) demonstrated that anthropogenic pressures on the high-elevation national parks of India not only altered the soil properties, but also potentially threatened the plant species composition. Another study also found that the decrease in native species richness and plant biomass was stronger at higher than at lower elevations after a small-scale mechanical disturbance along roadsides (Corcos et al. 2020).

Ecological recovery, refers to an ecosystem's ability to revert to its original state after disturbances, which is also affected by elevation gradients (Gunderson 2000; Holling 1973). For example, Cerioni et al. (2022) observed a negative impact of elevation on the regeneration density of mountain forests. However, Davis et al. (2022) pointed out that stands at higher elevations exhibited a stronger recovery of productivity in comparison to lower elevation stands. Similarly, studies conducted by Seidl et al. (2017) and Dodson and Root (2013) found that the recovery ability of coniferous forests was more pronounced at higher elevation sites, and decreased at lower elevations. These findings are not entirely consistent, while most of them have only focused on relatively low-elevation areas (e.g., below 2,000 m) (Geng et al. 2019; Moris et al. 2017; Rammer et al. 2021).

Considering the unique ecological significance and the imperative need for biodiversity conservation in high elevation zones, there is an urgent call to explore the impacts of transportation corridors on these fragile ecosystems (Li et al. 2022). On the one hand, most studies regarding the influence of road construction on plant communities have focused on a single vegetation type (Cui et al. 2009; Deljouei et al. 2018; Johnston and Johnston 2004; Yousefi et al. 2016), while the specific response of various vegetation types has yet to be thoroughly investigated. On the other hand, both plants and soil collectively constitute indispensable components of the ecosystem. Nevertheless, the majority of existing studies in high-elevation regions have primarily focused on the shifts in plant communities (Corcos et al. 2020; Haider et al. 2018; Li et al. 2022), leading to the systematic assessment of the impact of road construction on soil properties is deficient. Therefore, a comprehensive understanding of how soil properties and plant communities respond to road construction in high-elevation regions is urgently required for the effective conservation and management of these fragile ecosystems.

Here, paired plots (natural and disturbed plots) were established along the road route from Yunnan Province to Tibet Autonomous Region in Southwest China. Complex topography and climate conditions in these regions form a variety of vegetation types, with elevation ranging from 2,400 m to 4,900 m a.s.l. Paired investigation methods were used to compare the pattern of soil properties and plant diversity between the two categories along elevation gradient at the landscape level. The research contents of this research include: (1) investigate the impact of road construction on soil properties in high-elevation ecosystems; (2) evaluate the recovery response of different plant life forms to road construction; (3) estimate the effect of elevation on soil properties and vegetation restoration in these fragile ecosystems. Through this study, we aim to provide scientific evidence that can contribute to optimizing road construction practices and maintaining ecological environment in high-elevation fragile zones, thus promoting the coexistence of social sustainable development and ecological balance.

2. Methods

2.1 Study area

The survey route was along the National Highway 214 and 219, which is located in the northwest part of Yunnan Province and the southeast part of Tibet Autonomous Region in China between 96°44' E – 99°55' E longitude and 27°27' N – 30°12' N latitude (Fig. 1). The elevation of sampling sites ranges from 2,460 m a.s.l. in Dêqên Tibetan Autonomous Prefecture, Yunnan Province, to 4,878 m a.s.l. in Qamdo, Tibet Autonomous Region. The G214 and G219 were built in 1976 and 2012, respectively, and the road width is 16 m wide. The road range features a complex topography and diverse climate, encompassing subtropical, temperate high-mountain, and frigid high-mountain climate zones. Different ecosystems and vegetation types are formed along the route, viz., evergreen broad-leaved forest (EBF), deciduous broad-leaved forest (DBF), temperate coniferous forest (TCF), cold-temperate coniferous forest (CCF), warm-temperate shrub (WS), cold-temperate shrub (CS), and alpine meadow (AM). Detailed information about the survey plots such as vegetation type, longitude, latitude, and elevation were shown in Table 1 and Table S1.

Table 1
Information of the natural and disturbed plots in the study area

Natural vegetation type	Disturbed vegetation type	Number of locations	Mean elevation (m)
WS	WS	6	2949
EBF	EBF	1	3678
	CS	1	3766
	AM	1	4066
TCF	WS	2	2995
	TCF	1	3941
	DBF	1	3929
	CS	2	3182
	AM	1	3341
CCF	DBF	1	3817
	CS	5	4085
	AM	1	4090
CS	CS	4	4077
	AM	2	4316
AM	CS	1	3363
	AM	4	4491

Note: EBF: Evergreen broad-leaved forest; DBF: Deciduous broad-leaved forest; TCF: Temperate coniferous forest; CCF: Cold-temperate coniferous forest; WS: Warm-temperate shrub; CS: Cold-temperate shrub; AM: Alpine meadow.

2.2 Sampling design

A field sampling campaign consisting of a combined survey of vegetation and collection of soil samples were conducted from August to September 2021. Sampling locations were chosen based on the typicality of vegetation types. A pair of plots (natural and disturbed plots) were established in each sample location characterized by similar topographic conditions and soil parent materials. Overall, 34 sampling locations were selected.

