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Review

Rocky desertification in Southwest China: Impacts, causes, and restoration

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ABSTRACT

Rocky desertification, which is relatively less well known than desertification, refers to the processes and human activities that transform a karst area covered by vegetation and soil into a rocky landscape. It has occurred in various countries and regions, including the European Mediterranean and Dinaric Karst regions of the Balkan Peninsula, Southwest China on a large scale, and alarmingly, even in tropical rainforests such as Haiti and Barbados, and has had tremendous negative impacts to the environment and social and economic conditions at local and regional scales. The goal of this paper is to provide a thorough review of the impacts, causes, and restoration measures of rocky desertification based on decades of studies in the southwest karst area of China and reviews of studies in Europe and other parts of the world. The low soil formation rate and high permeability of carbonate rocks create a fragile and vulnerable environment that is susceptible to deforestation and soil erosion. Other natural processes related to hydrology and ecology could exacerbate rocky desertification. However, disturbances from a wide variety of human activities are ultimately responsible for rocky desertification wherever it has occurred. This review shows that reforestation can be successful in Southwest China and even in the Dinaric Karst region when the land, people, water, and other resources are managed cohesively. However, new challenges may arise as more frequent droughts and extreme floods induced by global climate change and variability may slow the recovery process or even expand rocky desertification. This review is intended to bring attention to this challenging issue and provide information needed to advance research and engineering practices to combat rocky desertification and to aid in sustainable development.

Contents

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1. Introduction

Desertification has long been recognized as a major economic, social, and environmental problem of concern to many countries in all regions of the world. A Plan of Action to Combat Desertification (PACD) was adopted at the United Nations Conference on Desertification (UNCOD) in 1978 (UNCCD, 1994). In 1994 the United Nations Convention to Combat Desertification (UNCCD) defined desertification as "land degradation in arid, semi-arid and dry sub-humid areas resulting from various factors, including climatic variations and human activities." However, this definition was considered biased (Yassoglou, 1999) since desertification has taken place under humid climates in Scotland and Iceland and in the tropical forest region in South Africa (Glantz and Orlovsky, 1983). Some karst areas in the Europe Mediterranean region fall into this dryland category because of its less than 0.65 aridity index.

Rocky desertification is used to characterize the processes that transform a karst area covered by vegetation and soil into a rocky landscape almost devoid of soil and vegetation (Yuan, 1997). It has occurred largely in the European Mediterranean basin (Yassoglou, 2000), the Dinaric Karst (Gams and Gabrovec, 1999), and in Southwest China (Yuan, 1997) due to extensive human activities on ecologically fragile carbonate rock formations. It has also occurred in other countries or regions in the world, such as in Belize, Guatemala, Mexico of North America, Israel of the Middle East, and East and Southeast Asia, including the Ryukyu Islands of Japan (Ford and Williams, 2007) and Gunung Sewu of Indonesia (Sunkar, 2008). Land degradation or even desertification is occurring in some of the Caribbean island countries such as Barbados (The Government of Barbados, 2002) and Haiti (Williams, 2011), where demands on land resources are high.

The Dinaric Karst in the Balkans covers an area of 60,000 square kilometers (km^2). The bare and stony epikarst, i.e. highly weathered carbonate bedrock exposed at the surface, largely devoid of trees and shrubs on rugged limestone terrains in the north westernmost plateau Kras (Carso in Italian, Karst in German) of the Dinaric Karst ridges was the origin of "karst" (Kranjc, 2012). Gams' (1991) research on Rillenkarren showed that the forest on the plateau Kras was destroyed and bare rock started to appear on the surface around 3000 to 3500 years BP, due to human activities such as stockbreeding and seasonal movement of people with their livestock between summer and winter pastures, slash-and-burn agriculture, firewood gathering, construction and different branches of industry, shipbuilding and metallurgy, and wars (Kranjc, 2012). The plateau Kras became a rock desert in the 18th century. Modern efforts toward reforestation began in the 18th century and successfully turned the rocky desert into dense pine forests. The forest in the plateau Kras increased from 20% in 1900 to 51% in 1989 (Gams, 1991). The chronology of desertification in the European Mediterranean region, including southern France, Spain, Italy, and Greece, is similar to the Dinaric Karst region. Yassoglou (2000) found that human disturbance to the land began around 8000 years BP. Desertification may have occurred after the Neolithic Age in the period 4000–3000 years BP due to intense human activities such as population growth, expanded agriculture, and deforestation in coastal areas where limestone formations lie. Yassoglou's (2000) study also showed that human disturbances had spatial and temporal variability throughout the region.

Rocky desertification has become the primary ecological disaster which has significantly hindered the economic growth in Southwest China and has a direct impact on the 1.7 million people living in the region (Jiang and Yuan, 2003). Although China does not have a record of ancient history of human disturbance to the land in its southwest karst region, the famous ancient geographer of the Ming Dynasty, Xu Xiake, described the rocky mountains almost without any forest or vegetation cover when he traveled to Guizhou on April 15, 1638 in "Xu Xiake's Travels." The "Great Leap Forward" from 1958 to 1961 resulted in large-scale rocky desertification when almost all trees were stripped to make charcoal for iron production across China. Cao et al. (2009) showed that the rocky desertification area expanded drastically by 3.76 times from 1970 to 2005 in Guizhou province.

A large number of studies have investigated the causes and impacts of rocky desertification, as well as issues in the physical sciences such as hydrology, soil erosion, sedimentation, water resources in terms of quantity and quality, and ecosystems in the world (NATO, 2003; Wang et al., 2004a,b; Millennium Ecosystem Assessment, 2005; NATO, 2007; UNECSO, 2009; Jiang et al., 2011). The goal of this paper is to present a comprehensive review of the causes, impacts, and restoration measures of rocky desertification from several decades of studies in the Southwest Karst region of China and from published works for some typical karst regions around the world.

2. Rocky desertification in Southwest China

China has approximately 3.44 million km^2 of karst areas (buried, covered, and exposed carbonate rock areas), about 36% of its total land, and 15.6% of all the 22 million km^2 karst areas in the world. The seven provinces including Yunnan, Guizhou, Guangdong, Chongqing, Hunan, Hubei, and Sichuan and the Guangxi Zhuang autonomous region in Southwest China have about 0.51 million km^2 of exposed/outcropped carbonate rock areas, 5.8% of the total land. As shown in Table 1 rocky desertification reached 35.6% of the exposed carbonate rock areas in Yunan in 2000, averaged to about 22% in the region. Up to 82% of the rock desertification areas are in Yunan, Guizhou, and Guangxi.

