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ORIGINAL ARTICLE

Relationship between karst rocky desertification and its distance to roadways in a typical karst area of Southwest China

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Abstract The presence and conditions of roadways determine the utilization of natural resources, which exert direct and indirect influences on karst rocky desertification (KRD) in undeveloped karst areas. This paper addresses the relationship between KRD and its distance to roadways in Pingguo County, a typical peak-cluster depression area in Guangxi Zhuang Autonomous Region in Southwest China, focusing on the three time periods of 1994, 2001, and 2009. KRD maps for each time period were interpreted by using remote sensing and GIS technology in buffer zones, which are 4.0 km wide and subdivided into eight strips of 0.5 km wide each. They are located alongside various classes of roadways, namely trunk, town, village, and unpaved roadways. Results demonstrate that slight KRD is the major type in buffer strips on both sides of roadways, which tends to decrease with an increase in distance to road baseline. In contrast, moderate and severe KRD cases cover relatively limited areas, which tend to change less rapidly. Moreover, these two KRD cases are less related to their distance to trunk and town roadways than to village and unpaved roadways. Therefore, the distance to roadways affects slight KRD distribution more than moderate and severe KRD. Temporal KRD patterns indicate that slight, moderate, and severe KRD areas alongside all roadway classes have comparatively similar trends in the periods of 1994, 2001, and 2009 KRD areas alongside various classes of roadways in the three periods (except some of those alongside the town and trunk roads) rank as follows from highest to lowest, 2001, 2009, and 1994. However, the total area in town and trunk roads is relatively small and varies little with distance from strip-to-road. KRD alongside various roadway classes is affected jointly by historical policy, distance to roadways, and landscape.

Keywords Karst area · Karst rocky desertification (KRD) · GIS · Roadway classes · Remote sensing · Pingguo

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Introduction

Karst rocky desertification (KRD) is a process in which soil is eroded so seriously or even thoroughly, that bedrock is widely exposed and land productivity declines seriously, and in the end, landscape appears similar to desert, under impacts of violent human activities on the vulnerable eco-geo-environment (Yuan 1993; Cai 1997; Huang and Cai 2006a; Xiong et al. 2008; Zhang et al. 2011). There are three large and continuous karst regions in the world, namely East Asia, the eastern part of North America and the middle and southern parts of Europe. The karst mountain region of the Southwest China is one of the largest karst geomorphology distributing regions among the three karst regions (Yuan 1993, 1997) and is one of the most serious regions of poverty and environmental degradation in China (Zhang et al. 2010). This region is also overpopulated, and the social economy is laggard (Zhang et al. 2011). So, people have to overexploit forest for cultivated land and firewood, leading to serious land degradation in the form of KRD, which has been taken seriously by both the government and the public (Yuan 1997; The Chinese Academy of Sciences 2003; Wang et al. 2004). In this region, people cannot utilize natural resources without roads and paths, and the magnitude of that use

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is closely related to road presence or absence and roadway quality classes as well (Jayanath and Gamini 2003; Ziegler et al. 2004; Shi et al. 2007). Roads have direct environmental impacts on water quality, hill-slope erosion, karst landscapes, and animal habitat and survival (Ziegler and Giambelluca 1997; Minten and Kyle 1999; Mick Day 2007; Motha et al. 2004; Tang et al. 2006; Costa and Bacellar 2007). Roads indirectly contribute to landscape degradation by providing accessibility (Arnaez et al. 2004; Morschel et al. 2004; Mick Day 2007).

Many researches on the KRD have been carried out and have included the definition (Wang et al. 2004), distribution (Huang and Cai 2006b), causes (Xiong et al. 2008), ecological-environmental effects (Zhang et al. 2011), and preventive strategies (Jiang et al. 2008). In addition, some researches about the relationship between human interaction and KRD have been carried out (Liu et al. 2008; Xiong et al. 2008), but the relationship between roadways and KRD has not been investigated. In karst mountain regions, however, KRD usually takes place alongside roadways after the surrounding forest is destroyed. This is because that tree cutting and firewood collecting are the most popular ways of utilizing forest resources in these areas. With the construction of roads in rural areas, human disturbance of natural resources accelerates forest destruction and hence accelerates KRD. Unfortunately, no sufficient deepgoing research on this issue has been reported thus far, although indirect impacts of this kind on the environment could be more significant than those triggered directly by roadways in those areas.