At each sample location, one plot adjacent to the roadside was referred to as the disturbed plot (representing the ecosystems affected by road construction). Correspondingly, another one plot was established parallel to the disturbed plot and was more than 100 m away from the road (representing the undisturbed ecosystems away from the road, hereafter referred to as natural plot). Overall, 68 plots were established in this study.

Independent 400 m^2 plots (20 m × 20 m) within each sampling location were designated for vegetation investigation and soil sampling. In each plot, all tree species with a diameter at breast height (DBH) ≥ 1 cm and corresponding number were recorded. Another 25 m^2 (5 m × 5 m) subplot and four 1 m^2 (1 m × 1 m) subplots were arranged in each plot for the investigation of shrubs and herbs, respectively. In the herbaceous subplots, the percentage cover of each species was visually estimated. In shrublands, only shrubs and herbs were investigated as no tree species were present. Similarly, only herbaceous species were surveyed in meadows. The dominant tree, shrub, and herbaceous species in each vegetation type were shown in the Supplementary Table 2–4, respectively.

2.3 Soil sample collection and analysis

During our plant community investigation, soil samples were collected at the same time from each investigated plot across all vegetation types. Briefly, five soil cores (10 cm in depth) were extracted from the four corners and center of each plot, then mixed homogeneously to form a composite sample, i.e., a single soil sample per plot. The composite soil samples were transported to the laboratory for soil properties measurement. Roots and stones were removed from the fresh soil and soil moisture content was determined using oven-drying method. The remaining soil samples were air-dried, ground, and sieved prior to chemical analysis. Standard soil test procedures were applied to determine soil pH, total carbon (TC), total nitrogen (TN), total phosphorus (TP), total potassium (TK), ammonia nitrogen (NH_4-N), nitrate nitrogen (NO_3-N), available phosphorus (AP), and available potassium (AK). Specifically, soil pH was determined by potentiometric method; soil TC by elemental analysis method; soil TN by the Kjeldahl method; soil TP by alkali fusion method; soil TK by a flame mission spectrophotometer; soil NH_4-N and NO_3-N by continuous flow analyzer; soil AP by colorimetric method and soil AK by inductively coupled plasma atomic emission spectrometer (ICP-AES), respectively. These above procedures were conducted at the Central Laboratory of Xishuangbanna Tropical Botanical Garden, Chinese Academy of Sciences.

2.4 Statistical analyses

Species richness was calculated as the total number of plant species belonging to different life forms (tree, shrub, and herb) investigated within a plot (Krebs 1989). The Shannon-Winner index was used to quantify the diversity of plant species within a community (Shannon and Wiener 1949). The difference in plant diversity and soil properties between paired plots was compared using the Wilcoxon test. Redundancy analysis (RDA) was used to evaluate the impact of road construction on plant community composition (Legendre and Andersson 1999). The analysis of plant diversity and RDA were carried out with “vegan” package in R (Oksanen et al. 2022). Regression analyses were performed to assess the relationships between soil properties and elevation, and the slope differences between natural and disturbed plots were compared by “simba” package in R (Jurasinski and Retzer 2012). Structural equation model (SEM) was applied to analyze the direct and indirect relationships among road construction, elevation, soil properties, and plant diversity, using the “lavvan” and “semPlot” packages in

R (Epskamp 2022; Rosseel 2022). “ggplot2” and “ggpubr” were used for figure visualization (Kassambara 2023; Wickham 2016). All statistical analyses were performed using R 4.3.1 (R Core Team 2023).

3. Results

In total, 495 vascular plant species were recorded in the survey area. Among the investigated plant species, Poaceae was the family with the highest species richness, followed by Rosaceae, Asteraceae, Fabaceae, Cyperaceae, Ranunculaceae, Caprifoliaceae, Ericaceae, et al. (Table S5). In terms of life forms, the recorded species included 26 tree species, 128 shrub species, and 341 herbaceous species.

3.1 Effect of road construction on soil properties

Through a comparative analysis of soil properties in paired plots, results showed that the significant impact of road construction on soil attributes (Fig. 2). Compared with the natural plots, substantial decreases were observed in the disturbed plots for soil moisture content ($p = 0.002$), TC ($p = 0.026$), TN ($p = 0.021$), TP ($p = 0.045$), NH_4-N ($p = 0.001$), and AK ($p = 0.016$). In contrast, soil pH exhibited a significant increase ($p = 0.002$) in these disturbed areas.

3.2 Effect of road construction on plant diversity

The impact of road construction on plant diversity displayed various patterns across different life forms (Fig. 3). Specifically, road construction exerted the most significant influence on the diversity of tree species in our study regions (Richness: $p = 0.004$; Shannon: $p = 0.008$). Moreover, it also demonstrated a marginally significant effect on shrub richness in these areas ($p = 0.087$). Conversely, little impact was observed on herb diversity (Richness: $p = 0.66$; Shannon: $p = 0.82$).