The severity of rocky desertification is classified into four categories in China: (1) no desertification when exposed bare rocks compose less than 30% of the land; (2) light desertification when exposed rocks compose between 30 and 50%; (3) moderate desertification with exposed rock between 50 and 70%; and (4) severe desertification with exposed rock greater than 70% as shown in Fig. 1. Remote sensing and GIS technologies were used to identify areas where rocky desertification has occurred in Southwest China (Li et al., 2008; Bai et al., 2011). The distribution of rocky desertification classifications in the three major river basins and their major tributary drainage basins in Southwest China are shown in Fig. 2 and summarized in Table 2. The rocky desertification area in the Yangtze River Southwest drainage basin is about 3.95% of its total land and 15.44% of the exposed carbonate area. For the Pearl River Basin, 95% of the rocky desertification area is located in the headwater Xi River subbasin, where 15.7% of the subbasin area or 33.2% of the exposed carbonate rock area was turned to desertification. Even though the exposed carbonate rock areas in each of the three transboundary river basins encompass less than 10%, 55% of the exposed carbonate rock areas have become desertification areas.

3. Environmental, social, and economic impacts

Rocky desertification is the ultimate result of deforestation and soil loss in the carbonate rock areas. It has tremendously affected the hydrologic, soil, and ecologic conditions at various scales and consequently causes more geologic hazards such as droughts, floods, landslides, and land subsidence. On a larger scale it even affects the carbon balance and regional climate conditions. The expansion of rocky desertification has put more strain on people's lives in areas where they are already living below the poverty line.

3.1. Environmental impacts

Rocky desertification has resulted in the loss of biomass in karst systems, changes in the physiological and ecological characteristics of plant communities, and the loss of forest and vegetation cover (Table 3). Ecologically, it has resulted in changes in germplasm and species composition and loss of species diversity in the system. Rocky desertification destroyed not only tall vegetation but also moss and algae on rock surfaces, which are pioneer species for vegetation growth.

Table 1
Area of rocky desertification in Southwest China in 2000 (all areas are in ×10,000 km^2).

Provinces and regions	Total land area	Exposed carbonate rock	Area of rocky desertification	I	II
Yunnan	38.43	9.34	3.33	8.7	35.6
Guizhou	17.61	12.66	3.25	17.1	25.7
Guangxi	23.64	9.17	2.73	11.5	29.8
Hunan	21.15	5.55	0.50	2.4	9.1
Chongqing	8.17	3.25	0.46	5.6	14.1
Hubei	18.56	4.45	0.43	2.3	9.6
Sichuan	48.11	4.69	0.41	0.9	8.8
Guangdong	17.65	1.47	0.24	1.4	16.5
Total	194.69	50.58	11.35	5.8	22.4

Note: I — Percent of rocky desertification area over total land area (%).
II — Percent of rocky desertification area over exposed carbonate rock area (%).

Their loss would make vegetation recovery very difficult. A study by Cao et al. (1995) showed that moss and algae can absorb or release 3 to 15 times more water than carbonate rocks. In areas where soil, algae, or moss are lacking, carbonate rocks cannot store sufficient water for vegetation to grow, and the survival rate of afforestation is usually below 40%. Notably rocky desertification has forced some of the vegetation or forest to adapt to new conditions. In large peak karst forest areas of Southwest China, tree roots often grow very deep through the crevices of rocks to obtain water from underground rivers.

Hydrologic characteristics of karst systems, particularly the rainfall runoff process, have been altered by rocky desertification as well. The removal of vegetation and soil in fractures would increase the infiltration to subsurface systems, reduce the flow storage capacity and residence time, and decrease the resistance to overland flow. As a consequence of rocky desertification, drought occurs more frequently in karst areas. The small springs from interflow or a shallow circulation karst flow system, which was used as the only source of water supply for 1.7 million people in the region, went dry (Jiang and Yuan, 2003); flow for the underground river and large karst springs was reduced in the low flow period; the surface water body or karst reservoirs and wetlands shrank in size; and groundwater levels were lowered. For example, the Huangguoshu waterfall in Guizhou has extended its annual dry season from two months in the 1980s to five months on average and sometimes even dries up.

Further, eroded soils from upland areas often fill in the karst conduits and block the drainage outlets in karst depressions, which often cause waterlogging in lowlands where limited arable lands are located. As a result of waterlogging, farms are submerged during the growing season. In some worst-case scenarios, houses and roads are destroyed and life, property, and livestock are lost. A typical example is the Jiashan Village in Guangxi, China. This village is situated in a typical karst depression with 33 families, 127 people, and about 6.8 ha of arable land. Waterlogging often occurred after the accumulated rainfall exceeded 200 mm during the rainy season from May to August. The 212 mm rainfall in three days in June 2005 resulted in flooded water up to 18 m deep in the depression, and this bottom land was flooded for more than two months.

The loss of vegetation and plant cover and soil erosion changed the physical, chemical, and microbiological characteristics of the land locally. On the regional scale, the increased sediment yield combined with the reduced flow rates endangers the navigation safety in the Pearl and Yangtze Rivers. The amount of sand flowing into the Yangtze River, the Pearl River, and their tributaries from rocky desertification-stricken areas in Southwest China is nearly five times the average

Fig. 1. The landscape of rocky desertification on hillsides near Liangsuatun village, Anshun, Guizhou Province.

