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Boundaries and Characteristics of Arid Regions in Mountain Valleys in Southwestern China

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Arid regions in valleys of southwestern China have steep topography and fragile ecosystems, making them a critical and challenging management issue in this region. A substantial amount of the research on these arid

regions in valleys took place in the 1980s; less work has been done since the start of the 21st century. Knowledge of the boundaries of arid lands within these valleys can provide basic data and a scientific foundation, and comparing and analyzing the characteristics of different valleys will help policymakers match management regimes to local conditions, assuring sustainability in these fragile areas. Using remote-sensing data, we extracted the boundaries of the arid regions within these valleys. We then calculated land cover, elevation, slope, and aspect data for the study area. Our results describe the basic

features of these valleys; they occur between 23°23' and 33°19'N and between 97°03' and 104°43'E, with a total area of 33,391.60 km² at elevations between 254 and 5707 m. The arid regions in valleys have slopes ranging from 0 to 87.17°, with a mean of 25.77°, and a slightly greater area and proportion of sunny aspects than of shady aspects. The main land covers in the arid regions in valleys are grasslands and shrublands. Our results indicate that (1) the arid regions within these valleys have expanded significantly, and their vegetation consists largely of grasses or shrubs; (2) the study area consists of interlaced mountains and valleys, with a terrain consisting of diverse slopes and aspects; and (3) the land cover gradually transitions from grassland to shrub, and elevation and slope decrease from northwest to southeast.

Keywords: Aridification; land cover; Hengduan Mountains; southwestern China.

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Introduction

Water is a defining factor of arid regions in valleys, where high solar radiation leads to excessive water loss (Valiente-Banuet et al 1991). Except for basic studies of floristic composition (Blanckaert et al 2004), most research on arid regions in valleys has focused on water resources. Groundwater (Oren et al 2004) and dew (Malek et al 1999) are essential in arid regions, and their flow and transport determine the water supply (Bauer et al 2006). Topography, vegetation cover, and land use influence water dynamics, as do geomorphologic factors, which include river channel processes and soil erosion (Coppus and Imeson 2002). Despite the importance of ecosystems of arid regions in valleys (Guo et al 2017), fundamental data such as topographic information are lacking for them.

To acquire these data, the spatial range of arid lands within these valleys should be determined using boundary research. Boundaries are not only a fundamental

characteristic of society (Hare 2004) but also physical entities that are important in the study of ecology (Li et al 2005). However, it is challenging to delimit naturally indistinct physical features, such as the boundaries between vegetation communities (Guo et al 2017). As a result of damaging human activities (Hu et al 2004), arid and semiarid areas have rapidly expanded (Oostwoud Wijdenes and Bryan 2001), which adds to the challenge of defining their boundaries.

This study focused on arid regions in valleys in the Hengduan Mountains in southwestern China, which are distributed throughout this mountain system and mostly have a north-south orientation. These fragile ecosystems are vulnerable to ecological degradation and difficult to protect (Zhang 1992). Because of their steep slopes and the high cost of irrigation, the soil moisture in arid regions in valleys is not adequate for forest growth (Ma et al 2004). These valleys generally have low plant species

richness and are sparsely vegetated with shrubs and grasses (Li and Bao 2014).

The ecosystems of arid regions in valleys are sensitive to small changes in climate (Kalthoff et al 2006), and aridification accompanying global warming has led to environmental damage and resource scarcity (Yang and Chang 2007). The ecological deterioration of arid regions in valleys not only compromises the ecosystems but also threatens the physical security of the middle and lower reaches of the Yangtze River, as well as the development of the Chengdu Plain (Shen 2003).

Research on arid regions in valleys in the Hengduan Mountains advanced in the 1980s and focused primarily on physical features, such as soil and soil-forming characteristics, vegetation, and species richness (Yang et al 1988), as well as on temperature and hydrology. There has been little research on arid regions in valleys in the Hengduan Mountains in the 21st century, although some studies have examined environmental degradation, development issues, and protection measures in relation to climate change. Data from 27 meteorological stations in the Hengduan Mountains for 1961–2012 reflect a declining trend in extreme precipitation events from southwest to northeast (Zhang, Pan, et al 2014). The average temperature of arid regions in valleys in the Hengduan Mountains increased, and relative humidity showed a decreasing trend (Ding 2013). The adaptability of land in the region was investigated in light of these changes (Li 1991), and research on sustainable development has been pursued (Sun et al 2005). Human activities in arid regions in valleys caused by global warming are among the main reasons for overexploitation of natural resources and degradation of the environment in this region and have deepened the conflict between needs of local populations and environmental protection in the past 2 decades (Tang et al 2004).

Under climate change, arid regions within the Hengduan Mountains valleys have expanded, including into higher elevations, and plant cover has declined. Since the mid-20th century, attempts have been ongoing, supported by local research, both to restore existing and historic plant communities and to plant new drought-resistant species. Efforts have included the establishment of production forests for water and soil conservation and the return of previously farmed hillsides to forest under the Grain for Green program. These efforts had a positive effect on net primary productivity slowing, but not reversing, the decline in plant cover, but their effect is now decreasing, creating an urgent need for effective long-term ecological projects (Zhou and Bao 2014; Wang, Zhang, Duan, Yang, Zhou 2015; Wang, Zhang, Duan, Yang, Zhou, Ye 2015; He et al 2016; Chen et al 2017; Guo et al 2017).

Studies have confirmed that the extent of arid regions in these valleys has increased and habitat has deteriorated, and they have recommended further research to support ecological protection (Yang, Chang, Bu, et al 2007; Yang,

Chang, Hu, et al 2007). Other work in arid regions in valleys in the Hengduan Mountains has focused on specific features of the valleys, such as rivers. Most river research took place in the upper reaches of the Min River (Hu et al 2004; Ye et al 2006; Li, Bao, et al 2011; Li and Bao 2014) and in the Jinsha River (Zhao and Zhao 2007), Lancang River (Zhang et al 2005), and Dadu River (Wang et al 2006). Other research investigated the situation in the administrative areas of the valleys, mostly in Sichuan Province (Cai et al 2009; Yan et al 2013).