The paper presents a case study in Pingguo County, Guangxi Zhuang Autonomous Region, Southwest China, known for its KRD. In the study, distribution of KRD alongside roadways of various quality classes is revealed by overlapping KRD maps representing three time periods of 1994, 2001, and 2009, and a traffic roadway map completed in 2003. The objectives of this study are to (a) reveal the spatial–temporal distribution of KRD in Pingguo County and (b) quantify relationships between KRD and its distance to roadways.

Materials and methods

Study area

Pingguo County is located in the southwest part of Guangxi Zhuang Autonomous Region (106°36′2.56″–106°36′28.36″E, 23°53′25.88″–23°53′40.94″N), covering a total area of 2,485 km^2. Carbonate rocks cover an area of 1,457.8 km^2 or about 58.7 % of the total area. The topography is characterized by typical karst peak-cluster depression landscape (a combination of clustered peaks with a common base) with the altitude ranging from 110 to 935 m above sea level. It has a subtropical monsoon humid climate with a mean annual temperature of 13–14 °C and abundant but seasonally uneven rainfall. The annual mean precipitation for the period from 1958 to 1992 is 1,347 mm, but over 86 % of this amount falls during the rainy season (April–October).

It is an undeveloped, densely settled area with a total population of 496,000, 82.71 % of which is agricultural population, with little farm land (20,300 ha) in 2009. The capita farmland area is 0.041 ha, a figure much lower than that of the Chinese national average of 0.117 ha. Per capita annual net income of rural households was about 3,451 Yuan in 2009. The study area is short of surface water resources, cultivated land and firewood, and is one of the poorest areas of Southwest China.

Data source and description of roadway quality classes

Remote sensing data for 1994, 2001, and 2009 (synthesized satellite TM 5, 4, 3 images), geological map, and digital elevation model (DEM) with the spatial resolution of 30 m of Pingguo County were used in the present case study. The road map completed in 2003 was used. It is a reliable reference of actual traffic status in this undeveloped karst area where road construction progressed quite slowly over these years except for highway.

Roadways are identified by four quality-based classes, namely, trunk roads (10–12 m wide), town roads (5–6 m wide), village roads(about 3 m wide), and unpaved roads (1–2 m wide) (Shi et al. 2007) (Fig. 1). In the study area, trunk roads with bituminous pavement are main roadways, providing access from the county seat to other counties or cities. Town roads with macadam pavement are those connecting towns and townships. Village roads also with macadam pavement are narrower, linking townships, and their villages. And, unpaved roads without macadam pavement and major construction are simple earthy roads, linking villages, and relating closely to daily life of rural residents. Jiang et al. (2009a) concluded that the impact of human activities on rocky desertification is exerted mainly to 4.0 km away from the construction land. So, in this study, two buffer zones, each 4 km wide, were set up on both sides of roadways, and eight buffer strips, 0.5 km wide each, were defined within each buffer zone in proper sequence. The distribution patterns of various types of KRD were identified by GIS overlay of buffer strips and KRD maps.

Because of the link between topography and KRD in karst areas (Huang and Cai 2006a; Jiang et al. 2009a; Zhang et al. 2010), it is important to account for the relationship between road class and terrain. Tables 1 and 2 describe the proportion of each road class as it corresponds