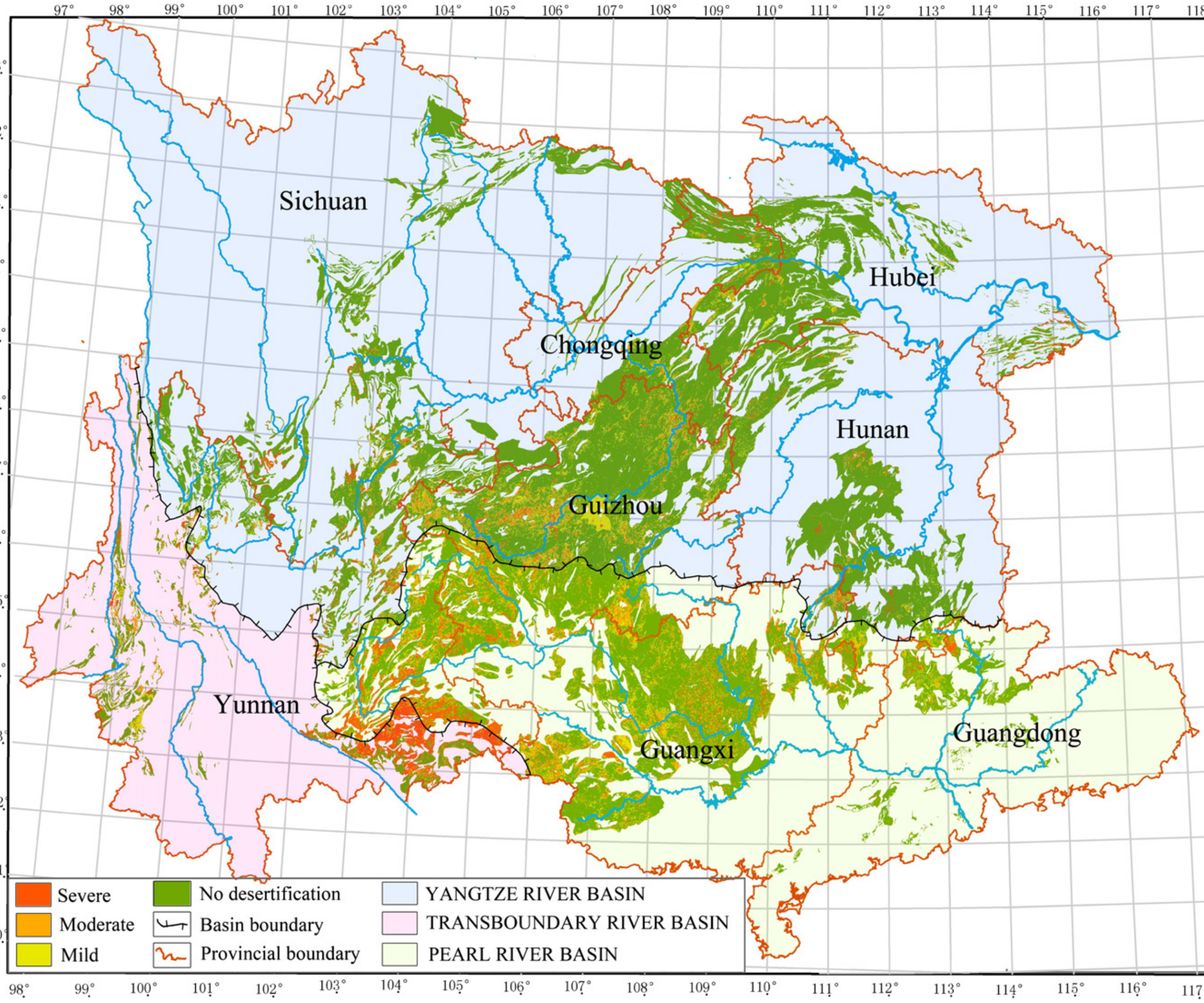

Fig. 2. Distribution and classification of rocky desertification areas in Southwest China.

Table 2
Statistics of rocky desertification (RD) areas for river basins in Southwest China (areas are in ×10,000 km^2).

Major river basin	Major tributaries	Total basin area	Exposed carbonate rocks	Area with different degrees of desertification			Total RD area	I	II	III
				Light	Medium	Severe				
Yangtze River Southwest Basin	Main stem	41.57	10.05	0.84	0.58	0.37	1.79	24.18	4.31	17.84
	Jialing River	10.90	1.29	0.013	0.018	0.007	0.04	11.80	0.35	2.95
	Ming River	12.67	1.36	0.044	0.028	0.015	0.09	10.73	0.69	6.40
	Han River	6.21	1.19	0.027	0.017	0.025	0.07	19.20	1.11	5.78
	Yake River	12.58	0.88	0.032	0.021	0.077	0.13	6.98	1.03	14.73
	Wu River	8.76	7.83	0.90	0.68	0.17	1.75	89.42	19.94	22.29
	Dongting Lake	25.87	7.72	0.42	0.30	0.11	0.82	29.84	3.16	10.60
	Sub-total	118.56	30.32	2.27	1.65	0.77	4.68	25.57	3.95	15.44
Pearl River	Xi River	34.02	16.09	1.64	2.00	1.70	5.34	47.29	15.70	33.20
	Bai River	4.76	1.29	0.14	0.09	0.05	0.28	27.06	5.83	21.54
	Chain of Rivers in the Pearl River Delta	2.27	0.06	0.0011	0.0006	0.0001	0.0018	2.83	0.08	2.80
	Rivers to the South Sea	4.95	0.11	0.0006	0.0014	0.0008	0.0028	2.20	0.06	2.57
	Dong River	3.12	0.09	0.0003	0.0001	–	0.0003	2.84	0.01	0.34
	Sub-total	49.12	17.64	1.78	2.09	1.75	5.62	35.91	11.45	31.88
Transboundary river	Yuan River–Red River	7.86	1.35	0.070	0.168	0.506	0.74	17.20	9.47	55.07
	Lu River–Irrawaddy River	5.45	0.77	0.063	0.062	0.046	0.17	14.16	3.15	22.24
	Lancang–Mekong River	9.12	0.50	0.066	0.034	0.031	0.13	5.47	1.44	26.23
	Sub-total	22.43	2.62	0.20	0.26	0.58	1.05	11.69	4.67	39.91
	Total	190.11	50.58	4.25	4.00	3.10	11.35	26.60	5.97	22.44

Table 3
Environmental impacts from rocky desertification in Southwest China.

Deforestation	a) Reduction of plant biomass, b) change in physical and ecological characteristics, c) change of plant community, d) reduction of forest and vegetation cover.
Ecology	a) Change of germplasm resources, b) species diversity, c) species composition.
Hydrology	a) Reduction of flow or dry up of creeks and small springs, b) reduced low flow for underground river and large karst springs, c) reduced surface water body and wetlands, d) reduced surface runoff and dry reservoirs, e) lowered groundwater levels.
Sedimentation	a) Soil loss to subsurface karst systems, b) altered rainfall–runoff processes, c) increased soil erosion from micro-geomorphologic units, d) excessive sediment load downstream.
Soil	a) Change of soil physical and chemical characteristics, b) change of soil microbiological characteristics.
Geological hazards	a) Increased drought due to water loss, b) increased flooding (water-logging), c) increased landslides.
Climate	a) Reduced capacity to absorb atmospheric carbon, b) temperature increase

eroded soil in eastern China, posing serious danger to electric power stations in the lower reaches, and threatening economic and social stability on a much larger scale.

Although further studies are needed, we infer that the expansion of rocky desertification areas in Southwest China has a negative impact on climatic conditions. The loss of vegetation cover and deforestation reduces photosynthesis of atmospheric CO_2, which would largely reduce the absorption of CO_2. Soil temperatures in Southwest China have had increasing trends over the last couple of decades (Lian et al., 2013).

3.2. Social and economic impacts

Rocky desertification has worsened the economy, social and cultural life (Table 4). Due to the heavy soil erosion and loss of water through the highly permeable bedrock, carbonate rock areas often have poor crop production. People in the remote karst areas lived in harsh conditions even before their land turned into rocky desert. Desertification has made the already difficult living conditions in the karst areas even worse. Eighty-eight of the 95 counties including 41 out of 50 counties in Guizhou, 25 out of 28 in Guangxi, and 22 out of 23 in Yunnan provinces are below China's state poverty line (The Ministry of Water Resources of China et al., 2010). On the local scale rocky desertification has resulted in the loss of agricultural production, loss of economic production from fruits and herbs, loss of tourism resources, and loss of properties from increased drought and flooding. By the end of 2000, 113,500 km^2 in Yunnan, Guizhou, Sichuan, Chongqing, Guangxi, and western Hunan had become rock deserts, and economic losses exceeded tens of billions of Chinese yuan annually. In Guangxi, where rocky desertification is a serious problem, natural disasters such as drought, flooding, and landslides have jumped from one in every eight or nine years to one in every two or three years and resu\lted in an annual economic loss of more than 400 million yuan (Jiang et al., 2011). On a regional scale, desertification forces local residents to migrate out of the poorer areas, which applies more pressure to other areas and towns and cities. The Huangguoshu waterfall in Huanglong, Guizhou lost its natural beauty and attraction due to the reduced inflow from upstream carbonate rock areas, which ultimately resulted in the loss of revenue from this tourism resource.