3.3 Effect of road construction on plant community composition

RDA results showed that the impact of road construction on tree community composition was marginally significant ($p = 0.060$), while the influence of elevation appeared to be limited ($p = 0.754$; Fig. 4a). In contrast, regarding the composition of the shrub community, elevation emerged as a significant factor exerting notable influence ($p < 0.001$), whereas the impact of road construction seemed comparatively weaker ($p = 0.16$, Fig. 4b). Furthermore, elevation was identified as the most important factor affecting the distribution of herbaceous community ($p < 0.001$), with the influence of road construction on herbaceous community appearing to be fairly limited (Fig. 4c).

3.4 The direct and indirect effects of road construction and elevation on soil properties and plant diversity

The SEM showed that road construction had a direct negative correlation with soil TC, soil TN, soil moisture, and tree diversity (Fig. 5). These changes in soil properties subsequently affected available nutrient content and pH level, further influencing the diversity of tree species. Elevation also indirectly impacted the tree diversity through its influence on soil properties. The diversity of shrub species was primarily governed by elevation, with relatively minor indirect effects from changes in soil properties. Furthermore, elevation mainly exerted an indirect effect on the diversity of herbaceous plants, mediated by its impact on soil moisture.

4. Discussion

4.1 The recovery process of soil properties is complicated and time-consuming

In our study area, soil TC, TN, TP, NH_4-N, AK, and moisture were significantly decreased in the disturbed plots. Previous studies conducted by Cui et al. (2009), Deljouei et al. (2018), Johnston and Johnston (2004), and Yousefi et al. (2016) also found similar pattern as our results. The significant decline in soil nutrient levels were primarily attributed to anthropogenic activities associated with road construction, such as geological exploration, engineering excavation, and the establishment of stacking yards. These behaviors resulted in the exposure of soil parent materials with low organic matter content (Cui et al. 2009; Hansen and Clevenger 2005; Olander et al. 1998). Moreover, the removal of original vegetation cover during road construction not only diminished the accumulation of soil organic matter and available nutrients, but also exacerbated surface runoff and leaching processes, ultimately leading to greater soil nutrient loss and deterioration of soil properties (Janeau et al. 2014; Misra and Teixeira 2001). Furthermore, the reduced canopy cover could elevate solar radiation and intensify soil water evaporation, resulting in considerable reductions in soil moisture.

Soil pH significantly increased in the disturbed plots in our study. Similar patterns were also found in prior researches which demonstrated that soil pH tended to be higher in areas affected by road construction (Cui et al. 2009; Deljouei et al. 2018; Johnston and Johnston 2004; Yousefi et al. 2016). This change may be attributed to the reduction in soil TC and NH_4-N caused by soil disturbance during road construction (Jiang et al. 2008; Yang et al. 2011; Zhang et al. 2022). Furthermore, the introduction of new pollution sources, such as machine emissions and road maintenance chemicals, may also increase soil pH levels (Auerbach et al. 1997; Johnston and Johnston 2004; Neher et al. 2013). However, contrasting patterns were observed by Olander et al. (1998) that soil pH was similar to the mature forest after 35 years of road construction. This suggests that the restoration of soil properties to their initial state after road construction is a prolonged process. In fact, an additional analysis of the sampling locations on the G214 which have been built for nearly 50 years was also conducted in our study and a similar pattern was found (Fig. S1-S2), indicating the soil properties and plant diversity were more difficult to recover in high-elevation fragile ecosystems even after a recovery period of 50 years. Understanding the specific mechanisms driving changes in soil properties and their subsequent impact on vegetation recovery is critical for developing effective management strategies and minimizing the ecological impact of road construction projects.

4.2 The vegetation recovery varied across different plant life forms

Our study did not detect significant differences in the diversity and composition of shrub and herbaceous communities between the natural and disturbed plots, revealing a robust recovery ability of these vegetation types. Similarly, Cui et al. (2009) even observed higher species richness and diversity of shrubs and herbs following the construction of the Dabao highway in Southwestern China. This could be attributed to their inherent ability for rapid revegetation and regrowth after disturbances (Fu et al. 2022; Liu et al. 2022; Vanha-Majamaa et al. 2017). Moreover, the reduced canopy cover resulting from construction activities allows more sunlight to reach the understory in disturbed areas, creating favorable conditions for the establishment and flourishing of shrub and herbaceous species (Gehlhausen et al. 2000; Kermavnar et al. 2021; Liira et al. 2007; Spicer et al. 2023).

Conversely, the diversity and composition of tree communities still failed to return to its original statue in our study. Many studies also highlighted the significant impacts of road construction on forest stands and productivity (Caliskan 2013; Cui et al. 2009; Melemez 2013; Saraswati et al. 2020). This can be predominantly attributed to the direct consequence of extensive vegetation removal during road construction. Moreover, the destruction of soil properties induced by road construction also indirectly hindered the recovery process of the tree community. Restoring the tree community is a multifaceted and time-consuming endeavor. As suggested by Olander et al. (1998), it may take 200–300 years for biomass to attain mature forest levels after road construction. In fact, the seedlings of tree species were also existing in our disturbed plots, although they were too small to be incorporated for analysis. However, Li et al. (2022) discovered that roads only accounted for marginal variations in plant richness after a recovery period of more than 50 years. This could be attributed to differences in vegetation types, elevation, climate, and topographical factors. These findings underscore the importance of considering the revegetation and adaptability of various plant life forms when assessing the recovery statue after road construction. Understanding the ecological dynamics of diverse vegetation types in response to disturbance is essential for developing effective conservation and management strategies.