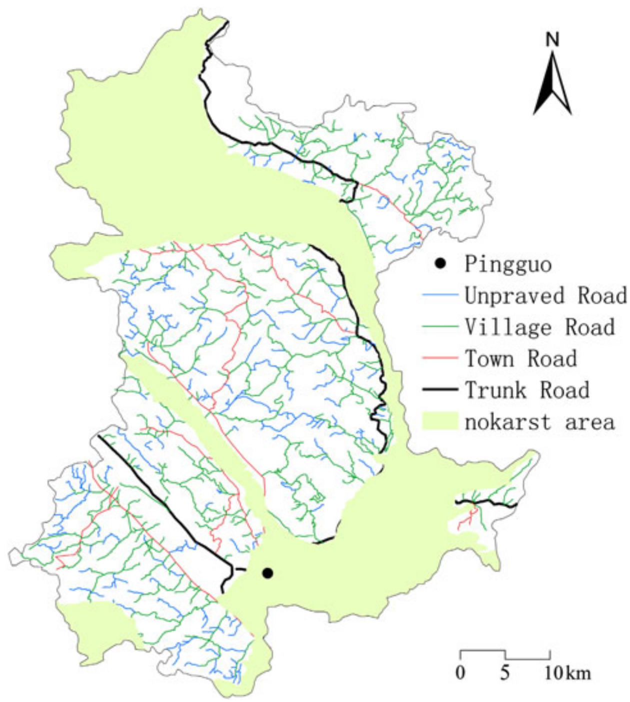


Fig. 1 Roadways of various classes in Pingguo County, China in 2003

Table 1 Slope (degree) distribution of different road classes in buffer strips of 4 km (percentage of area) in Pingguo County, China

Slope (°)	Unpaved road	Village road	Town road	Trunk road
<12	40.82	41.41	46.40	50.57
12–25	35.41	35.09	33.50	29.88
25–35	16.56	16.35	14.21	13.62
>35	7.21	7.14	5.89	5.92

Table 2 Altitude distribution of different road classes in buffer strips of 4 km (percentage of area)

Altitude (m)	Unpaved road	Village road	Town road	Trunk road
<150	7.00	6.70	10.11	–
150–200	5.38	6.07	7.39	100
200–300	20.72	22.14	20.06	–
300–500	50.83	49.65	48.86	–
>500	16.07	15.44	13.58	–

to different slope or altitude ranges. As can be seen, in karst peak-cluster depression area, the percentage of area of the four classes decreases with the slope increase, and trunk roads tend to have lower altitude, while town roads, village roads, and unpaved roads tend to have higher altitude.

Table 3 Classification standard of KRD

	Slight	Moderate	Severe
Bedrock exposure rate (%)	30–50	51–70	>70
Slope (°)	12–25	26–35	>35
Color of the RS image[a]	Green in red	Gray in red	White, gray
Shape of the RS image	Like star	Patch	Patch

Source: Huang and Cai (2006a) and Hu et al. (2008)

[a] Images displayed with Landsat TM bands 3, 4 and 5 (displayed as red, green and blue)

Karst rocky desertification (KRD)

KRD distribution was obtained by interpreting Landsat Images from 1994 to 2009 in Pingguo County, according to bedrock exposure rate and slope, as shown in Table 3. The classification process included three steps:

(a) Determination of desertification index model (Fraster et al. 1992; Tong 2003; Yang et al. 2012):

$$D_i = DN_{TM5} \times G_{TM4} / DN_{TM4} \times G_{TM5} \quad (1)$$

where D_i is the rocky desertification index of the i-th pixel; DN_{TM4}, DN_{TM5} are digital number(DN) of the i-th pixel of TM_4 and TM_5; G_{TM4}, G_{TM5} are average digital number of TM_4 and TM_5 for the entire scene image

(b) Calculation of bedrock exposure rate: First, the satellite data were preprocessed and combined to form false color images by displaying bands 3, 4, and 5, respectively, with red, green, and blue. Then, with the aid of the geological map, the study area was classified into karst area and non-karst area, through visual human–computer interactive interpretation in a geographical information system according to color and texture of the RS image (Hu et al. 2010). And last, the maximum and minimum values (namely, $D_{\max}$ and $D_{\min}$) of rock desertification index were determined for severe and non-karst desertification pixels. That is to say, $D_{\max}$ represents the maximum rock desertification index of the severe KRD pixel, whose bedrock exposure rate is 100 %, and $D_{\min}$ represents the minimum value of non-karst desertification pixel with forest covering well, whose bedrock exposure rate is 0 %. Then, bedrock exposure rate (Price 1993; Zhou et al. 2008; Yang et al. 2012) was calculated as:

$$D_{gi} = \frac{D_i - D_{\min}}{D_{\max} - D_{\min}} \quad (2)$$

where D_{gi} is bedrock exposure rate of the i-th pixel; $D_{\max}$ and $D_{\min}$ are described as above.

(c) KRD interpretation: with the data of bedrock exposure rate and DEM, the decision tree of remote sensing interpretation rocky types was established according to the classification standard, which was shown in Table 3.