Rocky desertification often indirectly causes a lack of transportation and communication in remote areas. Investments for economic development in those areas are much lower than the national average. As a result of migration, the local work force and resources are greatly reduced, which increases the economic and cultural gap compared to other regions in the country. Living conditions have worsened, and the illiteracy rate has risen even higher in areas affected by rocky desertification (Jiang et al., 2011).

4. Causes of rocky desertification

The “kras” terrain of bare, stony epikarst devoid of trees and shrubs in the plateau Kras of the Dinaric Karst Region was due to forest clearance and farming on limestone terrains (Kranjc, 2012). Human disturbances played a critical role in rocky desertification of the vulnerable and fragile karst systems (Table 5).

4.1. Natural processes

4.1.1. Geology

Carbonate rocks are highly soluble and not able to produce much soil. Soil cover is scarce and soil layers are thin in high slope areas. Chemical analysis and field observations were extensively conducted in the early 1970s to understand the dissolution rate of carbonate rock and the rate of soil formation from dissolved carbonate rocks. Cai (1989) reported that the estimated soil formation rate was about 11 tons per square kilometer annually in karst areas on average in Southwest China, which is up to 100 times less than the purple soil (with a formation rate of 800–1200 tons per square kilometer per year) in the non-carbonate rock area of the Sichuan Basin in Southwest China (Li et al., 2010). The low soil formation rate in the karst area is due primarily to the low silicate mineral content in carbonate rock especially limestone. A study by Yuan and Cai (1987) showed that to form 1 m thickness of soil in karst areas in Guizhou and Guangxi would take one- to three-quarters of a million years by dissolving 25 m thick of carbonate rocks. A similar analysis by Su (2002) from 133 samples in Guizhou showed that to form 1 cm of soil would take 4 to 8.5 thousand years. The low soil formation rates of carbonate rocks imply it would be extremely difficult to recover the soil layer in the karst area once it is lost. Data from a land resource survey (Jiang and Yuan, 2003) showed that rocky desertification correlates well with rock types (Table 6). Rocky desertification is more severe in areas where pure limestone, interbedded limestone, and dolomite dominate. At places where impure carbonate rocks are located, thick soil layers and better vegetation covers are observed, and rocky desertification is scarce or mild. Wang

Table 4
Social, cultural, and economic impacts from rocky desertification in Southwest China.

Local economy	a) Loss of agricultural production, b) loss of economic production such as fruits and herbs, c) loss of tourism resources, d) loss of properties from increased drought and flooding, e) under national poverty level.
Regional economy	a) Migrants, b) sedimentation affecting navigation and power generation in large rivers.
Social impacts	a) Increased literacy rates, b) loss of investment, resources, and work force, c) lack of development and competitiveness, d) lack of services and entertainment, e) lack of transportation and communication, f) fear and stress from drought and flooding, g) increased gap to outside world.
Cultural impacts	a) Isolated communities, b) low education level, c) difficult for marriages in small communities.

Table 5
Major natural processes and human activities as causes to rocky desertification.

Causes		Related activities
Natural processes	Geology	a) Soluble carbonate rocks; b) low soil formation rate; c) missing C-horizon; d) topography (steep land slope, large relief); e) high permeability; f) combination of carbonate rock and their spatial distribution; g) other karst features such as sinkholes.
	Hydrology	a) Climate condition (extremely dry or heavy rainstorms); b) deep water depth; c) underground river; d) surface streams/rivers; e) low soil moisture for vegetation growth.
	Ecology	a) Initial vegetation cover; b) organic materials; c) micro-organisms
Human activities	In Europe Mediterranean	Ancient time: pastoral and nomadic activities, forest clearance, population growth, expanded agriculture, cultivation on hilly lands, wars, cutting forest for ships, pottery kilns, and smelting ores, grazing, forest fires, etc.
		Since 1950: industrialization and mechanization of agriculture; overexploitation and clear-cutting of forests, overgrazing, burning of forests and shrubs, groundwater level drop, urbanization, abandonment of marginal lands, tourist influx, climate change, forest fires, etc.
	In Dinaric Karst region	Grazing, population growth, cutting timber for construction, shipbuilding, industry (ore smelting, charcoal and lime, pottery), heating, defense installation, transhumance, slash-and-burn agriculture, wars, wild fires.
	Southwest China	Cutting of forest and shrubs for cooking, heating, ore smelting during the “Great Leap Forward”, farming on hilly lands, grazing, slash-and-burn, irrigation, population growth
	Other places	Exploiting forests for energy and economy in Haiti, Barbados, and other Caribbean Islands.

and Zhang (2003) showed that the spatial distribution pattern of carbonate rocks has an impact on rocky desertification. For example, the rocky desertification area was about 27% in northeast Yunnan where limestone and dolomite are scattered, 29% in east Yunnan where limestone and dolomite are interspersed, but as high as 53% in southeast Yunnan where limestone is continuously distributed. Wang et al. (2004a,b) drew a similar conclusion on the impact of carbonate rock distribution to rocky desertification based on their study in Guizhou.

Quite often soil profiles in mountainous karst areas miss the C-horizon that keeps the soil layer attached to the bedrock, without which the adhesion and affinity between the topsoil and bedrock is greatly reduced and the topsoil can be easily eroded by heavy rainstorms, exposing the bedrocks to rocky desertification (Yuan, 1993). The huge relief in topography and steep land surface slopes created by multiple tectonic movements provide kinetic energy for overland flow, which enhances soil erosion and karstification (Bailey et al., 1998; Zhang et al., 2001). Areas of severe rocky desertification are located mostly in the middle and upstream river valleys such as in the Fengcong depression, Fenglin depression, rift basin, and karst valley, where land surface slopes are steep. Su's (2002) study in Guizhou showed that the soil layer thickness decreases but the soil erosion index increases as the land slope increases. The soil layer thickness is around 120 cm and the soil erosion index is a low as 285 tons/km^2 per year for land slopes between 10 and 15°, 86 cm and 3150 tons/km^2 per year, respectively, for slopes 20–25, and 71 cm and 11,700 tons/km^2 per year, respectively, for slopes 30–35. The soil layer is usually less than 20 cm thick when the land surface slope is greater than 40°, but the soil erosion index is the highest up to 32 ktons/km^2 per year, which is more than 100 times greater than in areas where the land slope is less than 15°. The soil erosion indices for land slopes greater than 20° in the carbonate rock areas in Southwest China (Su, 2002) exceeded the soil loss tolerance rate of 2 to 5 tons per acre per year (or 294 to 1235 tons/km^2 per year) in the U.S. (USDA, 2007). The United States Department of Agriculture's (USDA) Natural Resources Conservation Service (NRCS) defined the soil loss tolerance rate (T) as the maximum rate of annual soil loss that will permit crop productivity to be sustained economically and indefinitely on a given soil (USDA, 2007). Kereselidze et al. (2013) derived mathematical expressions to estimate the maximum allowable soil erosion rate and demonstrate its application for various soils in the country of Georgia. The maximum allowable (permissible) soil erosion load is the value under which the stability of the soil meets the regulation requirements to avoid catastrophic degradation in nature (Kereselidze et al., 2013). When loads exceed the maximum allowable values, the degradation becomes irreversible. Febles-González et al. (2011) showed that the soil erosion rate in some karst areas has surpassed the permissible erosion threshold (maximum permissible erosion rate) in Cuba. Yuan and Cai (1987) estimated that the annual soil loss from karst areas in Guizhou would be equivalent to the amount of soil formed in 60 years, indicating a significant imbalance between soil loss and soil formation rate in the region.