4.3 The elevation exerted both direct and indirect effects on vegetation restoration

The SEM results revealed a directly negative impact of elevation on shrub diversity, while an opposite pattern was observed in herbaceous communities through the indirect influence mediated by soil moisture. A study conducted by Lyu et al. (2021) also found a noteworthy positive correlation between the Shannon index of the herb layer and soil moisture content. However, due to the intricate interplay of factors such as soil nutrients, temperature and moisture, the diversity of tree species did not exhibit a directly significant trend with elevation. A parallel study conducted by Li et al. (2022) reported increasing recovery trends of plant communities along elevation gradients after a recovery period of more than 50 years, whereas Corcos et al. (2020) demonstrated that the native species richness and plant biomass along roadsides at higher elevations faced greater challenges in recovery process after a small-scale mechanical disturbance.

Note that, from the perspective of vegetation types, plant communities at higher elevations were more difficult to recover to their original states in our study (Table 1). For example, the evergreen broad-leaved forests were restored to evergreen broad-leaved forests, cold-temperate shrubs, and alpine meadows along the elevation gradient after road construction. Otherwise, cold-temperate shrubs could only recover to alpine meadows at higher elevation regions in our study. This phenomenon may be associated with a more pronounced decrease in soil nutrients in higher elevation areas after road construction, e.g., soil NH_4-N and moisture in our study (Fig. S3), which is also demonstrated by Zhang et al. (2021). Combining previous research with our findings, we conclude that there is still no consistent conclusion regarding the relationship between elevation and the recovery ability of plant communities after road construction due to the variations in road attributes, climate, ecosystem types, plant traits, soil characteristics, and other factors (Lee et al. 2012; McDougall 2001; Olander et al. 1998; Trombulak and Frissell 2000; Yousefi et al. 2016).

4.4 Management implications and future directions

Based on the findings of this study, appropriate management policies are needed to mitigate the environmental impact of road construction and facilitate the recovery of plant communities and soil properties in high-elevation fragile ecosystems. Firstly, considering the differential recovery responses of various plant life forms to road construction, we should prioritize choosing secondary forests rather than mature forests if it is unavoidable to destroy a forest during road construction, and low-impact road designs should be employed to minimize tree felling and soil disturbance. Secondly, targeting different disturbed ecosystems along the road, planting dominant species that are suitable for the local climate and soil conditions will effectively restore vegetation coverage and ecological functions (Cowan et al. 2021; Heneghan et al. 2008; Suding et al. 2004). Thirdly, using excavator instead of bulldozer in clearing, gribbing, slash disposal and excavation phases, as it has more control on materials and it has higher maneuverability. Moreover, choosing soil bioengineering methods to control erosion and instability can make the establishment of vegetation easier (Dhital et al. 2013; Zaimes et al. 2019). Lastly, establishing long-term ecological monitoring programs is strongly recommended to track the recovery progress of different ecosystem types after road construction. Through continuous monitoring, protective measures can be promptly adjusted to mitigate negative impacts and enhance recovery effectiveness (Moreno-Mateos et al. 2020; Wardle and Jonsson 2014).

Despite the valuable insights gained from this research, there are still some limitations that should be addressed in future studies. Particular emphasis should be focused on exploring the influences of different road attributes (e.g., age, distance, slope, and aspect) on the disturbed ecosystems to enhance the accuracy and applicability of these findings (Cui et al. 2009; Neher et al. 2013; Olander et al. 1998; Yousefi et al. 2016). By addressing these gaps, a more comprehensive understanding of the ecological consequences of road construction will be provided, ultimately leading to more informed and effective strategies for sustainable road development and ecosystem conservation.

5 Conclusion

This study conducted a systematic assessment of the impact of road construction on soil properties and plant communities in high-elevation fragile ecosystems. Our results demonstrated the restoration of soil properties emerged as a complicated and time-consuming process. Specifically, the disturbed plots exhibited a significant increase in soil pH, while soil moisture, TC, TN, TP, NH_4-N, and AK suffered substantial reductions. Moreover, plant community status indicated the robust recovery ability of shrub and herbaceous species, contrasted with the enormous challenges in restoring tree communities to their original state. Furthermore, we also found that the influence of elevation on vegetation restoration varied depending on the plant life form. In response to these findings, we suggest (1) secondary forests should be prioritized if it is unavoidable to destroy a forest during road construction; (2) planting dominant species after road disturbance will effectively promote soil and vegetation restoration; (3) bioengineering methods could be adopted to control soil erosion and instability caused by road construction (4) long-term ecological monitoring programs are strongly recommended to track the recovery progress. Ultimately, this research strives to encourage the development of road construction practices that prioritize environmental sustainability, ensuring a harmonious coexistence between economic development and ecological balance.

Declarations

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.

Data availability

Data will be made available on request.