Because of the expansion of the arid regions in the valleys in the Hengduan Mountains, their precise current boundaries are not known. In the 1990s, their area was estimated as 11,300 km² (Zhang 1992) or 12,000 km² (Wang et al 1988). However, the arid regions in valleys in Sichuan Province alone (which contains almost one-third of the arid regions in the valleys of the Hengduan Mountains) were calculated to cover as much as 9500 km² in 2004 (Cai et al 2009) and 11,000 km² in 2013 (Yan et al 2013)—a striking increase in less than a decade.

Understanding the boundaries of arid valley lands is important to understand factors that influence water availability, an understanding that is essential to the protection of the local environment. The objective of this study was to fill the gap in large-scale boundary research in arid valley areas of the Hengduan Mountains by (1) defining the arid-land boundaries from a landscape-ecological perspective using remote-sensing technology to obtain basic data and (2) analyzing similarities and differences among arid lands in river valleys according to their spatial distribution to inform the formulation of environmental protection policies and regulations for different river valleys.

Study area and methods

Study area

The Hengduan Mountains are located in the southeastern part of the Qinghai-Tibet Plateau, adjacent to the northwestern boundary of Yunnan Province. They range from 24°40' to 34°00'N and from 96°20' to 104°30'E (Li 1987). This area is part of China's subtropical climate zone, under the influence of high-elevation westerly wind currents, the Indian Ocean, and the Pacific monsoon. Winters are dry, and summers are rainy. There is a distinct division between dry and wet seasons; the wet season normally occurs from mid-May to mid-October, but precipitation is concentrated in June, July, and August. The dry season occurs from mid-October to mid-May (Sun et al 2005). Inflow of water vapor from the southwest is obstructed by mountains that run from north to south (Zhang 1992).

In addition, the foehn—a strong, warm, and dry wind that blows downslope from the mountains—makes the region's extensive valleys extremely hot and dry (Seluchi et al 2003). The foehn effect, high temperature and low

relative humidity, occurs when the air descends adiabatically from the lower-middle troposphere to the foothills on the lee side of a mountain range (Brinkmann 1971). High south–north mountains and deeply dissected rivers in the Hengduan Mountains provide appropriate topographical conditions for the formation of foehn, which is one of the main contributors to the dryness of the valleys (Tang et al 2004; Guo et al 2017). The presence of foehn results in higher temperatures and evaporation and less rainfall in arid regions in valleys than in neighboring areas (Ding et al 2014). The highest temperatures in the Hengduan Mountains are observed in the arid regions in valleys, where the annual mean temperature is $>20^{\circ}\text{C}$ at lower elevations in the Yuan, Lancang, and Nu River Valleys (Pan et al 2012). Arid regions in valleys are suitable growing areas for some species, such as *Osteomeles schwerinae* (Wang, Chen, et al 2015). However, human activity and settlement, concentrated in arid regions in valleys because of their greater light and heat, have led to the expansion of the arid regions and the deterioration of the environment (Tang et al 2004).

These valleys mainly occur along the Jinsha, Nu, Lancang, Yuan, Yalong, Min, Dadu, Baishui and Anning Rivers and some of their tributaries (Zhang 1992). The climate of the arid regions in valleys has a clear vertical distribution. They have few plant species and a low percentage of cover, with more shrubs than trees. Shrubs are the dominant drought-tolerant species; their morphological adaptations to the dry conditions include thorns, hairiness, and anhydrobiosis, a form of dormancy induced by desiccation. There are striking differences in plant species composition between northern and southern valleys (Li 1987). The soils are acidic and include red soils and heavy clay. Most of the soils are leached, iron or aluminum enriched, thin, and severely eroded and degraded as a result of human activity (Yang and Chang 2007; Tian 2011).

Methods

To cover the whole of the Hengduan Mountains, we chose 32 images from Landsat 8 (GSCloud 2018) across the dry valley range, recorded under low levels of cloudiness in the 2014 dry season. Atmospheric preprocessing and georeference calibration were carried out using ENVI5.1 software, and image mosaics were used as the basis for land cover classification. We downloaded Google high-definition (HD) topography (Google 2018) as a base map, selected the global digital elevation model (DEM) 30-m elevation data (GSCloud 2018) for the study area, and created a mosaic as an auxiliary map to extract the valleys.

Using ArcGIS10.0, the major rivers—the Jinsha, Nu, Lancang, Yuan, Yalong, Min, Dadu, Baishui and Anning Rivers—were extracted from the map of Chinese rivers. We selected the rivers that flowed through arid regions in valley areas based on the information we collected in the

literature. We then generated buffer zones extending 1, 5, 8, 10, and 12 km from the centers of the rivers. We found that a 10-km buffer covered most of the arid land in the valleys, and we used this buffer to clip the basic data mosaicked by Landsat 8. Using ENVI5.1, the clipped data were converted using the Tasseled-Cap Transformation, and then the ISODATA Unsupervised Classification tool was used to divide the study area into 7 categories: forest, shrubland, grassland, water, farmland, settlement, and unused land. The Kappa coefficient was 81.32, indicating that the classification results were accurate (Congalton 2001).

Based on high-resolution remote-sensing and elevation data, the arid-land boundaries were modified in ArcGIS10.0 according to vegetation and topographic features. Arid regions in valleys are known to exist along deeply dissected rivers at high elevations in the Hengduan Mountains and to contain vegetation that is underdeveloped and typically composed of drought-tolerant herbaceous plants and dwarf shrubs (Tang et al 2004). The boundaries of the arid regions are located in the ecotone between local xeromorphic species and mixed evergreen and deciduous forests (Guo et al 2017). Valleys characterized by these arid regions mainly occur along the Jinsha, Nu, Lancang, Yuan, Yalong, Min, Dadu, Baishui and Anning Rivers and some of their tributaries (Ma and McConchie 2001). Therefore, we first focused on these rivers. Next, based on topographic features, we narrowed the range of our search to high mountains next to deep rivers. Then, based on vegetation features, we retained only the grass- and shrub-dominated landscapes on both sides of the rivers. These formed our study area. Finally, the basic data and the land cover data were statistically analyzed, and the arid lands in river valleys were compared.