Certain geological factors such as rock types and their distributions, the structure of soil profiles, and land surface slopes exacerbate rocky desertification. However, the chemical composition of carbonate rocks is an essential factor in the formation of soil layers and in rocky desertification. Rocky desertification is severe where limestone dominates because of its low silicate mineral content and thus the low soil formation rate, but would be minor in areas where dolomite dominates.

4.1.2. Hydrology

Karst flow systems typically have surface and subsurface dual drainages that are very well connected through sinkholes and fractures (Yuan and Cai, 1987). Conduits and underground rivers in Southwest China can be as deep as a few hundred meters. Groundwater tables in the middle and upstream river valleys are often deep. The unsaturated zone or shallow karst zone can't maintain the water level due to the high permeability of fractures and karst features. Even with 1000 to 2000 mm annual precipitation, the storage capacity of water in the soil layers is low, which results in the deficiency of soil moisture for vegetation growth. Areas with less dense surface streams tend to have more soil erosion and subsequently a higher tendency toward desertification (Jiang et al., 2011). In addition, heavy rainfall on exposed carbonate rock surfaces has more energy than on vegetation-covered land surfaces to carry sediment load for soil erosion. In the eastern region of the Europe Mediterranean basin the high permeability of limestone bedrocks and the thin layer of soil formed in this geologic environment were responsible for irreversible desertification (Yassoglou, 1999).

Climate change and variation have resulted in changes of precipitation, temperature and other climate parameters, which subsequently

Table 6
Percentage of rocky desertification area for different carbonate rock types in Southwest China ($\times 10^5$ km^2).

	Pure limestone	Pure dolomite	Limestone and dolomite interbedded layer	Impure carbonate rocks
Rock area	18.22	3.31	6.70	13.75
Desertification area	4.64	0.63	2.13	3.1
Ratio (%)	25.6	19.0	31.8	22.6

affected the hydrologic cycle, water resources, and the ecologic environment. Impact of climate change on hydrologic cycle has been observed in Southwest China although its direct relation to rocky desertification remains to be studied. Publications by Nijssen et al. (2001) and Costa-Cabral et al. (2008) indicated that Mekong in Yunnan Province has observed an increase in precipitation during early monsoon and increased runoff, and predicted future increase in precipitation and extreme floods. Studies by Su et al. (2005), Wang et al. (2005) and Zhang et al. (2006) have shown an increase in precipitation, extreme rainfall and more frequent floods in Southwest China. A study by Zhang et al. (2013) indicated that the extreme drought frequency has significantly increased in the past 50 years in the many parts of Southwest China. The SFA (2012) report showed that the three-consecutive-year drought in Qujin, one of the tributaries to the Pearl River Basin, has resulted in the expansion of the desertification area by 6.8% per year from 2005 to 2011.

4.1.3. Ecology

Initial vegetation cover is essential to rocky desertification potential. In areas where vegetation cover is more than 60% there is almost no rocky desertification. When the vegetation cover is less than 20%, the limited soil and vegetation may not maintain sufficient soil moisture and become vulnerable to soil erosion even with slight disturbance from human activities. Almost 90% of severe rocky desertification occurred in this kind of fragile environment (Jiang et al., 2011).

Rich organic material and thick soil are favorable for vegetation growth. Algae and lichens can enhance weathering to produce more soil. Moss, fern, and grass can increase the humus, nutrients, and soil fertility (Jiang et al., 2011). Grass would be a perfect vegetation cover; not only would it increase soil fertility but also protect soil from erosion. Unfortunately, the reality is it is very difficult to grow grass over a large area on the hill slopes of carbonate rocks; instead, arbors, shrubs, and bushes are often found, which can also provide good protection of soil from erosion. The large amount of residual organic materials left by vegetation in soil and fractures needs fungus, worms, and bacteria to convert them into humus. Micro-organisms in soil decompose dead animal and vegetation into humus to enrich nutrients in the soil. They can also increase porosity and permeability in soil layers and release CO_2 and organic acid, creating a more favorable environment for forest. However, any damage to the vegetation cover or to the micro-organism community can destroy the balance in the ecosystem, potentially resulting in rocky desertification (Deng et al., 2009).

4.2. Human activities

Human disturbances to land often involve various activities for food, energy, and economy to accommodate population growth (Table 5). In as early as classical Greek times (Gams, 1991) rocky desertification occurred when the originally wooded but stony regions were transformed into farmland. In Roman times tall pines were logged for shipbuilding. Historic farming practices (Ford and Williams, 2007) had resulted in the abandonment of the once intensively farmed karst uplands in Europe. In southern France, Corsica, and Sardinia the lands are reverting to garrigue. In areas of Belize, Guatemala, and Mexico, population growth has forced traditional smaller farmers to use the once abandoned lands. Mechanized farming in the 20th century, especially after 1945, transformed much of the subdued types of karst topography in central and southern Europe, Israel, Japan, and the Ryukyu Islands where land prices are high. Also in China, the huge population growth has forced people to farm the land wherever it is accessible. Grazing by goats and sheep in the succeeding centuries caused severe soil loss in the epikarst regions.

The nationwide "Great Leap Forward" campaign virtually eliminated all forests except for a few reserves. Rocky desertification continued with a population growth that exceeded 200 people per square kilometer in southwest karst areas (SFA, 2012). In order to feed themselves, local residents had no choice but to grow corn on steep hill slopes. Such farming practices resulted in severe soil erosion and loss of most of the soil after a few years. In the remote mountainous areas, residents used to cut short shrubs and trees for cooking and heating. This practice not only destroyed the vegetation cover but also hindered plant recovery. Farmers typically burned the bushes on hill slopes for fertilization in the fall, which accelerates soil loss. A portion of the lost soil was flushed to the karst depressions, causing the blockage of natural drainage, which consequently caused water-logging in those bottom land areas.

Generally, whether in Europe, China, or other places of the world, deforestation and soil erosion resulting from various activities lead to rocky desertification. When soil loss is severe enough to reach a certain threshold, desertification may become irreversible (Kereselidze et al., 2013).