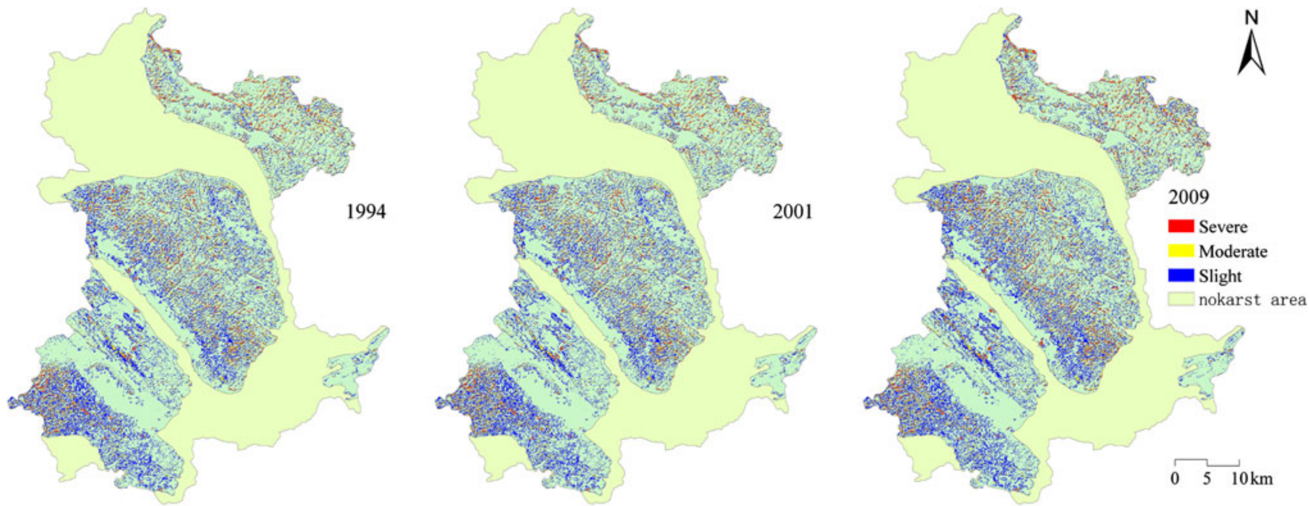


Fig. 2 KRD maps of three temporal phases in Pingguo County, China

The KRD areas were classified into slight, moderate, and severe types. The results are shown in Fig. 2.

Results

In order to understand KRD heterogeneity alongside roadways of karst rocky areas, first, it is necessary to generally describe KRD evolution from 1994 to 2009. The 2009 data were used as an example to analyze distribution patterns of slight, moderate, and severe KRD in various buffer strips alongside the different roadway classes. Further, slight, moderate, and severe KRD in buffer strips alongside the four roadway classes have similar trends spanning the mentioned three time periods, and slight KRD is the major degradation type in the study area (Fig. 3), so the trends of slight KRD were used to illustrate variability in the general KRD.

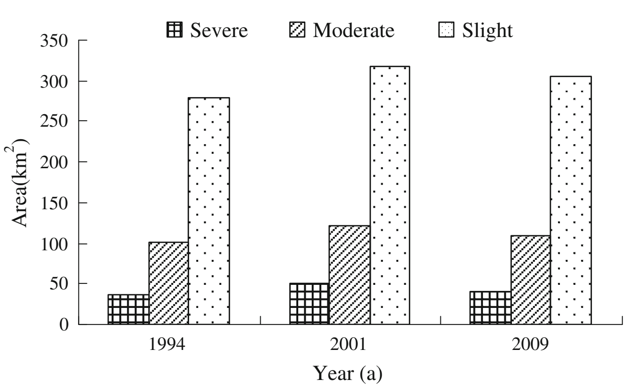


Fig. 3 Degradation trends of KRD in the three temporal phases in Pingguo County, China