Results

Basic statistics

According to our calculations, the arid regions in valleys in the Hengduan Mountains occur between $23^{\circ}23'$ and $33^{\circ}19'N$ and between $97^{\circ}03'$ and $104^{\circ}43'E$ (Figure 1). Most of the arid regions in valleys are located in Sichuan and Yunnan Provinces; arid regions in valleys also exist in eastern Xizang and southeastern Gansu Provinces. The extent and degree of aridity were different in the different river valleys. The westernmost arid region in a valley in our study area occurred along the Nu River, the northeasternmost region occurred along the Baishui River, and the southernmost region occurred along the Yuan River. Most of the valleys were oriented north–south, forming vertical barriers. The southern part of the Jinsha River Valley was oriented east–west.

Arid regions were identified in the 9 valleys shown in Figure 1. The total arid area was calculated as $33,391.60\text{ km}^2$, the total river length was 5666.39 km , and the total length of the boundaries around the dry areas was $39,834.25\text{ km}$.

FIGURE 1 Map of the study area. (Map by Shu Fang)

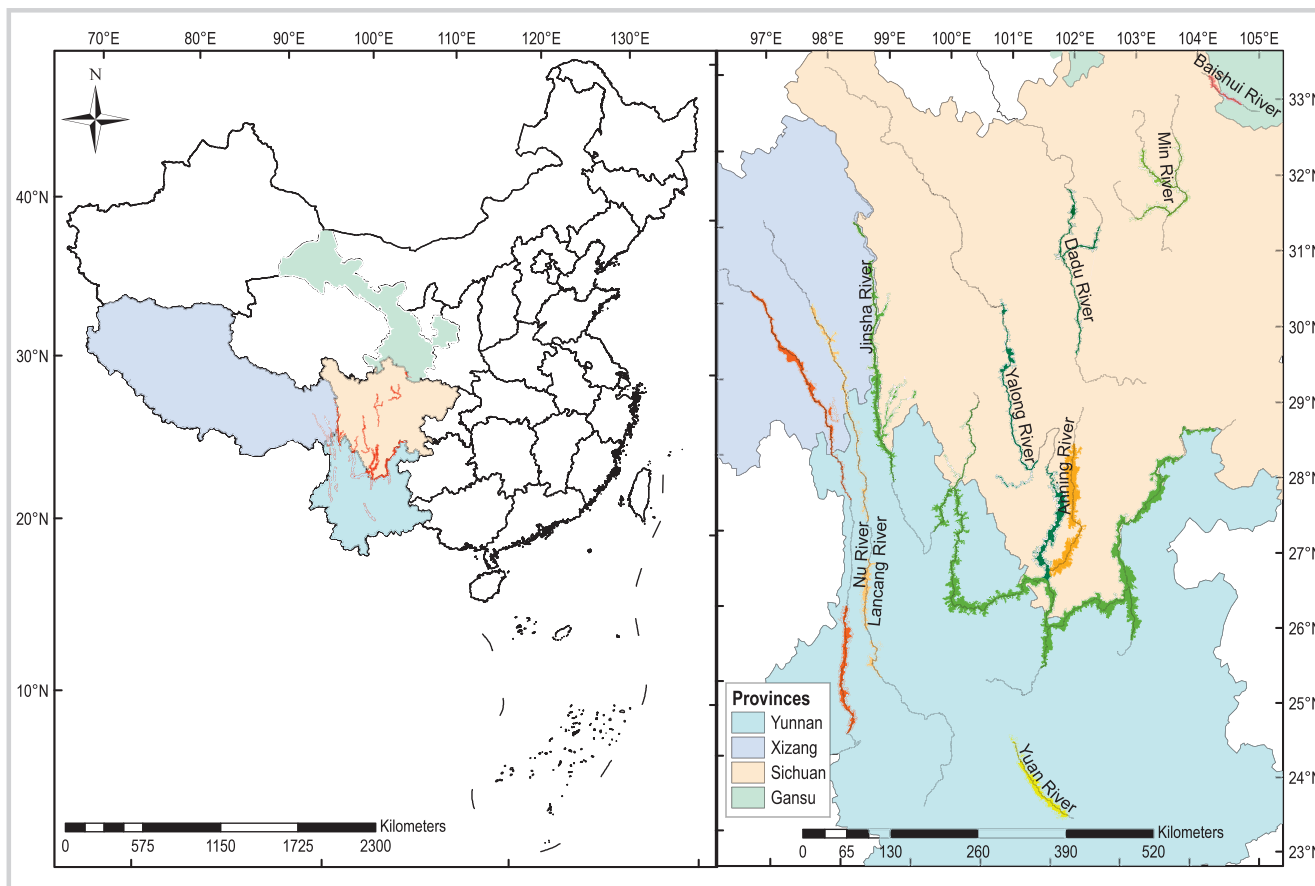


TABLE 1 Area and length of the arid regions in each valley.

| Valley | Arid regions within the valley | | |
|---------------|--------------------------------|----------------------|-------------------------|
| | Area (km ²) | Length of river (km) | Length of boundary (km) |
| Baishui River | 331.50 | 72.23 | 430.18 |
| Dadu River | 1202.11 | 229.23 | 2845.23 |
| Yuan River | 1378.76 | 187.50 | 1357.49 |
| Min River | 1489.17 | 404.41 | 3330.44 |
| Anning River | 2693.62 | 677.71 | 2781.95 |
| Yalong River | 3347.99 | 340.33 | 5734.65 |
| Lancang River | 3457.13 | 586.16 | 4197.94 |
| Nu River | 4100.81 | 730.54 | 3312.10 |
| Jinsha River | 15,390.53 | 2438.28 | 15,844.28 |
| Total | 33,391.62 | 5666.39 | 39,834.26 |

Features of the arid areas differed (Table 1). The smallest arid region, approximately 331 km², occurred in the Baishui River Valley in the northeast section of our study area. Arid regions in the Dadu, Yuan, and Min Rivers Valleys varied between 1000 and 2000 km². The arid regions in the Anning, Yalong, Nu, and Lancang Rivers Valleys were larger but still under 5000 km². The arid region in the Jinsha River Valley was the widest and longest, occupying approximately 15,390 km². The lengths of the arid regions followed a pattern different from that of their areas. Although the Dadu River Valley was longer than the Yuan River Valley, its arid area was smaller. In contrast, the Yalong River Valley was shorter than either the Min or the Dadu River Valley, but its arid area was more extensive.