5. Rocky desertification control and ecosystem restoration

In 1150 AD when rocky desertification had become sufficiently intense, the government in Trieste, Italy restricted cutting trees for firewood and prohibited goat breeding (Ford and Williams, 2007). The recovery of decertified karst areas is possible, although the process could be long and the area may never revert to its original "natural" condition. Even "Kras" terrain in the plateau Kras increased its vegetation cover from 20% in 1900 to 50% in 1989 (Gams, 1991). In Southwest China projects funded by the Chinese government at different levels in recent decades have resulted in some progress in ecological restoration. The goal for rocky desertification control and ecosystem restoration was to adopt control measures and ecosystem restoration practices that can maximize the land and water resources to create a favorable living environment for the local residents. Successful practices (Fig. 3) applied in Guangxi and some other regions in Southwest China include reconstruction of vegetation cover, land treatment, water and soil conservation, water resource development, improved soil quality, increased grass breeding for livestock, improved drainage and flow control structures to prevent water-logging and flooding in karst depressions, use of best agricultural management practices, and new energy sources and energy-saving technologies.

5.1. Land practices for rocky desertification control

Arable lands are scarce in areas where rocky desertification has a high potential to occur. A GIS-based system was developed to take into account a wide range of factors to classify land areas into four types of ecologic fragile zones: none/little fragile, light fragile, moderate fragile, and severe fragile zones. These factors include the potential for photosynthesis, carbonate rock distribution, geomorphology, land use, land production capacity, crop production, soil quality, vegetation and forest cover, degree of rocky desertification, soil erosion, and frequency and extension of drought and flooding (Fig. 4). The rocky desertification index (R) proposed by Lu (1993) can be used to evaluate the likelihood of rocky desertification.

Specific practices could vary for different zones, but the goal is to use land management to reconstruct the vegetation/forest cover. For better land treatment, a database can be developed for available land resources to understand existing issues and their potential for farming and for ecosystem restoration, and new technologies can be developed for better management practices. At the same time, land use practices, such as growing more green manure fertilizer and edible fungas brans, are expected to help improve the soil quality. Any agriculture practice that may lead to further rocky desertification has to be stopped. Instead, modern agricultural technologies have to be ecologic-oriented to combine food production with economic profit. In Guangxi and some regions in Southwest China, terraces and walls were constructed on hill slopes to prevent soil from further erosion. Berms and earth dams were used to keep water in farming areas and to raise the water level in creeks for irrigation, providing sufficient soil moisture for regrowth

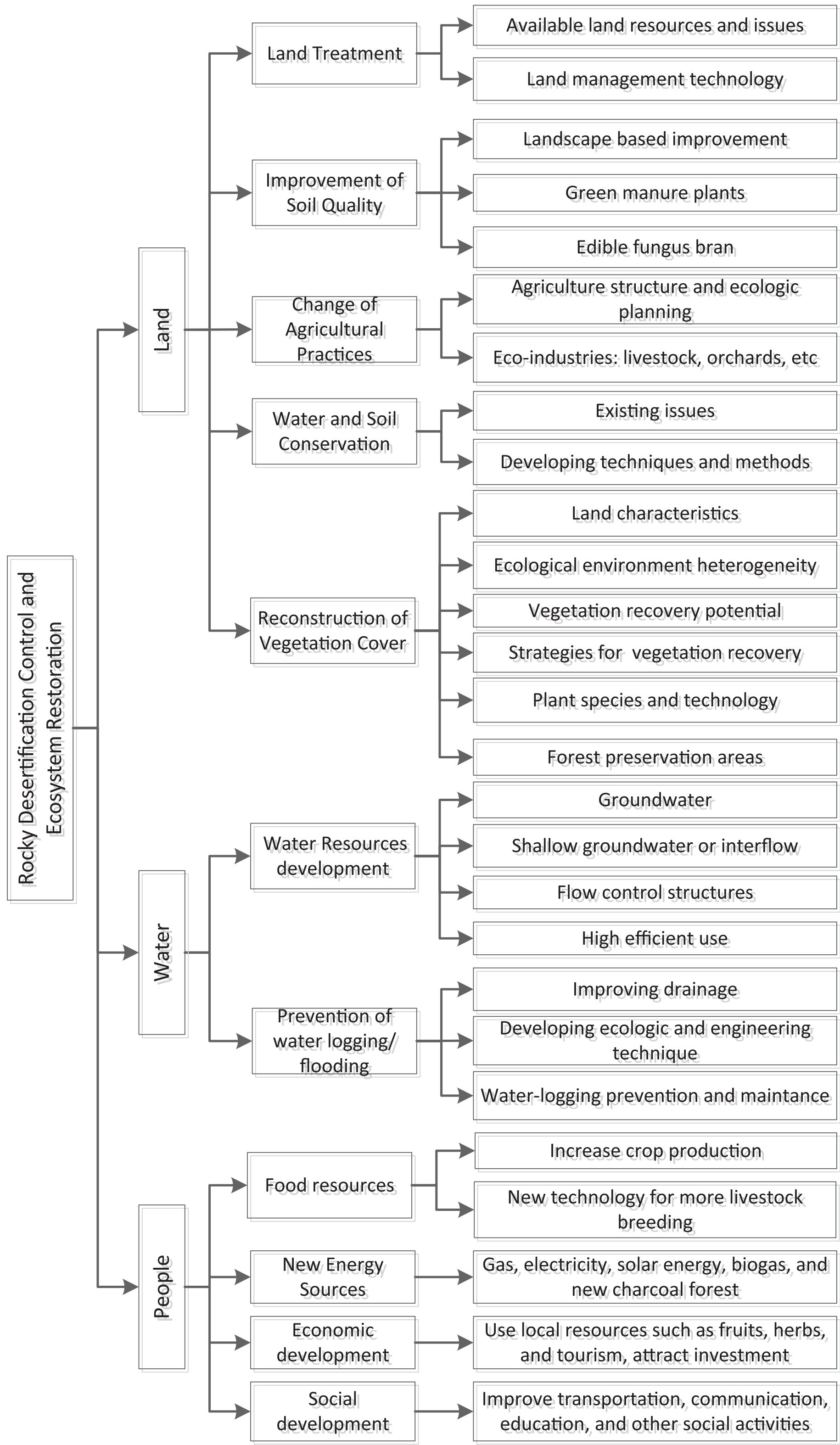

Fig. 3. Rocky desertification control and eco-system restoration.

of vegetation and plants. Terrace farming and an irrigation-based sustainable agricultural system were used by the Arabs in the Mediterranean Europe region around 1250 years BP after their conquest of the area (Yassoglou, 2000). Reconstruction of vegetation cover in carbonate rock areas is a slow and lengthy process. The land characteristics in terms of the geologic, hydrologic, ecologic, chemical, and microbiologic conditions are diversified, and the ecological environments are heterogeneous in karst areas. In regions where the population is low, the development of forest conservation areas was revealed to be the most effective practice where physical