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Figures

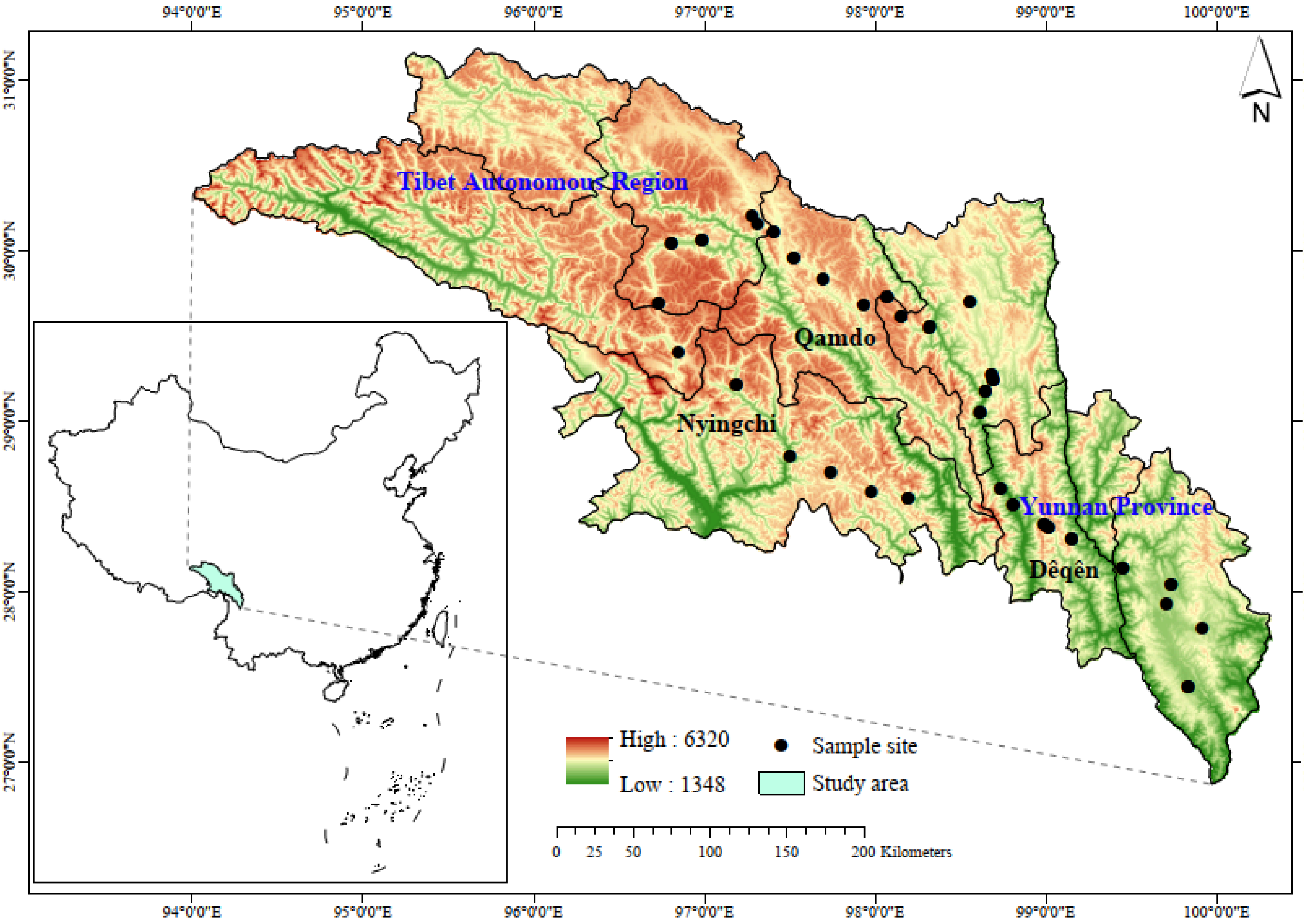

Figure 1

Distribution map of sampling locations along the road range