The lengths of the borders around the arid regions were inconsistent with the distribution of their areas. The boundaries of the arid regions in the Dadu River Valley were more complex than those in the Yuan River, and those of the Min River were more complex than those of the Anning. Although the Nu River Valley was the second largest after the Jinsha River Valley, the length of the Nu River arid-region border was less than that of the Yalong or Lancang River Valley, indicating that its border was more regular. In contrast, the arid region of the Yalong River Valley was smaller than that of the Nu and Lancang

TABLE 2 Elevation ranges in the arid regions in each valley.

| Valley | Arid regions within the valley | | | |
|---------------|--------------------------------|---------|-------|---------|
| | Minimum | Maximum | Range | Mean |
| Baishui River | 789 | 3059 | 2270 | 1623.09 |
| Dadu River | 1091 | 4284 | 3193 | 2387.66 |
| Yuan River | 266 | 1897 | 1631 | 807.46 |
| Min River | 1304 | 4198 | 2894 | 2377.56 |
| Anning River | 1004 | 3063 | 2059 | 1649.52 |
| Yalong River | 917 | 5707 | 4790 | 2177.29 |
| Lancang River | 1061 | 5273 | 4212 | 2572.87 |
| Nu River | 574 | 5666 | 5092 | 2264.63 |
| Jinsha River | 254 | 5076 | 4822 | 1927.06 |

Rivers, and its border was longer, indicating that its boundaries were more convoluted.

The relationships among arid region length, arid region area, and length of the river that flows through the arid region differed in the arid regions of valleys. The largest arid region in our study area occurred in southwestern Yunnan, and the shape of the valleys became more complex and irregular toward the southwest.

Land cover

The spatial distribution of land cover in the arid regions is shown in Figure 2 (and in detail for each valley in Figures S1–S9, Supplemental material, <http://dx.doi.org/10.1659/MRD-JOURNAL-D-17-00010.S1>). The proportions of land cover types were obtained from ArcGIS.

Land cover in the arid regions consisted mostly of grass and shrubs (>33% and ~33% of total area, respectively). Land use was extensive: farmland occupied close to 20% of land area. Forests covered only 6% of the total area; surface water, including the rivers, covered close to 2%; and settlements and bare land covered less than 1%. Most arid regions extended to either side of the river that ran through their valley. Farmland occupied a relatively large proportion of land in the Dadu and Anning River Valleys. The area of farmland in arid regions of other valleys made up less than 20% of the total area of these arid lands in valleys.

The area and percentage of shrubland was highest in the Baishui, Dadu, Min, and Yalong River Valleys, where it was the predominant land cover. The Yuan, Lancang, Nu, and Jinsha River Valleys were dominated by grassland, and the valleys in Sichuan Province had a more forested landscape. From a spatial perspective, the arid regions in valleys of Xizang and Yunnan, which were close to the southwest of our study area, were mainly grassland, while the arid regions in valleys in Sichuan and Gansu were mainly shrubland.

Elevation, slope, and aspect

Elevation: The elevation distribution of the arid regions in valleys is presented in Figure 3. Elevation ranged from 254 to 5707 m, and most of the area was alpine or subalpine. Elevations were normally distributed (Shrout and Fleiss 1979); most were between 1000 and 3000 m. Elevation rose continuously with distance from the rivers, showing an obvious valley shape.

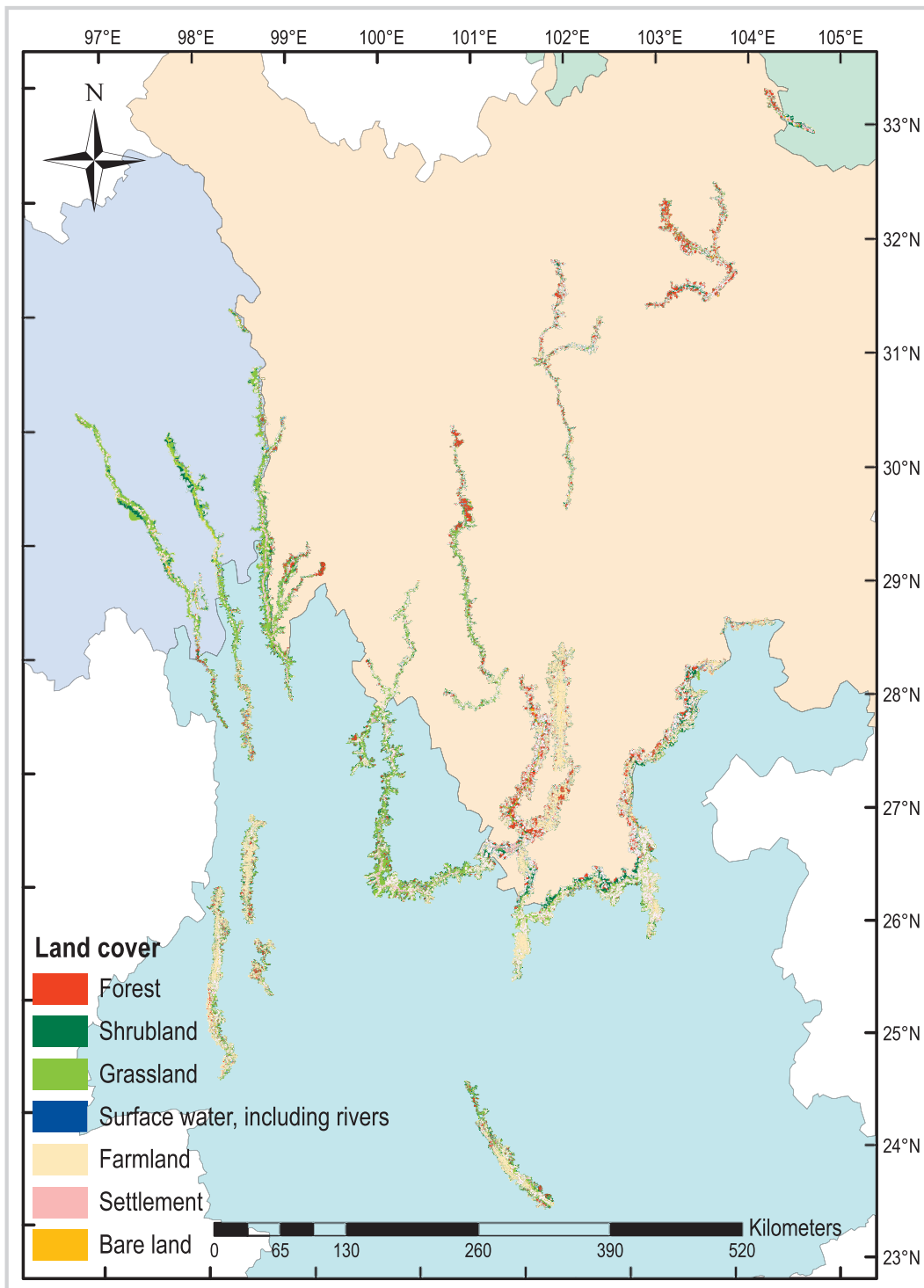
Table 2 summarizes elevation patterns in the arid regions in valleys under study. Arid regions in valleys in the northwestern part of the study area had alpine topography. The arid land in the Nu, Lancang, and Jinsha River Valleys had high mountains on both sides, the highest of which was >5000 m, with an average elevation of >4000 m. The arid land in the Dadu, Min, and Yalong River Valleys were also bordered by high mountains on both sides; the highest peak occurred in the Yalong River, but the overall average elevation (~2300 m) was less than that of the arid regions in valleys in the northwest. The Baishui River included high mountains, with a maximum elevation of 3059 m. With the exception of the arid region in the Lancang River Valley, the arid regions in southern valleys in our study area were subalpine on both sides. The highest areas in the Anning and Yuan Rivers were below 2100 m, and the lowest elevation occurred in the arid region in the Jinsha Valley.