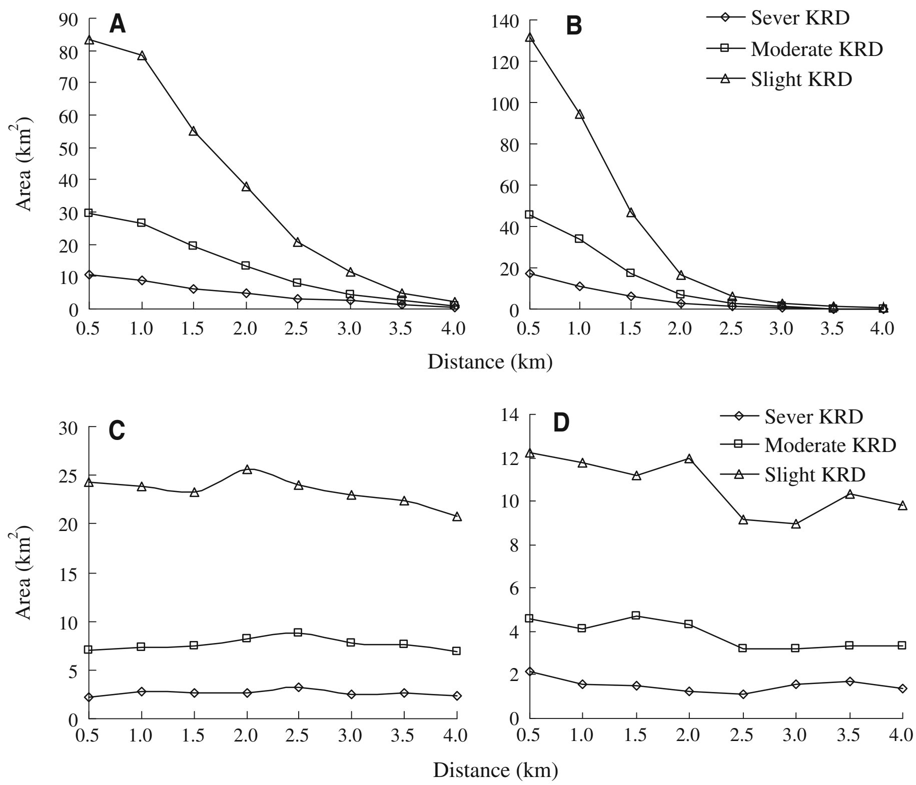
Spatial–temporal distribution of KRD

Generally, area of KRD in karst areas of Pingguo County tended to increase in the time period spanning 15 years (1994–2009). For example, the percentage of area of non-karst rocky desertification decreased from 73.14 % in 1994 to 70.55 % in 2009. However, the development of KRD in the mentioned period as a whole underwent an evolution from fast to slow (Figs. 2, 3). The evolution process of KRD in the county might be divided into the following two phases. First, degradation phase (1994–2001)—KRD increased and the percentage of area of KRD increased from 26.86 to 31.74 %, and area percentages of slight, moderate, and severe KRD cases increased from 2.31, 6.50, and 18.05 to 3.28, 7.90, and 20.56 %, respectively; Second, ecological reconstruction phase (2001–2009)—ecological reconstruction measures in karst region have played an increasingly important role in the study area, with non-KRD accounted for over 70.55 % of the county's karst area, and slight, moderate and severe KRD types decreased from 3.28, 7.90, and 20.56 to 2.63, 7.12, and 19.70 %, respectively (Fig. 3).

KRD distribution in buffer strips alongside four roadway classes

Figure 4 shows KRD distribution patterns in 2009 alongside four roadway classes. Slight KRD is the major type in buffer strips on both sides of roadways. Total area of slight KRD reduces with increasing distance to roadways: maximum KRD area is found in the strip 0.5 km away from the road, and the minimum one is found in the strip 4.0 km away from the road. One exception is a maximum KRD area, which is found 2.0 km away from the town roads.

Fig. 4 Distribution of KRD in buffer strips alongside four roadway classes in Pingguo County, China. (**a** unpaved roads, **b** village roads, **c** town roads, **d** trunk roads) (Note: road map in 2003 was used in this figure)



Another exception is one minimum, found 3.0 km away from the trunk roads. In contrast with slight KRD, moderate, and severe KRD cover relatively limited areas which tend to change less rapidly. Moreover, KRD areas in these two cases are less related to the distance to town and trunk roadways than village and unpaved roadways. In other words, no significant changes in terms of moderate and severe KRD areas are found with the increased distance to trunk and town roadways (Fig. 4c,d). Therefore, the distance to some roads affects slight KRD distribution more than moderate and severe KRD. Furthermore, it was observed that difference in areas between slight KRD and moderate and severe KRD cases is declining around village and unpaved road, especially in the cases of buffer strips 2.5 km or more from the road baseline.