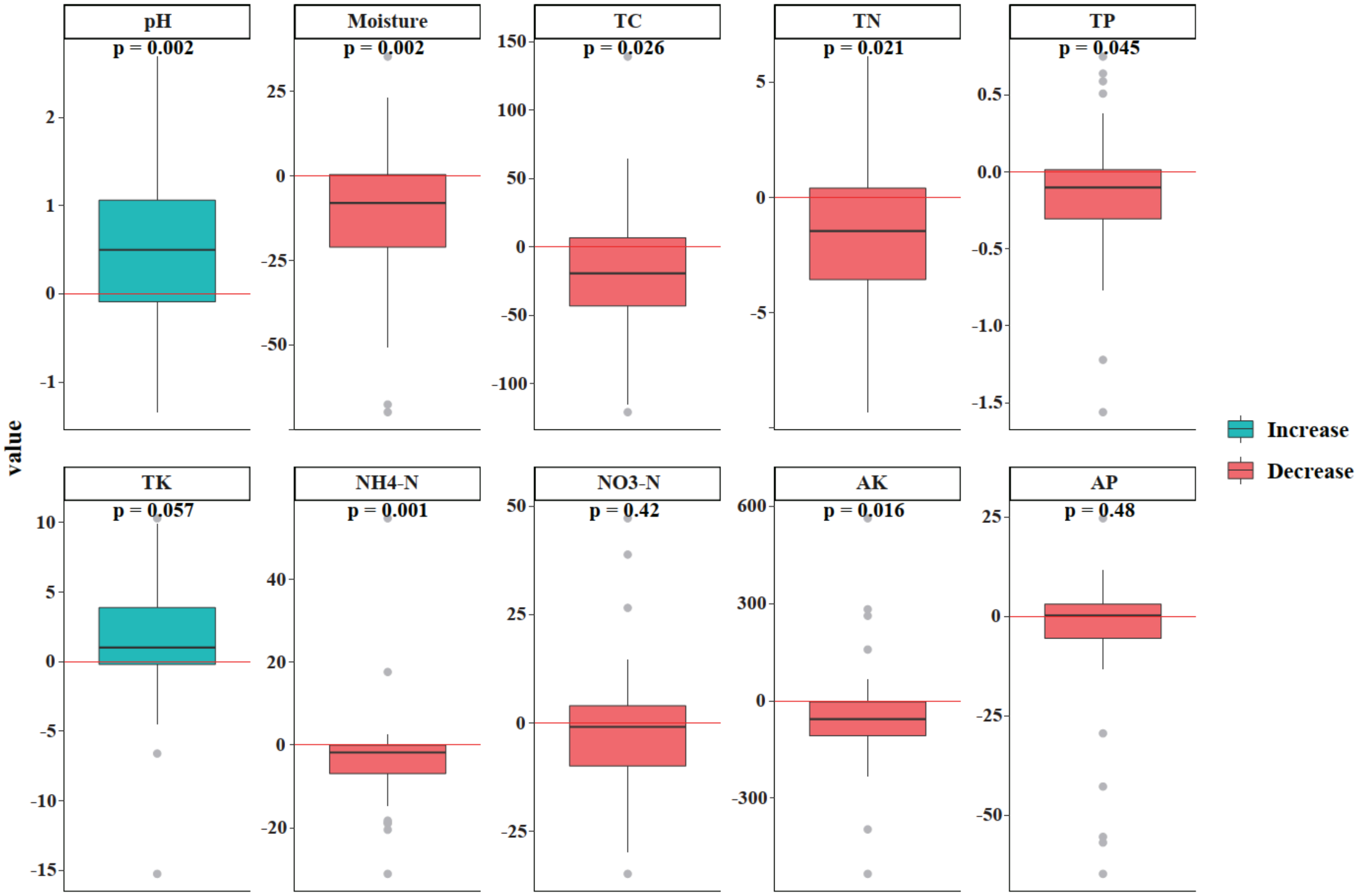

Figure 2

Paired comparison of soil properties between the natural and disturbed plots (Use the natural plot as baseline)