The lowest elevation range occurred in the arid region in the Yuan River Valley, and the largest range occurred in the arid region in the Nu River Valley. The arid region in the Yuan and Lancang River Valleys had the lowest and highest mean elevation, respectively. Elevation of the arid regions in valleys showed an increasing trend from southeast to northwest. The Nu, Lancang, and Jinsha Rivers fell along the tectonic line that splits the Qinghai–Tibet Plateau into valleys, with part of their slope falling vertically, breaking a series of north–south-oriented mountain systems from the Pamir Plateau to eastern China, and then forming the 3 deep valleys.

Slope: The DEM data were used to calculate slopes in the study area (Figure 4). These ranged from 0 to 87.17°, that is, from flat to almost vertical. The most frequently occurring slopes were in the range of 25 to 35°; the mean slope was 25.77°. Thus, most slopes were steep and not suitable for farming.

Slopes and their distribution differed across the arid regions in valleys (Table 3). In the north, the steepest slope in the Nu, Lancang, Jinsha, Yalong, Dadu, and Min Rivers was ~80°; the mean slope in these areas was >25°, a steep gradient that cut from the alpine zone to the deep canyon. The Anning River, located in the middle of the study area, was the flattest and had the lowest average slope (15.10°); the terrain was gentle, and the valley was wide. Slopes in the southern parts of the Nu, Lancang, Jinsha, and Yuan Rivers ranged from gentle (0°) to abrupt (25°), with medium to deep valleys.

FIGURE 2 Land cover in the arid regions in mountain valleys. (Map by Shu Fang)