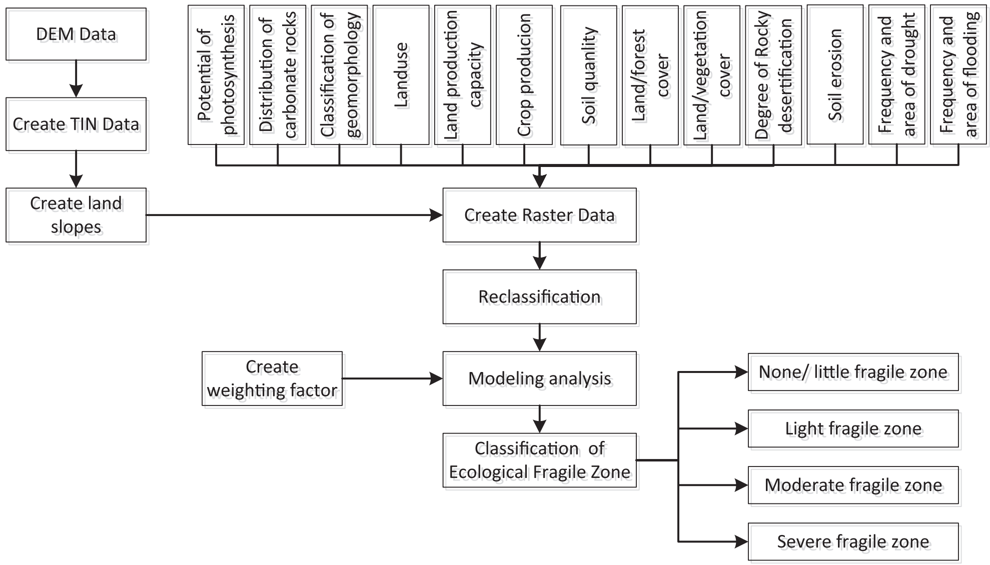

Fig. 4. GIS-based system for rock desertification management and control.

conditions allow. For example, Nongla village in Mashan, Guangxi has been a forest conservation area for more than 30 years. No grazing or deforestation activities were allowed in the area. It is now a Chinese herb medicine base with more than 200 kinds of herbs in merely a 1 km^2 area (Jiang, 2001). For areas with a high population density, new plant species and technologies that can be adapted to the disturbed environment need to be developed. International successes can be adopted as well. For example, Kosmas et al. (1996) found that the olive grove with understory vegetation is one of the most land-protective systems in the Mediterranean region.

5.2. Water resource management for rocky desertification control

Contrary to the dry climatic conditions in the desert areas of northwest China and some other regions of the world, water resources are abundant in Southwest China with an annual average precipitation of 1000–2000 mm. However, high percentages of these water resources are stored in the subsurface karst system a few hundred meters below the surface. A land resource survey (Yuan, 2007) has identified 3066 underground rivers in Southwest China, with an estimated total discharge of 1482 m^3/s, which is almost equivalent to the average discharge of the Yellow River. Increasing the use of subsurface water, which will not only relieve the water shortage problems in the region, but also improve ecological conditions, remains to be a great challenge.

Some pilot and demonstration projects in Southwest China have shown that appropriate and applicable practices could include: (1) construction of dams on underground rivers to raise water levels and generate hydropower; (2) construction of reservoirs in karst depressions to store storm water; (3) construction of flow diversion channels to use water resources available from the region; (4) improvement of geophysical exploration methods to identify groundwater storage for proper drilling and pumping; and (5) construction of small detention storage facilities to capture seepage from epikarst systems for small residential areas (Zhang et al., 2001). One successful example of such practice is the construction of the Wulichong reservoir in Mengzi of Yunan province. Before 1995 this area was one of the largest drought areas in Southwest China. The reservoir was constructed to use the Wulichong karst depression by blocking all underground river drainages. Three years after its completion in 1995, the water storage reached 76 million cubic meters of water, about 96% of its capacity. This reservoir since has provided the irrigation for 50,000 ha of farmland. Not only did it stop any further desertification but also provided sufficient soil moisture for ecosystem restoration in the area.

5.3. People as an ultimate goal for rocky desertification control

Rocky desertification control and ecosystem restoration should be designed to use available land, water, social, and cultural resources to create an environment that maximizes the ecological and economic outcomes, and ultimately to improve the living conditions and protect the environment for the people. In addition to reconstruction of vegetation, development of more forest reservations, development of water resources, and reduction of natural hazards, new technologies need to be developed or adopted to increase crop production and livestock breeding for food and the economy. A sufficient energy supply would reduce and even eliminate the need for firewood from cutting trees and bushes. With the economic development in China these past few years, villages close to towns and cities started to have gas or electricity services. Solar energy, biogas, and even new charcoal forests are gradually introduced into some remote villages.

In recent years, the central and local governments in China have developed policies and provided resources and financial supports to improve the economic and living conditions in rocky desertification areas. Farmers were given incentives for projects such as restoring forest from farmland and soil and water conservation. Another practice is conserving forests on mountain tops. Damaging activities in the forest have been stopped, and walls and terraces have been constructed on slopes to prevent soil loss. Farmers are encouraged to grow economical plants such as the lacquer tree (*Rhus verniciflua* Stockes), mulberry, tung tree (*Aleurites fordii* Hemsl), plum, economical crops, and honeysuckle and other herbs (CGS, 2006) in forest conservation areas to improve their economic conditions. Southwest China is also abundant with tourist resources characterized by combinations of beautiful karst landforms, underground rivers, and caves. The development of tourism resources can improve the local economy and in return will reduce the demand on land and other natural resources, which will ultimately improve the eco-environment in those areas.

Plans for large-scale desertification control should be unified, and biological, engineering, and management steps should be organically combined to form a highly effective, comprehensive system. Large investments have been made in a number of ecological projects by the central government of China, for instance the Yangtze River Shelter-Forest Project, the Pearl River Shelter-Forest Project, various water and soil conservation projects, and poverty-alleviation projects, as well as some international support programs since 1999 (SFA, 2012). The overall rocky desertification area in Southwest China has been reduced 7.4% from 2005 to 2011. Specifically, the light desertification area has increased 21.1%; the moderate, heavy, and extremely heavy desertification areas were reduced 12.3%, 25.8%, and 41.3%, respectively. However, with a remaining 0.12 million km^2 of rocky desertification area in China and population density as high as 217 people/km^2 and 50 million people under poverty in the southwest karst region, challenges remain in combating rocky desertification.

Technologies such as the GIS-based decision support system, coupled with physical modeling of hydrology and sediment and social economic modeling with respect to global climate change and variation and optimal management strategies can be developed to protect and rejuvenate vegetation and plant growth, thus building Southwest China into the biggest green resource bank, tropical fruit base, and ecological tourist garden. Fig. 5 shows the framework for a decision support system being developed for the Guangxi Zhuang Autonomous Region.

6. Summary and conclusion

Rocky desertification is one of the most critical ecological and environmental problems in areas underlain by carbonate rocks globally. This review shows that rocky desertification has occurred in many parts of the world, particularly in the European Mediterranean and Dinaric Karst regions of the Balkan Peninsula, in Southwest China on a large scale, in other countries and regions such as Malaysia, Indonesia, Japan, Belize, Guatemala, Mexico, and Israel, and even in the tropical rainforests in Haiti and Barbados.