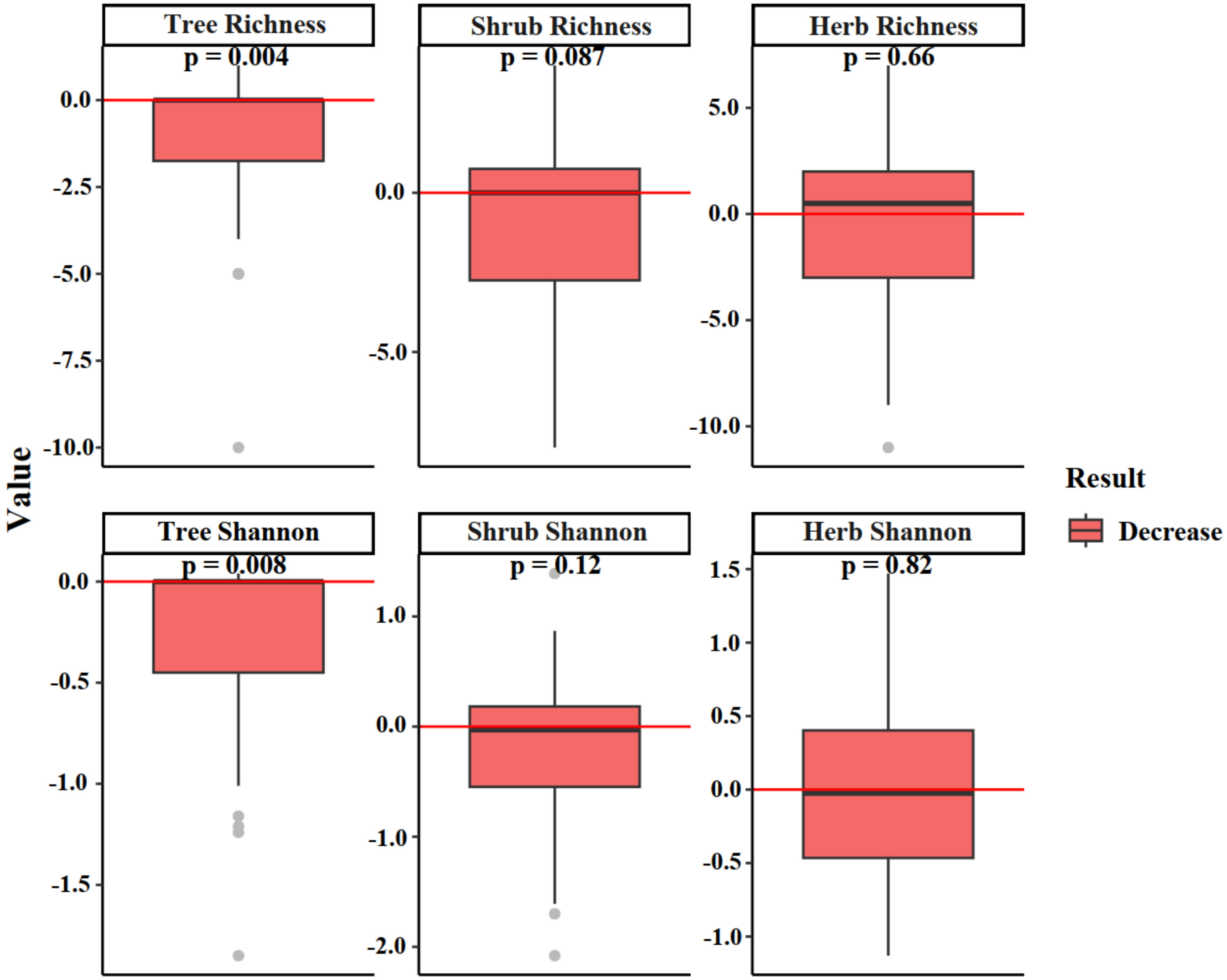

Figure 3

Paired comparison of tree, shrub, and herb diversity between the natural and disturbed plots (Use the natural plot as baseline)

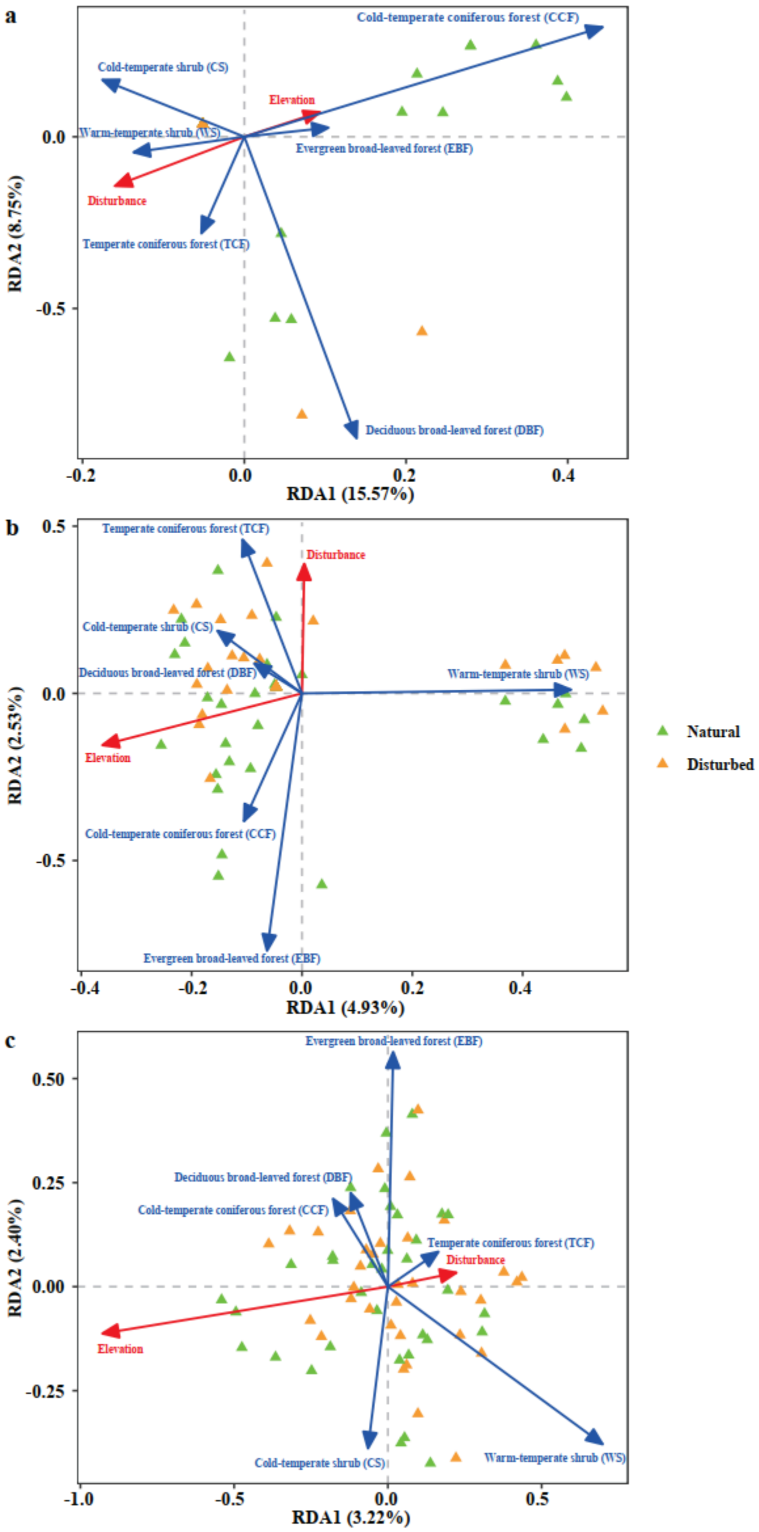

Figure 4

Redundancy analysis of tree (a), shrub (b), and herbaceous (c) community composition (Disturbance represents road construction)