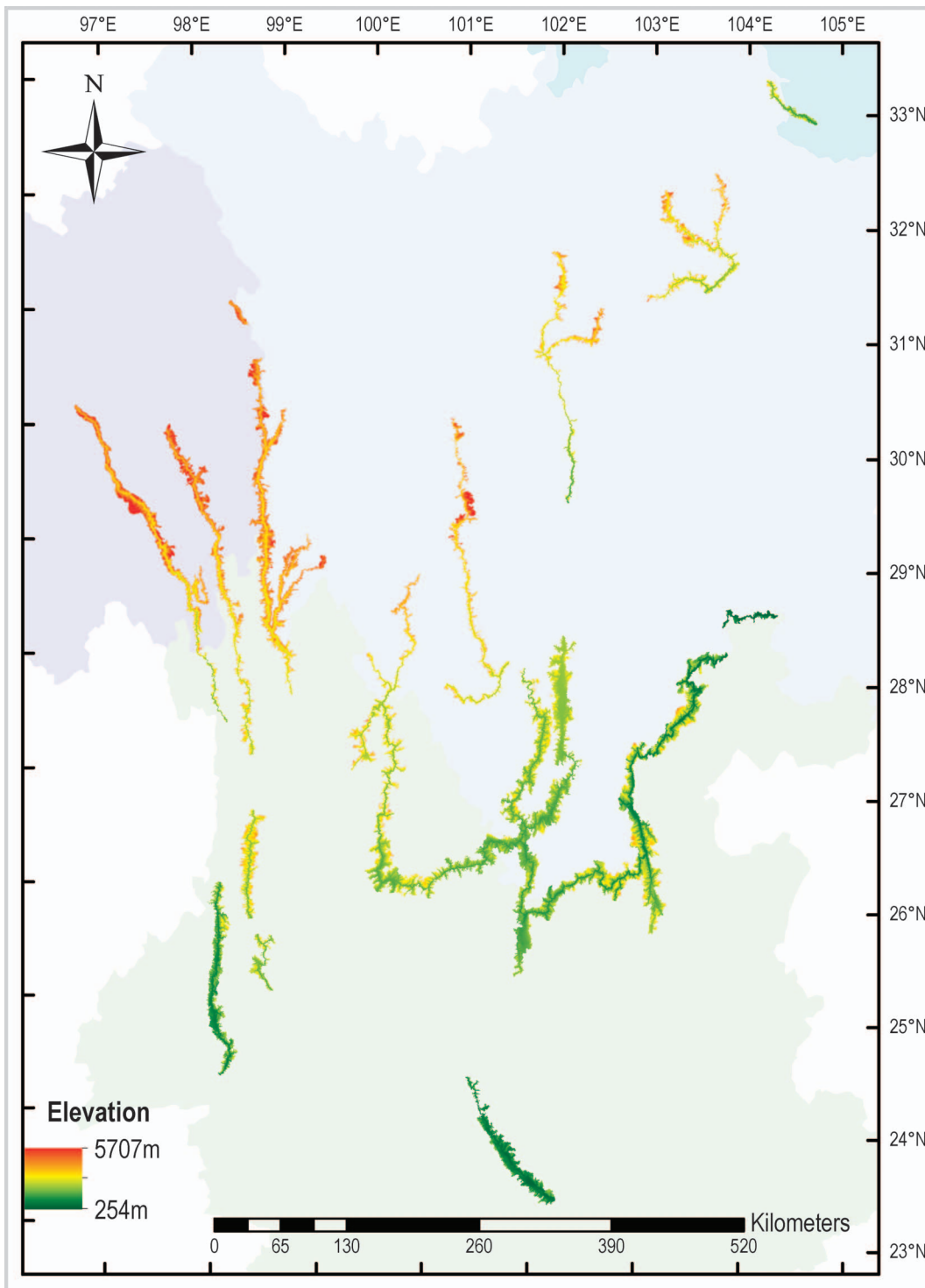


Aspect: In China, south-facing slopes are generally sunny, and north-facing slopes are generally shady. In mountainous regions, differences in solar radiation, temperature, and humidity lead to significant environmental differences among slopes, including in

vegetation, soil, hydrology, and landform characteristics (Lin and Li 1985).

Aspects were calculated from the DEM data (Figure 5; for details in each valley, see *Supplemental material*, Figures S10–S18: <http://dx.doi.org/10.1659/MRD->

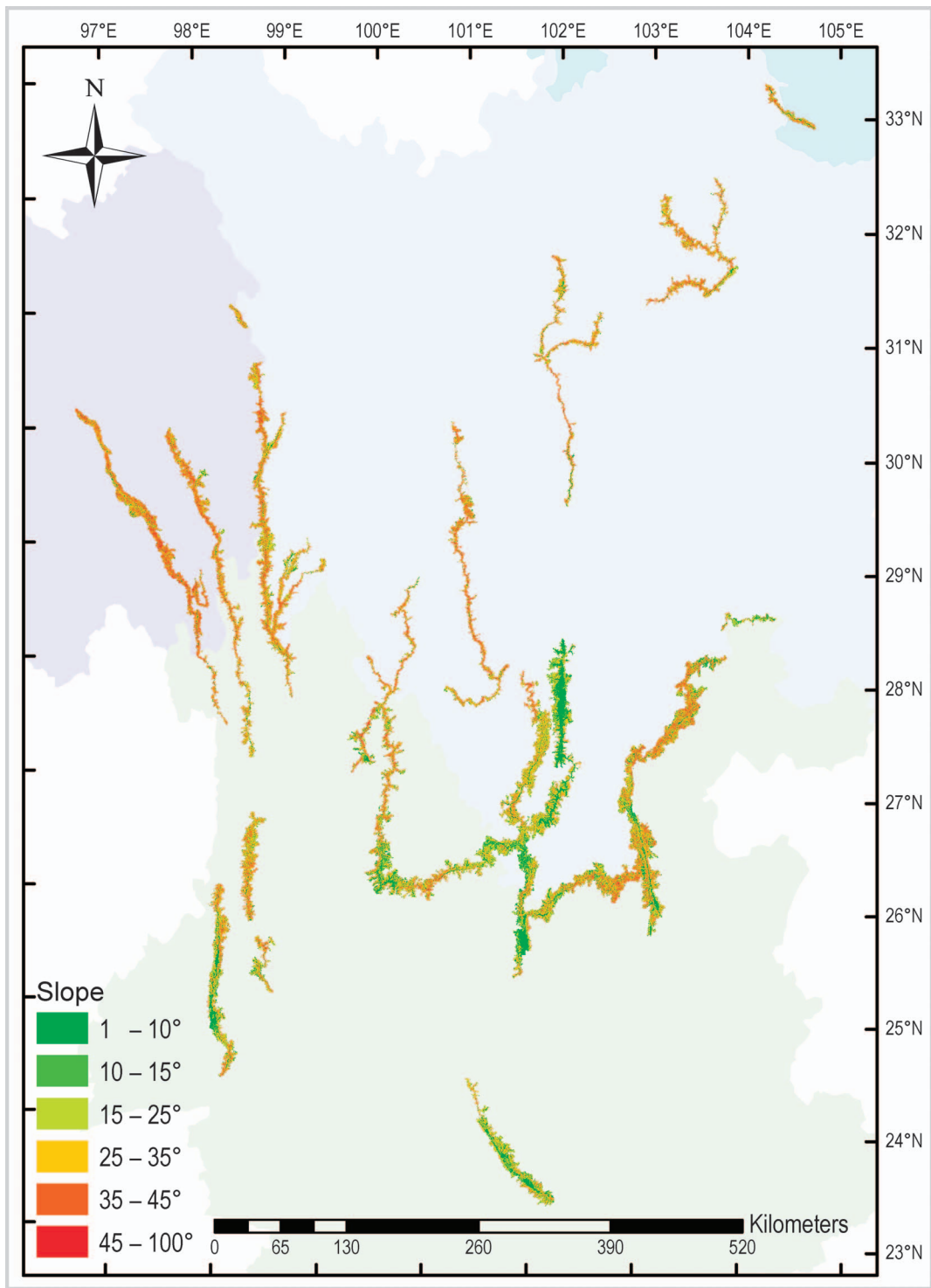
FIGURE 3 Elevation of the arid regions in mountain valleys. (Map by Shu Fang)



JOURNAL-D-17-00010.S1). The arid regions in valleys had a range of aspects that varied across all compass directions. The proportions of aspects in the study area are summarized in Table 4. The arid regions in valleys

were mostly oriented east–west and received a large amount of solar radiation, and there was a larger amount of south-facing than of north-facing area. Flat areas made up the smallest part of the study area

FIGURE 4 Slope in the arid regions in mountain valleys. (Map by Shu Fang)