Rocky desertification occurs in areas where carbonate rocks dominate. The high solubility and as low as 2% weathering rate result in thin soil profiles in mountainous karst areas missing the C-horizon, a crucial layer that keeps the soil layer attached to the bedrock, thus

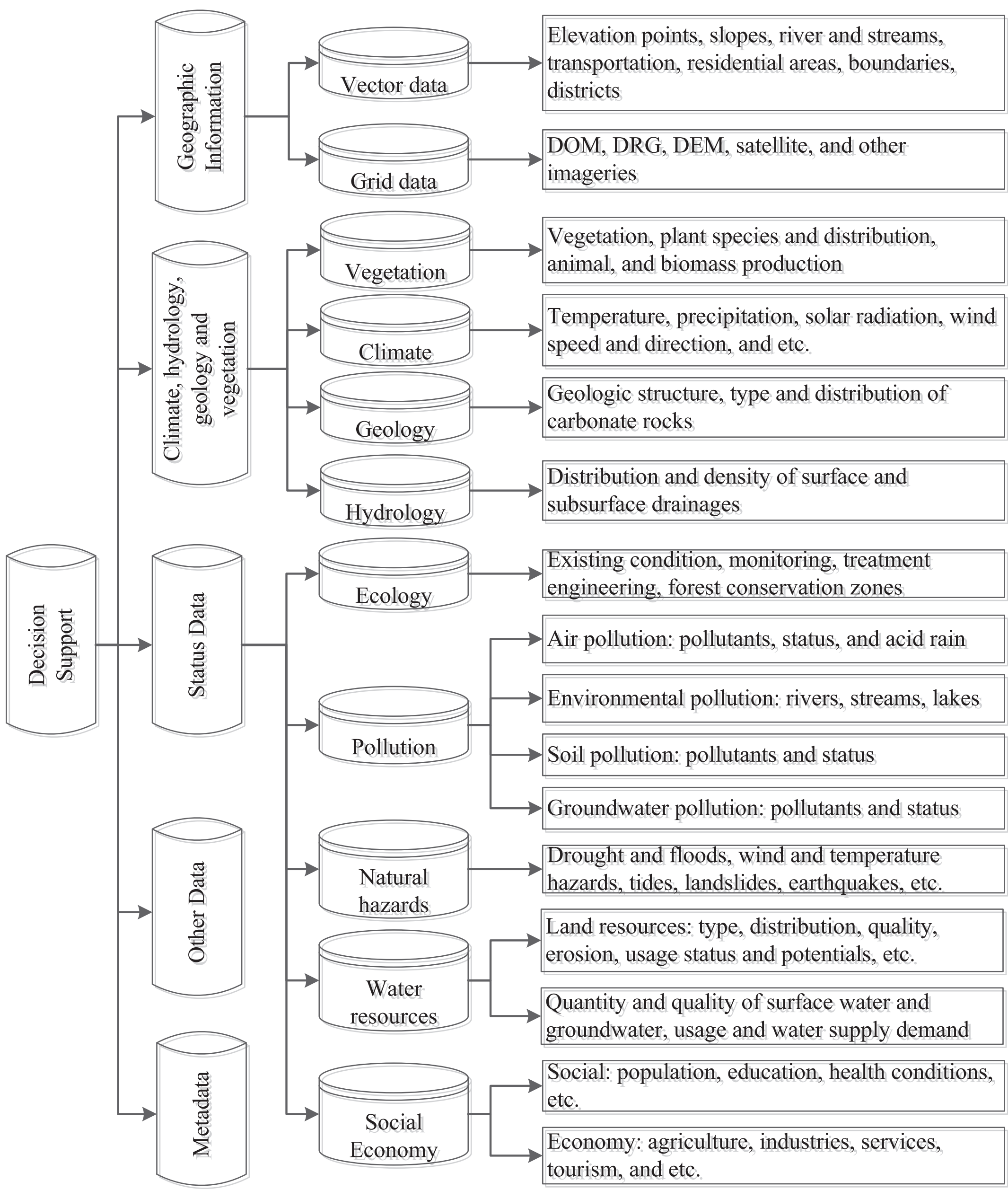

Fig. 5. The decision support system for rock desertification management and control in Guangxi, China.

making the topsoil vulnerable to soil erosion. Karst areas with steep slopes are sensitive to rocky desertification because of the low soil formation rate of carbonate rocks and thin soil layers. The overland flow on steep slopes has more kinetic energy to accelerate soil erosion and karstification. Even though the Europe Mediterranean basin has dry weather and Southwest China is in the sub-tropical zone, the well-developed karst flow system and high permeability conditions in the upper layer don't maintain sufficient soil moisture for vegetation and plants, which makes restoration difficult.

This study also shows that activities for the human demands for food, energy, and economy to accommodate population growth vary from region to region all over the world and have varied from ancient time to the modern era. These human disturbances have been responsible for the deforestation that led to rocky desertification, and rocky desertification in turn has had great impacts to people and societies in many aspects as a result of the loss of arable land, reduction of crop production, and loss of tourism and other economic resources. Such impacts may not be felt when land resources are abundant, but in Southwest China where the population density is already high, the expansion of rocky desertification has added pressure to people's lives in areas that are already below the poverty line. More frequent droughts and floods are occurring in the Southwest karst region possibly due to rocky desertification, global climate change and variability, or a combination of both. Further, the loss of forests, trees and shrubs, other organic materials, and soils will greatly reduce the storage and absorption of atmospheric CO_2, and thus will have a negative impact on global climate warming, although further work is needed to understand the degree of such impact.

Over the past several decades, many pioneering projects were designed to maximize the available land and water resources to reconstruct vegetation cover, develop forest conservation areas, develop the economy, improve education, and ultimately create a cohesive eco-friendly environment for a life people can dream of in the region. Successful practices applied in Guangxi and other regions in Southwest China include reconstruction of vegetation cover, land treatment, water and soil conservation, water resource development, improved soil quality, increased grass breeding for livestock, improved drainage and flow control structures to prevent water-logging and flooding in the karst depression, use of best agricultural management practices, and new energy sources and energy-saving technologies.

This review shows that rocky desertification is a global phenomenon that has occurred in Europe, South China, and some other regions of the world. It has affected millions of people in Southwest China alone. Human activities that have resulted in rocky desertification are happening in some third world countries, such as Haiti, Barbados, and Cuba. Although progress for desertification control and ecosystem restoration has been made in Southwest China, challenges remain as more frequent droughts and extreme floods induced by global climate change and variability slow down the recovery process and even expanded rocky desertification areas in some regions could experience second desertification if not effectively managed. Hopefully the review of the impacts, causes, and successful control measures in this paper can aid in sustainable development in developing countries, and the successes can be adapted to other areas where restoration efforts are needed.

Acknowledgments

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