Evolution of slight KRD in buffer strips alongside four roadway classes

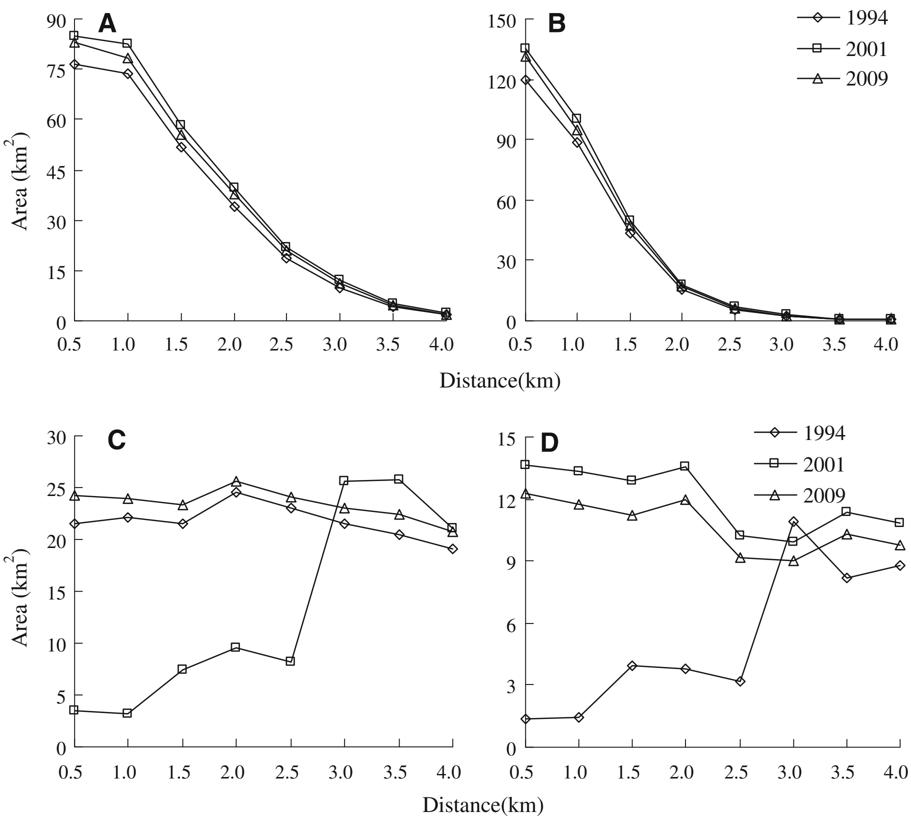
Figure 5 shows the evolution pattern of slight KRD distribution alongside unpaved, village, town, and trunk roads in various time periods. Generally, a similar tendency is found in various buffer strips alongside different roads in various temporal phases: the area of KRD in 2001 is larger than that in 1994 and 2009. However, for town road cases the lowest values of KRD area occur in 2001 at a distance of 0.5–2.5 km and for trunk road case the peak value occurs in 1994 at a distance of 3.0 km. Also, the more distance from a strip-to-road baseline, the less total KRD areas are. There are two exceptions, namely the cases alongside town roads in 1994 and trunk roads in 2001, which are rising with the distance increasing to roads. Further, village and unpaved roads are characterized by a distinctive and quick decrease of slight KRD areas with the increase of distance to roadways for time periods 1994, 2001, and 2009. This indicates that KRD areas were largely impacted by roadway classes in karst areas during the 1994–2009 periods.