(0.04%). The other aspects were fairly balanced, and there was a slightly greater area and proportion of sunny aspects than of shady aspects. The distribution of aspects was fairly even. Most of the arid region in Jinsha

Valley faced east, west, southeast, or southwest. There was a lower proportion of south- and southeast-facing slopes in the arid region in the Nu River Valley than in the other valleys. Aspect was similar in the other arid

TABLE 3 Slope ranges in the arid regions in each valley.

| Valley | Arid regions within the valley | | |
|---------------|--------------------------------|---------|-------|
| | Minimum | Maximum | Mean |
| Baishui River | 0.00 | 77.09 | 28.60 |
| Dadu River | 0.00 | 86.06 | 29.31 |
| Yuan River | 0.00 | 67.73 | 19.41 |
| Min River | 0.00 | 84.71 | 30.46 |
| Anning River | 0.00 | 69.68 | 15.10 |
| Yalong River | 0.00 | 86.73 | 27.89 |
| Lancang River | 0.00 | 79.84 | 29.68 |
| Nu River | 0.00 | 87.17 | 29.13 |
| Jinsha River | 0.00 | 82.96 | 25.58 |

region in valleys, with north-facing slopes being least represented.

Discussion

Boundary research is essential for understanding landscapes (Guo et al 2017). Arid regions in valleys are a special landscape feature in China; research on these systems not only needs to address small-scale, local issues but also needs to take into account basic characteristics and regional to large-scale similarities and differences. This will enable management and regulatory decisions to be unified yet specific and appropriate to local conditions in the arid regions in valleys, which face serious ecological and environmental threats (Li 1987).

Basic characteristics of arid regions in valleys

Most of the 9 river valleys with arid regions included in this study are located in Sichuan, Xizang, and Yunnan Provinces. The total arid area in these valleys was calculated as 33,391.60 km². The extent of the arid area has increased relatively rapidly, presumably as a result of global warming. In the 1980s and 1990s, the size of the arid regions within these valleys was estimated at 12,000 km² (Wang et al 1988) and 11,300 km² (Zhang 1992), respectively, but the area has expanded to almost 3 times that amount. Arid regions in Sichuan form almost one-third of the total area, calculated as 9500 km² in 2004 (Cai et al 2009) and 11,000 km² in 2013 (Yan et al 2013); thus, our estimate of 33,391.60 km² is credible. At the same time, river length in arid valley areas has increased by more than 1000 km as a result of new arid regions forming along the Yuan and Baishui Rivers. Under the influence of human activity and climate change in recent years, the size of the arid areas has expanded in both elevational and geographical dimensions (Seluchi et al 2003). The

TABLE 4 Aspect in the arid regions in each valley.

| Aspect | Arid regions within the valley | |
|------------------|--------------------------------|--------------------------|
| | Area (km ²) | Percentage ^{a)} |
| None (flat land) | 12.62 | 0.04 |
| North | 3337.75 | 9.84 |
| Northeast | 4085.27 | 12.05 |
| East | 4633.14 | 13.66 |
| Southeast | 4656.71 | 13.73 |
| South | 4328.61 | 12.77 |
| Southwest | 4741.21 | 13.98 |
| West | 4444.56 | 13.11 |
| Northwest | 3666.75 | 10.81 |

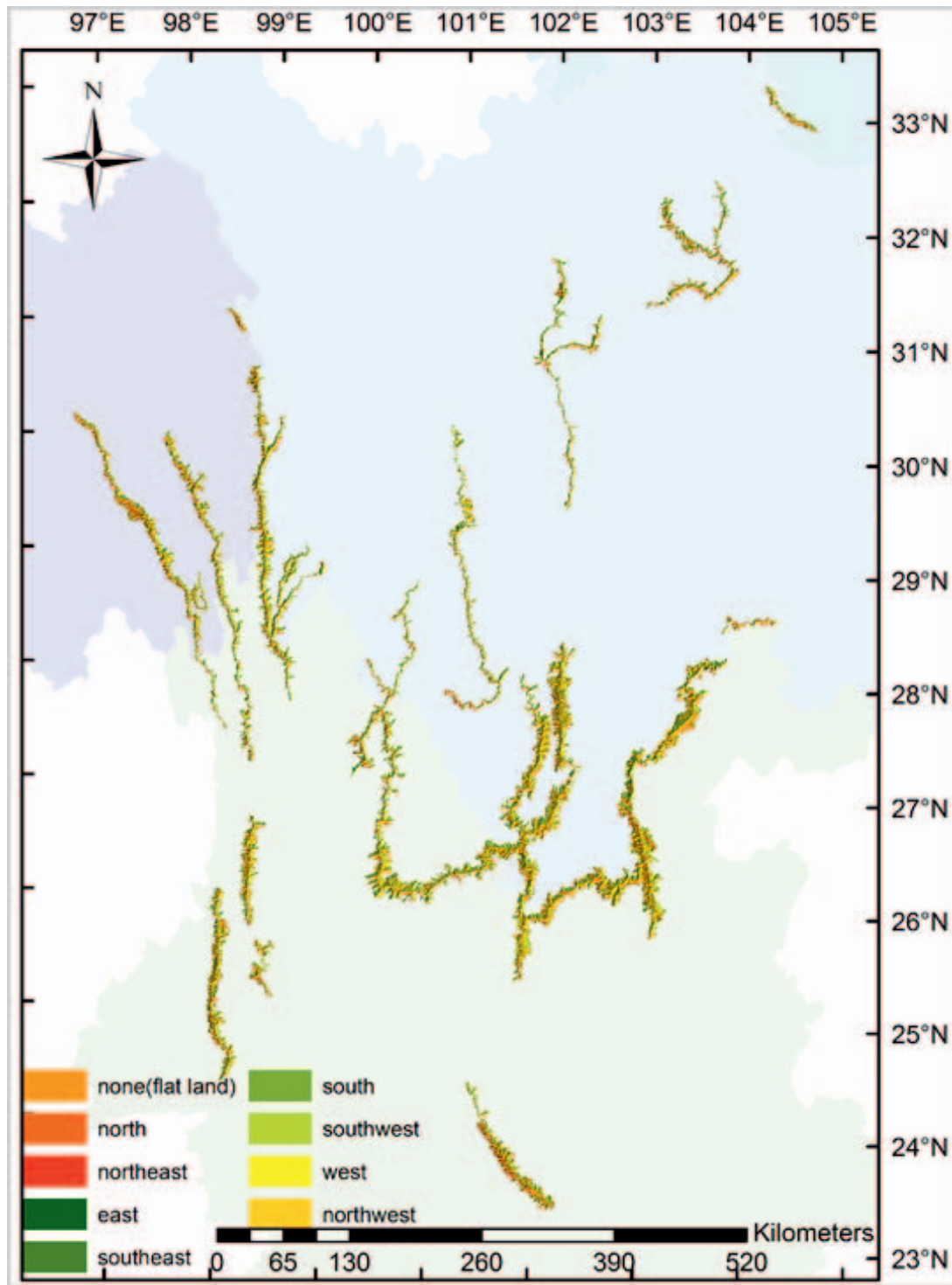
^{a)} Percentages represent rounded values.