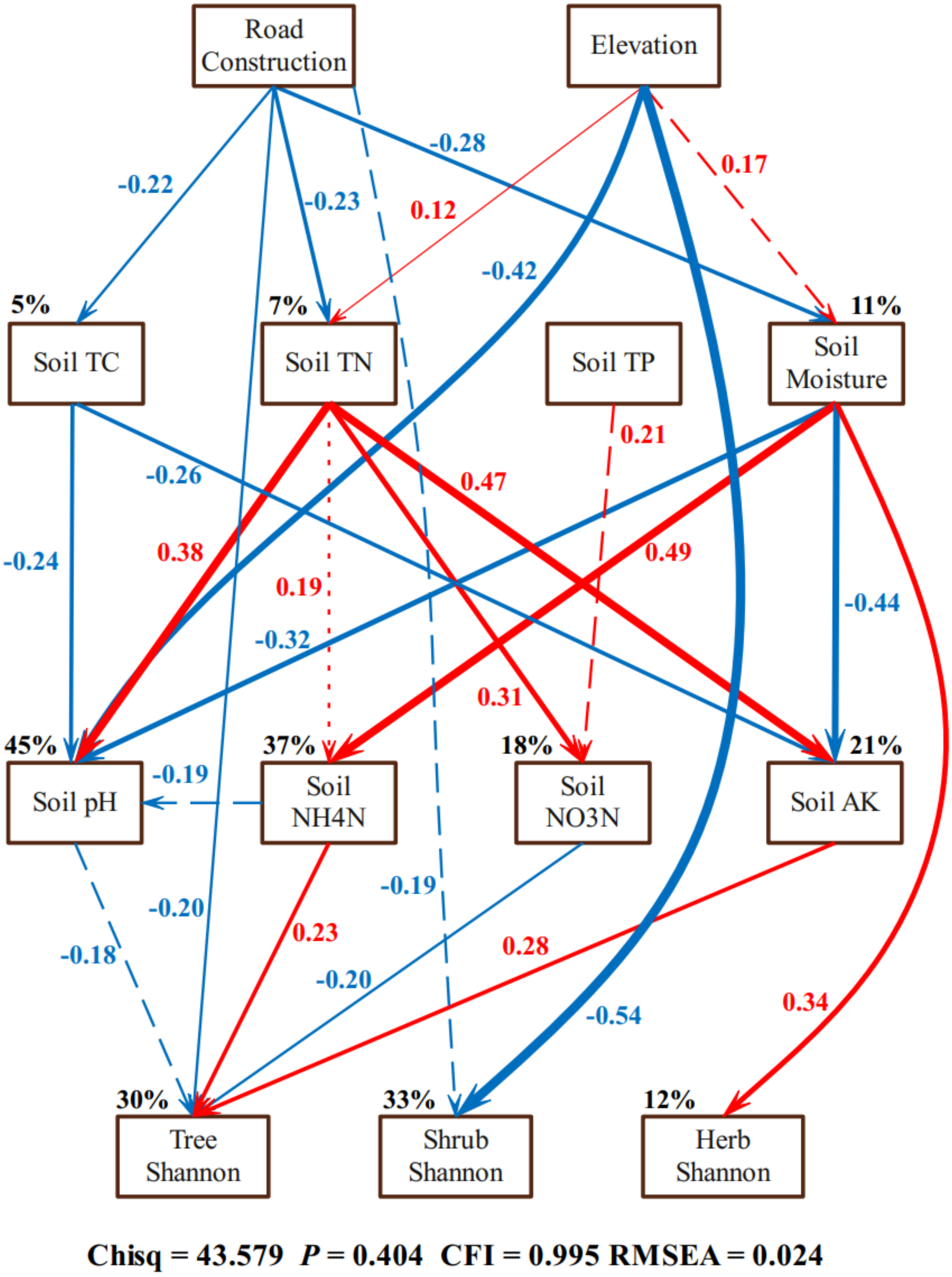

Figure 5

Structural equation models of the direct and indirect effects of road construction and elevation on the recovery of soil properties and plant diversity.

Note: Red and blue solid arrows represent significant positive and negative effects ($p < 0.05$), respectively. Pathways without a significant effect are indicated by dash arrows ($p > 0.05$). The width of the arrows indicates the strength of the relationships. Numbers adjacent to arrows are standardized path coefficients and are indicative of the effect size of the relationship.

Supplementary Files

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- FigureS1soilproperties50years.pdf
- FigureS2plantdiversity50years.pdf
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