Discussions

Impact of historical policies and human activities on KRD

Pingguo County, located in Southwest China, is a poor and undeveloped county, which is a typical peak-cluster depression county. However, through examining the KRD process that took place alongside roadways of various classes, it is found that areas of KRD reached a peak in 2001 and then gradually decreased in the county. This trend is closely related to the policies applied in karst area of China, especially those to remedy some mistakes of ignoring of environmental protection before 1990s. At that

Fig. 5 Evolution of slight KRD in buffer strips alongside four roadway classes in Pingguo County, China



time, the needs of a fast increasing population required accelerated forest cutting and fire wood collecting to obtain more cultivated lands and firewood. After repeated felling, continuous reclamation and herding, the soil gradually erodes and rock exposes, and KRD takes place. Fortunately, the central and local governments at different levels have taken this seriously, and the 'Green for Grain' program was initiated to protect the fragile environment. The Chinese government has decided to appoint the county as one of the 'one hundred typical counties for karst rocky desertification control', and a series of important projects have been carried out since 2000, such as 'Technology Development and Demonstration of Karst Ecological Reconstruction in China's Tropical and Subtropical Karst Areas', 'Demonstration of Ecological Reconstruction of Karst Peak-cluster depression' and 'National "Eleventh Five-Year" Plan Technology Support Program issues—fragile ecosystems reconstruction of Karst mountain peak-cluster areas' (Jiang et al. 2009b). Guohua Ecological Experimental Area was founded in 2001 in Pingguo County, and the knowledge of protecting karst environment was trained and propagandized in the public. Since then, forests in hilly areas have been effectively managed and protected, and illegal wood cutting has been restrained. With the gradual recovery of vegetation, the area of KRD alongside roadways of various classes gradually shrank.

Impact of landscape and the distance to roadways on KRD

The present study indicates that in undeveloped karst areas, some KRD takes place on either side of four different types of roads within the 4.0 km corridor. Further, the number and severity of KRD areas gradually decrease with an increase in the distance to the roadway baseline. Slight KRD cases occur most frequently near the roadways, especially near the unpaved and village roads. These trends indicate that in the peak-cluster depression areas people tend to utilize forest resources in a limited range alongside roadways. As a result, the extent of forest destruction decreases with the increase of distance from their working sites to the roadway baseline, with KRD intensities decreasing in the same way. Bååth et al. (2002) concluded that the probability of fire wood harvesting decreases by over 50 % beyond a buffer zone of 300 m alongside roadways. Matthew et al. (2004) argued against the destruction of lowland forests and found that the areas closest to roadways are the easiest to destroy. Shi et al. (2007) indicated that the severe soil erosion is the major type in buffer strips on both sides of roadways, and increasing distance to roadways can reduce total soil eroded area. Although many researchers conducted studies on impacts of road and residence properties on KRD (Jiang et al. 2009a; Zhang et al. 2010; Yang et al. 2011) the present study indicates that it is not prudent to evaluate the impact of roadways on KRD entirely based on KRD related to road surface properties, because numerous KRD are widely found in areas along both sides of roadways in karst areas, and KRD associated with these cases are much higher than those triggered by roadways themselves.

Impacts of landscape on KRD alongside roadways of various classes relate to natural factors like rock property, slope, land-use, parent material and soil property (Yang et al. 2011). In this study, most unpaved and village roads are constructed on comparatively uneven terrain and valleys where farmlands, residences, woods, and grasslands are found. These roads serve to intensify KRD, which is aided by steep terrain, intense human activities, and abundant rainfall. These construction practices resulted in vast areas of slight KRD distributed proximal to those roadways.

Conclusions

Analysis of KRD distribution patterns in buffer strips along four types of roads indicates that roadways influence the distribution of KRD in the study area. Generally, slight KRD is the major type in buffer strips on both sides of roadways. Also, increasing distance to roadways can reduce the area of slight KRD. In contrast, moderate and severe KRD cases cover relatively limited areas, and their areas tend to change less rapidly compared to slight KRD. Moreover, KRD areas in these two cases are related less to their distance to trunk and town roadways than to village and unpaved roadways. Therefore, the distance to roadways affects slight KRD distribution more than moderate and severe KRD. Total area of slight KRD alongside roadways of all classes in the 1994, 2001 and 2009 periods are all high and are comparatively similar to each other. Temporal KRD patterns indicate that areas of slight KRD associated with roadways, except some of the town road and trunk road cases, rank as follows from highest to lowest, 2001, 2009, and 1994. However, the total area in town and trunk roads is relatively small, and varies little with strip-to-road distance. It may be concluded that human activities associated with roadways as a projector of anthropogenic impacts relate closely to KRD in undeveloped karst areas. Further, KRD control policies and measures can be formulated and applied on the basis of understanding KRD patterns and its proximity to roadways of various classes and the timing of these actions are critical to abate negative impacts of road construction.

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