boundary of the arid region in the Min Valley rose at the rate of 0.83 ± 0.21 m/y during 1999–2013 (Guo et al 2017).

Elevations in the study area ranged between 254 and 5707 m, with most between 1200 and 3600 m in the eastern part of the Qinghai–Tibet Plateau (Zhou and Bao 2014). Gradients ranged from 0 to 87.17°, with a mean of 25.77°. In other words, arid regions in valleys are spread over high mountains and deep rivers in the Hengduan Mountains (Tang et al 2004; Zhou et al 2017). The main land cover in arid regions in valleys consists of grass and shrubs (>33% and ~33% of total area, respectively). Similarly, Ma and McConchie (2001) found that savanna and xerophilous deciduous shrubs were the dominant vegetation in arid regions in valleys in this part of China.

The basic characteristics of arid lands varied in valleys within our study area. Much of this variation occurred along a gradient from northwest to northeast: in the northwest, the Nu and Lancang Rivers and the upper reaches of the Jinsha River form 3 deep valleys. This region receives little rainfall; most precipitation is snow, and groundwater is recharged by runoff (Li, He, et al 2011). Because of the steep terrain, there is little forest cover, and the land cover consists of grasses. Precipitation and runoff increase toward the southeast (Li, He, et al 2011). The terrain gradually transitions from alpine canyons to broad plains and from grassland to shrubland. Combined with the foehn effect, geothermal conditions are favorable for urban expansion and human activity, and overuse of natural resources and excessive land development have occurred in this area (Wang, Zhang, Duan, Yang, Zhou 2015; He et al 2016). The arid region in the Anning River Valley in Sichuan Province has the lowest elevation, and its gentle terrain is suitable for cultivation. As a result, more than half of its area has been developed. The arid region in the Yuan River Valley in

FIGURE 5 Aspect in the arid regions in mountain valleys. (Map by Shu Fang)



central Yunnan Province has also been extensively developed for agriculture, and its main land cover is grass.

Different arid regions in valleys have different dominant species. Biological communities in the arid regions in Nu, Jinsha, Lancang, and Yuan Valleys in

Yunnan Province consist mainly of grass, with scattered shrubs and trees (Wang, Zhang, Duan, Yang, Zhou, Ye 2015). Arid regions in valleys in Sichuan Province have a forested landscape; an example is the arid region in Min Valley, where the land cover consists mainly (73%) of

shrubs (Zhang, Zhao, et al 2014). Adequate light and heat and relatively low elevation are conducive to agriculture in the arid region in Anning Valley (Liu et al 2013); the proportion of farmland and settlement in this area is therefore high. According to our analysis of the terrain, the variations in the land cover in the arid regions in these valleys is connected with terrain conditions.

Environmental protection of arid regions in valleys

The arid regions in valleys have steep gradients, which create spatial heterogeneity and make the mountain systems inaccessible. The arid lands within these valleys have expanded rapidly in recent years, a process that is in urgent need of control. Since the mid-20th century, efforts at vegetation protection have been ongoing, including the establishment of production forests for water and soil conservation and limitation of access to hillsides to facilitate afforestation. However, the positive effects of these efforts have not been obvious and have decreased over time (Zhou and Bao 2014; Wang, Zhang, Duan, Yang, Zhou, Ye 2015). Based on the results of this study, we recommend that further management of the arid regions in valleys take into account their different characteristics.

Ecosystems in arid regions in valleys are fragile; in our study area, they show 3 characteristic terrains from northwest to southeast. Management and regulatory decisions should be tailored to each condition. In the northwest, farmland and settlements occupy a small proportion of the area and the topography is steep. To maintain balanced development and to prevent the further expansion of arid lands, the natural landscape and resources should be protected. Arid regions in valleys in the southeast have been damaged by human activity, including overconsumption of natural resources (Zhou and Bao 2014). Therefore, to improve the environment of

arid valleys, development should be controlled. In the middle part of the study area, the land showed relatively little change from human activity. Development and use of resources in these areas needs to include measures for environmental protection.

Conclusion

Arid regions in valleys in the Hengduan Mountains in southwestern China are fragile landscapes. Delimitation of the boundaries and calculation of the area of the arid regions within these valleys can increase understanding of their characteristics. Based on the investigation of the features of arid regions in different valleys, recommendations can be made for their sustainable development at local levels. We calculated the area of these arid regions to be 33,391.60 km², which is nearly 3 times the area calculated in the 1980s. Their area has expanded in both elevation and width under the influence of climate warming and human activities. The arid regions are spread over a landscape of high elevations and steep terrain. Their land cover includes shrubs and grasses. Farmland and human settlements account for a large portion of some arid regions in valleys.

In different valleys, topography and vegetation in the arid regions change from northwest to northeast, as does the degree of human disturbance. Therefore, we propose to protect the arid regions in valleys according to their local conditions. Ecological processes are complex and occur over long time frames; therefore, a combined approach—using policy, basic and applied scientific research, environmental regulations, and public education—is required to achieve the sustainable development of arid regions in valleys.

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Supplemental material

FIGURES S1–S9 Land cover details for the arid regions in each valley. (Maps by Shu Fang)

FIGURES S10–S18 Aspect details for the arid regions in each valley. (Maps by Shu Fang)

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